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**The Proceedings of the 1st International Workshop on
Laboratory Astrophysics Experiments with Large Lasers**

B. A. Remington

W. H. Goldstein

August 9, 1996



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**The Proceedings of the
1st International Workshop on
Laboratory Astrophysics Experiments
with Large Lasers**

**February 26-27, 1996
Pleasanton, California**

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**Printed by
Document Services Dept.
Lawrence Livermore National Laboratory
Livermore, CA 94550 USA
July 25, 1996**

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Preface

With the advent of modern large telescope facilities (such as the Kitt Peak and Cerro Tololo 4-meter telescopes in Arizona and in Chile, and the Keck 10-m telescope in Hawaii) and orbiting observatories (such as the Hubble Space Telescope and ROSAT) the quality and detail of astrophysical data being taken today is without parallel. Many objects currently under intensive observation exhibit temporal variations with time scales of order weeks, such as Type Ia supernova light curves, and months, such as the evolution of the ejecta from supernova SN1987A on its impact course with its circumstellar nebula. This opens the possibility to test predictions of the macroscopic evolution of such objects in real time with computer models which typically include an immense amount of microscopic physics. Unfortunately, one does not have the luxury in astrophysics of setting up clean, well controlled experiments in the universe to test the ingredients, in particular the microphysics, contained in the astrophysical models. Often times, debates about the details of various models continue for years, and in some cases decades. Creating a surrogate environment to serve as an astrophysics testbed would obviously be very desirable.

On the terrestrial front, the world has stood witness to the development of a number of highly sophisticated and flexible, high power laser facilities (energies and powers of up to 50 kJ and 50 TW), driven largely by the world-wide effort in inertial confinement fusion (ICF). The charter of diagnosing implosions with detailed, quantitative measurements has driven the ICF laser facilities to be exceedingly versatile and well equipped with diagnostics. Interestingly, there is considerable overlap in the physics of ICF and astrophysics. Both typically involve compressible radiative hydrodynamics, radiation transport, complex opacities, and equations of state of dense matter. Surprisingly, however, there has been little communication between these two communities to date.

With the recent declassification of ICF in the USA, and the approval to commence with construction of the next generation "superlasers", the 2 MJ National Ignition Facility in the US, and its equivalent, the LMJ laser in France, the situation is ripe for change. Access to these large laser facilities, present and future, is becoming available to the outside academic community. Given the physics similarities that exist between ICF and astrophysics, one strongly suspects that there should exist regions of overlap where supporting research on the large lasers could be beneficial to the astrophysics community.

As a catalyst for discussions to this end, Lawrence Livermore National Laboratory sponsored the 1st International *Workshop on Laboratory Astrophysics Experiments with Large Lasers* in Pleasanton, California, USA, over a two day period at the end of February, 1996. Approximately 100 scientists attended from around the world, representing eight countries: the USA, Canada, UK, France, Germany, Russia, Japan, and Israel. A total of 30 technical papers were presented. The two day workshop was divided into four sessions, focusing on nonlinear hydrodynamics, radiative hydrodynamics, radiation transport, and atomic physics-opacities. Copies of the presentations are contained in these proceedings.

The conclusion of the meeting was a consensus that there indeed do appear to be areas where careful laser experiments could serve as an astrophysical testing ground, a setting where emerging theories can have a "dry run". The challenge is to match the right astrophysics questions with the right laser experiment. We hope that the outcome of this workshop will be the start of a continuing dialog between the astrophysics and laser experiments communities, which will hopefully lead to more discriminating astrophysics experiments on the large laser facilities around the world.

It is our great pleasure to acknowledge the significant expert assistance we have enjoyed in putting this workshop together. We are particularly indebted to Misty Riendeau, Laurie Pinkerton, and Karen Queheillalt for their assistance in planning, organizing, and running the conference. We also acknowledge the assistance of Sandy Lynn and Cheryl Swinkels from our Document Services Department. We are deeply indebted to Bruce Fryxell for sharing his exquisite color images from his supernova simulations with us, examples of which appear on the announcement poster, the name tags, and on the cover of these proceedings.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

Bruce A. Remington
William H. Goldstein

WORKSHOP SUMMARY

Monday morning: Hydrodynamics I, Bruce Remington presiding

Mike Campbell (LLNL) welcomed the participants to the workshop, and stressed the need to include academia and basic physics experiments into the use of large lasers built for inertial confinement fusion (ICF) research. Mike pointed out that only with outside users of lasers such as Nova and the future National Ignition Facility, can the full potential of these ICF lasers be realized.

Joe Kilkenny (LLNL) gave an overview of large lasers around the world that might potentially be useful for astrophysics experiments. He then focused on laser capabilities at LLNL, covering the parameter regimes accessible with Nova, the 100 TW laser, the petawatt laser, the USP laser, and standard diagnostic capabilities at Nova.

Dave Arnett (University of Arizona) discussed the role of hydrodynamic instabilities, in particular, buoyancy driven convection and Rayleigh-Taylor instability, in the dynamics, evolution, and observables from Supernova 1987A. He stressed the importance of testing current theories and models of supernova in any way experimentally possible. One promising, and hitherto untried testing ground is using large lasers to mock up subsets of the physics of supernova. The current supernova experiment on the Nova laser is a model for designing experimental benchmarks of the supernova codes.

Gail Glendinning (LLNL) discussed an experiment that is being designed, together with Jave Kane (University of Arizona), a graduate student of Dave Arnett's, to test the modeling of deep nonlinear instability evolution using the astrophysics code PROMETHEUS. This appears to be the first experimental test of the nonlinear hydrodynamics predictions of this widely used supernova code. The experiment has progressed past its initial "shake-down" phase, and meaningful comparisons of experimental results with PROMETHEUS simulations has just started.

Dick McCray (University of Colorado, Boulder) discussed the imminent collision predicted to occur in 5 years of the expanding ejecta from SN1987A with its surrounding circumstellar ring nebula. He summarized models and current understanding of the ring, and predictions of x-ray, UV, and optical emissions expected when the collision ensues. He stressed the multiple shock interactions predicted, and pointed out the need to test modeling of these strong radiative shocks in advance of the event.

Paul Drake (LLNL and University of Michigan) discussed the final design of an experiment being developed for Nova, in collaboration with Richard McCray from the University of Colorado at Boulder and Edision Liang from Rice University, to look at the colliding plasma effects relevant to the SN1987A ring collision presented by McCray. This experiment will use the Nova laser to generate the strong shock that produces the laboratory equivalent of the expanding supernova ejecta. This expanding ejecta will then impact a surrounding "ring nebula" of plasma created by foam. The goal of the experiment is to examine the nonlinear shock hydrodynamics expected in the collision, and characterize the radiation emitted in the multiple shock interactions.

James Stone (University of Maryland) described his new model for the formation of hydrodynamic "bullets". The interesting hypothesis of this presentation was that deep nonlinear hydrodynamic instabilities are the cause of a broad array of astrophysical phenomena hitherto unexplained. He stressed the need to access the regime where radiative cooling behind the shock front affects the hydrodynamics. He emphasized that if laser experiments could be designed that investigate any part of this broad area of radiative hydrodynamics, then one might be able to impact the development of astrophysics theories and codes that are still in their infancy. This is exciting, because this is precisely the regime that the Drake-McCray-Liang experiment is being designed to address.

Monday afternoon. Hydrodynamics II, Paul Drake presiding.

The theme of the Monday afternoon session, chaired by Paul Drake, was the study of hydrodynamic phenomena in astrophysics and in the laboratory. Three of the speakers (**Grun** of NRL, **Dimonte** of LLNL, and **Schappert** of LANL) discussed experimental results from laser-based studies of the instability of Taylor-Sedov blast waves. In such experiments, a target immersed in gas is struck by a concentrated laser pulse. This produces a blast wave, similar to those described by Sedov and by Taylor in the 1950's, which takes hundreds of nanoseconds to propagate across the experimental chamber. Such Sedov-Taylor blast waves are believed to occur in a wide range of astrophysical systems including supernova explosions. The experiments found that the blast waves were sometimes stable and sometimes strongly unstable, depending upon a number of factors including the properties of the gas and the presence of a magnetic field.

The instability of Sedov-Taylor blast waves is related to the hydrodynamic instabilities which have produced mixing in supernova 1993J, discussed by **Iwamoto** of the University of Tokyo, who reported that the profiles present in the progenitor star can have a substantial impact on the instabilities which occur when the star explodes. Similarly, the explosion of a type Ia supernova is believed to produce a thin combustion layer which has some similarities to a blast wave and is most definitely subject to strong hydrodynamic instabilities, as discussed by **Khokhlov** of University of Texas at Austin. Both Sedov-Taylor blast waves in astrophysical systems, and the shocks driven by flowing plasmas, can become radiative, in the sense that they radiate power more quickly than they receive power. This can lead to density collapse and strong hydrodynamic instability, as discussed by **Blondin** of North Carolina State University and by **Klein** of LLNL. Although laboratory studies have not yet dealt with radiative shocks, some strongly-nonlinear hydrodynamic systems have been studied. Experiments on the interaction of shock waves, on jets, and on colliding plasmas were reported by **Perry** and **Miller** of LLNL. Additional, possible experiments to look for pair production and to simulate other aspects of supernovae were discussed by **Liang** of Rice. The general properties of late-time, nonlinear hydrodynamic mixing in non-radiative systems are beginning to yield to theoretical analysis, as **Shvarts**, of Negev Nuclear Research Center in Israel,

showed. He also pointed out that the behavior is qualitatively different when a shock passes through a previously-shocked medium, as is common in astrophysical environments, and that this problem deserves study.

Tuesday morning: Atomic physics / opacities, Bill Goldstein presiding

The session on opacity, spectroscopy and radiation transport opened with a historical overview of astrophysical opacity research from Arthur Cox, of Los Alamos National Laboratory. Cox introduced the Hertzsprung-Russell diagram, and described the large range of variable stellar systems whose evolution and characteristics depend sensitively on radiative opacity. He identified banner years in the ~55 year history of opacity calculations, including the appearance of Los Alamos opacities in 1964-70, and culminating with the publication of new results from LLNL's OPAL group in 1991-93. These improved tables evinced enhancement factors of three in opacity owing to previously neglected bound-bound transitions in iron. As Cox pointed out, the new calculations affected our understanding of a long list of variable systems, including double-mode cepheids, delta Scuti variables, and solar oscillation frequencies.

Cox went on to describe his recent work on the effects of convection on the behavior of variables, and concluded that modern opacities may not, in fact, fully explain observations of stellar pulsations.

The themes introduced by Cox were elaborated later in the session by Carlos Iglesias, who addressed remaining uncertainties in stellar opacities, and by Paul Springer who discussed experiments relevant to stellar atmospheres. Iglesias pointed out that uncertainties in the solar interior opacities deduced from code comparisons are as large as 35%, especially near the bottom of the solar convection zone. The source of the discrepancies was traced to uncertainties in the ionization balance. Present theories that describe the behavior of bound states in dense matter do not agree, and there have been few experiments to test them. Iglesias described recent laser-driven absorption measurements that have proven valuable in validating some aspects of these theories, and proposed that these experiments be extended to provide detailed input for ionization balance models.

Paul Springer also pointed to discrepancies between models of stellar opacity, particularly those arising from line-shapes, and the merging of lines into quasi-continua. These uncertainties are most pronounced at densities of 10^{-3} g/cc and lower, and experiments to access this regime are highly constrained in time-duration, spatial size and spectral resolution. Springer concluded by describing a nested-hohlraum design that produces the right conditions in simulations.

Steve Rose, of the Rutherford Appleton Laboratory, and the Department of Physics and Space, University of Birmingham, followed Cox with a wide-ranging review of current and proposed laser experiments in the UK with relevance to radiation flow in astrophysics. Rose showed that the opacity measurements he was describing - including high-density, short pulse laser experiments - mapped out typical temperatures and densities in the sun. He also

described line transfer experiments in the presence of large velocity gradients, an important effect Type Ia Supernovae, among other astrophysical systems. Rose also proposed novel experiments to address the role of Compton scattering in the energy balance of accretion-powered objects. He presented simulations showing that the effects of Compton scattering on the radiation emitted from compressed balls of DT gas was profound and measurable.

Rose concluded that the plasma conditions achievable with high-power lasers are comparable to those found in certain astrophysical plasmas. He added that complex laser experiments are underway in which the conditions are controlled to investigate specific, relevant physical processes.

Phil Pinto of the University of Arizona picked up one of Rose's threads in a talk on Radiation Transport in Flows with Large Velocity Gradients. He described the light curve of Type Ia supernovae as a competition between radioactive energy deposition, adiabatic decompression, and radiative transport to the surface. The transport is dominated by line absorption in large velocity gradients. Escape is effected through exotic processes like Doppler downshifting of thermal radiation and "photon-splitting." Outside of the supernovae light curve itself, there exists little data to guide the theorists in modeling the opacity of such unique systems. Pinto suggested that laboratory experiments could test elements of the models by measuring transport in laser-produced blow-off plasmas, and by testing iron group atomic physics and branching ratios.

Tim Kallman of NASA and Duane Liedahl of LLNL discussed the modeling and laboratory simulation of X-ray photoionized nebulae. The opportunity to perform detailed studies of the X-ray emission from these accretion-powered sources is among the most exciting prospects in astrophysics for the next decade. But the analyses of spectra from accretion-powered X-ray sources, which will comprise a substantial portion of the high-energy astrophysics database, are likely to severely tax the capabilities of the currently available analytical resources. The reason is clear: understanding of atomic physics processes and the matter/radiation interactions in X-ray photoionized plasmas is sketchy.

The essential aspect of an X-ray photoionized plasma is the high degree of overionization relative to a steady-state collision-driven plasma at the same temperature. The ionization state is characterized by the quantity, $\xi = 4\pi F/n$, the ratio of the ionizing radiation flux to the electron density. Whenever ξ exceeds ~ 10 (cgs), electron impact ionization is less important than photoionization in establishing the charge state distribution. Similarly, the role of electron impact excitation is reduced in comparison to recombination cascades as a population mechanism. At present, the physical processes of "X-ray nebulae" are modeled by complex computer codes which, nevertheless, rely on untested, simplifying assumptions and approximations.

Liedahl pointed out that conditions achievable in targets using the Nova laser, and conditions projected for the planned National Ignition Facility (NIF), have excellent overlap with the parameters expected to characterize accretion-powered plasmas. In proposed experiments, uniform, photoionized plasmas are

created by illuminating a low density gas target with broad-band ionizing radiation from a laser-irradiated high-Z converter target. Preliminary experiments and predictions for gas cell targets have already been made and a box-like target has been designed in which argon gas is contained by thin-foil windows. This target allows argon pressures from 25 Torr (corresponding to ion densities near 10^{18} cm^{-3}) down to pressures several orders of magnitude lower. A gold converter spectrum has also been measured on the Nova Two-Beam Facility using .53 mm light in a line-focus geometry at an irradiance of $10^{14} \text{ W cm}^{-2}$. This spectrum has been used to estimate the values of x achievable at laser facilities that are precisely those expected to obtain in the X-ray emitting regions of accretion disks. Design calculations for an argon experiment using the 25-Torr gas cell and the measured gold spectrum have predicted ionization into the middle of the L-shell. Then, using absorption and emission spectroscopy, respectively, to measure ionization distribution and temperature, a direct comparison with the predictions of astrophysical simulation codes could be carried out at known – and controllable – density (gas pressure) and ionization parameter (luminosity).

Tuesday afternoon: Radiation transport, John Castor presiding

In the Tuesday afternoon session Nigel Woolsey (LLNL) began with a discussion of "Spectroscopy of Compressed High Energy Density Matter." He reported the results of a series of Nova experiments on implosions of capsules filled with D₂, CD₄, N₂ or Ne, doped with Ar, whose K-line spectrum is measured. The object of the experiment was to make a sensitive test of line-shape theory as applied to the K lines, and in particular to assess the importance of ion dynamics to the line shape, which should be a much greater effect with light perturbing ions (D) than heavy ones (Ne). The same line shapes also provide diagnostics of temperature and electron density. The theoretical comparison was made to the FLY code of Lee, *et al.* The experimental results confirmed that the FWHM of the He-like Ar K β line is a good density diagnostic, while the Li-like satellites of the same line provide a T_e diagnostic. The surprising experimental result was that the central dip in He-like Ar K β , indicative of a *lack* of ion dynamics, was absent in every case for which the spectrum could be measured, perhaps owing to gradient effects.

Dick More (LLNL) described "Physics on Short Pulse, High Intensity Lasers," referring to the capabilities of LLNL's Ultra-Short-Pulse laser facility. The USP can deliver a pulse of 0.1 Joule with a pulse length of order 100 fs, and the promise is to perform experiments on matter at $>1 \text{ keV}$ temperatures at solid density, since the heating and ionization time scales can be made short compared with the time scale for hydrodynamic motion. A variety of LASNEX simulations was shown to indicate how the sample approaches LTE and steady-state ionization equilibrium as a function of time and laser intensity. The interferometric techniques for probing the velocity and density distributions in

the exploding sample were illustrated. Finally, some results were shown for the spectrum of a sample of germanium.

"Femtosecond-Laser Driven Heat Waves in Solid" was the topic of the presentation by Andrew Ng (University of British Columbia). The stimulus was the experiment by Vu, Szöke and Landen with a buried layer of carbon in a glass target exposed to a 5×10^{14} W/cm² intensity for 100 fs. The preliminary analysis of the experiment used LASNEX and the classical (Spitzer) conductivity model. In his study, Ng applied a hydrodynamic simulation coupled with a wave equation solver (for the EM field), and used a more sophisticated plasma conductivity theory. These simulations elucidate three different phases of thermal wave propagation: skin-depth deposition, thermal conduction and shock compression. The suggestion is made that the high velocity observed in the Vu, et al., experiment might have been due to laser penetration. It is concluded that accurate measurements of front velocity are a good discriminant for models of electrical and thermal conductivity.

Astrophysics was represented in the session with the presentation "Astroseismology of White Dwarf Stars" by Paul Bradley (LANL). Bradley reviewed the classification of variable (pulsating) white dwarfs into DOV, DBV and DAV, based on surface temperature, ranging from 10^5 K for DOV to 10^4 K for DAV. These stars are oscillating in a mixture of many so-called g-modes, which, like water waves, are based on buoyancy. The evolution of the cooling white dwarfs is modeled, and at each point of its evolution the spectrum of g-mode oscillating frequencies is computed. Fitting the computed spectrum to the observations of individual stars allows their masses and surface temperatures to be inferred, and also the amount of residual hydrogen-rich material left at the outside of the white dwarf. The total masses that are found agree well with other estimates of white dwarf masses, and with masses for white-dwarf progenitor stars. The residual hydrogen masses turn up some surprises, and suggest that DA and DB white dwarfs have different origins.

Anatolly Orishich (Novosibirsk) discussed "Interaction Processes Between Exploding Plasmas and Media in Space," based on experiments with the KI-1 CO₂ laser at the Institute of Laser Physics of Novosibirsk State University, which can deliver 1 kJ to targets up to 100 μ g in mass, possibly with a magnetic field of 1 kG. The experiments are intended to simulate the deceleration of nova and supernova ejecta by interstellar material, the movement of plasmoids in the earth's magnetosphere, interplanetary shock waves generated by solar flares, and the influence of the galactic magnetic field on the expansion of planetary nebulae. The governing processes, which are studied using KI-1, are the collisionless interaction of super-Alfvenic plasma flows; collisionless energy coupling to the background gas; interaction of the plasma flow with a magnetic field and the role of turbulence; the formation of compact plasma shells; and ionization waves.

**A Quick Look at the Capabilities of Nova and
its Accessibility to Outside Users**

Joseph D.ilkenny
Lawrence Livermore National Laboratory

A Quick Look at the Capabilities of Nova and its Accessibility to Outside Users*



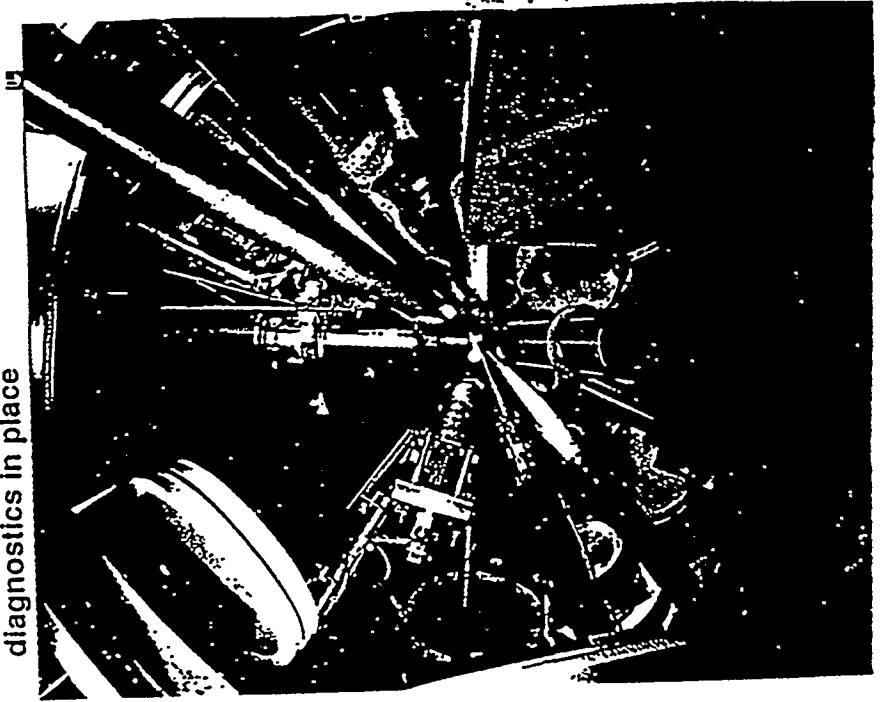
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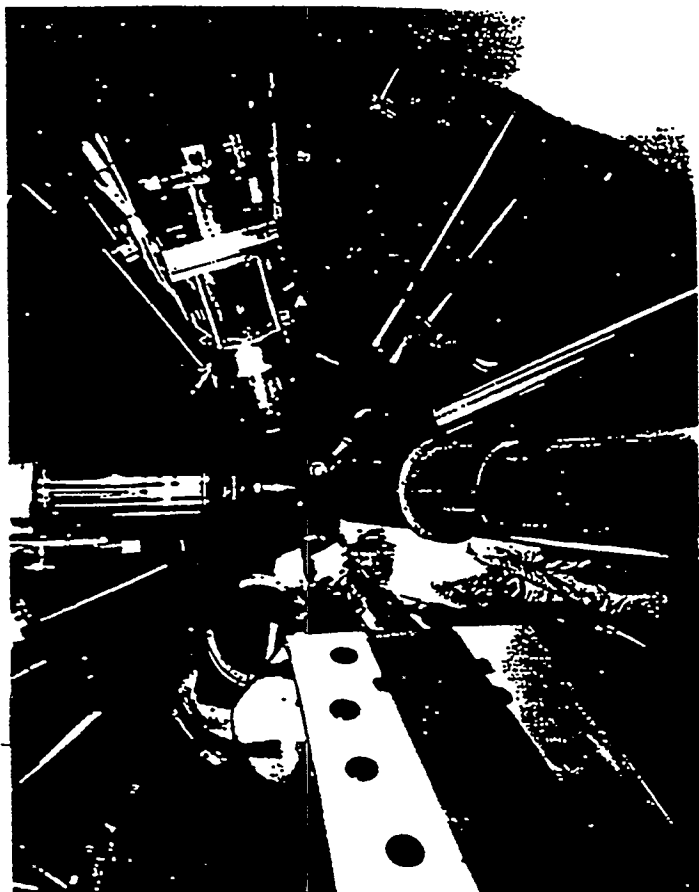
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Pleasanton Hilton
February 26, 1995

*This workshop was supported by the Lawrence Livermore National Laboratory under contract No. W-7408-ENG-88.

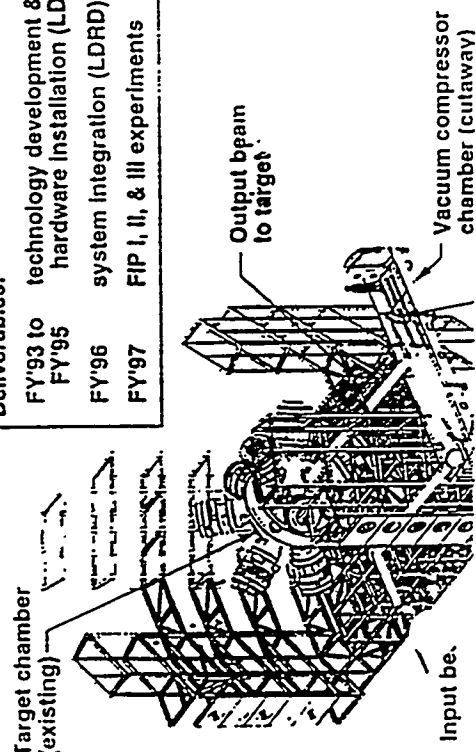
The Nova target chamber with
diagnostics in place



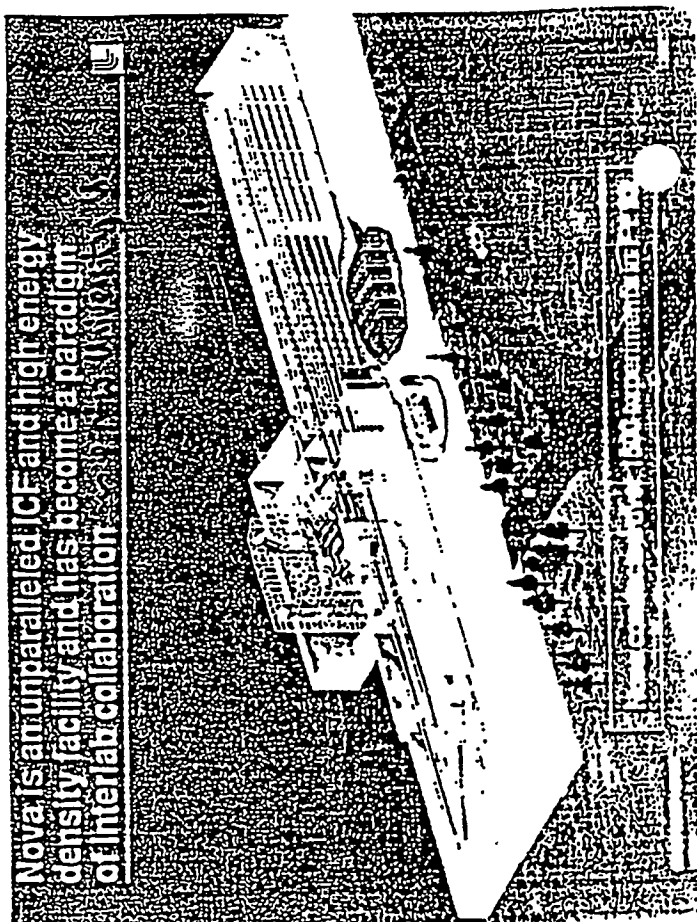


An LDRD-funded Petawatt modification to Nova will be used in FY'97 for Fast Ignitor Physics (FIP) experiments

Deliverables:	
FY'93 to FY'95	technology development & hardware installation (LDRD)
FY'96	system integration (LDRD)
FY'97	FIP I, II, & III experiments



Nova is an unparalleled ICF and high energy density facility and has become a paradigm of interlab collaboration

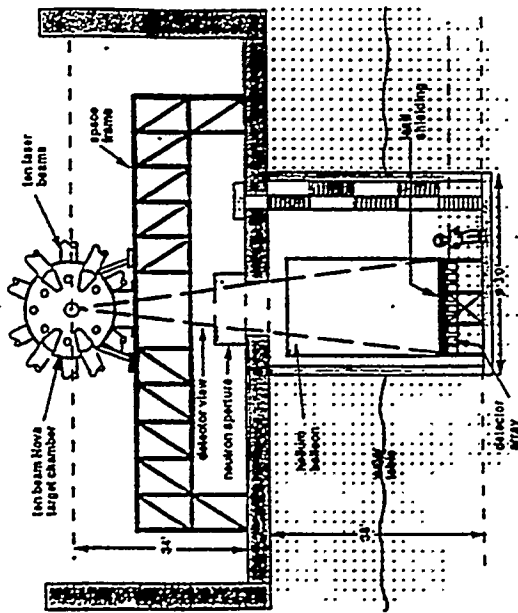


The Target Physics Program Advisory Board Committee (TPPAC) consists of:

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The Large Neutron Scintillator Array (LaNSA) is located under the Nova target chamber.



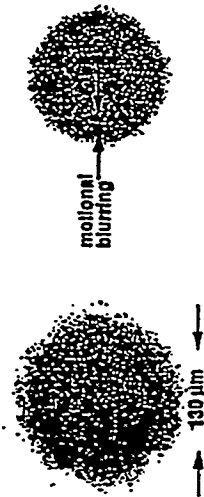
For FY96, a peer-reviewed pilot scheme for University Use of Nova for high energy density physics is in place and working

- A call for proposals was made in Spring '95 with the criterion of quality high energy density physics, with small funding by ORF via LLNL for miscellaneous expenses. Shot expenses are paid for by LLNL-ICF.
- Eighteen proposals were received in astrophysics, atomic physics, high density physics, x-ray instrumentation, high magnetic fields, plasma physics and ICF
- An external 13-member committee of scientists (Chaired by Dr. B. Ripin), judged the proposals and recommended proceeding with nine proposals, anticipating using ~100 shots in FY96
- By December '95, ~35 shots had been used with promising results in five of the approved investigation

For FY97, the pilot scheme could be expanded with increased resources identified for supporting research at Universities

Higher Speed Gating has Clearly Demonstrated Reduced Motion Blurring

Direct drive Implosion of a glass microballoon at 1/2 Initial radius on the Omega laser

130 μm

35 psec gating

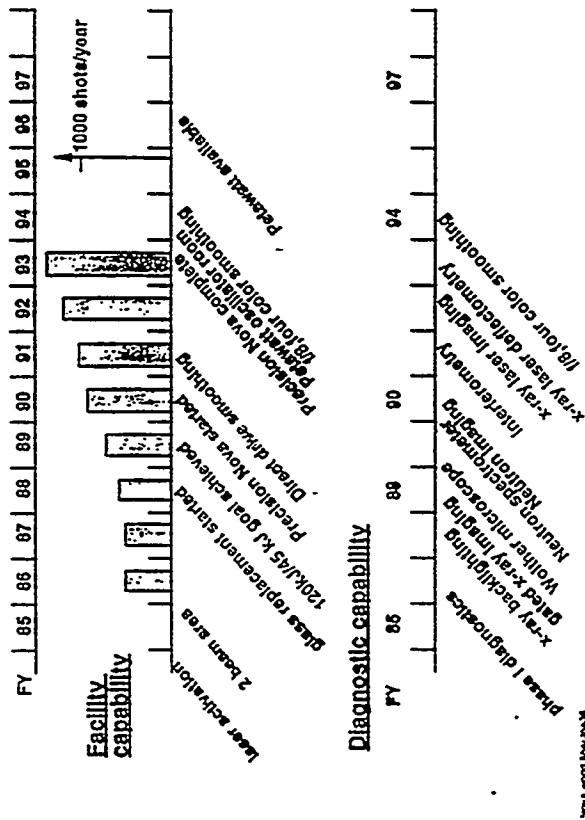
100 psec gating

Nova has approximately 60 established diagnostics: most of them are run by the facility

no	X-ray images	no	Neutron diagnostics	no	Optical spectrometers and imagers
3	Wide area microscope	3	Yield	3	Streaked and imag
4	Quasi-s-ray pin hole camera	4	Bug into	4	SOP
5	Quasi-s-ray pin hole camera	5	Beam-kill	5	Streaked optical spectrometers
6	Quasi-s-ray pin hole camera	6	High res. high sens. spectrometer	6	SOI,SS
7	Quasi-s-ray pin hole camera	7	High res. high sens. spectrometer	7	SOI,SS
8	Quasi-s-ray pin hole camera	8	High res. high sens. spectrometer	8	SOI,SS
9	Quasi-s-ray pin hole camera	9	High res. high sens. spectrometer	9	SOI,SS
10	Quasi-s-ray pin hole camera	10	High res. high sens. spectrometer	10	SOI,SS
11	Quasi-s-ray pin hole camera	11	High res. high sens. spectrometer	11	SOI,SS
12	Quasi-s-ray pin hole camera	12	High res. high sens. spectrometer	12	SOI,SS
13	Quasi-s-ray pin hole camera	13	High res. high sens. spectrometer	13	SOI,SS
14	Quasi-s-ray pin hole camera	14	High res. high sens. spectrometer	14	SOI,SS
15	Quasi-s-ray pin hole camera	15	High res. high sens. spectrometer	15	SOI,SS
16	Quasi-s-ray pin hole camera	16	High res. high sens. spectrometer	16	SOI,SS
17	Quasi-s-ray pin hole camera	17	High res. high sens. spectrometer	17	SOI,SS
18	Quasi-s-ray pin hole camera	18	High res. high sens. spectrometer	18	SOI,SS
19	Quasi-s-ray pin hole camera	19	High res. high sens. spectrometer	19	SOI,SS
20	Quasi-s-ray pin hole camera	20	High res. high sens. spectrometer	20	SOI,SS
21	Quasi-s-ray pin hole camera	21	High res. high sens. spectrometer	21	SOI,SS
22	Quasi-s-ray pin hole camera	22	High res. high sens. spectrometer	22	SOI,SS
23	Quasi-s-ray pin hole camera	23	High res. high sens. spectrometer	23	SOI,SS
24	Quasi-s-ray pin hole camera	24	High res. high sens. spectrometer	24	SOI,SS
25	Quasi-s-ray pin hole camera	25	High res. high sens. spectrometer	25	SOI,SS
26	Quasi-s-ray pin hole camera	26	High res. high sens. spectrometer	26	SOI,SS
27	Quasi-s-ray pin hole camera	27	High res. high sens. spectrometer	27	SOI,SS
28	Quasi-s-ray pin hole camera	28	High res. high sens. spectrometer	28	SOI,SS
29	Quasi-s-ray pin hole camera	29	High res. high sens. spectrometer	29	SOI,SS
30	Quasi-s-ray pin hole camera	30	High res. high sens. spectrometer	30	SOI,SS
31	Quasi-s-ray pin hole camera	31	High res. high sens. spectrometer	31	SOI,SS
32	Quasi-s-ray pin hole camera	32	High res. high sens. spectrometer	32	SOI,SS
33	Quasi-s-ray pin hole camera	33	High res. high sens. spectrometer	33	SOI,SS
34	Quasi-s-ray pin hole camera	34	High res. high sens. spectrometer	34	SOI,SS
35	Quasi-s-ray pin hole camera	35	High res. high sens. spectrometer	35	SOI,SS
36	Quasi-s-ray pin hole camera	36	High res. high sens. spectrometer	36	SOI,SS
37	Quasi-s-ray pin hole camera	37	High res. high sens. spectrometer	37	SOI,SS
38	Quasi-s-ray pin hole camera	38	High res. high sens. spectrometer	38	SOI,SS
39	Quasi-s-ray pin hole camera	39	High res. high sens. spectrometer	39	SOI,SS
40	Quasi-s-ray pin hole camera	40	High res. high sens. spectrometer	40	SOI,SS
41	Quasi-s-ray pin hole camera	41	High res. high sens. spectrometer	41	SOI,SS
42	Quasi-s-ray pin hole camera	42	High res. high sens. spectrometer	42	SOI,SS
43	Quasi-s-ray pin hole camera	43	High res. high sens. spectrometer	43	SOI,SS
44	Quasi-s-ray pin hole camera	44	High res. high sens. spectrometer	44	SOI,SS
45	Quasi-s-ray pin hole camera	45	High res. high sens. spectrometer	45	SOI,SS
46	Quasi-s-ray pin hole camera	46	High res. high sens. spectrometer	46	SOI,SS
47	Quasi-s-ray pin hole camera	47	High res. high sens. spectrometer	47	SOI,SS
48	Quasi-s-ray pin hole camera	48	High res. high sens. spectrometer	48	SOI,SS
49	Quasi-s-ray pin hole camera	49	High res. high sens. spectrometer	49	SOI,SS
50	Quasi-s-ray pin hole camera	50	High res. high sens. spectrometer	50	SOI,SS
51	Quasi-s-ray pin hole camera	51	High res. high sens. spectrometer	51	SOI,SS
52	Quasi-s-ray pin hole camera	52	High res. high sens. spectrometer	52	SOI,SS
53	Quasi-s-ray pin hole camera	53	High res. high sens. spectrometer	53	SOI,SS
54	Quasi-s-ray pin hole camera	54	High res. high sens. spectrometer	54	SOI,SS
55	Quasi-s-ray pin hole camera	55	High res. high sens. spectrometer	55	SOI,SS
56	Quasi-s-ray pin hole camera	56	High res. high sens. spectrometer	56	SOI,SS
57	Quasi-s-ray pin hole camera	57	High res. high sens. spectrometer	57	SOI,SS
58	Quasi-s-ray pin hole camera	58	High res. high sens. spectrometer	58	SOI,SS
59	Quasi-s-ray pin hole camera	59	High res. high sens. spectrometer	59	SOI,SS
60	Quasi-s-ray pin hole camera	60	High res. high sens. spectrometer	60	SOI,SS
61	Quasi-s-ray pin hole camera	61	High res. high sens. spectrometer	61	SOI,SS
62	Quasi-s-ray pin hole camera	62	High res. high sens. spectrometer	62	SOI,SS

AN EVEN MORE COMPREHENSIVE SET WILL EVOLVE FOR THE NIF

The laser and diagnostic capability of Nova has steadily increased



We have overcome the limitations of spatial and temporal scales for weapon physics on Nova by advanced diagnostic development

- temporal resolution of 30 psec with x-ray framing cameras
- spatial resolution of 3 μm FWHM with xrl microscopy
- soft x-ray backlighting with xrl's for interferometry and deflectometry of hohlraum plasmas
- high-energy x-ray backlighting: photon energies up to 6-8 keV, delay times up to 50 nsec
- high-resolution x-ray spectroscopy

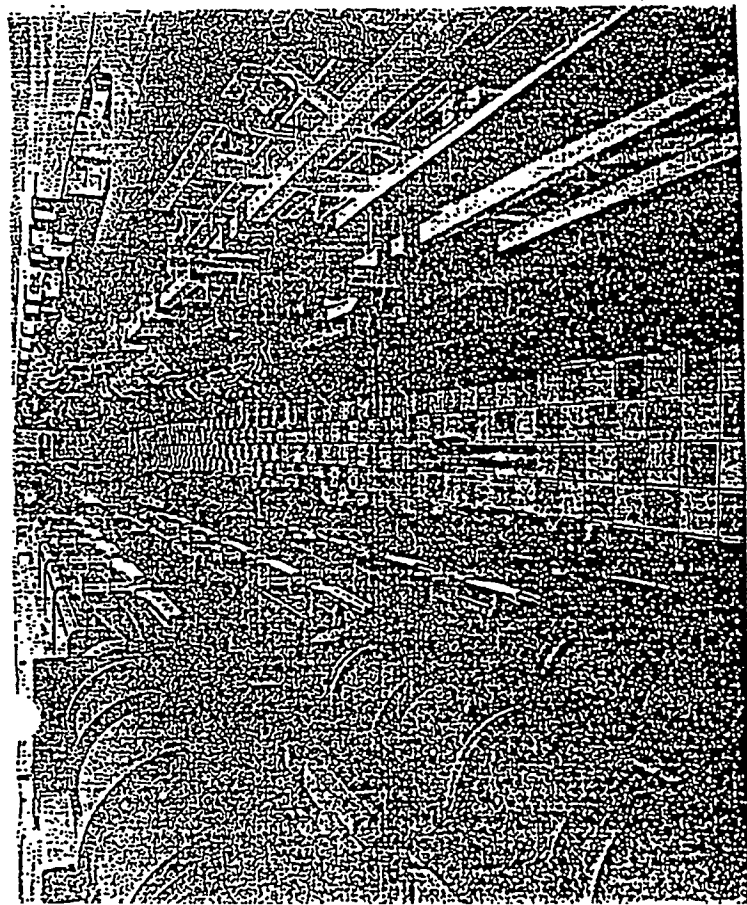
Much development motivated by weapon physics needs

Accessibility of U.S. ICF lasers to non-ICF users

<u>Novae</u>	— FY96 pilot program for University Use in place
—	Shots, targets, miscellaneous support supplied
—	18 proposals/9 agreed
—	Proposals judged on scientific merit by independent review committee
—	For FY97 new call for proposals expected in Spring '98
—	Shots, targets, miscellaneous support and small contracts expected
<u>Omega</u>	— <u>National Laser Facility in Place</u>
—	Shots, targets through Rochester, grants through DOE
—	9 proposals/8 agreed in FY98
—	Call for proposals for FY97 in summer — Contact J. Knauer
<u>Nike (NRL)</u>	— Less formal arrangements
<u>Trident (LANL)</u>	Contacts — Steve Obenshain (NRL) — Bob Watt (BNL)

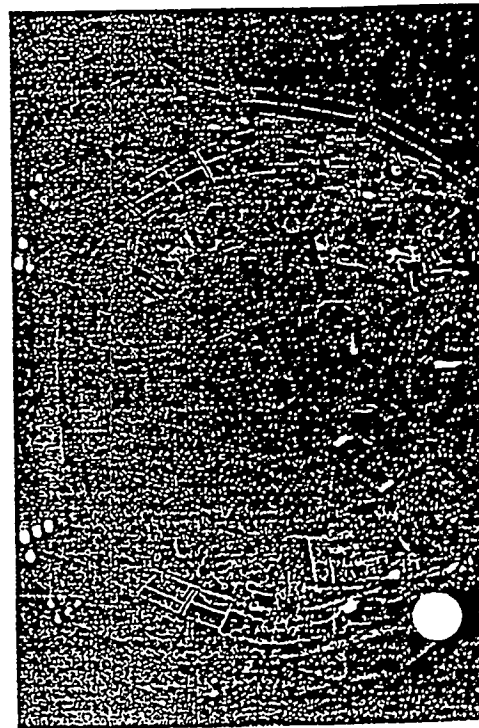
Draft four year plan for use of Nova





OMEGA has irradiated targets with >37 kJ UV in 60 beams

UR
LLNL



We have achieved >50 joules in a 400-fsec pulse producing a new world record for peak power (125 TW)



Laser facilities in ICF have large and diverse capabilities for high energy density physics experiments

Nova (LLNL - 1984) - 40 kJ/30 TW, 0.35, 0.53 μm ; primarily Indirect drive ICF, also planar direct drive ICF; HEDP physics on opacity, radiative transfer, EOS, x-ray laser.

- 100 TW (1995); 100 TW, 1 ps, 1.05 μm ; Independent beam synchrotron with 1 Nova beam; fast Ignitor ICF; High density plasmas
- PetaWatt (1995); 1 PW, 1 ps, 1.05 μm ; 1 Nova beam synchrotron with the other nine beams; fast Ignitor ICF; High density plasmas

Omega upgrade (U Rochester - 1995) - 30 kJ/30 TW, 0.35 μm ; primarily direct drive implosion facility; potentially can do indirect drive experiments with ~20 TW.

Trident (LANL - 1992) - 2 beams, 100 J/beam 1.06, 0.53 μm + a backlighter beam; diagnostic development, plasma physics, planar hydro and direct drive.

Nike (NRL - 1995) - 2 kJ/0.4 TW, 0.26 μm + a backlighter beam near direct drive and planar hydro experiments

Hydrodynamic Instabilities in Type II Supernovae

**Dave Arnett
University of Arizona**

(Analog)

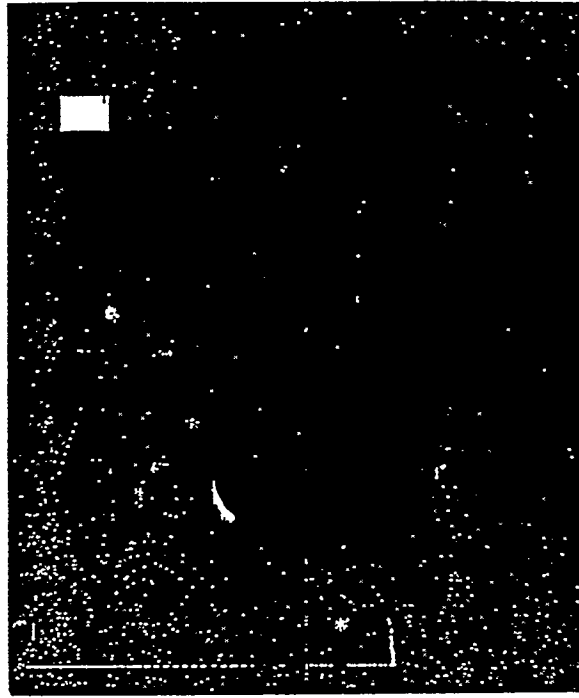
ASTROPHYSICS Collaborations:

O and Si burning:
Grant Bagan

87A Rings:
Crystal Martin

Detonation/Deflagration
Willy Benz
Eli Livne

Light Curves
Philip Pinto



Martin & Arnott 1995 ApJ

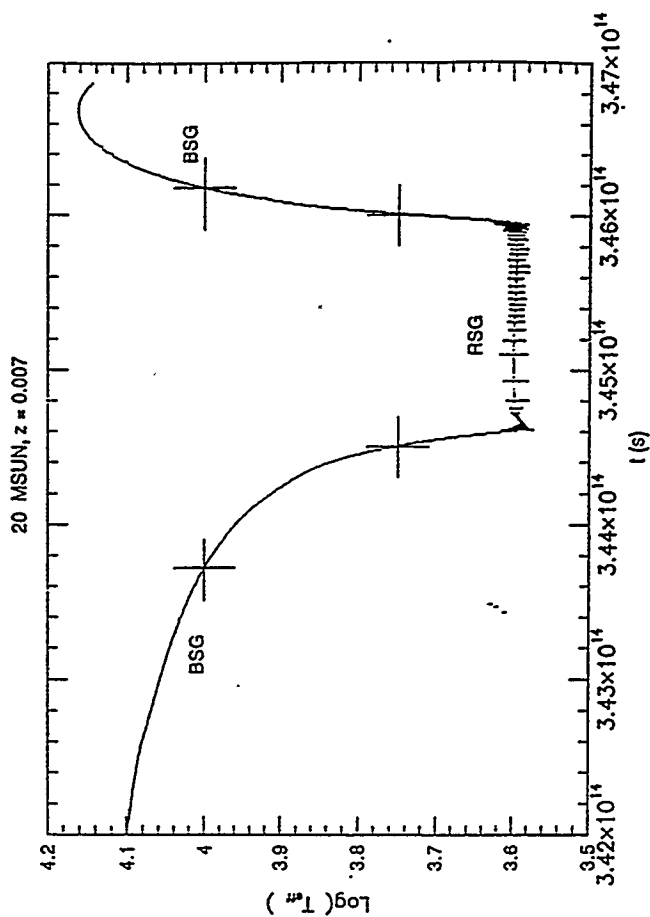
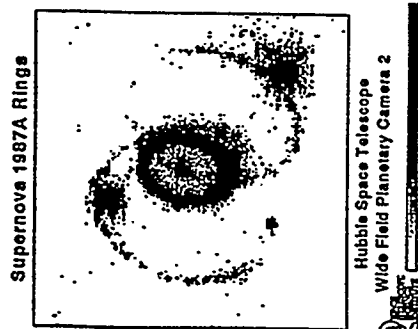
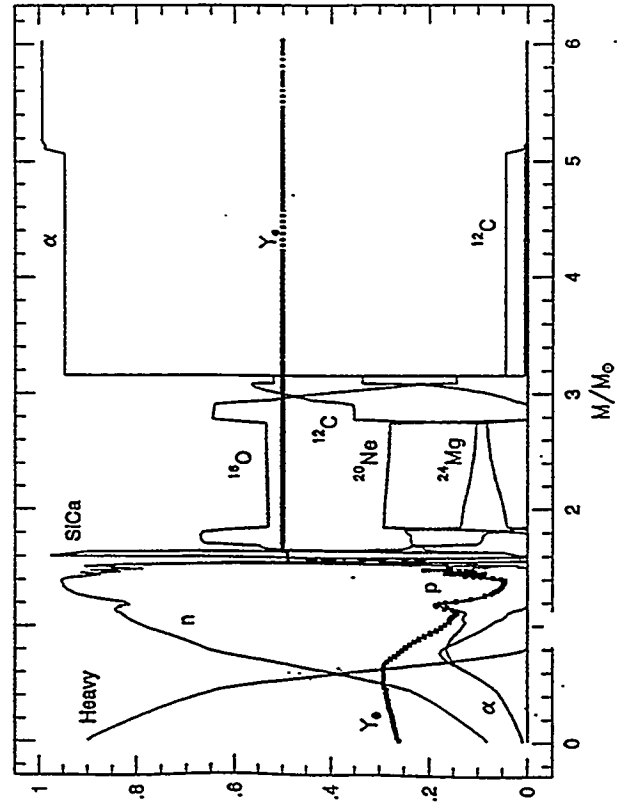
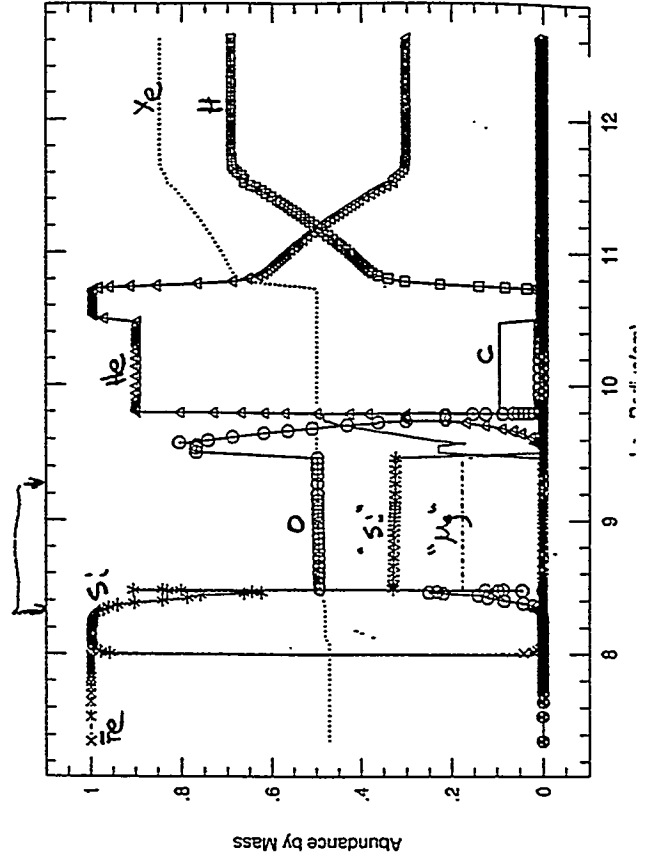
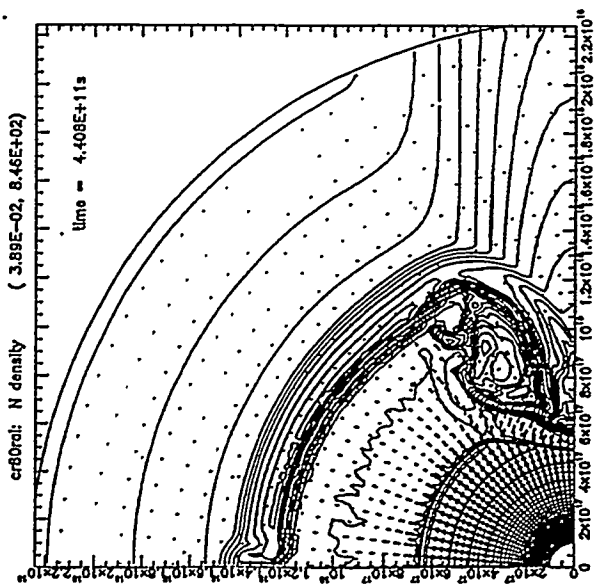
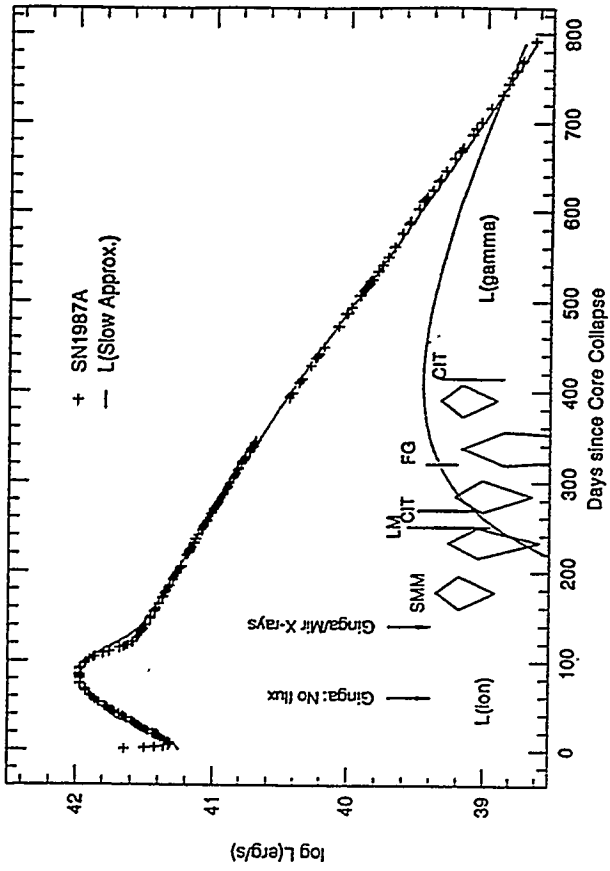
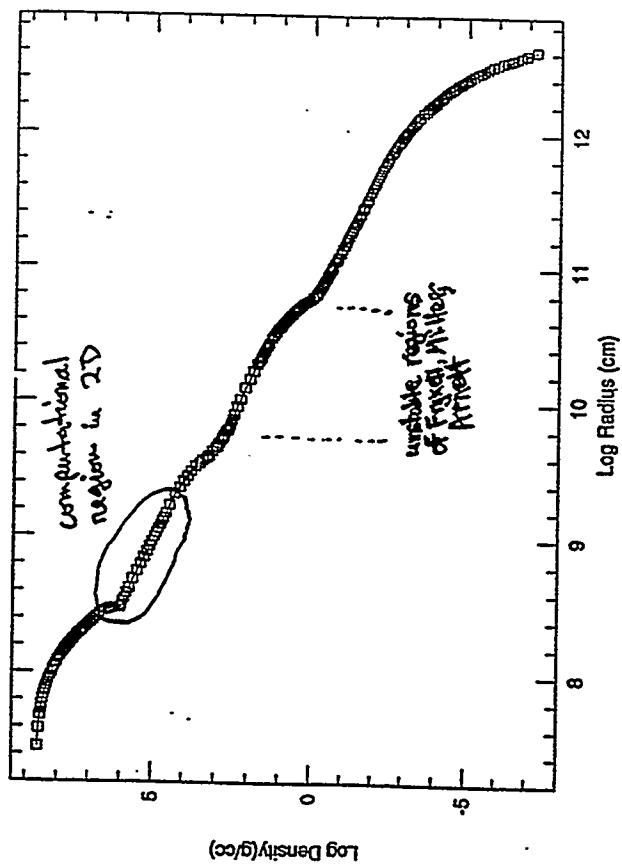


FIGURE 13



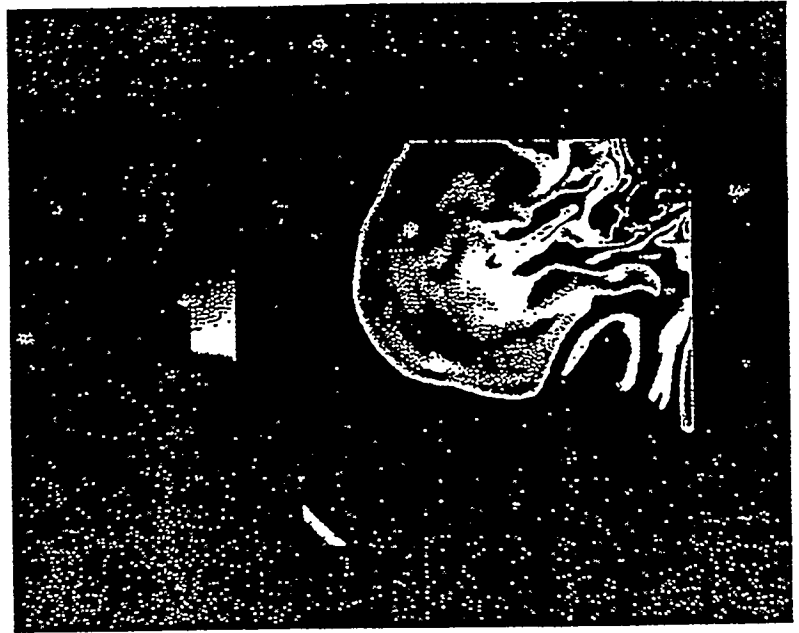


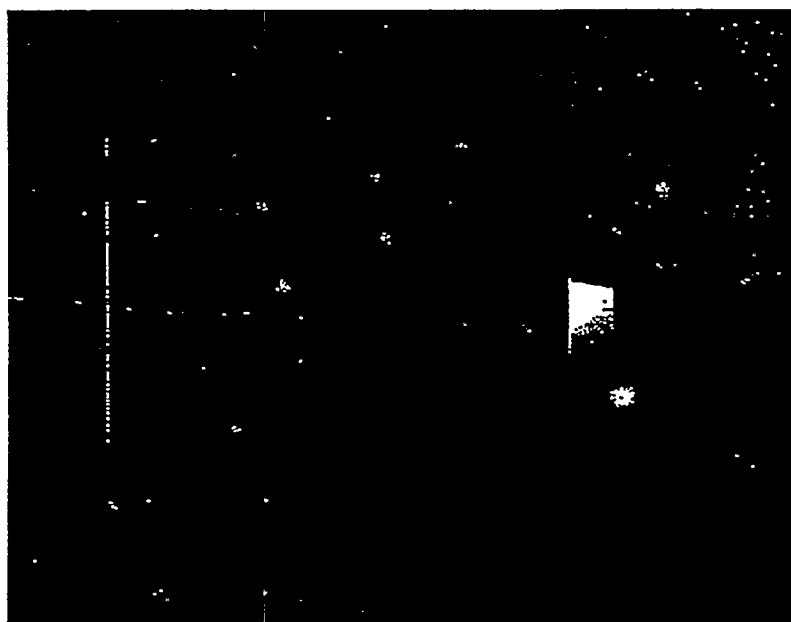
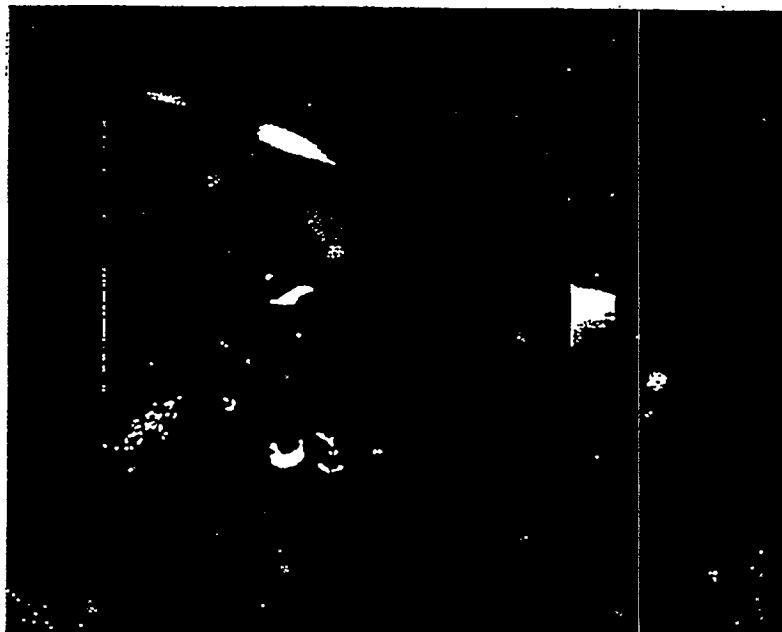
Direct hydrodynamic simulation:

O shell - "hydrostatic"

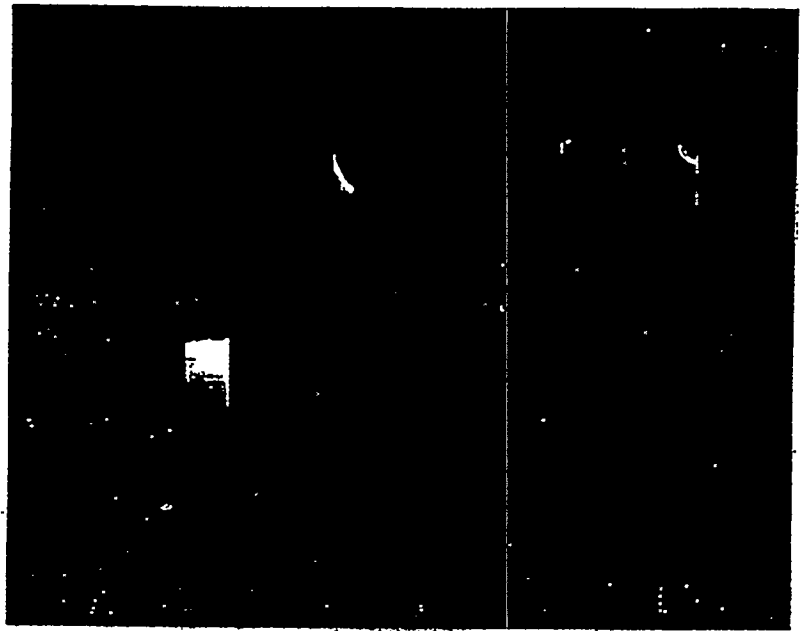
Si shell - "hydrostatic"

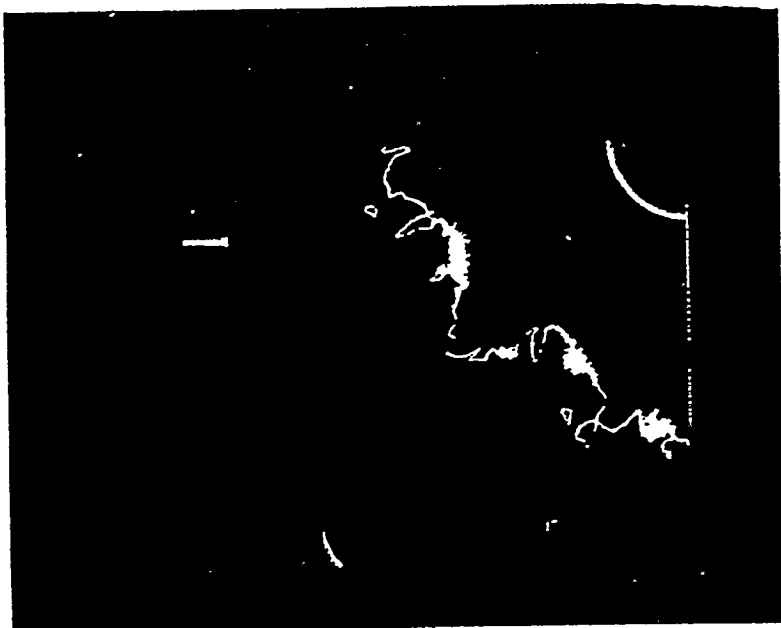
O shell - explosive











Hydrodynamic Instability Experiments for Supernovae

**S. Gail Glendinning
Lawrence Livermore National Laboratory**

Hydrodynamic Instability Experiments for Supernovae



Möller et al., density at He-H interface, $t = 12557$ s



Nova experimental data at $Cu-Cu^{14}$ 10^{14} dyn/cm²
-log₁₀(exposure) 1.3-1.6 sec

S.G.Glendinning¹, D.Arnett²,
M.Berning³, J.Castor¹, J.Kane⁴,
B.A.Remington¹, A.Rubenchik⁴
¹LLNL; ²Univ of Ariz, Tucson;
³Heinrich-Heine-Universität Düsseldorf; ⁴Univ
of Calif, Davis

Workshop on Laboratory
Astrophysics Experiments
with Large Lasers
Pleasanton, CA
26 February, 1996

On Nova, we can examine hydrodynamic growth from well-characterized initial conditions at relevant conditions

Supernova measurements (SN1987A) and simulations indicated important role for turbulence and mix at every interface

Conditions for Nova experiments are similar to SN conditions

- Shock pressures ~ 100 MBar (10^{14} dyn/cm², 10^{13} Pascal)
- Growth scaling (time $\propto$ acceleration/spatial scale) ~ 10
 - 30 ns laser experiment $\approx$ about 10 hrs of hydro (SN) growth
- Reynolds number $\sim 3 \times 10^6$ (about 10^7 for SN)
- Temperatures: 10-30 eV (100-500 eV for SN)

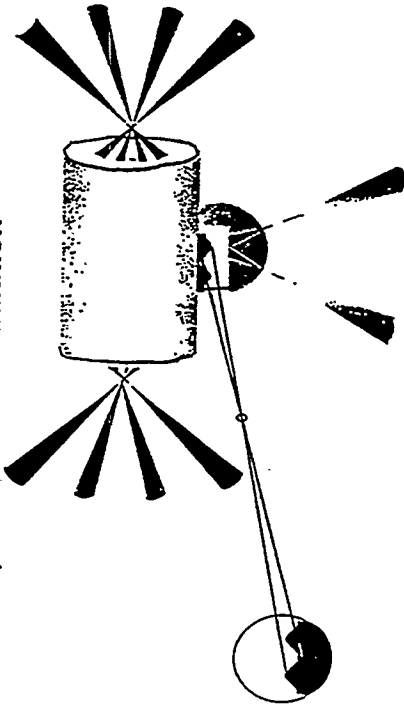
Goals:

- first year:
 - identify and characterize suitable drive and target
 - examine growth (two-dimensional)
 - connect with two-dimensional astrophysical modeling
- second year:
 - two-dimensional experiments
 - feed-through (multiple layers)
 - single and multiple initial modes
 - model with astrophysical codes
- third year: examine effects of three-dimensionality

This talk describes current experimental status

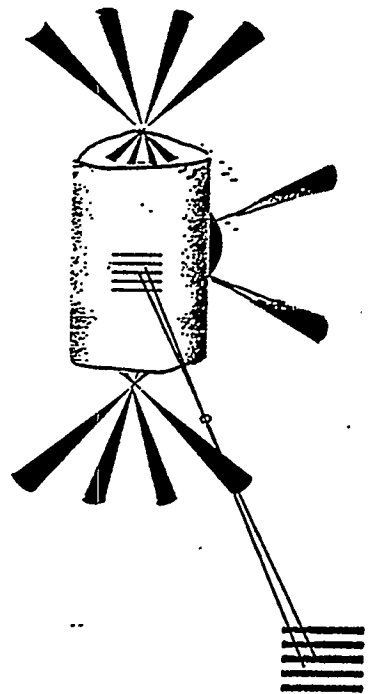
- We have examined various shaped drives and target configurations
- We have best results from single-shock experiments
- Experiments with two-dimensional (single-mode) initial perturbation are in progress
- We have some quantitative comparisons with codes
 - HYADES for one-dimensional predictions
 - CALE and PROMETHEUS predict hydrodynamic evolution of material interface

Our experiment uses x-ray drive to drive a planar interface and x-ray radiography to determine the interface position and modulation

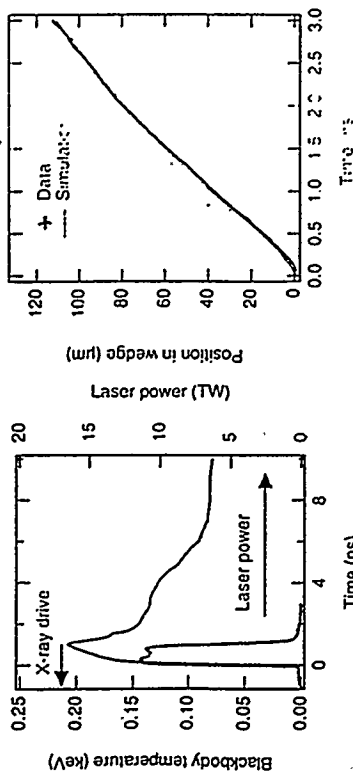


- The primary diagnostic tool is a time-resolving pinhole camera with multiple frames
- Instrument spatial and temporal response functions are well known

For thin targets, we can backlight through the target and use the variation in x-ray transmission as a measurement of surface modulation

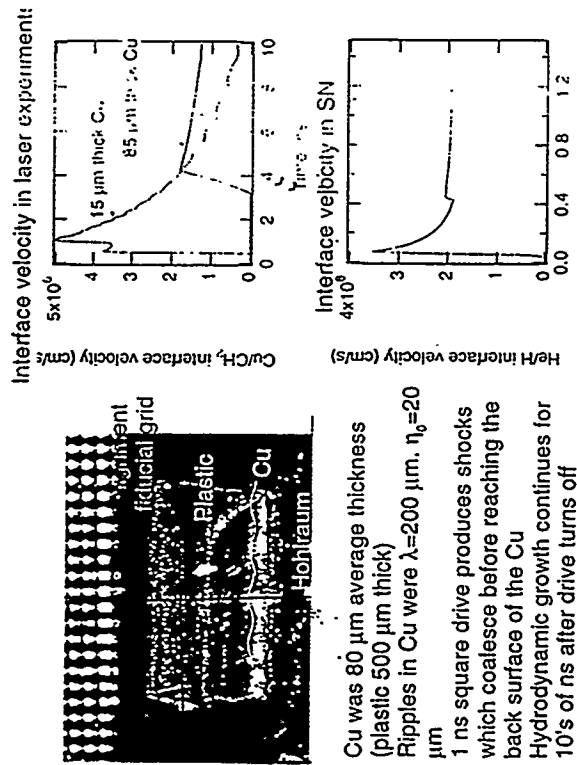


We measure the x-ray drive with time- and spectrally- resolved absolutely calibrated x-ray diodes (DANTE)



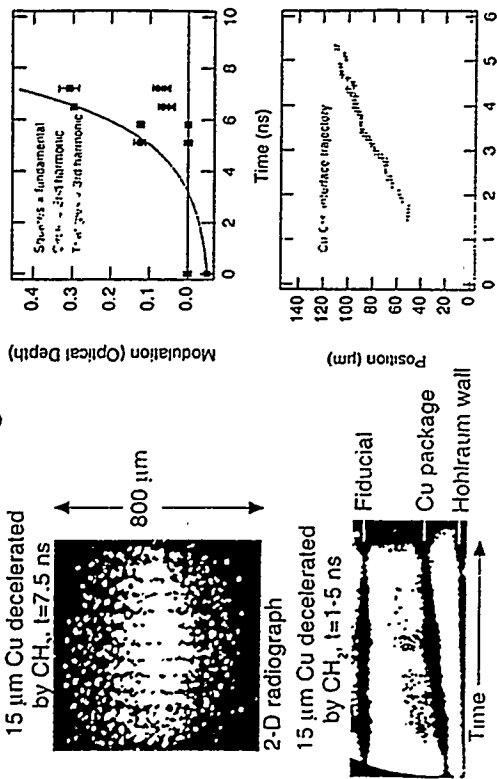
- We check the x-ray drive measurement with shock velocity measurements
- One-dimensional codes (typically HYADES) use x-ray drive measurements to predict conditions within planar targets
- We map 1D results as conditions for two-dimensional codes (CALE, Prometheus) just prior to arrival of shock at interface

Increasing the Cu thickness improves the velocity profiles at the interface



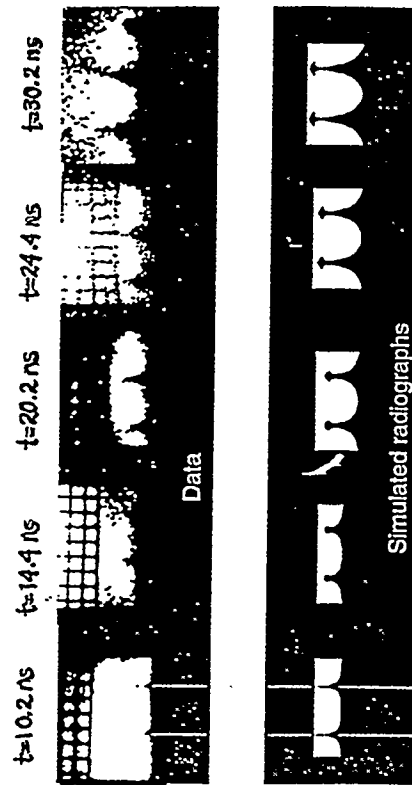
- Cu was 80 μm average thickness (plastic 500 μm thick)
- Ripples in Cu were $\lambda=200 \mu\text{m}$, $\eta_0=20 \mu\text{m}$
- 1 ns square drive produces shocks which coalesce before reaching the back surface of the Cu
- Hydrodynamic growth continues for 10's of ns after drive turns off

Supernova relevant measurements to date include face-on and edge-on views



- Two-dimensional imaging is required for measurements of modulations
- Cu package was too thin for this drive; multiple shocks reached the interface (not enough growth)

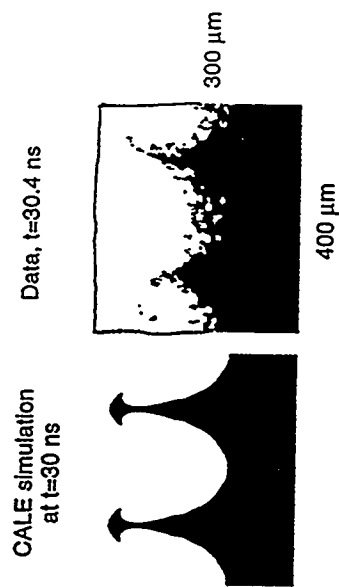
We have a sequence of images vs time (from 3 shots) which extend to 35 ns and show clear evidence of nonlinear behavior



Initial thinnest Cu

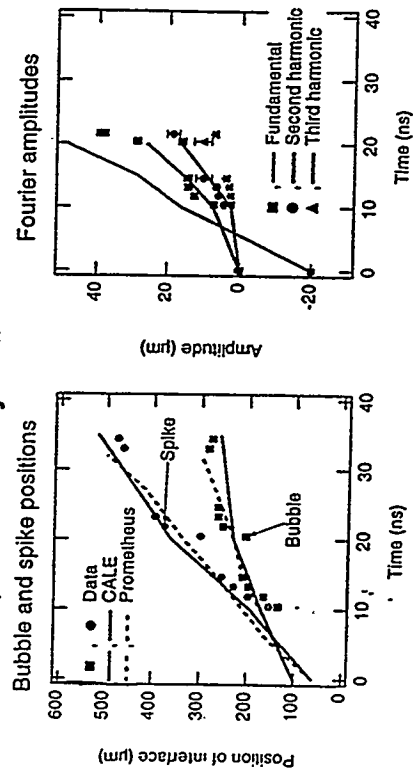
- Phase of modulation has inverted, as anticipated

CALE predicts similar structure to that observed



- The code predicts significant spike-formation and roll-up
- Observed structure is more complicated

CALE and PROMETHEUS both predict bubble and spike positions very well

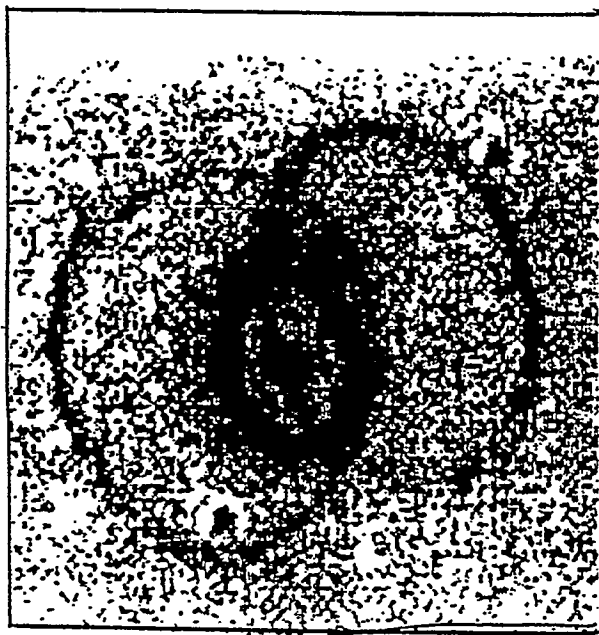


- Early in the evolution, Fourier harmonics are easily determined and show some difference between codes and data

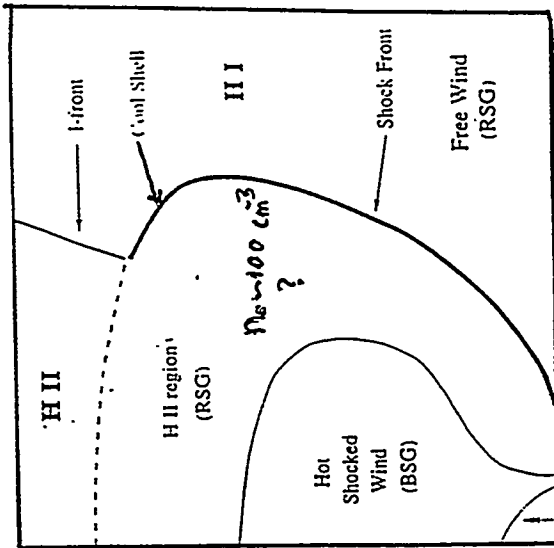
Collisional of SN1987A with Circumstellar Nebular Ring

**Richard McCray
JILA, University of Colorado**

Richard McCray
 DING LUD }
 JON SLAVIN } OPTICAL,
 UV, HST
 KAZIK BOROWSKI } X-RAYS.
 JOHN BLONDIN }

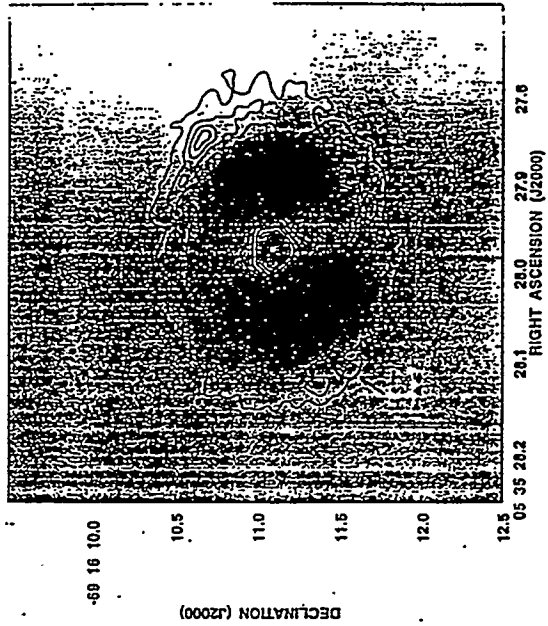


CHEVALIER & DWARAKES 1995



Free Wind (BSG) $\sim 3 \times 10^{17}$? $R_{eq} \sim 6 \times 10^{17} \text{ cm}$

MODEL REQUIRES
 • WEAK BSG WIND - (old previous estimate)
 • RADIO TURN-ON
 • X-RAY TURN-ON
 • KEY TEST X-RAYS

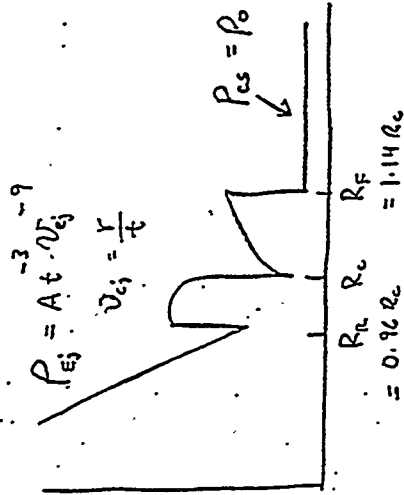


STAVE EX - SMITH ET. AL.
 AUSTRALIA TELESCOPE 8.8 GHz
 $t = 5.8 \text{ yr}$

"IT AIN'T EASY TO PREDICT THINGS
— ESPECIALLY IF THEY'RE
IN THE FUTURE"

— YOGI BERRA

EXPANSION OF SUPERNOVA ENVELOPE
INTO UNIFORM CIRCUMSTELLAR MEDIUM
(CHEVALIER 1982)



$$R_F(t) = K t^\alpha \quad \text{SELF-SIMILAR SOLUTION}$$

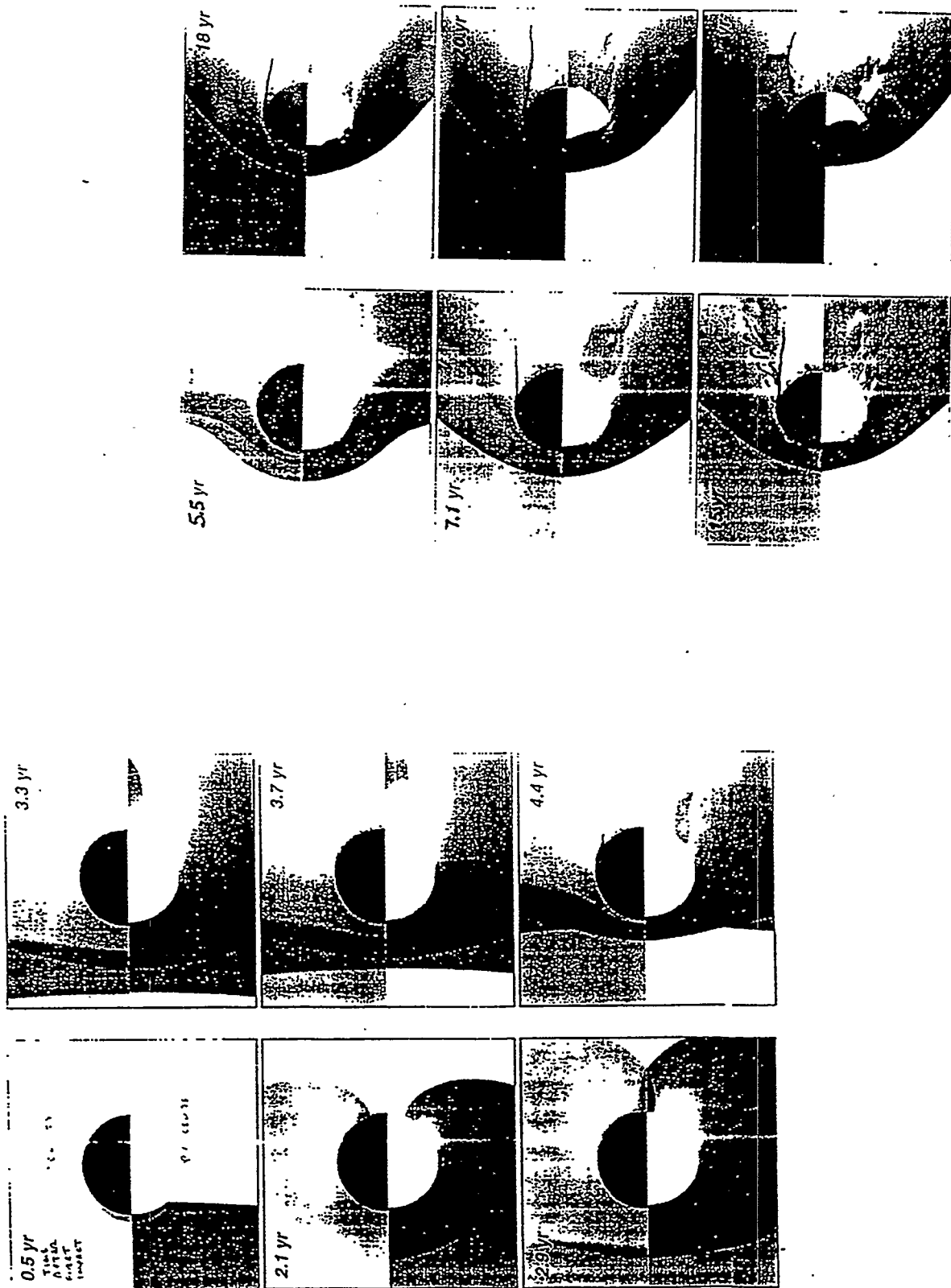
$$\text{SET } \rho_{ej} (\dot{M}_{ej} - \dot{M}_R)^2 = 0.55 P_0 \dot{M}_R^2$$

$$\Rightarrow R_F(t) = 0.54 \left(\frac{A}{P_0} \right)^{1/9} t^{2/3}$$

$$\Rightarrow t_1 = 13 \text{ yr} \left(\frac{\dot{M}_0}{10 M_\odot} \right)^{1/6}$$

A: WELL-MEASURED FROM MODEL-ATMOSPHERE
FIT TO EARLY SN PHOTOGRAPHIC SPECTRUM

P_0 ; MUST GUESS, [SHOCKED SN
PROGENITOR WIND?



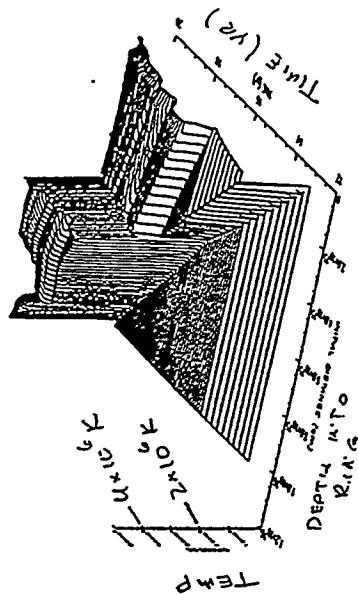


Fig. 6.—Temperature evolution as a function of the initial fluid location.

Fig. 1.—(a) and (b) SN 1981A with its circumstellar ring.

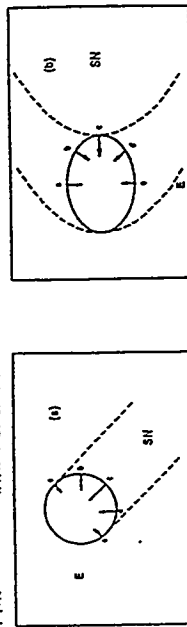


Fig. 1.—(a) and (b) SN 1981A with its circumstellar ring. (a) Side view of the ring, (b) top view of the ring. "E" indicates the geometry of the ring, "SN" indicates the geometry of the star. The dashed lines represent the ring's structure, and the solid lines represent the star's structure. The ring is shown in two different orientations, (a) and (b), to illustrate its geometry.

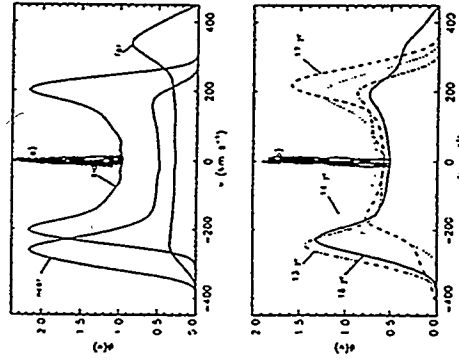
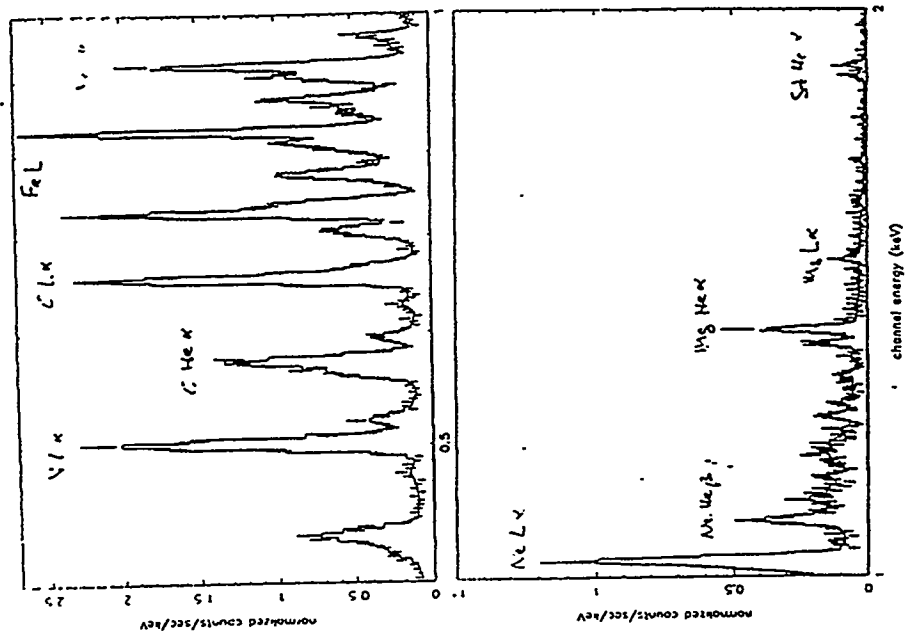
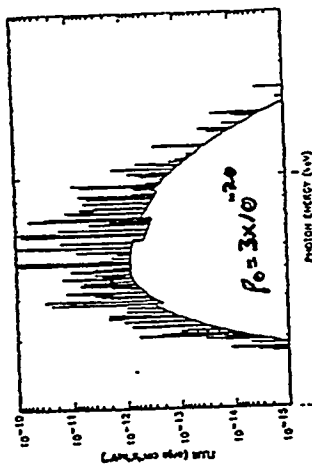
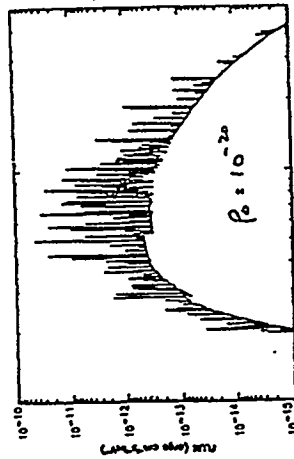
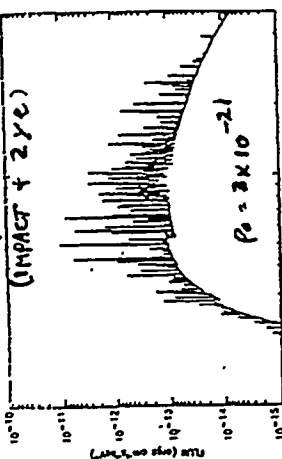


Fig. 1.—(a) and (b) SN 1981A with its circumstellar ring. (a) Side view of the ring, (b) top view of the ring. "E" indicates the geometry of the ring, "SN" indicates the geometry of the star. The dashed lines represent the ring's structure, and the solid lines represent the star's structure. The ring is shown in two different orientations, (a) and (b), to illustrate its geometry.

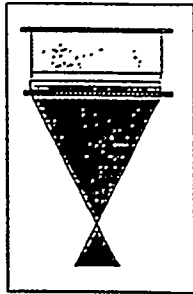
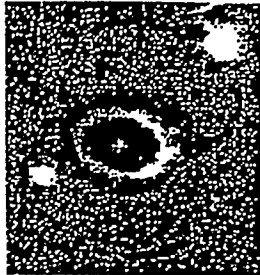
X-RAY SPECTRA AD 2002



**An Experiment Relevant to the Supernovae
Ejecta-Ring Collision**

**R. Paul Drake
Lawrence Livermore National Laboratory
and
University of Michigan**

An Experiment Relevant to the Supernova Ejecta-Ring Collision



R. Paul Drake
Lawrence Livermore National Laboratory,
and University of Michigan

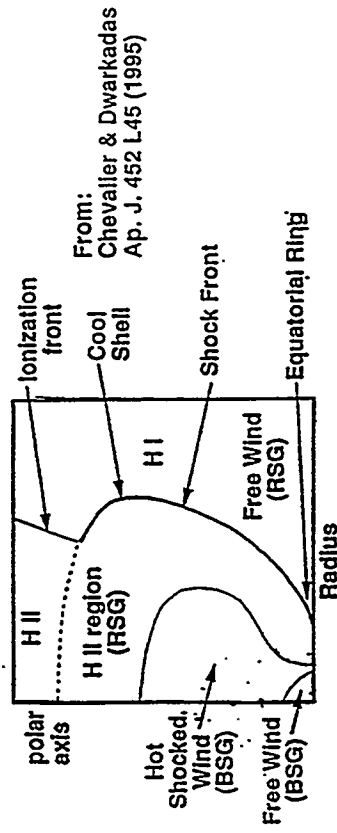
Workshop on Laboratory
Astrophysics Experiments
With Large Lasers
February, 1996

Work partially performed under the auspices of the U.S. Department of Energy by the Lawrence
Livermore National Laboratory

Laboratory Astrophysics 276

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The Ejecta from SN 1987A are now plowing through the circumstellar matter



- The structure developed during this period will determine the emission we observe when the ejecta strike the ring
- In any event, the emission from the ring will be multi-wavelength and informative

Here's what I'll show you

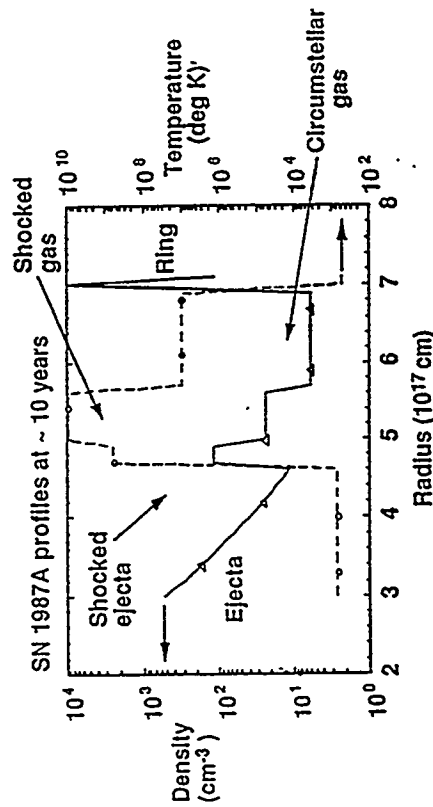
- > SN 1987A provides the context and real-time data
- > How we can simulate the SN environment using Nova
- > Issues and options for such an experiment

Collaborators:

Lawrence Livermore National Laboratory
Bruce Remington, Kent Estabrook, Gail Glendenning,
John Castor, Rich London, Claire Max
University of Colorado, Boulder
Richard McCray
University of California, Davis
Alexander Rubenchik
Rice University, Houston
Edison Liang

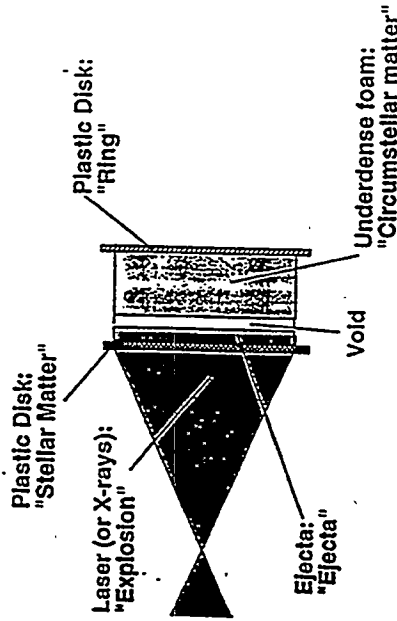
Laboratory Astrophysics 276

A rough schematic of current-day profiles will motivate the layout of a simulation experiment



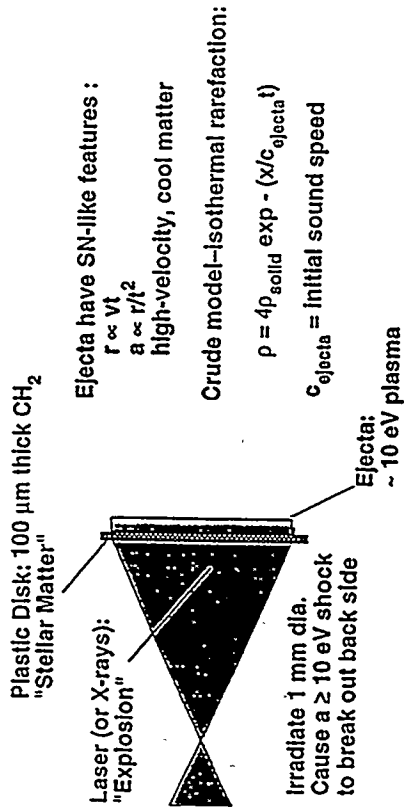
The H II zone, if present, will cause higher densities and lower temperatures in the shocked matter. Both forward and reverse shocks will be strong.

Here is one way to simulate the circumstellar environment



Let's examine this one piece at a time

We can make ejecta much like the star does



For H , $c_g = 30$ km/s at 10 eV and $Is \propto T^{1/2}$

The ejecta can drive a strong shock in low-density foam

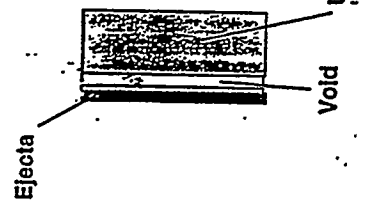
Interaction occurs where $\rho_{ejecta} \sim \rho_{foam}$

Thus $x/t = c_{ejecta} \ln(4 \rho_{solid} / \rho_{foam})$

So the upstream Mach number is

$$M_u = (x/t) / c_{foam} = (c_{ejecta} / c_{foam}) \ln(4 \rho_{solid} / \rho_{foam}) \sim \ln 400 = 6$$

A strong shock requires $(c_{ejecta} / c_{foam}) > 2$, so preheat of the foam must be controlled



Foam preheat limits the ejecta velocity

The foam is irradiated by the shocked disk until the ejecta strikes it after ~ 1 ns.

Assume that the foam absorbs σT_{BB}^4 for 1 ns

We can infer a preheat depth by making $T_{foam} = T_{BB}$ in the heated region

For C foam at 20 mg/cc one finds

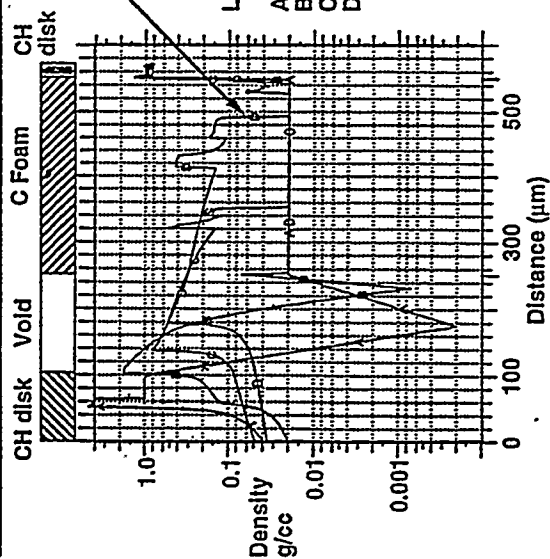
$$d_{preheat} = 3 \mu m (T_{BB} / 10 \text{ eV})^3$$

Thus, shock temperatures up to several times 10 eV are plausible.

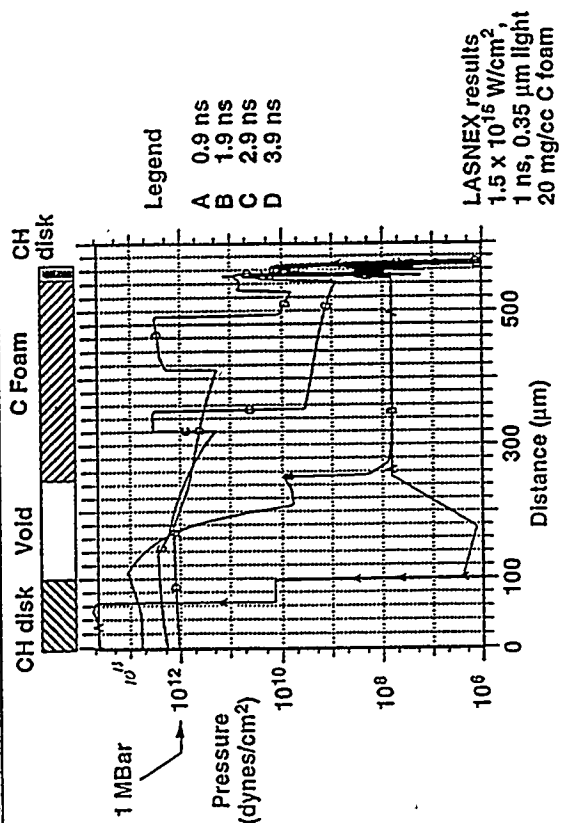
Preheat is more of a problem as density drops and atomic mass increases.

The shocked foam and ejecta

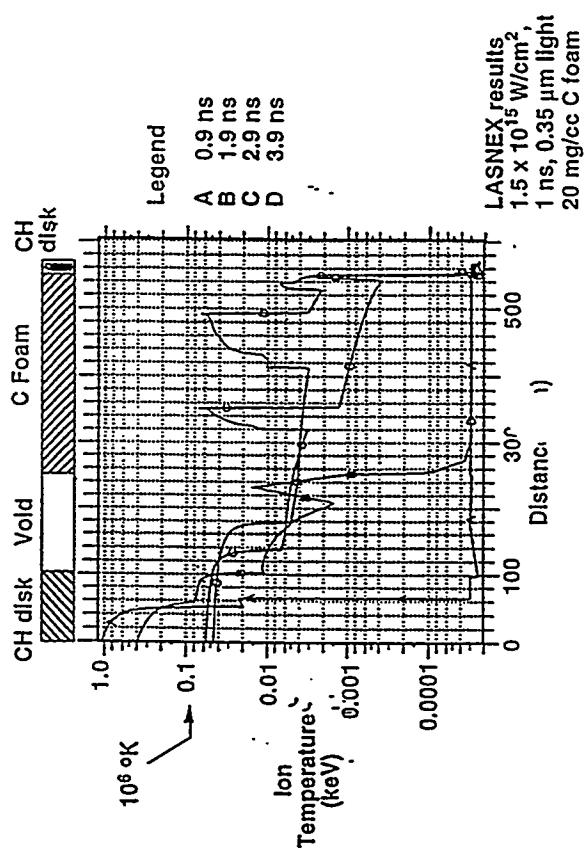
can strike the "ring" hard enough to emit



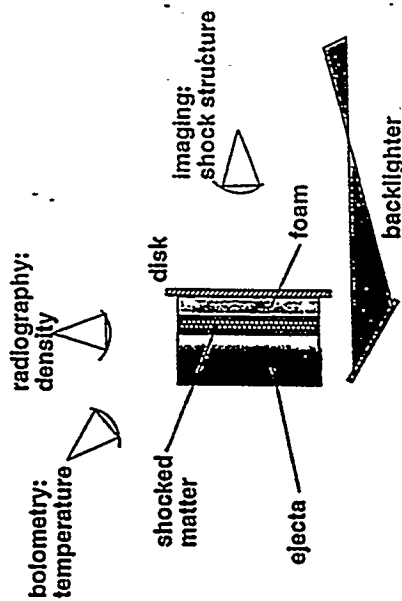
The shock produces a large pressure impulse



The ion temperature shows strong heating



We can diagnose the shock using established techniques



Typical dimension: 1 mm for entire target; 100 μm for shock
 Typical resolution: 10 μm
 Timescales: 1 ns for shock propagation; 100 ps for diagnostics

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We are improving this design and working on scaling

- > Modeling x-ray driven designs to get stronger, more uniform shocks
- > Exploring doped foams to obtain radiatively-cooled shocks – plan to greatly vary the hydrodynamic instability growth rates
- > Varying the geometry to seek scale-free behavior
- > Using gas rather than foam to access collisionless shocks
- > We will propose Nova shots this spring and hope to obtain the first data during the next year

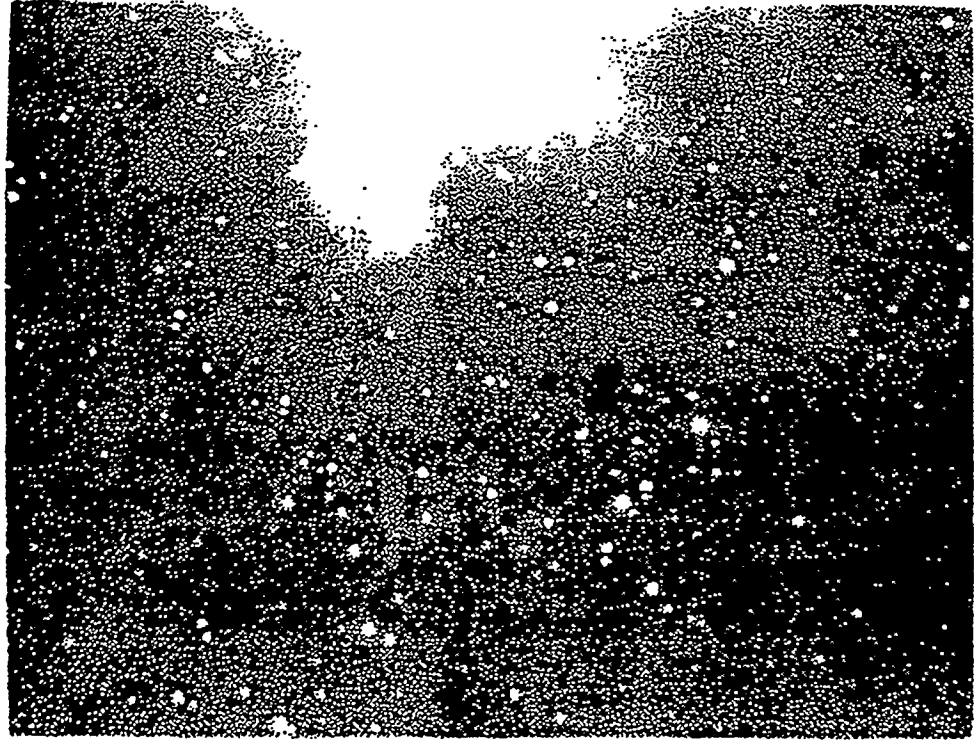
**Formation of "Bullets" by Hydrodynamical
Instabilities in Stellar Outflows**

**James M. Stone
University of Maryland**

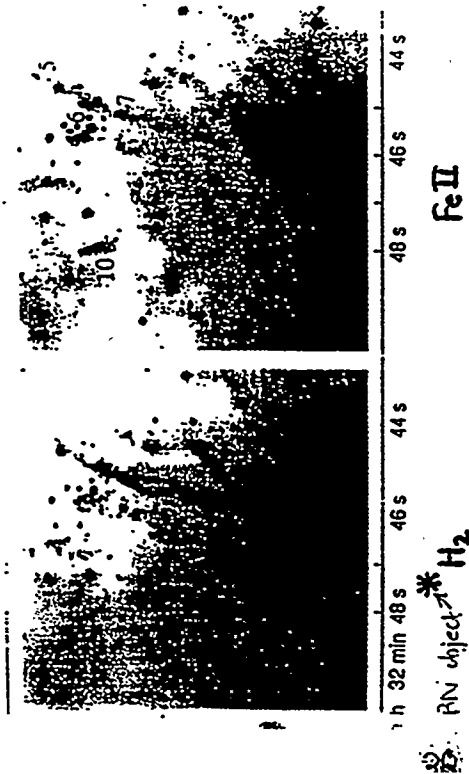
Formation of "Bullets" by
Hydrodynamical Instabilities
in Stellar Outflows

Jim Stone
Lee Mundy
Jianjun Xu
University of Maryland

- Observations of "bullets" in Orion
- An interpretation
- Hydrodynamical Modeling
- "Bullets" in other contexts
- Conclusions



Motivation: IR observations of the star-forming region ONC-1 by Allen & Burton (1993)



Use of the word "bullet" is provocative

Allen & Burton (1993) refer to "Explosive ejection of matter..."

Implies knots are accelerated to supersonic speeds at source.

But studies of interaction of dense clump with supersonic wind show this is difficult
 $\Rightarrow$ clump is fragmented

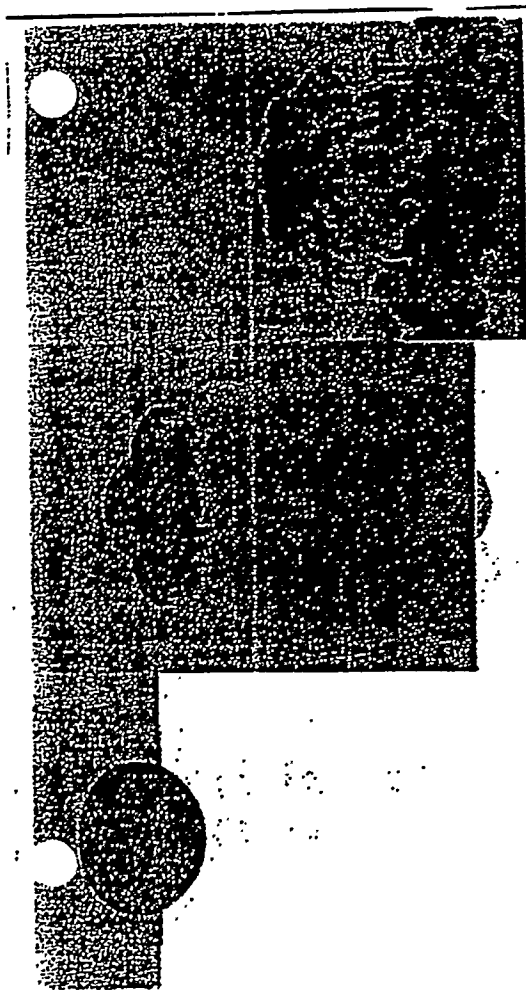
e.g. Stone & Norman (1992)

Klein, McKee & Colella (1994)

Xu & Stone (1995)

An alternative explanation: "bullets" form in situ in a supersonic wind

Stone & Norman (1993a, 1993b, 1994) demonstrated that dense knots can form in highly collimated outflows (i.e. protostellar jets).



2.5

2.5

4.5

$\log(\text{density})$



0.5

2.5

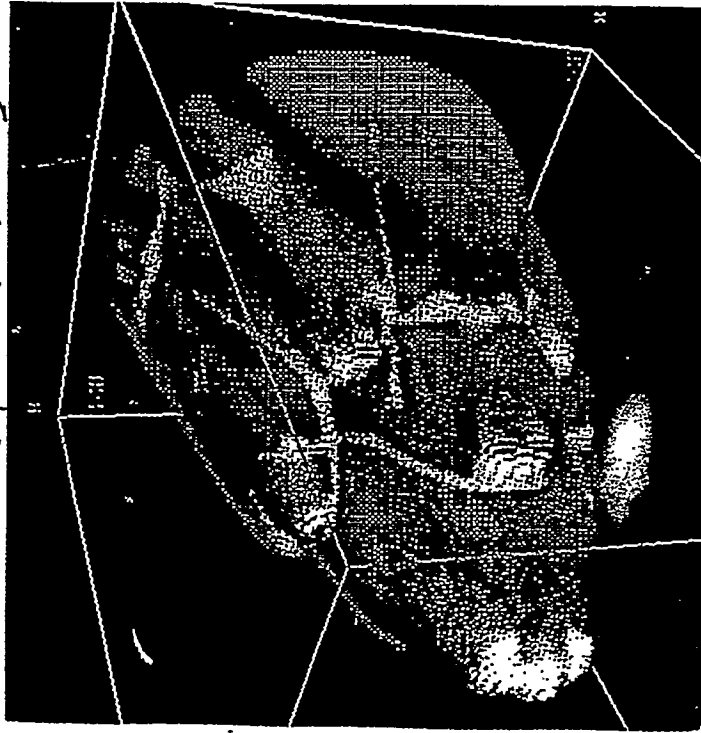
4.5

$|\partial \times v| = \text{vorticity}$

3D Simulation of $q=10$, $M=20$ jet:

fragmentation of shell $\Rightarrow$ "interstellar bullets"
"shocked cloudlets" (in $q=1$ jet)

[only last 20% of jet shown]



• A key ingredient is that gas must be strongly cooling
to form dense structures

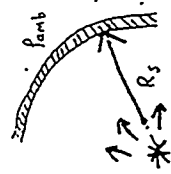
• Wind in OMC-1 is also strongly cooling.

$t_{\text{dyn}} \sim 10^3$ yrs

$t_{\text{cool}} \sim 1$ yr

• How do "bullets" form in wind?

Spherical wind will sweep up thin, dense shell of
shocked ambient + wind gas



If luminosity of wind

$L_w \propto \dot{M}$

density of ambient gas

$\rho_{\text{amb}} \propto r^{-n}$

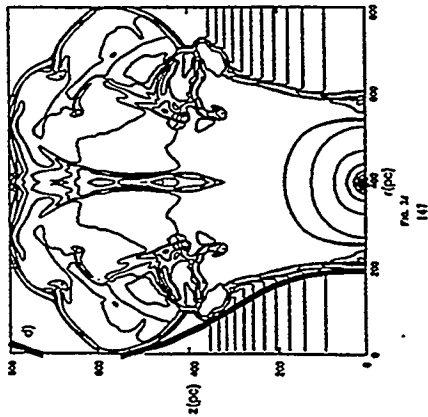
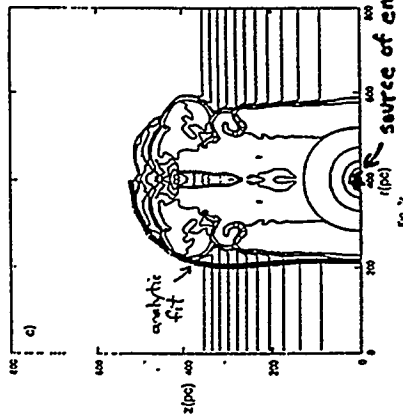
Then Weaver et al (1977) showed shell will accelerate
($\frac{dR_s}{dt} > 0$) if $n+M > 2$ Acc'n of shell R-T unstable.

Two possibilities: (1) external density gradient is steep ($n > 2$)

(2) wind is time-variable

MacLow et al (1989) studied case (1) $\Rightarrow$ "superbubble blowout"

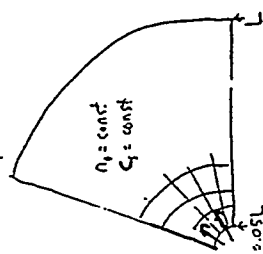
from unalactic disk



We have explored case (2).
Hydrodynamical Modeling:

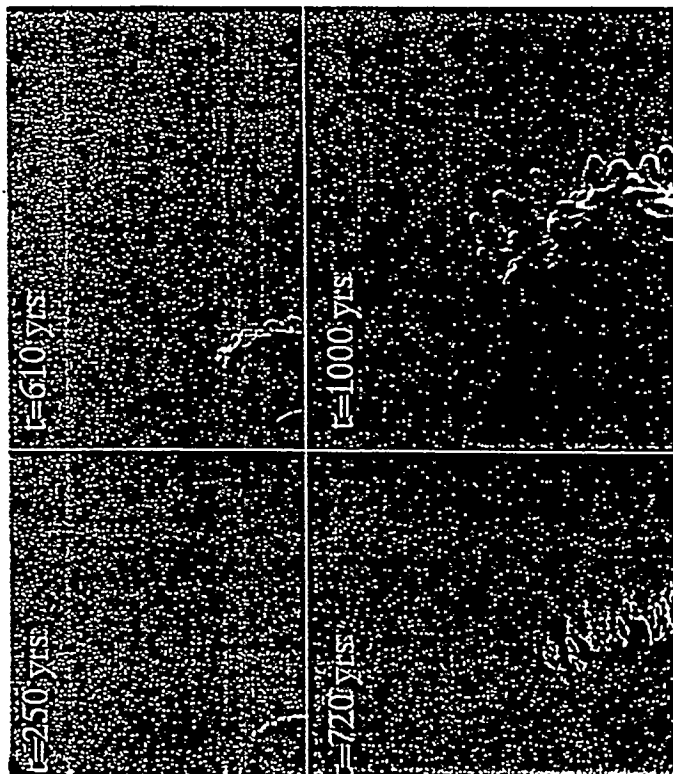
Use PPM code on spherical polar mesh

- Introduce wind through inner B.C
- Ambient gas isothermal, homogeneous
- Small amplitude perturbations near source
- Initial wind velocity corresponds to $M=10$. At late times, increase to $M=100$

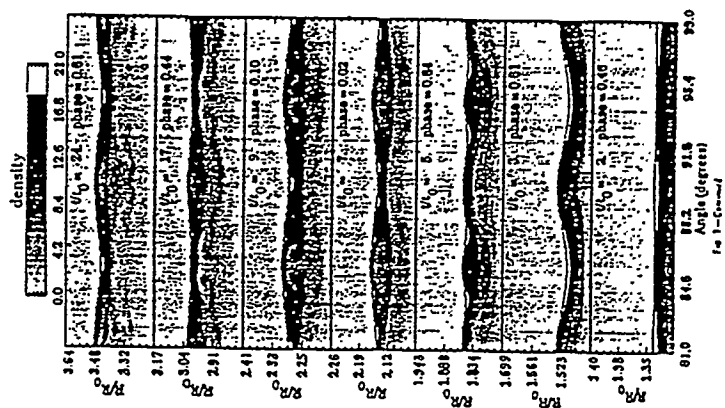


For QMC-1: $L \sim 0.1 \text{ pc}$
 $C_s = 20 \text{ km/s}$ } $L/C_s = 5,000 \text{ yrs}$
 $V_{\text{wind}} = 200 \text{ km/s}$
 $n_0 = 10^3 \text{ cm}^{-3}$
 $\dot{M}_{\text{wind}} = 10^{-6} \text{ Mo/yr}$

What fragments shall? 1) R-T instability
2) Vishniac thin-shell instability



MacLew & Norman (1993)
Nonlinear evolution of thin-shell instability

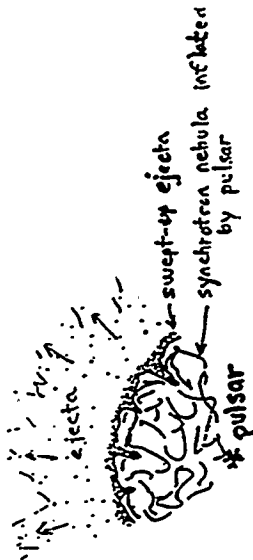


We expect "bullets" to form in stellar outflows in many other contexts, eg.

- 1) Evolution of LEV (García-Segura et al 1991)
- 2) PN (O'Dell & Wang 1996)
- 3) SNR est. Crab

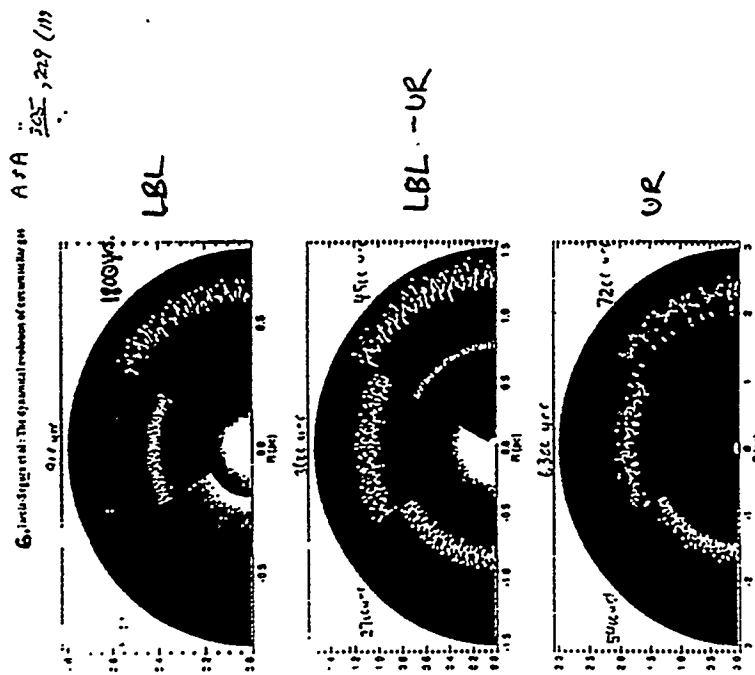
HST has observed dense "fingers" in ejecta swept-up by synchrotron nebula

Hester, Stone, et al. (1996) suggest fingers formed by magnetic R-T instability at surface of expanding synchrotron nebulae.



∴ Dense knots formed in this way will catch up to knot wave in ~3,000 yrs.

Perhaps an explanation for the x-ray "bullet" observed in Vela SNR (Strom et al 1995)

[illegible]

WFPC-2 image of crab

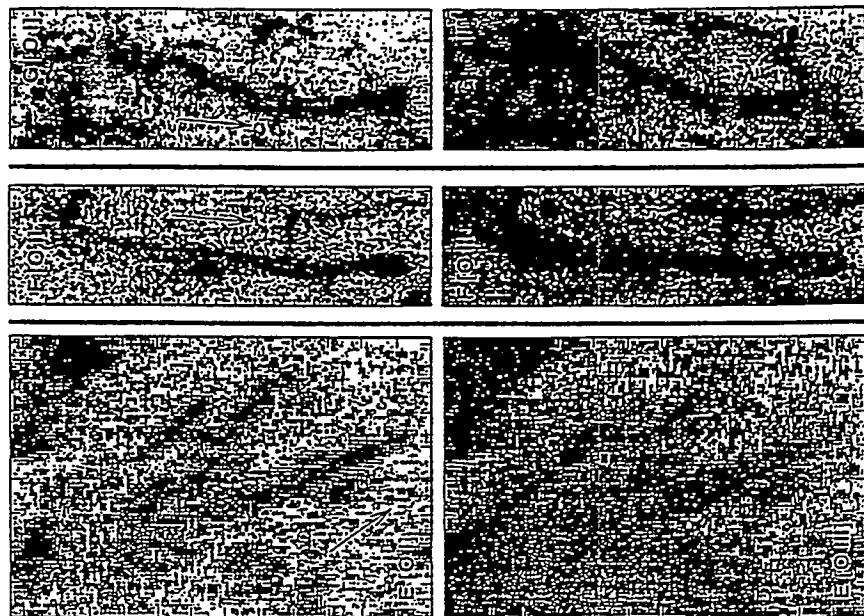
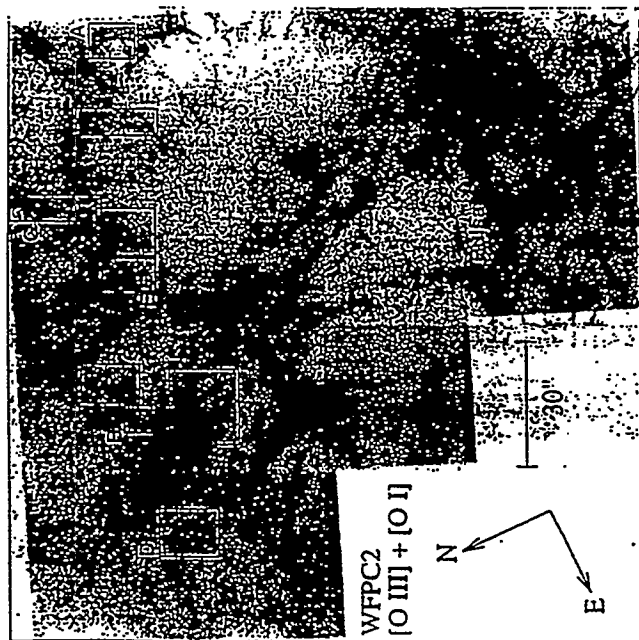


Figure 6.

Figure 1.

From Jin, Norman, & Stone (1995)
 Nonlinear stage of hydromagnetic vs. magnetic
 R-T instability

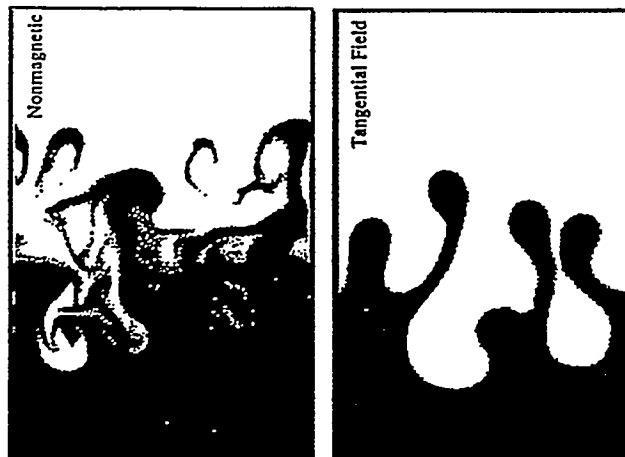


Figure 3.

We conclude:

- (1) "bullets" are formed in situ in outflow
- (2) Strong cooling is essential for forming dense structures
- (3) Many modes of instability can fragment shell
- (4) Provides an interpretation for "bullets" in many contexts

Detailed modeling of line-emission from knots would be fruitful.

**The Hydrodynamics of Shock-Cloud
Interactions in the Interstellar Medium**

**Richard I. Klein
Lawrence Livermore National Laboratory**

The Hydrodynamics of Shock-Cloud

INTERACTIONS IN THE INTERSTELLAR MEDIUM.

Richard T. Klein

Collaboration: Chris McKee

Interaction of shock waves with

diffuse atomic clouds ($T \sim 10^4 K$) and

dense molecular clouds ($T \sim 10-20 K$)

in interstellar medium is a problem

of fundamental importance in

interstellar gas dynamics. It provides us

with a space-based laboratory with which to study the array of hydrodynamic instabilities to complement experiments we can do on the Nova laser.

- ⇒ crucial to understanding the evolution of ISM → { shocks develop from supernovae; stellar winds; cloud collisions; spiral density waves. }
- Shock waves arise in
 - heat the coronal plasma of the star
 - determine the velocity dispersion of clouds ⇒ governs the scale height of the ISM.
 - may be effective in destruction of clouds ⇒ mixing of clouds with ISM.
 - compression of clouds ⇒ gravitational collapse → star formation.

Interaction of SNR Diast-Wave - Cloud

can alter the appearance of ISM

⇔ Cloud inhomogeneities can

have a profound effect on

structure and appearance of SNR

IC 443 (Blaug, '86)

Filamentation structures

(Blaug '88) → 1984, 1985, 1986, 1987

Observations of SNR IC 443

with the ROSAT

Proposal with James Graham (5x10⁸ sec)

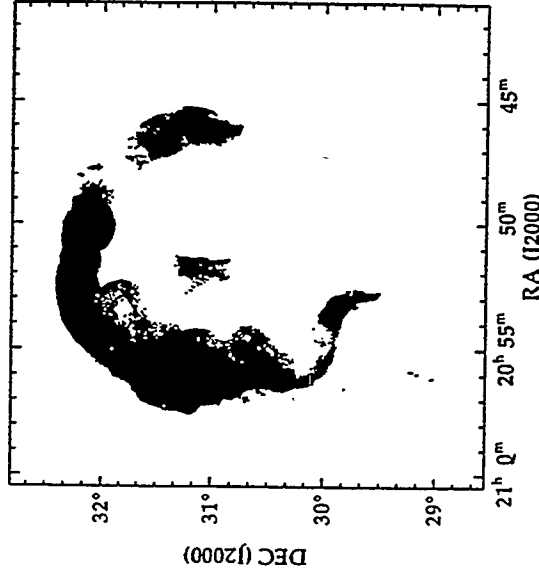
to map entire Cygnus Loop in X-rays

with German X-ray satellite ROSAT

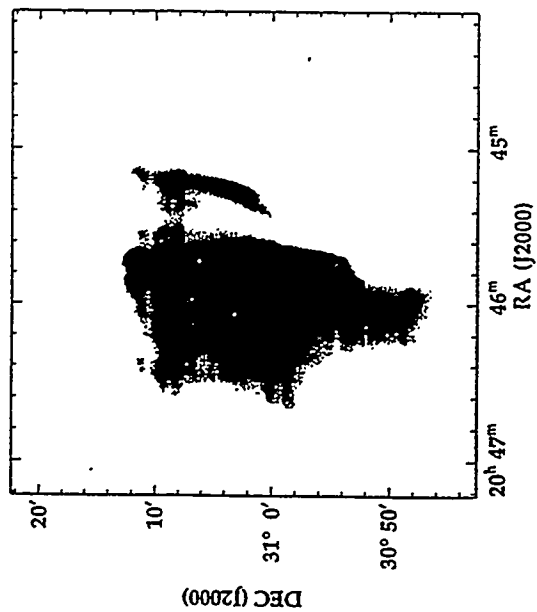
and find out entire Cygnus Loop with

Cygnus Loop X-ray Mosaic (ROSAT)
31 Fields

J. GRAHAM et al.
+ LEVINSON 1996

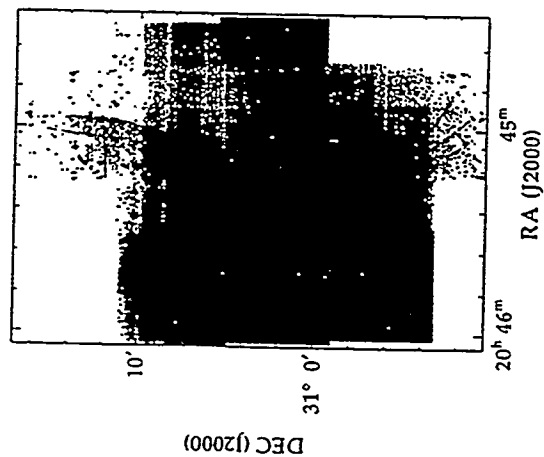


X-RAY (ROSAT) IMAGE OF WESTERN EDGE



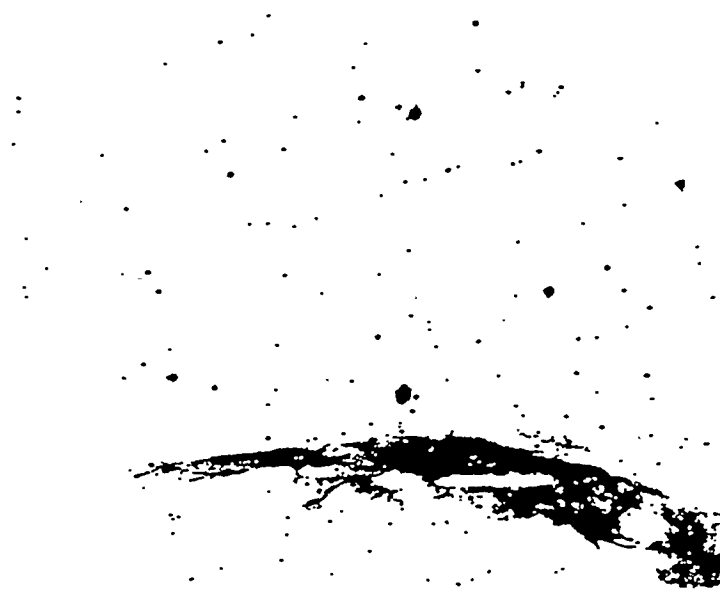
69

OPTICAL IMAGE OF WESTERN EDGE (LEVINSON '96)



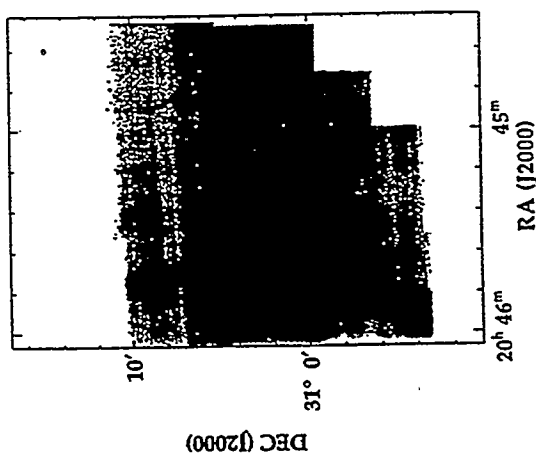
H α

Comp-5172 (H α + III + XRAY)



YELLOW = XRAY
 TURQUOISE = H α
 DARK GREEN = H α + III + XRAY

O III

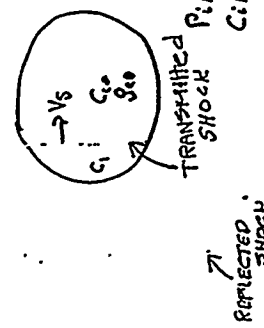


2. INITIAL CONDITIONS SPECIFY $M_{shock} = |v_s|/c$

$\chi = P_0/\rho_0$
 $\rho_0 = \text{initial cloud radius}$
 ρ_{20}

SHOCK PROPAGATION

INITIAL SHOCK



SNR EXPANDS THROUGH ICM $\Rightarrow$ DRIVES SHOCKS INTO ENGULPHED CLOUDS.

Assume shocks strong $P/\rho \gg 1$
 $\Rightarrow$ HIGHLY SUPERSONIC

Pressure behind blast wave $\sim \rho_0 v_b^2$

Pressure behind cloud shock $\sim \rho_{c0} v_s^2$

Pressures comparable

$v_s \sim (\rho_{c0}/\rho_0)^{1/2} v_b$ (Blast Wave)

If $v_s, v_b < 0$ then accurate cal.

3.

BLAST WAVE RADIATIVE

$$v_s \sim (\rho_{c0}/\rho_0)^{1/2} v_b$$

ρ_{c0} = density of shocked ICM $\sim 100 \rho_0$

$\Rightarrow v_s$ (radiative) $\gg v_b$ (non-radiative)

TIMES SCALES

ASSUMING SPHERICAL CLOUD WITH VARIOUS α

FOR SEDOV-TAYLOR BLAST WAVE

$$R_b \propto t^\alpha \quad \alpha = 2/5$$

Assume $\chi \gg 1$ where $\chi = P/\rho_{c0}$

cloud crushing time
 $t_{cc} \equiv \frac{R_c}{v_b} = \chi^{1/2} \frac{a}{v_b}$
 (cloud eroded from both sides)

Intercloud crossing time

$$\tau_{ic} \equiv \frac{2a}{v_b}$$

SNR AGE

$$t \equiv \frac{R_{1/2}}{v_b} = \frac{2}{3} \frac{R_{1/2}}{v_b} \quad (v_b = \frac{R_{1/2}}{t} = \alpha r)$$

IF $N \gg 1 \Rightarrow t_{cc} > t_{ic}$

Clouds are characterized in 3 sizes

SMALL CLOUDS $t > t_{cc} \Rightarrow \alpha \ll \frac{0.4R}{v_{1/2}}$

SNR DOES NOT EVOLVE SIGNIFICANTLY DURING CLOUD CRUSHING - CLOUD IS PROBABLY CRUSHED. VS A CON PRESSURE ON CLOUD BY STEADY MEDIUM CLOUDS $t_{cc} > t_{ic}$

$$\Rightarrow \frac{0.4R}{v_{1/2}} < \alpha < 0.2R$$

BUT WAVE DOES EVOLVE DURING THE TIME TO CRASH THE CLOUD. v_b deceleration
LARGE CLOUDS. $t < t_{ic} \Rightarrow \alpha > 0.2R$

Blast Wave weakens significantly over time to cross cloud force on cloud IMPULSIVE

Methodological Approach

Local Adaptive Mesh Refinement

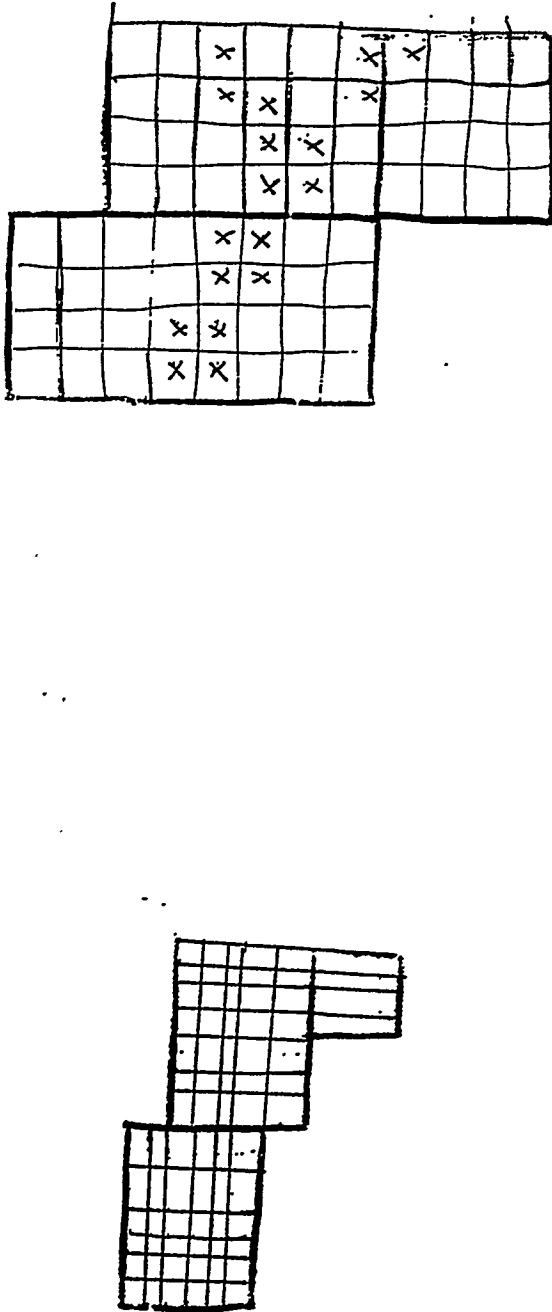
Berger and Oliger 1984

Berger and Colonna 1989 2D

Ball et al. 1991 3D, Stokes Morrison 93, Kulsrud & Macgregor 1994, Colonna et al (1994, 1995) 3D 93
Goals: Avoid unnecessary computation

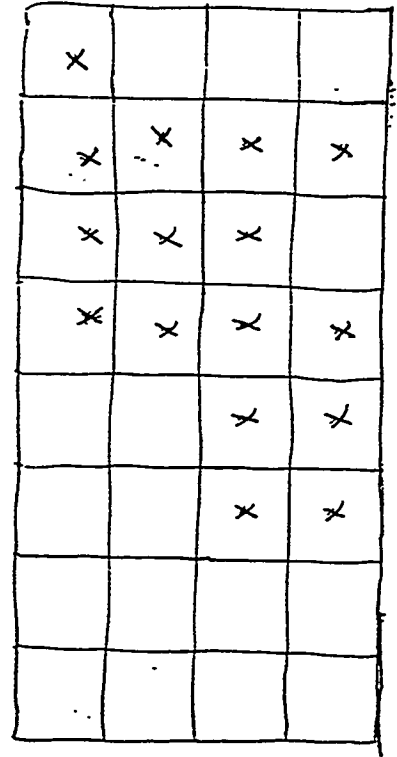
$\Rightarrow$ exploiting high resolution discretization
Huge advantage in cost of calculation
Approach: Locally refine "patches" of the grid in space and time

Local refinement is necessary to resolve complex shock interactions as well as instabilities and complex evolving structures.

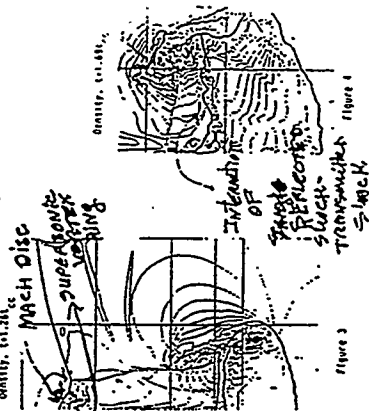
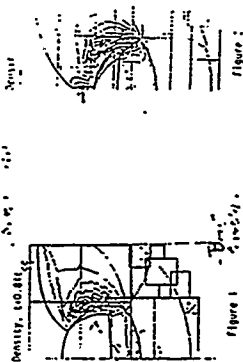


ADAPTIVE MESH REFINEMENT

IDENTIFY CELLS WHERE ADDITIONAL RESOLUTION IS
REQUIRED → Refine patches of the grid in space and time



122 Klein, Melior, Calabro



Indicating contours of cloud and lower cloud water at different times

121 Klein, Melior, Calabro

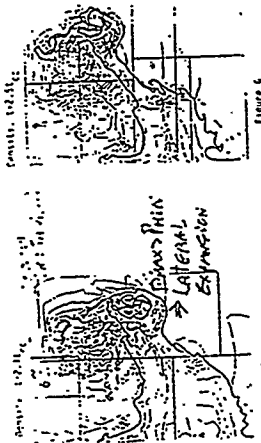


Figure 3

Density, 1.0, 20.5

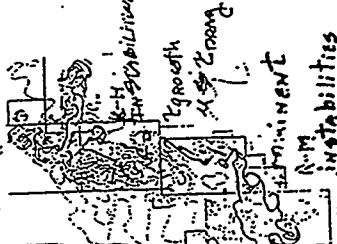


Figure 4

Density, 1.0, 20.5

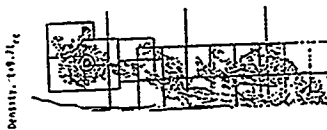


Figure 5

Density, 1.0, 20.5

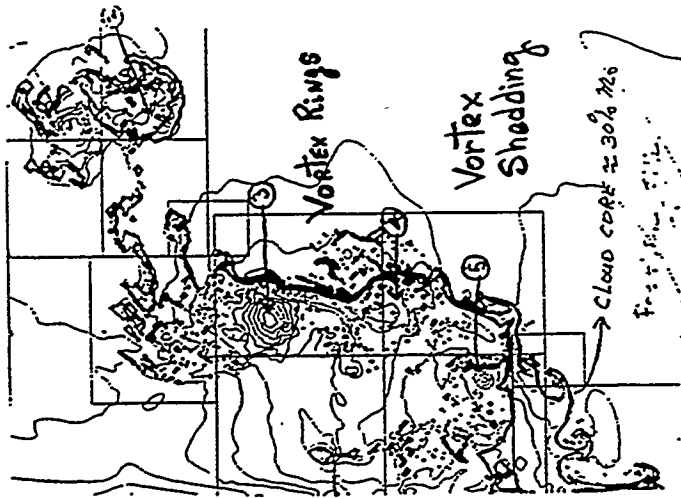
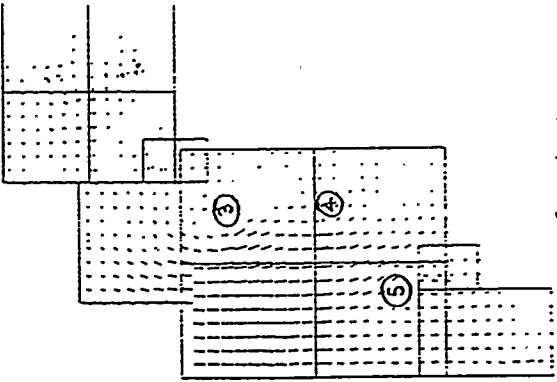


FIGURE 1. VELOCITY FIELD. TIME = 0.200



$n_0 = 10, \chi = 10$
 $t = 4.2 \tau_{cc}$

Vorticity Production
Associated With Cloud-Shock Interactions

$$\Gamma \approx \int \omega \cdot dA$$

$$\frac{d\Gamma}{dt} \approx \int (\nabla \times \dot{v}) \cdot dA \propto \nabla p \cdot \nabla (1/\rho)$$

CIRCULATION CAN BE BROKEN INTO 4 PARTS

(i) Vorticity produced as shock sweeps over cloud surface

Since there is a large difference in the acceleration of the fluid outside the cloud compared to inside
 $\Rightarrow \nabla \times \dot{v} \neq 0 \Rightarrow \frac{d\Gamma}{dt} \neq 0$ as

vorticity is generated

$$\Gamma_{\text{shock}} \approx -2.25 V_0 \rho_0 (1 - \gamma^2)^{1/2} \quad (\text{Meyers et al. 1974})$$

(ii) Vorticity generated in Post-Shock flow by baroclinic term

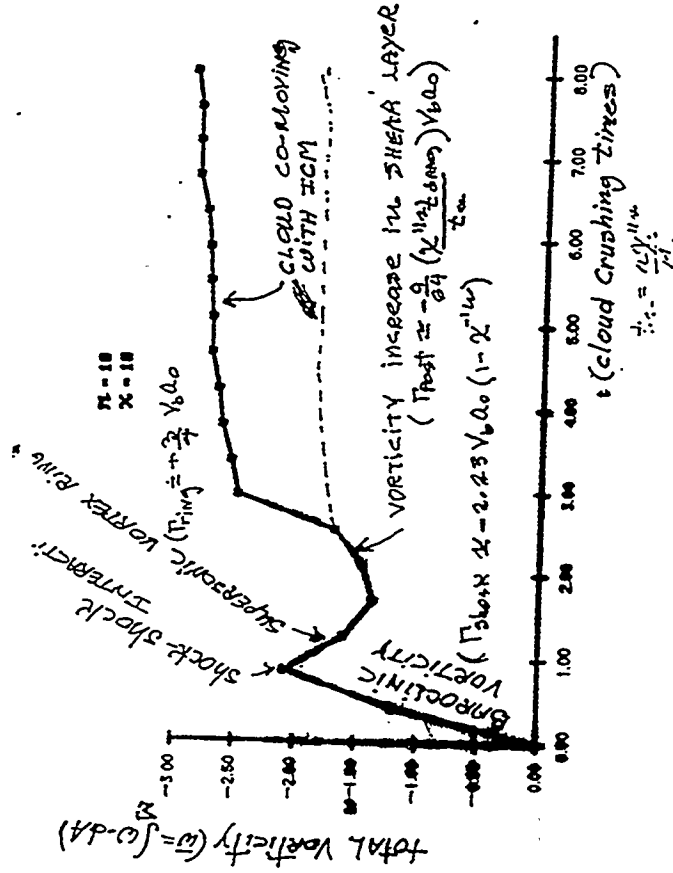
$$\Gamma_{\text{Post}} = \frac{\rho}{\rho_0} \left(\chi \frac{v_{\text{Post}}}{r_{\text{Post}}} \right) v_{\text{Post}} \rho_0$$

Soil Vorticity generated in intercloud medium behind cloud - Vorticity here is NOT associated with cloud boundary

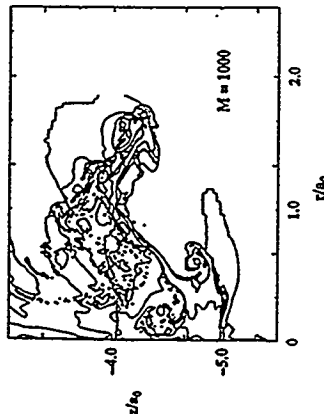
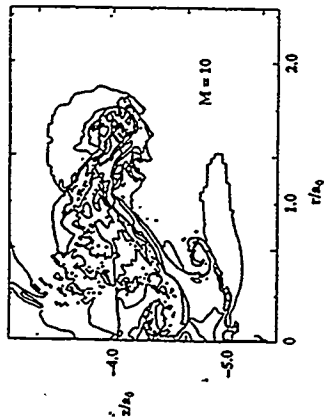
$$\Gamma_{\text{ring}} = \pm \frac{\rho}{\rho_0} v_{\text{Post}}$$

Vorticity is generated at triple point

(vi) Vorticity produced in the cloud near shock triple points associated with Mach reflected shocks but vorticity at $\frac{v_{\text{Post}}}{r_{\text{Post}}}$ in cloud is small for $M \gg 1$



MACH SCALING



Hydrodynamic
Equations Invariant
 $x \rightarrow xM$
 $v \rightarrow v/M$
 $p \rightarrow p/M^2$

• cloud destruction time $t_d \sim 3-4 t_{cc}$
 over a large dynamic range in χ
 $3 \leq \chi \leq 400$

Destruction proceeds extremely rapidly then time for a cloud to
 = leave out its own mass.

• Cloud accelerated to $v \sim \frac{1}{4} V_b$
 in $t_{drag} \sim \text{few } t_{cc}$.

Destruction of shocked cloud due
 to fragmentation on large and small
 scales $\rightarrow$ K-H; R-T; R-M instabilities
 2 MEASURES OF CLOUD DESTRUCTION:

I. $t_{dust} = \text{time } m_{clump} = m_{0.5}$
 LARGE SCALE FRAGMENTATION

Very Robust $t_{dust} \approx 3.5 t_{cc}$ $3 \leq \chi \leq 100$

$\Rightarrow \Delta z_b(t_{dust}) = V_b t_{dust} \approx 3.5 \chi^{1/2} z_0$
 $\Rightarrow$ for cloud $\chi=10$; substantially

destroyed when shockwave advances

10. cloud radius

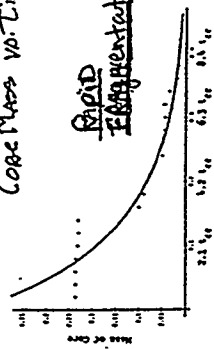
(14) 130

Klein, Melick, Corliss, 1990

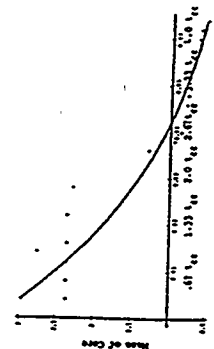
Core Mass vs. Time

Rapid
Fragmentation

$\chi=10$



$\chi=100$



$\chi=400$

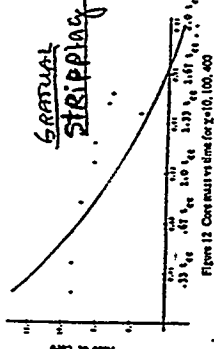
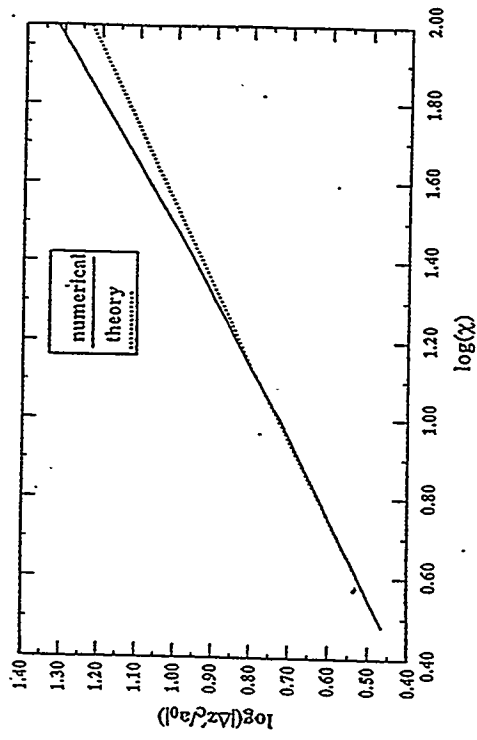


Figure 12 Core evolution for $\chi=10, 100, 400$



$$\left| \frac{d\gamma}{d\omega} \right| \propto \chi^{1/2}$$

Distance cloud travels in ICM
over time to fragment to small scales.

⇒ $\chi > 100$, DIFFERENT PROCESS OF FRAGMENTATION

II. MIXING

$\tau_{mix} \rightarrow$ time for a cloud to
 $\frac{1}{2}$ mass mixed with ICM
 ⇒ 2-FLUID HYDRODYNAMICS

→ MIXING MOST RAPID FOR $\chi \gg 1$

Consider decay time:

FF. decay of cloud A $\Rightarrow \frac{\partial A}{\partial t} = 0$

$$\tau_{dmg} = \frac{\chi \rho_0}{\text{cov}_b} = \chi^{1/4} \frac{t_{cc}}{C_D}$$

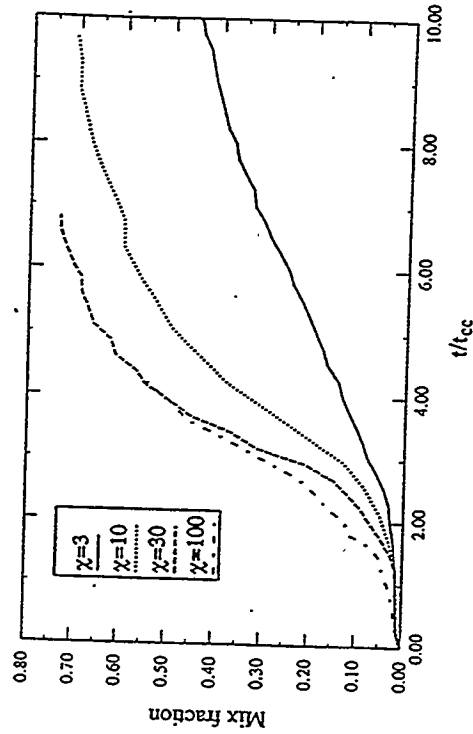
But, cloud has large lateral expansion

⇒ decay increased

$\tau_{dmg} \propto \chi^{1/4} t_{cc}$

⇒ $\tau_{dmg} \approx \text{few} \times t_{cc} \quad \Rightarrow \chi \approx 400$

$$\left[\frac{V_{c,193}}{V_{c,0}} \right]_{193} = \frac{V_{c,193}}{V_{c,0}} = \frac{1}{1 + \left(\frac{8}{3} \frac{C_D}{\chi^{1/4}} \right) \frac{t_{cc}}{t_{cc}}} \left[1 + \frac{1}{3} \left(\frac{C_D}{\chi^{1/4}} \right)^2 \right]$$



HIERARCHICAL FRAGMENTATION

- Scaling extremely well obeyed
 $3 \leq \chi \leq 100$

LSF $\rightarrow$ (LARGE SCALE FRAGMENTATION OF CLOUD) CORE

- scaling starts to break down
 $\chi > 100$

$\Rightarrow$ Change in fragmentation process

LSF $\rightarrow$ SMALL SCALE STRIPPING OF SURFACE
 $\chi \leq 100$ $\chi > 100$

Hierarchical Fragmentation is most rapid provable mixing since it continually exposes interior of cloud to mixing

small scale stripping sum surface of clouds is less efficient

TESEN
AD
MARCH 1992

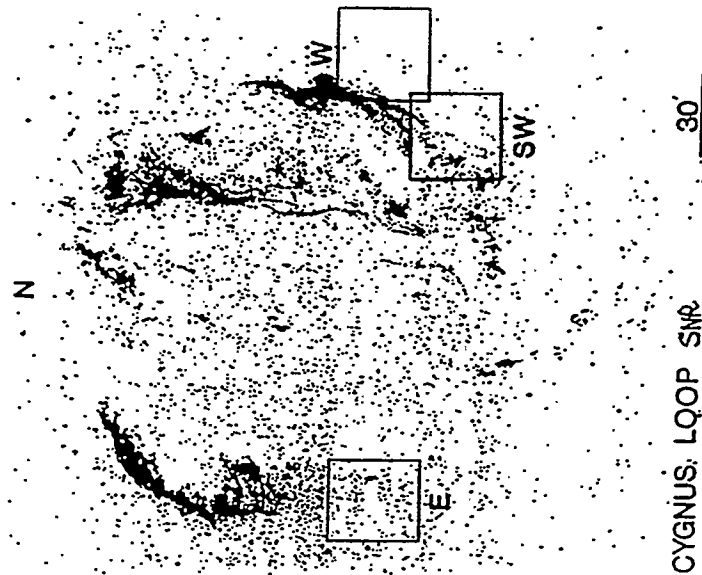


Figure 1

EASTN. 1072
 10.0000
 58
 EASTERN
 =LOW
 REL. C. 5pc
 M...
 R.A. 17h 22m
 V. 14.44
 T. 4.1513 yr.

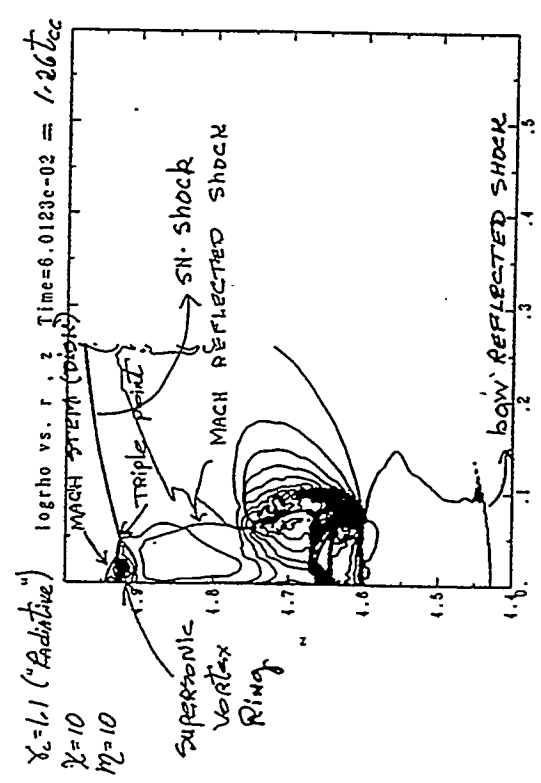
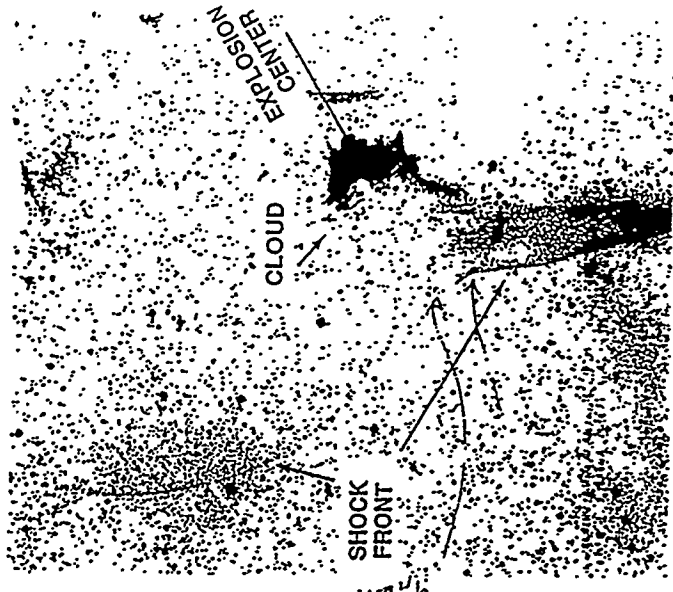
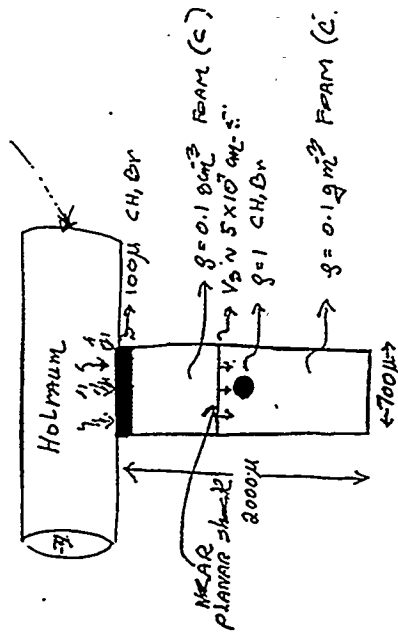


Fig. 10

$t_{cc} = \gamma_c \chi^{1/2} / V_0$
 $\log \rho$ { 75.253 } min
 $\gamma_c = 1.1$
 $\chi = 10$
 $\mu = 10$
 $V_0 = 0.77 pc$
 $\gamma = 10$
 $t_{cc} = 2.8 \times 10^3 yr.$

Cloud Shock Interaction
EXPERIMENTS ON NOVA
 R. KLEIN, T. PERRY



Shock propagation from $t = 4 \times 10^{-9}$ s - etc

⇒ We can investigate R-M, R-T, R-H

instabilities SAR into the non-linear regime

Experimental investigation will cover

$\lambda \rightarrow 10-100$

$m \rightarrow 1-11$ (TEST MACH RE SCALING AND)

Colliding Plasma Experiments

Ted Perry
Lawrence Livermore National Laboratory

Colliding Plasma Experiments

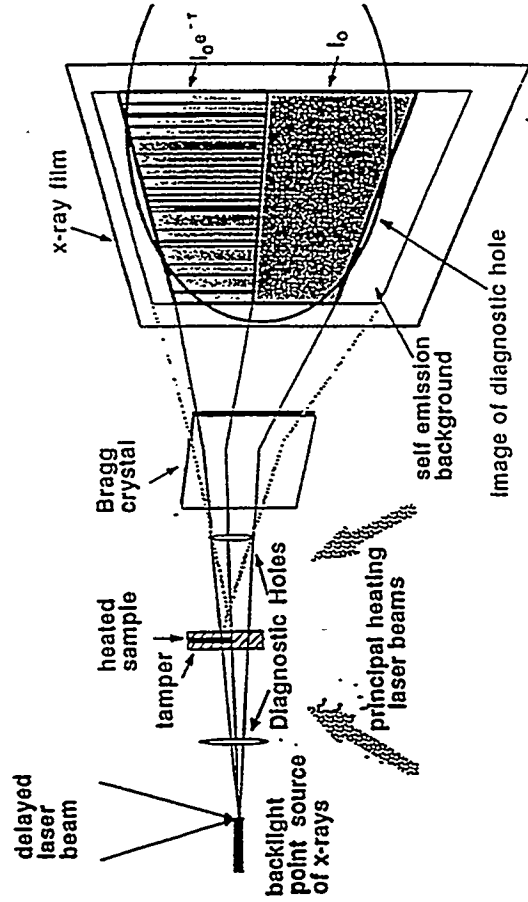
Outline

- Determining temperature by measuring ion balance
- Measuring density through radiography
- Heating samples volumetrically using gold M-band radiation

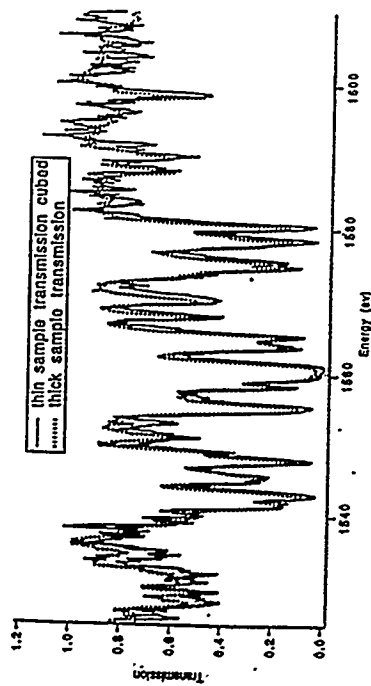


Ted Perry
Defense and Nuclear Technologies
Lawrence Livermore National Laboratory
February 26, 1996

Point Projection Spectrometry



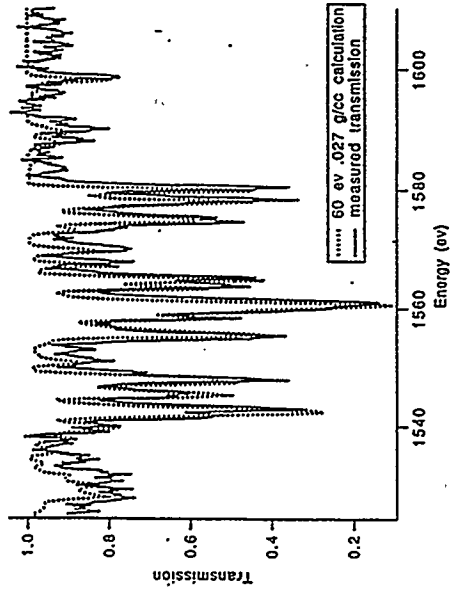
The two thicknesses give similar results



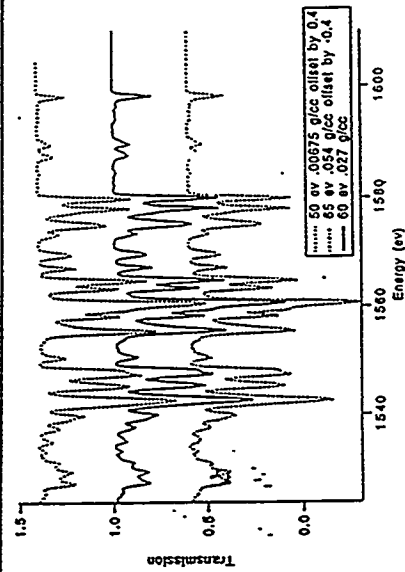
The two different thicknesses of aluminum provide a consistency check on the data reduction. Since the thick sample is three times the thickness of the thin sample, the cube of the transmission of the thin sample should equal the transmission of the thick sample.

1482090

Experiment agrees well with calculation

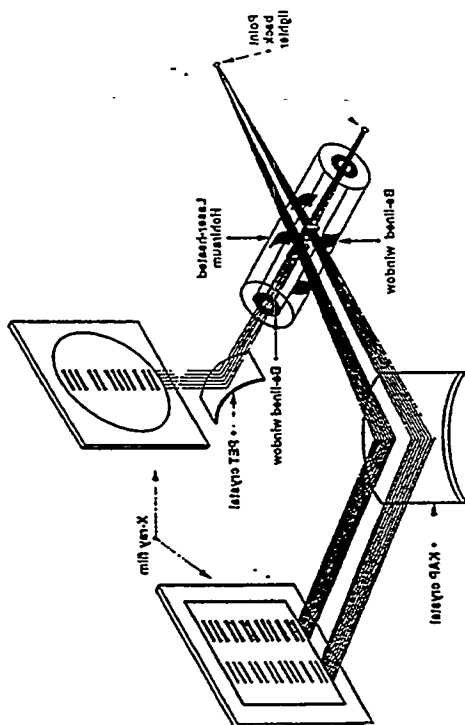


5 eV change in temperature is equivalent to a factor of 2 change in density

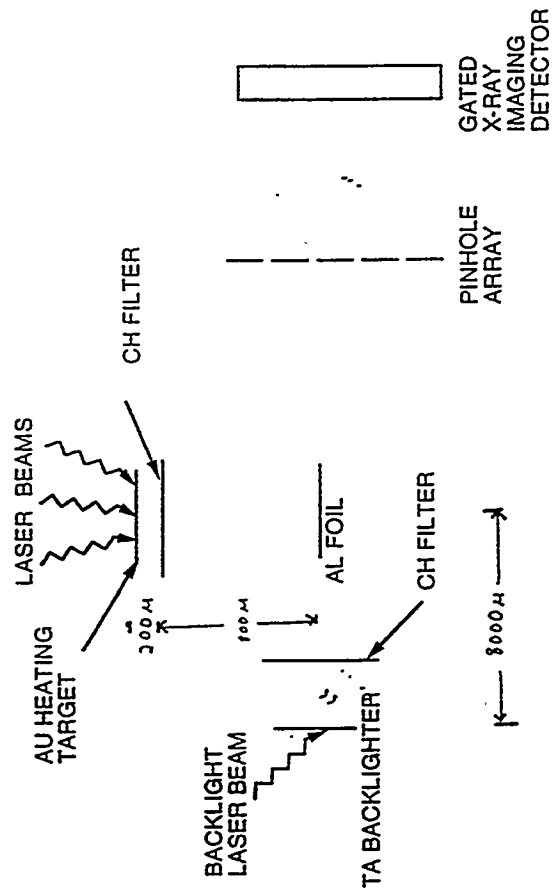


Goal was to have simple, well-characterized system

- We wanted to avoid any problems with laser - matter Interactions
- We wanted to have well-characterized x-ray deposition.
- We wanted to avoid strength of material problems
- We wanted to have space and time resolved density and temperature measurements.
- We wanted to be able to make rigorous comparison to code calculations.



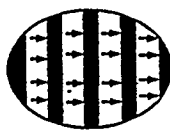
ARRANGEMENT OF RADIATIVELY DRIVEN ALUMINUM FOIL EXPERIMENT



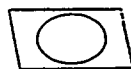
GXI (gated x-ray imager)



Pinhole array
has 16 holes
to produce
16 images



Sample
position



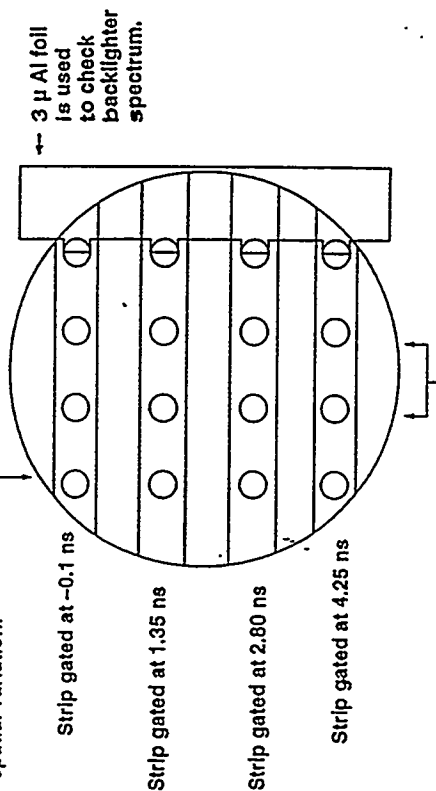
Laser beam hits
piece of tantalum
producing x-rays to
backlight sample

Microchannel plate x-ray
detector has four strips
which are gated at
four different times.

All 16 GXI channels necessary for proper data analysis



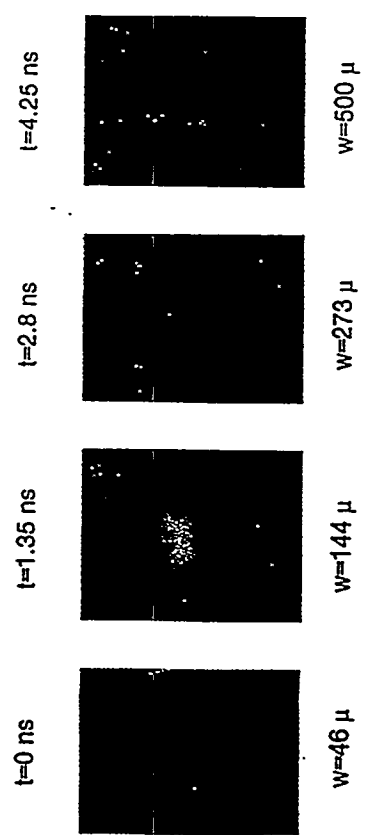
This column of images
used to remove backlighter
spatial variation.



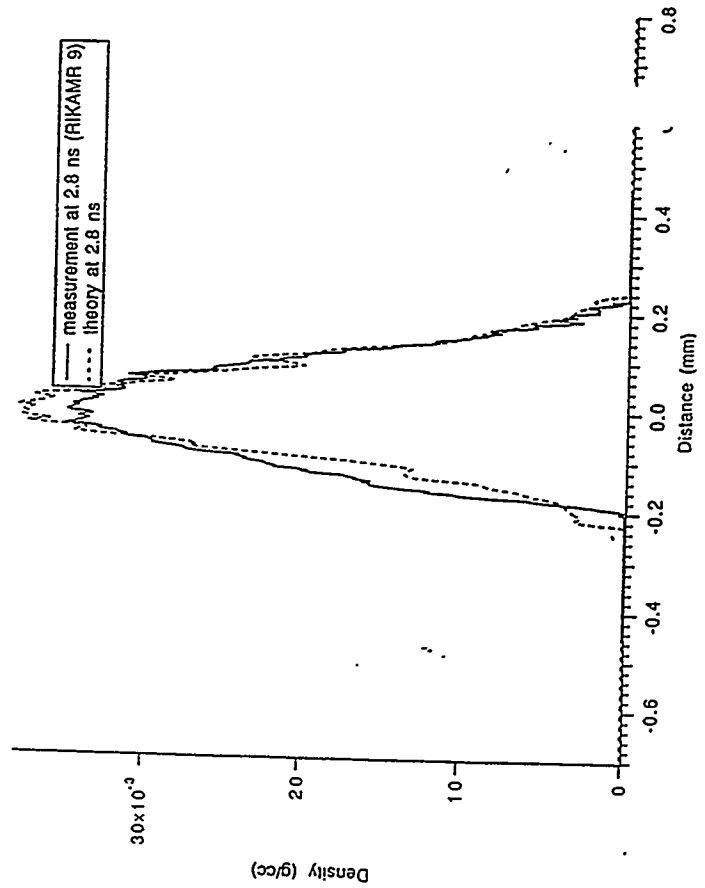
These columns used to image aluminum sample.
(we use column with best alignment.)

END OF LINE

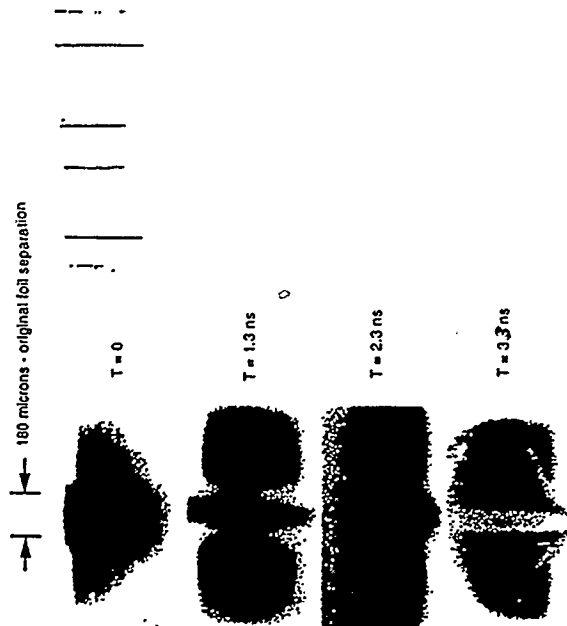
Expansion of an x-ray heated Al foil



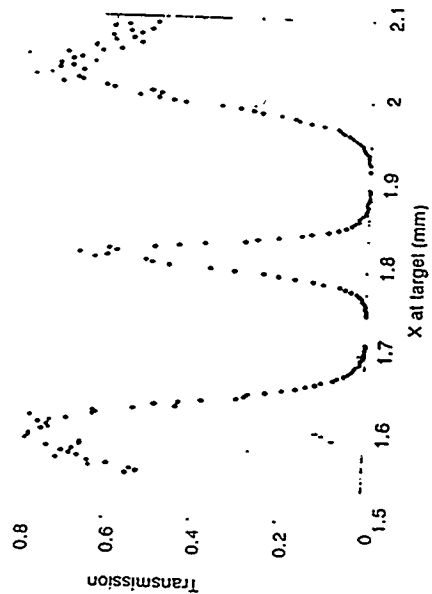
(The foil was 1000 μ long and 2 μ wide viewed at an angle of 2.5°.)



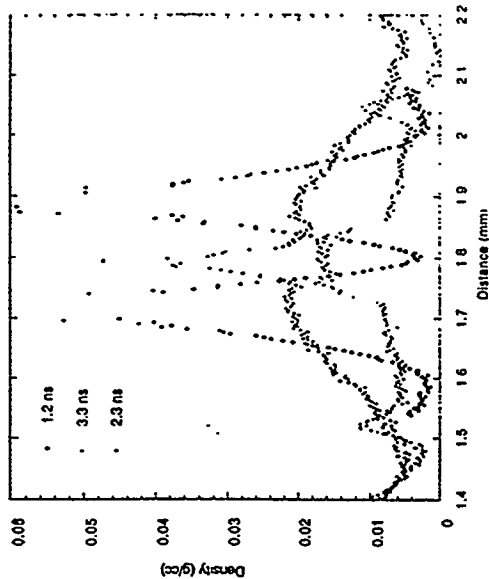
FRAMING CAMERA DATA FROM PARALLEL FOIL EXPERIMENT



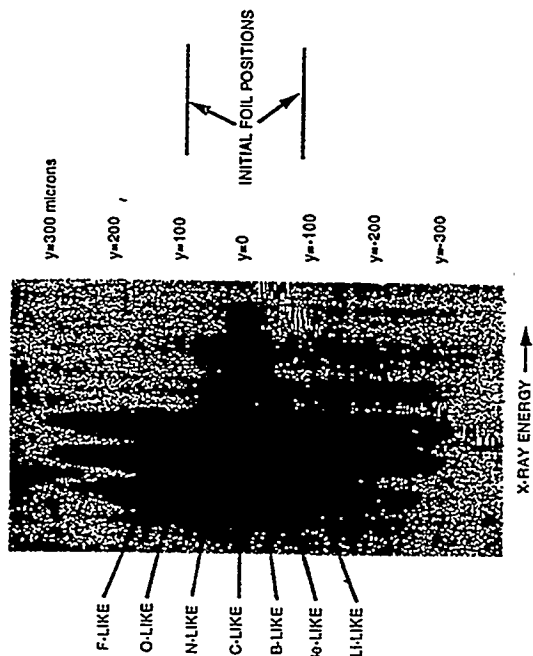
TRANSMISSION OF PARALLEL FOILS AT 1.3 NS



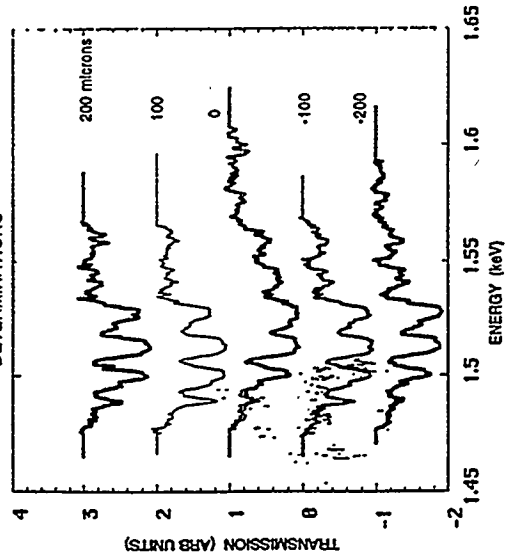
DENSITY DISTRIBUTIONS FOR DOUBLE FOIL EXPERIMENT



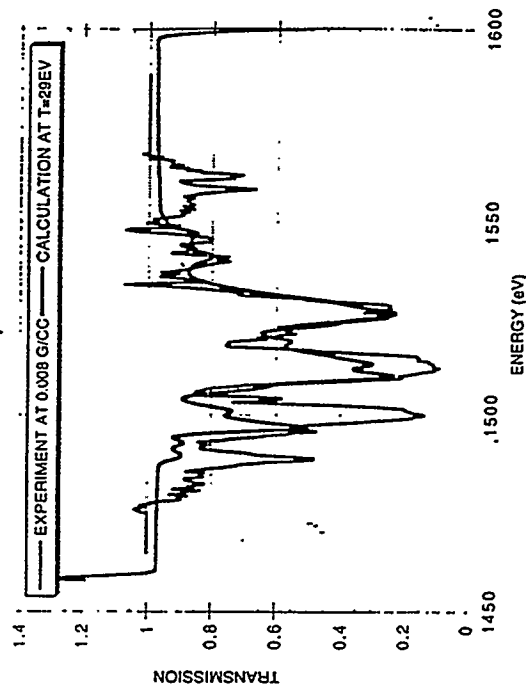
X-RAY IMAGE OF DOUBLE FOIL EXPERIMENT AT 2 NS
SHOWING 1-2 ALUMINUM LINE ABSORPTION



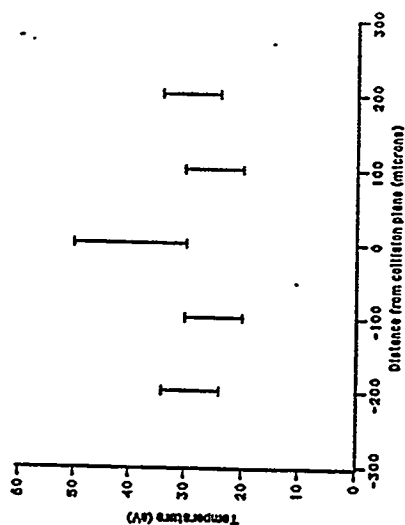
TRANSMISSION AT 2 NS FOR TEMPERATURE
DETERMINATIONS



COMPARISON OF MEASURED AND CALCULATED TRANSMISSION
PARALLEL FOIL EXPERIMENT

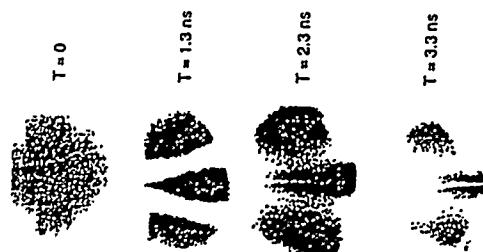


Temperatures for colliding foils



193193

FRAMING CAMERA DATA FROM ANGLED FOIL EXPERIMENT



Summary



- Temperature can be measured to $\pm 4\%$.
- Density can be measured to $\pm 25\%$.
- Gold M-band radiation can be used to heat matter to 10's of eV.
- These techniques have been used to study two colliding plasmas.

Instabilities and Mixing in SN1993J

Kohichi Iwamoto
University of Tokyo

Instabilities and Mixing

in SN1993J

K. Iwamoto, T.R. Young, T. Shigeyama, K. Nomoto

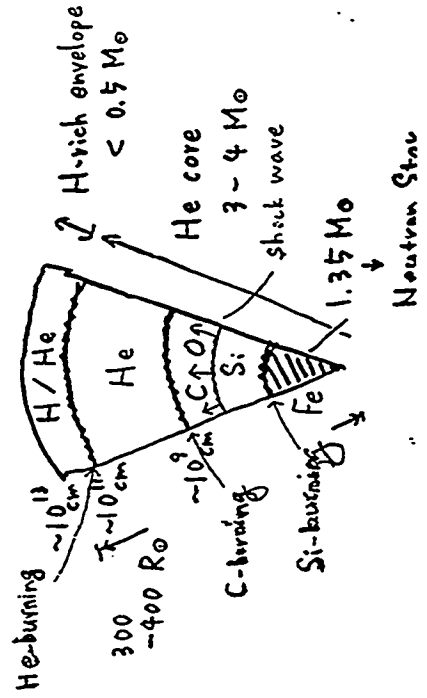
and
I. Hachisu

(University of Tokyo)

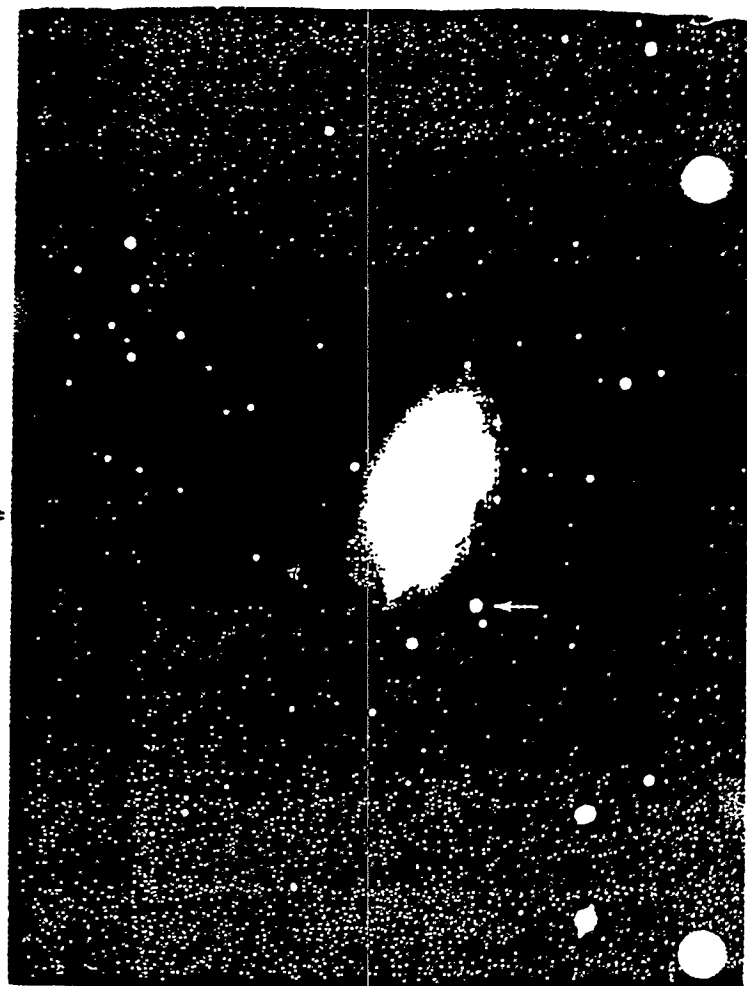
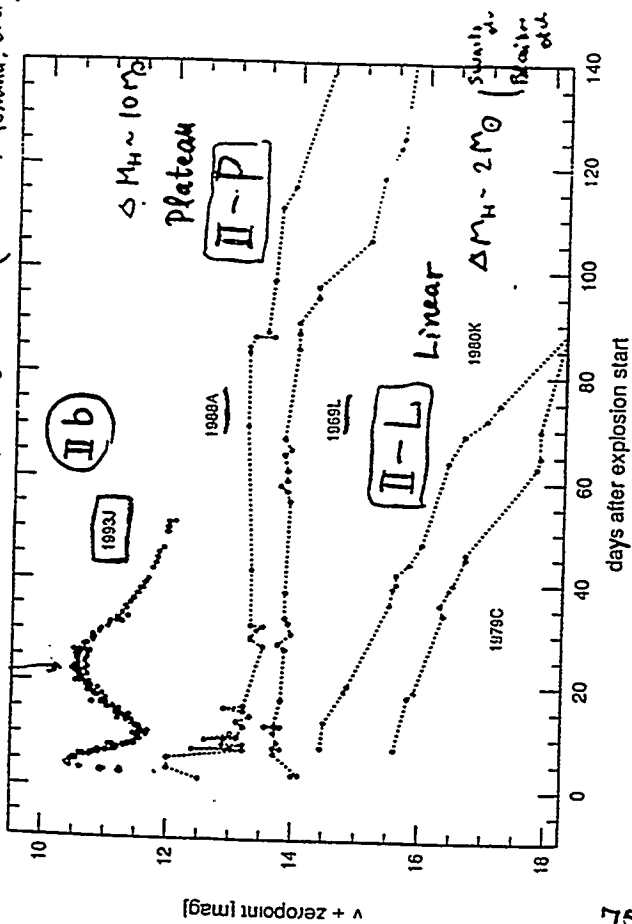
and
H. Saio

(Tohoku University)

1. Introduction
'peculiar' SN1993J in M81 Mar. 1993
H lines $\rightarrow$ Type II
2nd peak
spectral feature change
(H $\rightarrow$ He) $\rightarrow$ I-b like
 $\Downarrow$
'Type II-b' model (Podlowski et al. 1993
Nomoto et al. 1993
Woosley et al. 1994)

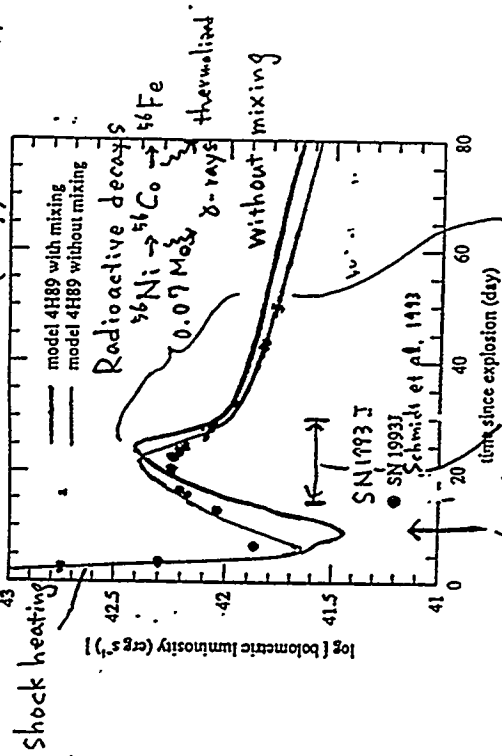


SN1993J - comparison light curves (Van Brui, Yoshida, et al)

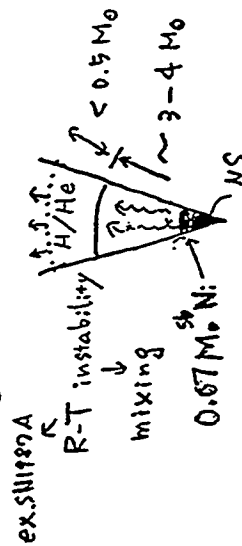


Light Curve Modeling

(Shigeyama et al. 1994)



$M(\text{H-rich envelope}) < 0.5 M_{\odot}$
 $M(\text{He core}) = 3 - 4 M_{\odot}$



2. Rayleigh-Taylor Instability

$$\frac{\rho_+}{\rho_-} \xrightarrow{\downarrow g} \omega_{RT}^2 = \frac{\rho_+ - \rho_-}{\rho_+ + \rho_-} k g$$

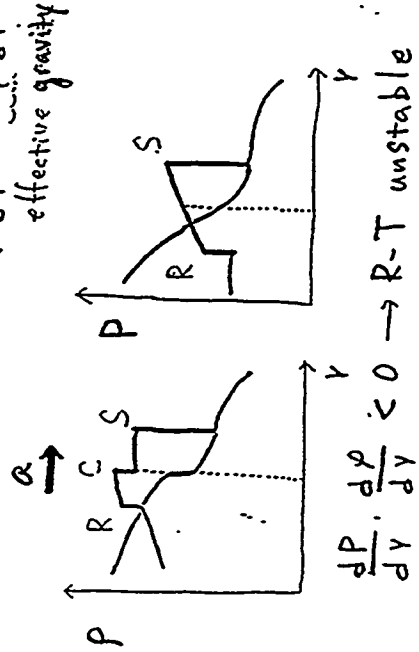
k : wavelength

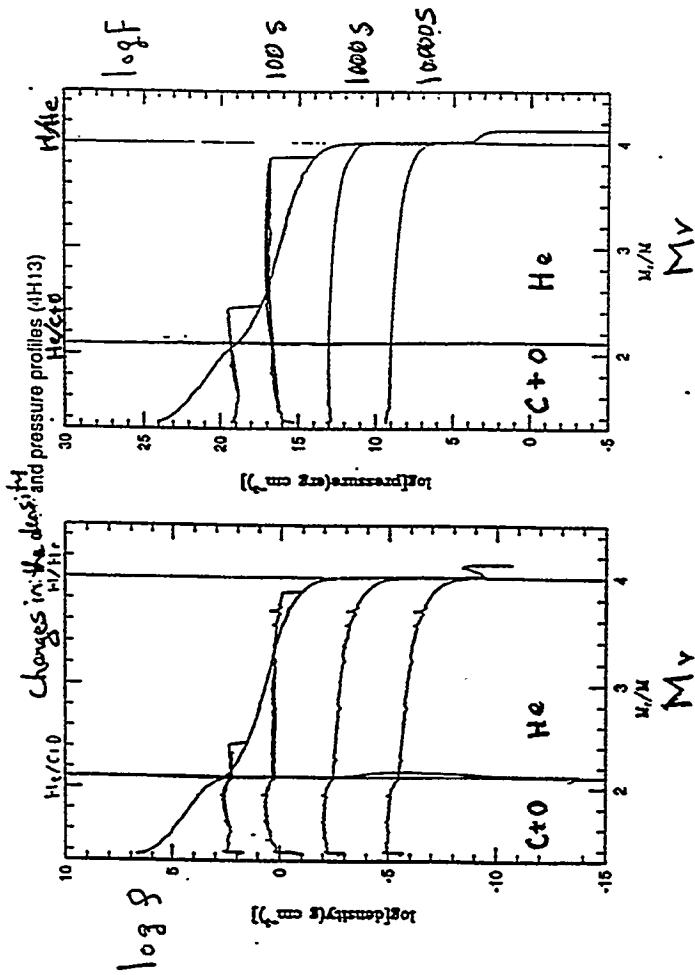
g : gravity

if $\rho_+ > \rho_-$, R-T unstable

In shocked ejecta of supernovae

$$\text{acceleration } a = -g - \frac{1}{\rho} \frac{d\rho}{dy} \approx - \frac{1}{\rho} \frac{d\rho}{dy} \text{ effective gravity}$$





Multi dimensional Simulations of the R-T instability in Supernova Ejecta

previous works
Arnett et al. (1989),
Hachisu et al. (1991),
Müller et al. (1991), ...

Initial Models

	$M_{\text{He}}/M_{\odot}$	$M_{\text{H}}/M_{\odot}$	$R/R_{\odot}$	$E (10^{51} \text{erg})$
3H11	3.3	0.11	450	1.0
4H13	4	0.13	580	1.0

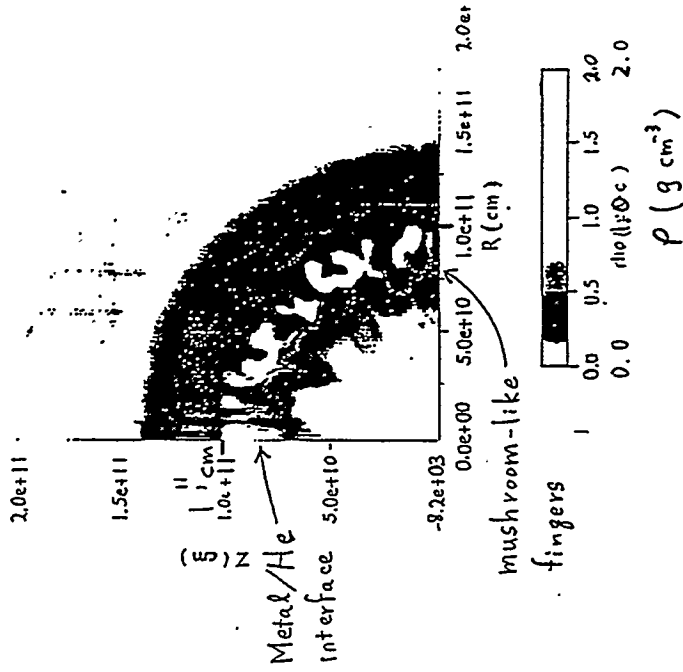
He core from Nomoto & Hashimoto (1988)
hydrostatic envelope model (H. Saio)

Method of Calculation

- 1-D Lagrangian PPM code (~ 10 sec)
- 2-D axisymmetric hydrodynamic code with 3rd order Roe scheme (I. Hachisu)
- EOS ... ideal fluid with $\gamma = 4/3$
- 512² grids
- random perturbation (5%)
- remapping procedure (> 10 times)

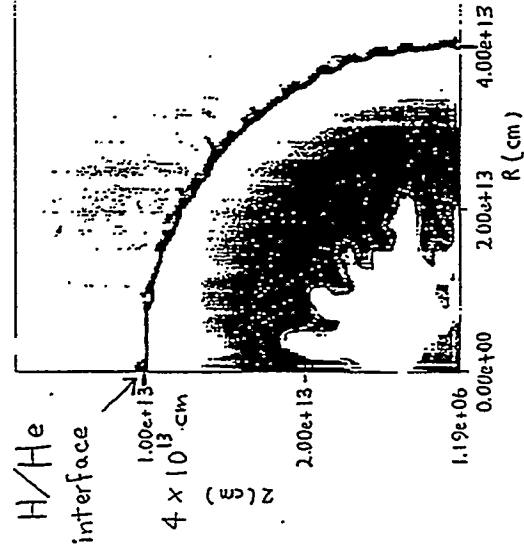
3H11 at 120 sec

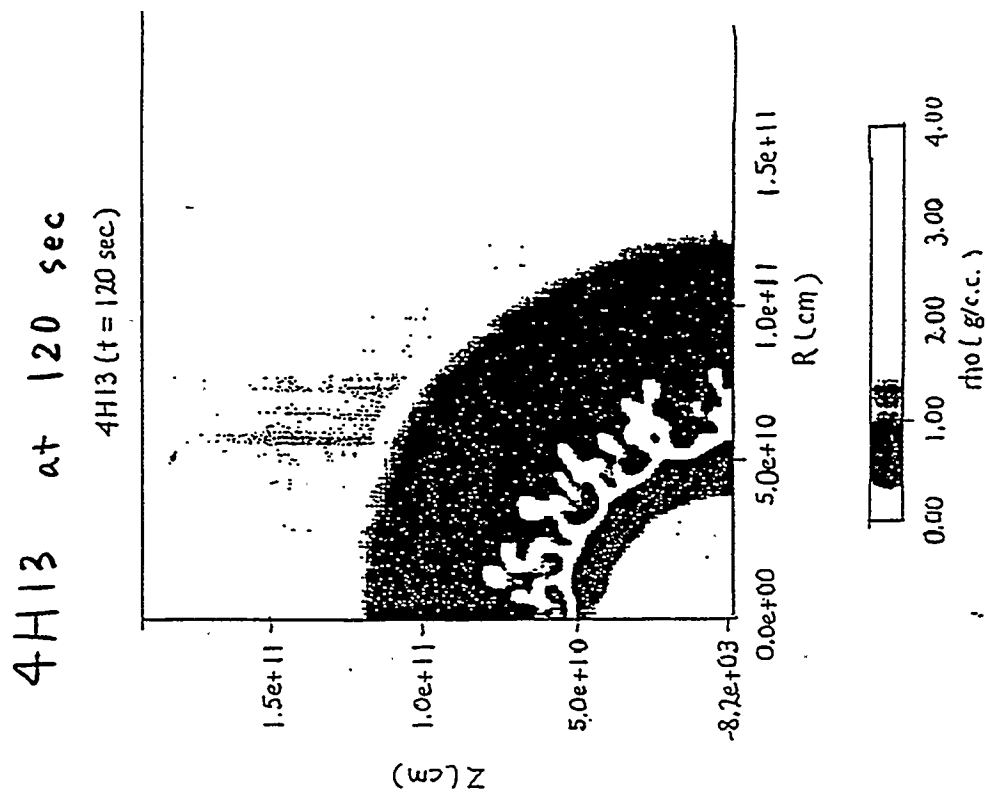
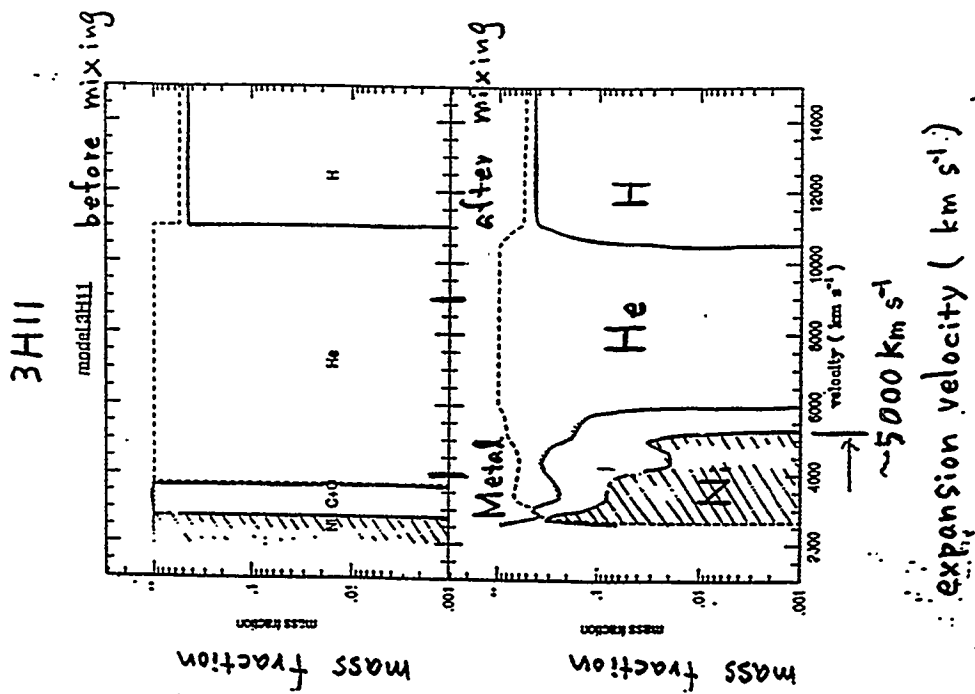
3H11 (t = 120 sec)



3H11 at 5×10^4 sec

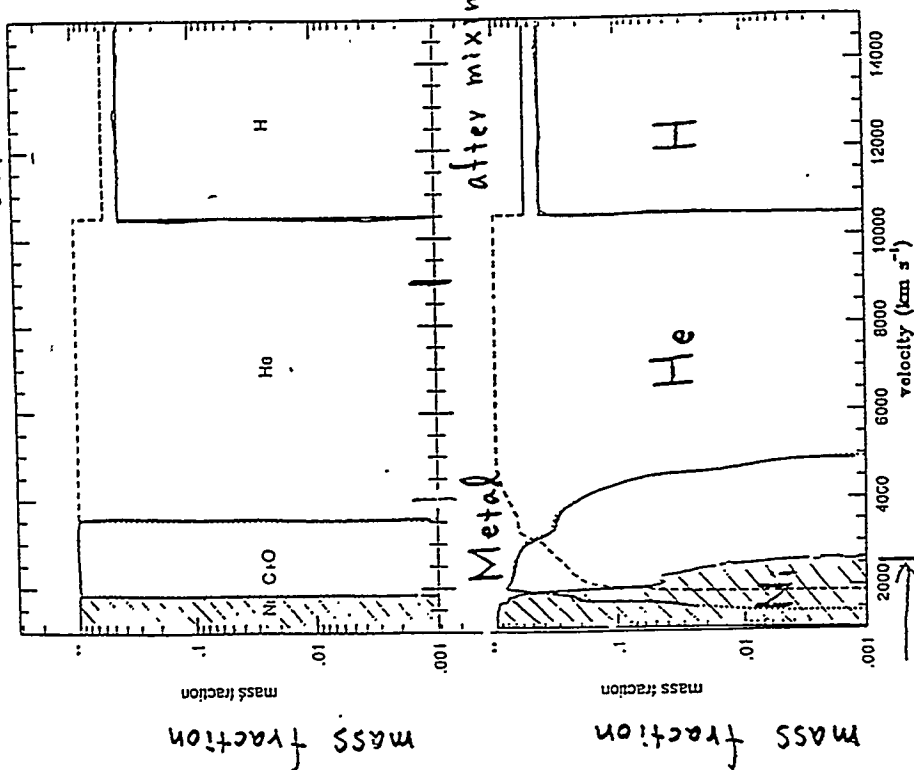
3H11 (t = 5E4 sec)





4H13

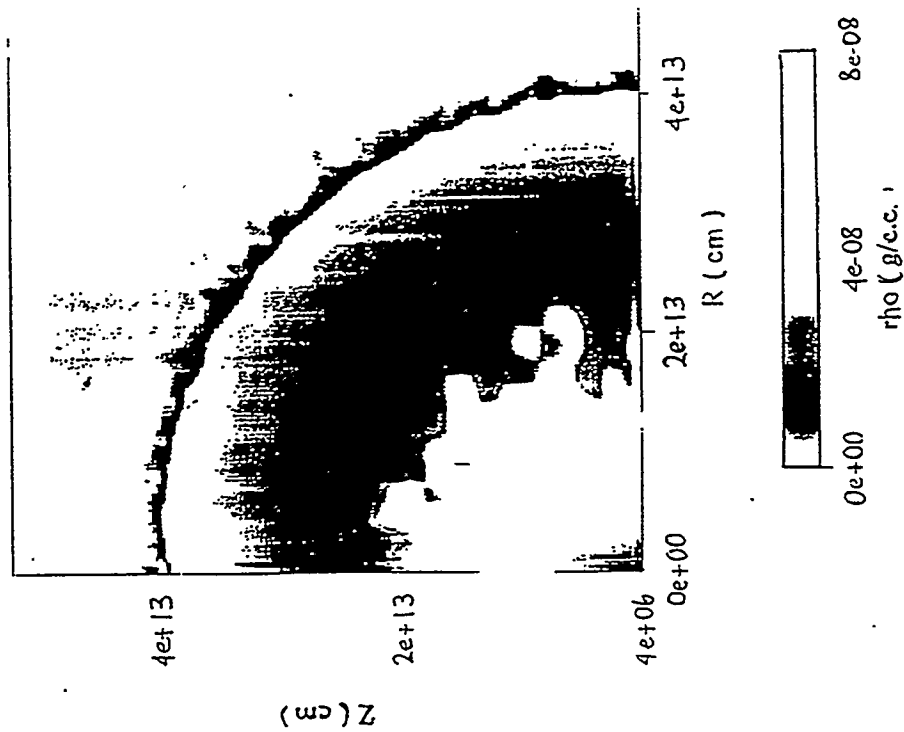
before mixing



$\sim 2500 \text{ km s}^{-1}$

expansion velocity (km s^{-1})

4H13 at $4 \times 10^4 \text{ sec}$



3. Discussions

(1) dependence on progenitor models steeper
Metal/He ... 3H11 has smaller core mass $\rightarrow d\rho/dy$
 $\rightarrow$ more R-T unstable $\rightarrow$ more mixing
than 4H13

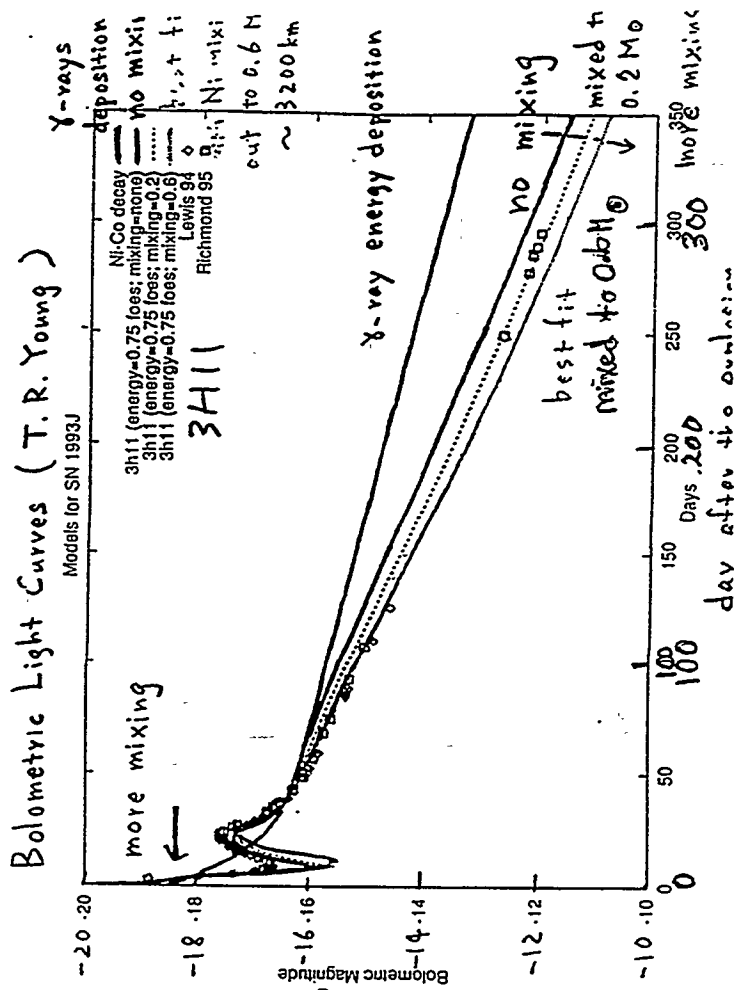
H/He ... small envelope mass
 $\rightarrow$ weak deceleration of shock $\rightarrow$ little mixing
 $\leftrightarrow$ SN1987A larger core mass $\sim 6 M_{\odot}$
 $\rightarrow$ little mixing at Metal/He
larger envelope mass $\sim 10 M_{\odot}$
 $\rightarrow$ much mixing at H/He

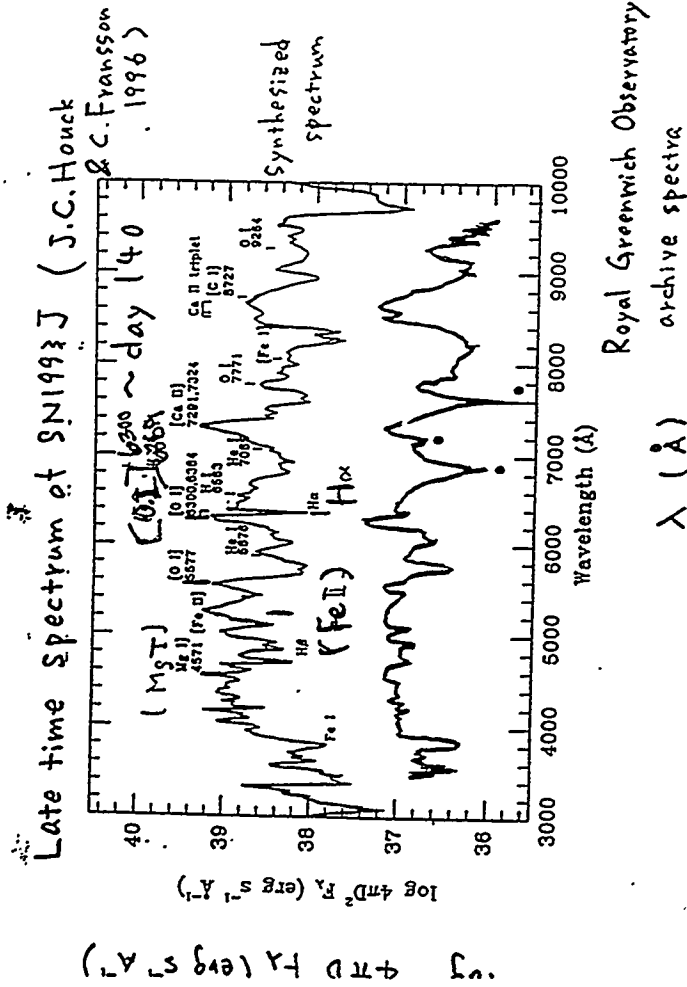
(2) influence on light curve shape
mixing $\rightarrow$ { earlier 2nd peak
faster decline in tail

best fit LC
by 3H11 with ^{56}Ni mixing up to $0.6 M_{\odot}$
 $\rightarrow$ consistent with 2-D results

(3) constraints from spectroscopic obs.

$O \sim (1-4) \times 10^3 \text{ km/s}$
 $H \sim (8.5-10) \times 10^3 \text{ "}$ c.f. preferable
 $\text{Ni mixing } > 3 \times 10^3 \text{ "}$ $\rightarrow$ 3H11 $\sim 5 \times 10^3 \text{ km/s}$
4H13 $\sim 2.5 \times 10^4 \text{ km/s}$





Conclusions :

1. The extent of mixing depends sensitively on the progenitor's structure.
more mixing with smaller core mass
2. In SN1993J, in contrast to 87A, there appears a large scale mixing at Metal/He interface due to the smaller core mass, but no prominent mixing at H/He interface due to the tiny H-rich envelope.
3. The study of Rayleigh-Taylor instability is important to identify the progenitor of supernovae.

Shock and Jet Experiments on Nova

Paul Miller
Lawrence Livermore National Laboratory

Shock and Jet Experiments on Nova

Paul Miller, Tom Peyser, Pete Stry,
Kim Budil, Debbie Wojtowicz, Don Griswold,
Bruce Hammel, Ted Perry, Larry Logory, and Gene Burke

Presented to the Workshop on Laboratory Astrophysics,
26 February 1996



Lawrence Livermore National Laboratory
University of California

Work performed under the auspices of the U.S. Department of Energy by the
Lawrence Livermore National Laboratory under Contract W-7405-Eng-48

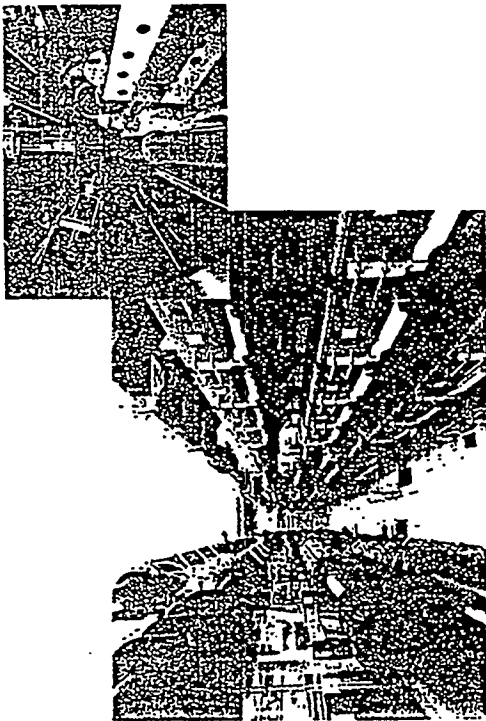
We are exploring a variety of flows

We are investigating shock-induced hydrodynamics with experiments on the Nova laser and with numerical simulations, including:

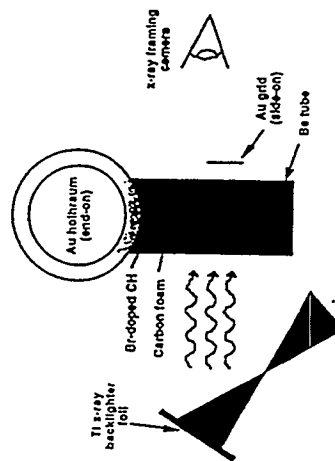
- The generation of flat shocks to drive our flows
- Flow peculiar to our non-rigid shock tube
- Hypersonic jet flows generated by a hemispherical protrusion at a density interface*
- The shock-induced mixing region between two materials of different densities with known, nonlinear initial interface perturbations*



The Nova laser delivers 25 KJ (3 ω) in 1 ns



Schematic of the experiment

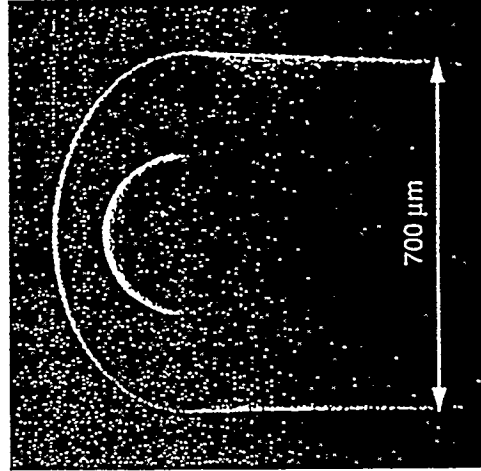


1. Eight of Nova's beams heat the hohlraum to ~ 230 eV (over 2×10^6 K)
2. Ablation drives a shock into the cylinder
3. The flow is backlit with a titanium backscatterer and imaged using a gated 2-D x-ray framing camera

Our shock tube is the size of the "I" on a dime



The jet is seeded by a hemispherical feature at a plastic / foam interface (foam part shown)

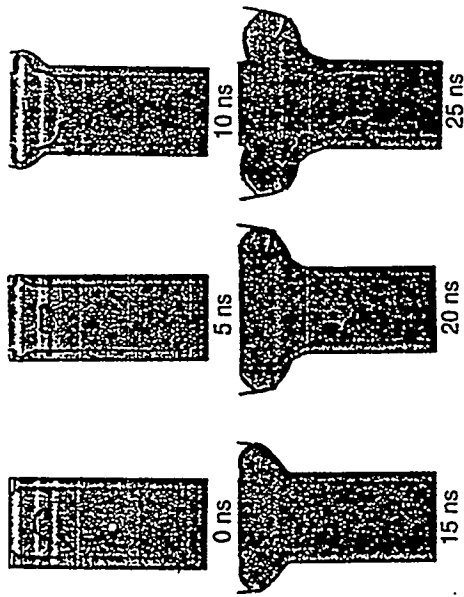


- micromachined with diamond tools
- hemisphere radius: 150 μm
- cylinder radius: 350 μm
- foam density: 0.1 gm/cc
- pore size < 1 μm
- surface finish $\approx$ 3 μm

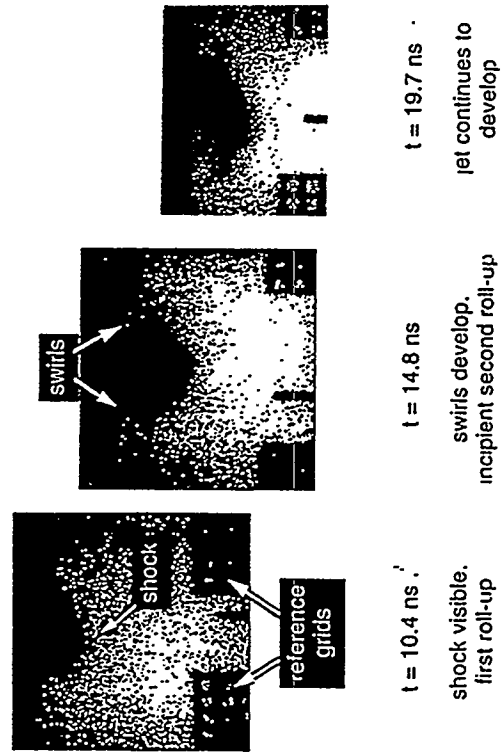
Scanning electron microscope image:
low-density, carbon foam piece
(oblique view)

Temporal progression of the high-speed jet (calc)

Material plots: pink – high density plastic, blue – low density carbon foam



Temporal progression of the high-speed jet (data)



Comparison of data and simulation images

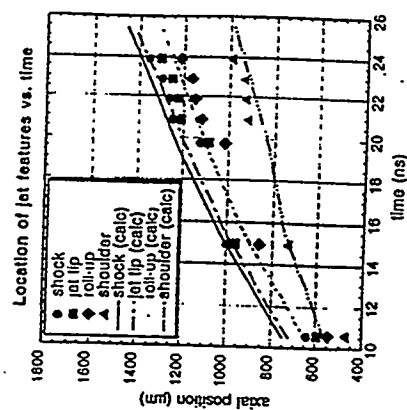
Simulated radiographs from CALE calculation



Data radiographs



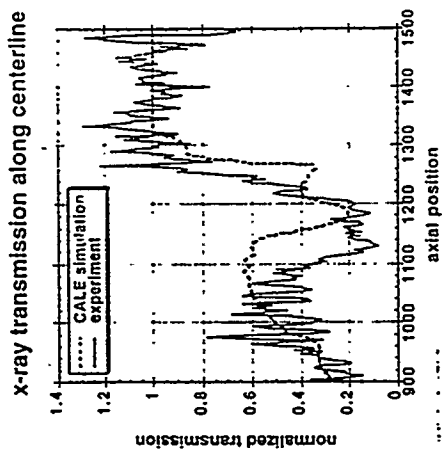
Jet features vs. time from data and simulations



Jet image at 21.9 ns

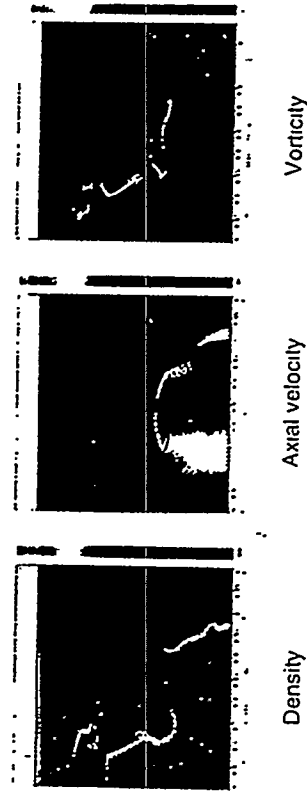
Comparison of lineouts from CALE and data

- both traces at 21.9 ns
- lineouts 100 μm wide
- backlighter nonuniformity removed from the data lineout
- max transmissions normalized to 1.0



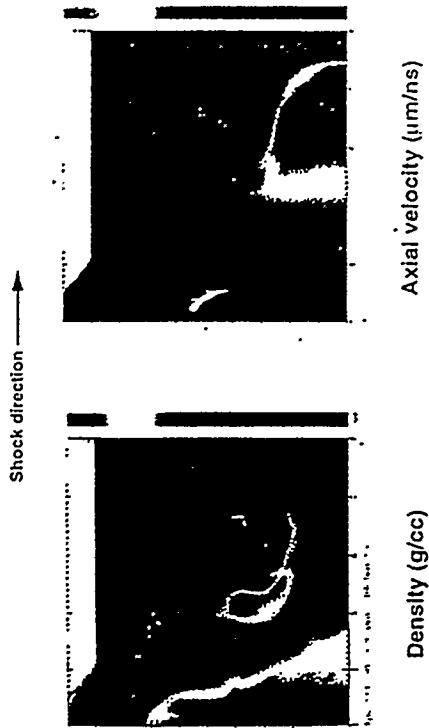
Agreement between experimental and simulated radiographs supports further use of simulations

- 2D CALE calculations of density, axial velocity and vorticity (15.5 ns)



Simulations permit examination of unmeasured quantities

Density and axial velocity from CALE simulations at 10.5 ns



The experiment is also being calculated with AMR

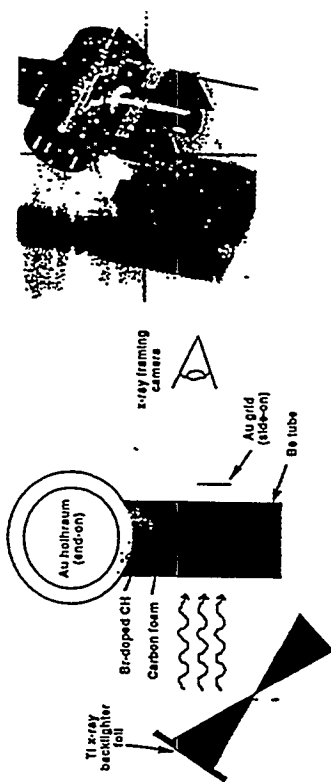
Jeff Greenough is using his Adaptive Mesh Refinement code on the jet

- ideal gas, two fluid, equal gammas
- second order Godunov, two levels of 4x refinement (1 μm finest)



log density contours

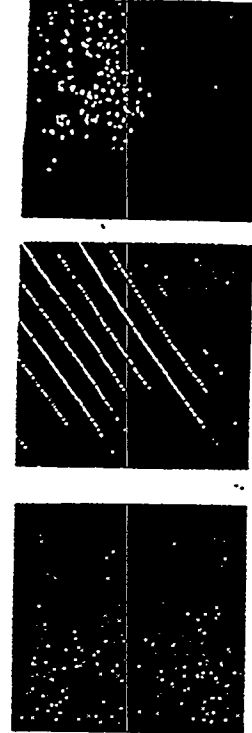
Schematic of the experiment



1. Eight of Nova's ten beams heat the hohlraum to about 230 eV
2. Ablation drives a shock into the cylinder
3. The flow is backlit with a titanium backscatterer and imaged using a gated 2-D x-ray framing camera

We employ a variety of interface perturbations in our Richtmyer-Meshkov experiments

three types of perturbations used on planar interfaces



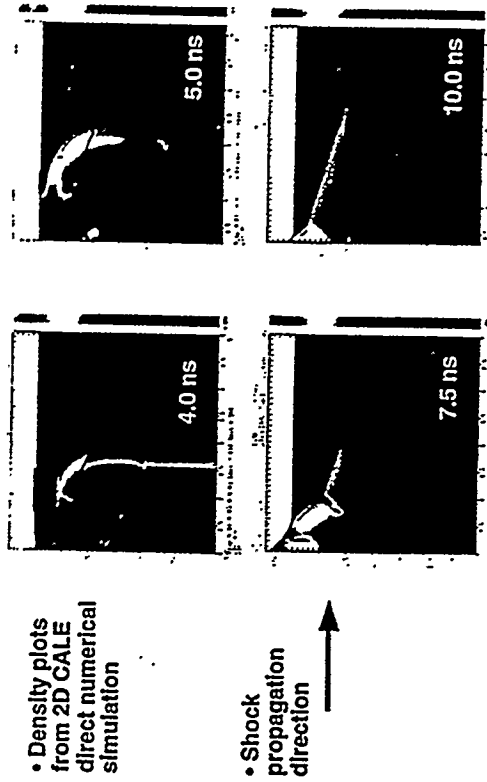
smooth

sawtooth

"astroturf"

scanning electron microscope images
(80 x 80 μm fields of view)

Temporal progression of sawtooth interface (calc)



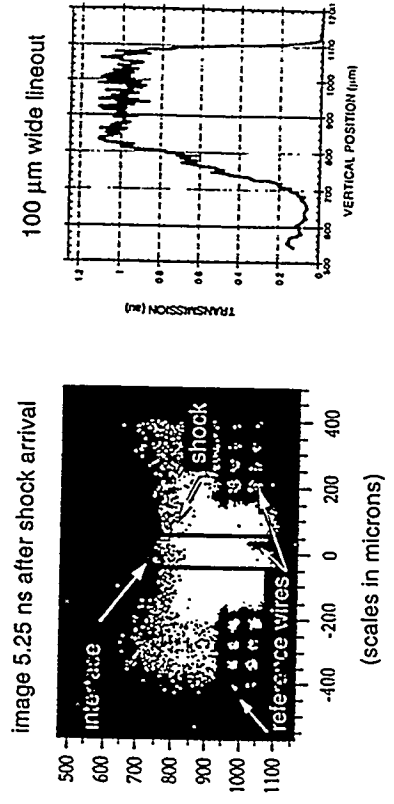
• Density plots from 2D CALE direct numerical simulation

• Shock propagation direction

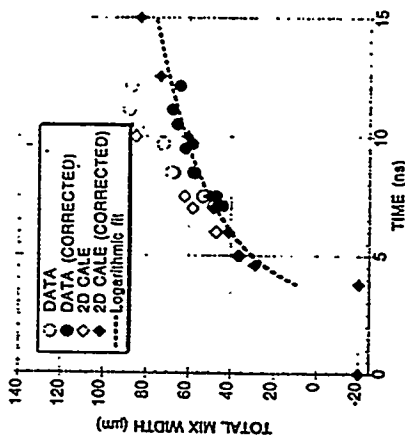
Shock-induced mixing experiments

We are making quantitative measurements of the mixing region widths

This example had a 20 μm sawtooth perturbation



Comparison of mix data and 2-D CALE calculation for 10 μm amplitude sawtooth perturbation



- Mix width for data and calculations based on 5 ~ 95% transmission criteria
- Effect of decompression obtained from LASNEX and CALE tracer layer calculations
- Experimental values in good agreement with macroscopic mix width results from CALE

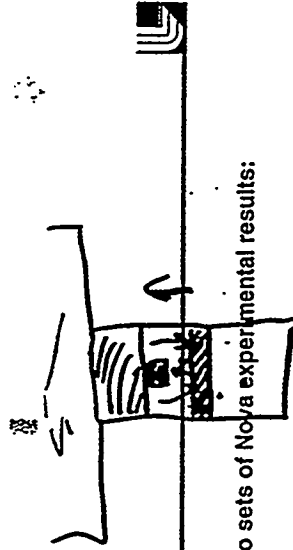
When the effects of target decompression are removed, the width of the mix region is consistent with a theoretical logarithmic behavior

ISSW - 19

Summary

We have described two sets of Nova experimental results:

- high-speed jet characterization
- Richtmyer-Meshkov instability growth leading to mixing



The experiments:

- demonstrate a general class of experiment which is possible on the laser
- yield data on physical mechanisms such as Richtmyer-Meshkov mixing
- provide well-diagnosed laboratory data in high-speed, compressible plasma flows for potential use in astrophysical code validation

Type Ia Supernovae

John Blondin
North Carolina State University

John Blondin

INSTABILITY OF HYDRODYNAMIC

SHOCKS

Radiative Shocks

- What is a radiative shock?
- Instabilities on scales $\sim L_{cool}$
- Instabilities on scales $\gg L_{cool}$ (isothermal shocks)

Shock/Shell Collisions in SNRs

Cassiopeia A

Kepler

SN 1987A

Postshock Thermal Energy

$$n k T \sim \rho V^2 \quad \text{ergs/cm}^3$$

Postshock energy loss rate

$$\sim n^2 \Delta(T) \quad \text{ergs/s/cm}^3$$



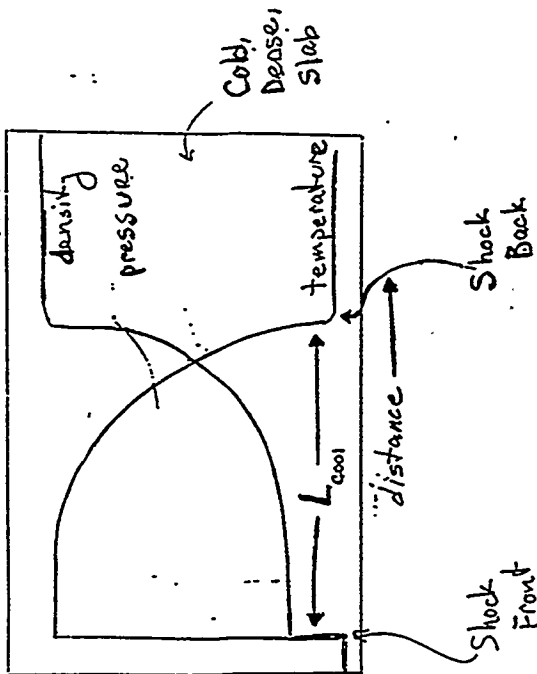
Cooling timescale

$$t_{cool} \sim \frac{k T_{sh}}{n \Delta(T_{sh})}$$

How far downstream will gas start to cool

$$L_{cool} = \frac{V_0}{4} t_{cool} = \frac{\bar{m} V_0^3}{85 n_0 \Delta(T_{sh})}$$

Radiative Shock Profile



Supersonic Flow
onto a Wall

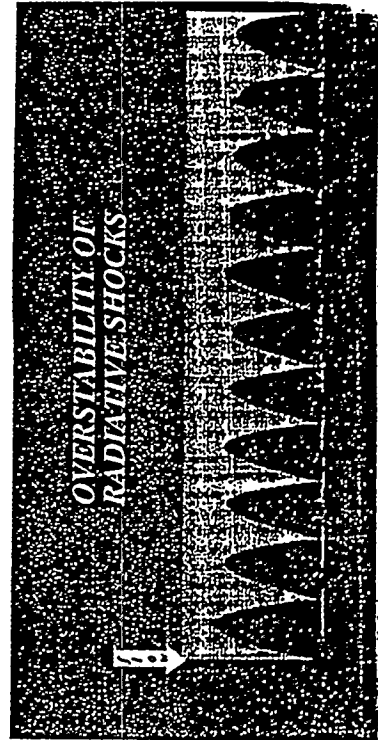
e.g. accretion onto
a white dwarf



SHOCK FRONT

Cooling, Settling gas

COLD DENSE GAS



time →

Overstability of Radiative Shocks

for $n = n_0 T^\alpha$ $t_{cool} \approx \frac{k T_{sh}}{n_0 T_{sh}^\alpha} \propto V_{sh}^{2(1-\alpha)}$

Consider a radiative shock compressed from equilibrium



The postshock gas does not cool by L' , so cooling region is too hot - overpressured.

Extra pressure pushes shock front out.



Now shock velocity is higher than normal

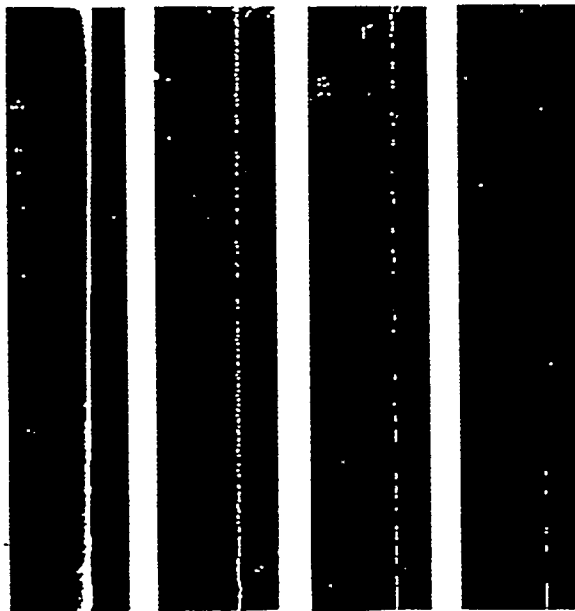
If $\alpha < 1$, higher $V \rightarrow$ larger t_{cool}
postshock continues to push overstable

If $\alpha > 1$, higher $V \rightarrow$ shorter t_{cool}
postshock cools, stops pushing

Shocks with $\alpha > .75$ are stable.

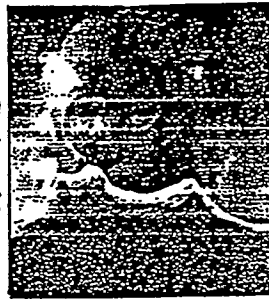


Stability increases with Mach #



Instability of Radiative Shock in 2D

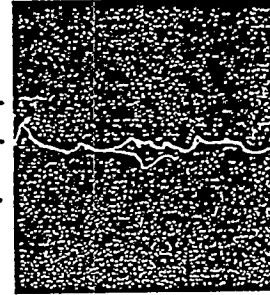
$\alpha=0$ $M=5$



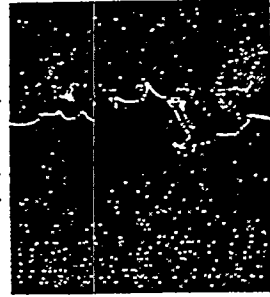
$\alpha=1$ $M=5$



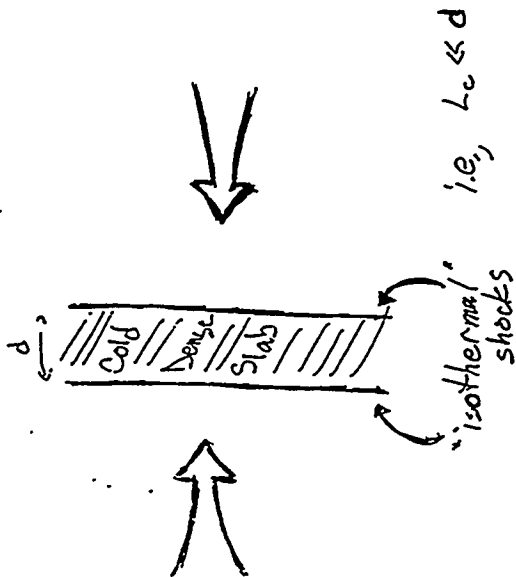
$\alpha=0$ $M=40$



$\alpha=1$ $M=40$



THE SHOCK-BOUNDED SLAB

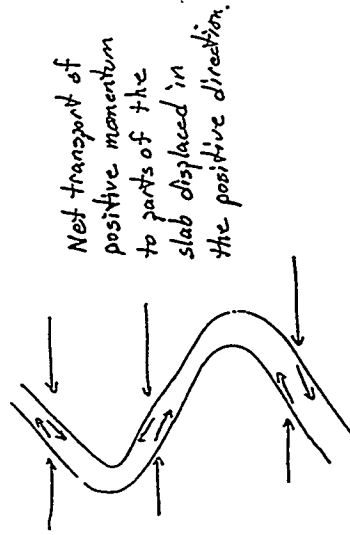


- Molecular Clouds.
- Stellar Winds.
- Planetary Winds / Cosmological.

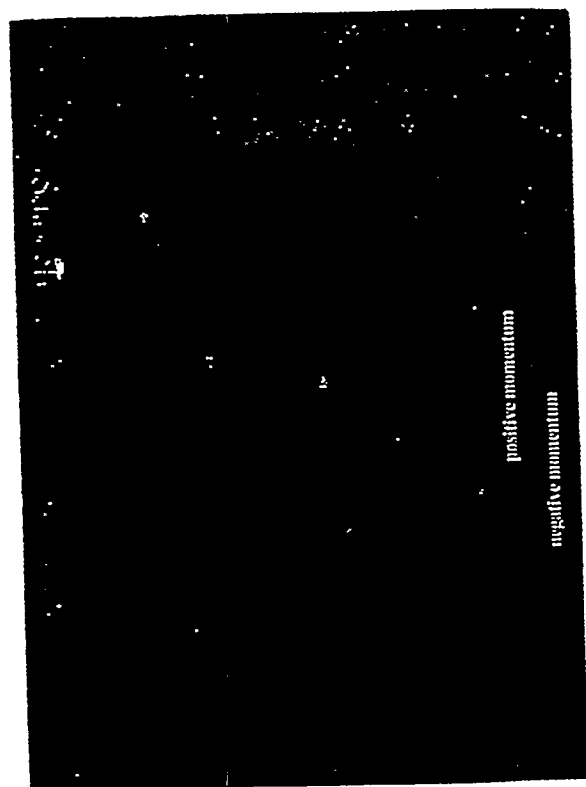
Vishniac (1994):

Nonlinear
Thin
Shell
Instability

- Cold, Shock-bounded is
- Stable to linear perturbations
 - Unstable to nonlinear perturbations

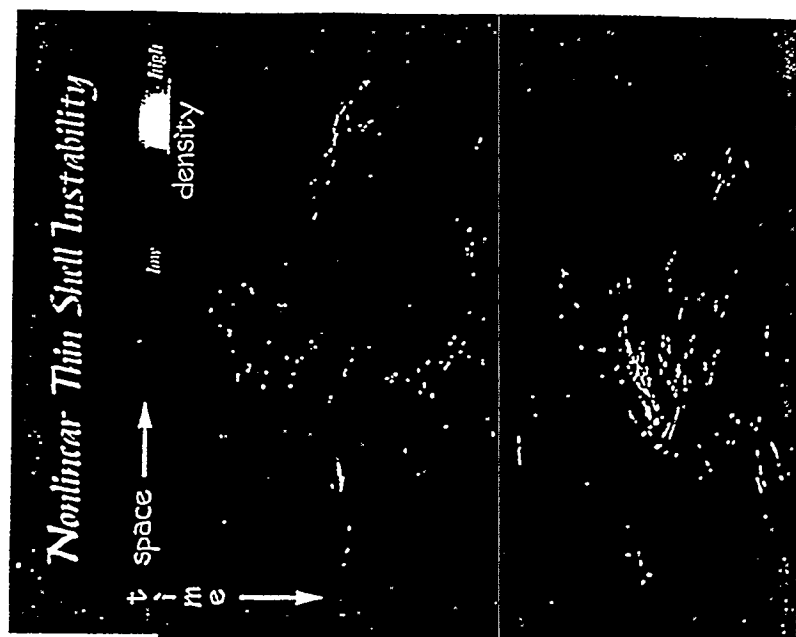


also Nonlinear Deceleration Instability



positive momentum

negative momentum



Nonlinear Thin Shell Instability

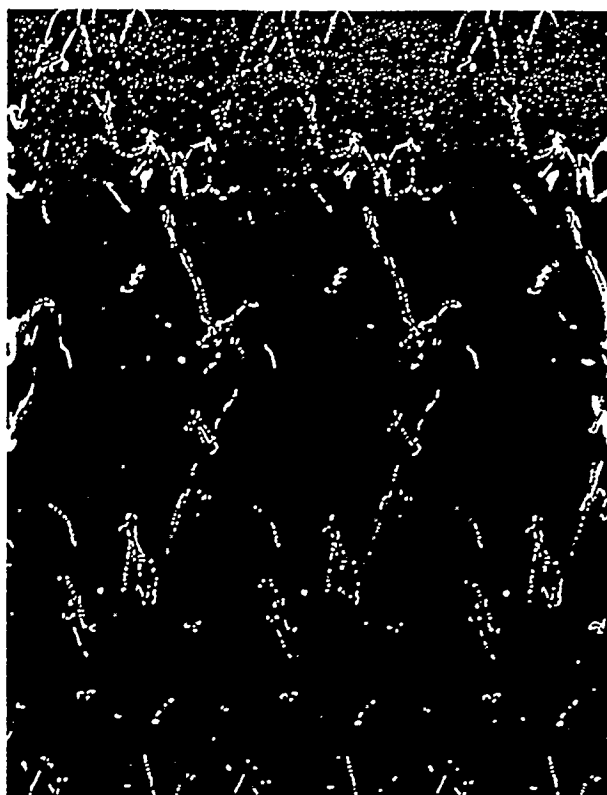
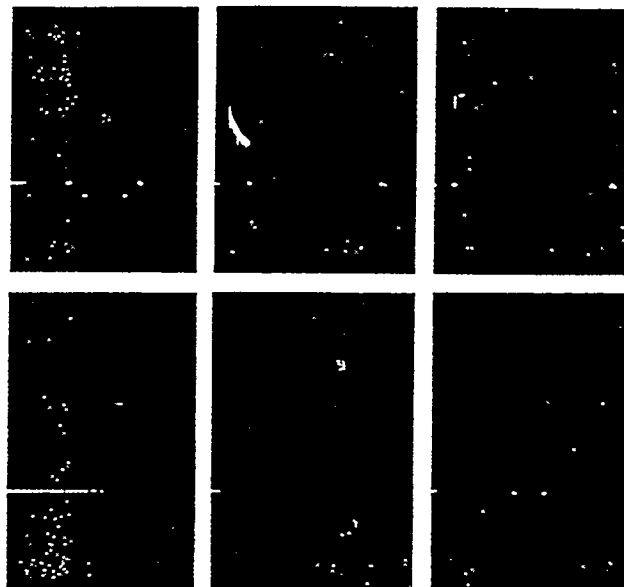
space →

time ↓

low

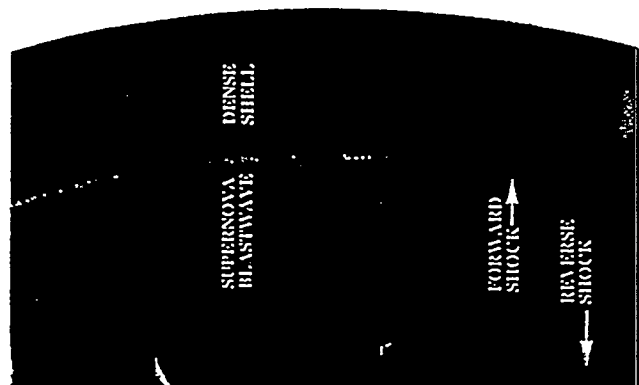
high

density



CASSIOPEIA A SUPERNOVA REMNANT: A 2D HYDRODYNAMIC MODEL

Borkowski, Szymkowiak, Blondin, Saraz



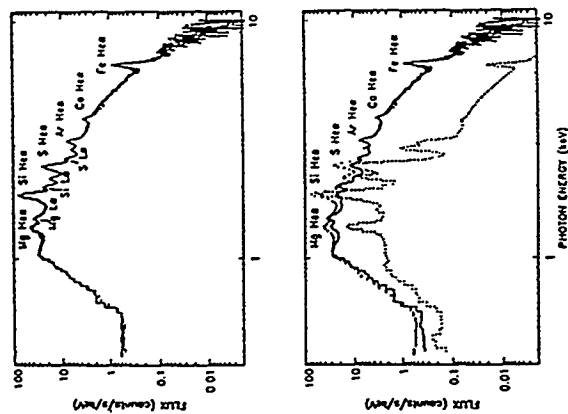


Fig. 2.— The spatially-integrated spectrum of Cas A obtained with the ASCA Solid-state Imaging Spectrometers. The calculated X-ray spectrum is shown by the solid curve in the top panel, while the bottom panel shows the contributions from the CSM (solid curve) and from the SN ejecta (dotted curve) separately. The Ar He line at 3.12 keV was not included in these calculations — this line was simply fitted by a Gaussian.

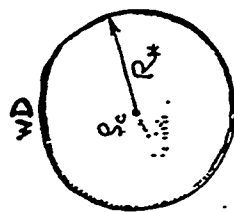
Instability of Hydrodynamic Shocks

Alexei Khokhlov
University of Texas/Austin

Alexi Khokhlov

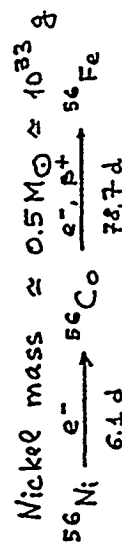
Type Ia Supernovae

- explosion of a $1.4 M_{\odot}$ carbon-oxygen degenerate star.



- Mass $\approx 3.8 \times 10^{33}$ g
- Radius $\approx 2 \times 10^8$ cm
- $S_c \approx 2 \times 10^9$ g cm⁻³
- $a_s \approx 10^9$ cm s⁻¹

- Explosion time ≈ 1 sec.
- Kinetic Energy $\approx 10^{51}$ ergs.
- Expansion velocity $\approx 10^9$ cm s⁻¹.



Luminosity at maximum $\approx 10^{43}$ ergs per sec.

$t \approx 1$ year

FLAME

- $^{12}\text{C} + ^{12}\text{C}$ heat conduction
- δ_ℓ - FLAME THICKNESS: $\frac{10^{-2} - 10}{10^7 - 10^4}$ cm
- S_ℓ - FLAME SPEED: $\frac{10^7 - 10^4}{10^7 - 10^4}$ cm/s

FLAME IS A THIN SURFACE

- $\delta_\ell \ll R_{WD}$
- $U'(S_\ell) < S_\ell \Leftrightarrow \lambda_C > \delta_\ell$

$$\lambda_C \approx \lambda : U'(\lambda) \approx S_\ell$$

BENCHMARK PROBLEM

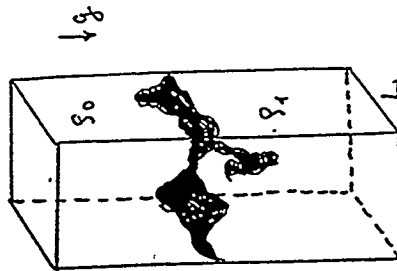
FLAME IN A UNIFORM GRAVITY IN A BOX

$$g, L, S_0, \frac{g_0}{g_1} \quad S_{\text{turb}} =$$

$$- \frac{g_0}{g_1} > 1$$

$$- F_r = \frac{S_0^2}{gL}$$

- BOUNDARY CONDITIONS



$$S_{\text{turb}} = S_0 f_1(\alpha, F_r) \\ = \sqrt{gL} f_2(\alpha, F_r)$$

LIMIT $F_r \rightarrow 0$

BUOYANCY DOMINATES

$$S_{\text{turb}} = C \sqrt{gL} f(\alpha)$$

• $C = ?$

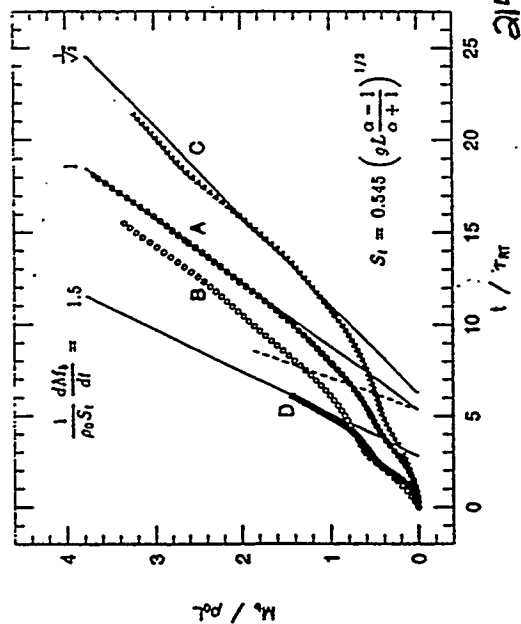
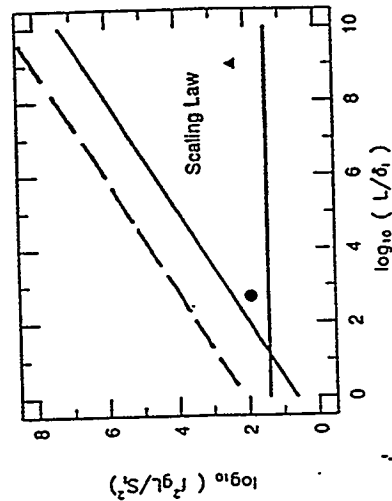
• $f(\alpha) = \frac{\alpha-1}{\alpha+1} \quad - ?$

- Surface $A \propto \frac{1}{S_0} \quad - ?$

Experimental calibration
(Khokhlov, Oran, Wheeler, 1994)
Combustion & Flame

▲ - SN

- - experiment: $L = 50 \text{ cm}$, $H = 4 \text{ m}$
methane
 $\phi = 0.6$
 $g = 980 \frac{\text{cm}}{\text{s}^2}$
 $S_{lam} = 10 \text{ cm/s}$



**Laser-Generated High Mach-Number
Shocks in Lab Simulations of
Astrophysical Phenomena**

**Jacob Grun
Naval Research Laboratory**

Laser-Generated High Mach-Number Shocks in Lab Simulations of Astrophysical Phenomena by Jacob Grun

Naval Research Laboratory

Outline

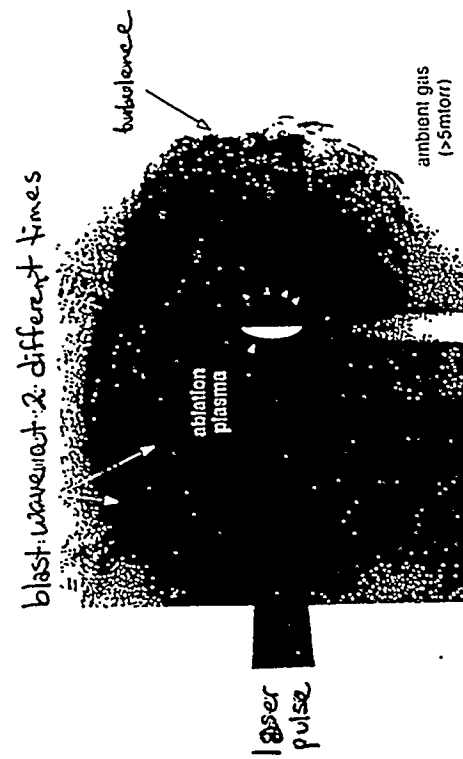
- how lasers generate shocks and turbulence
- shock wave instability experiment
- shock-turbulence interaction experiment

Colleagues:

A. Buckingham, R. Burris, J. Crawford, C. Manka, B.H. Ripkin, J. Stamper

Laser as a source of shocks, blast waves and turbulence
little mass to obscure hydro
energy density = $\text{kJoule}/\mu\text{gram}$

Naval Research Laboratory



Blast waves in a uniform ambient gas Are they stable?

Naval Research Laboratory

relevance to astrophysics (from Mac Low and Norman, Astr. J. 497, pg. 207 (1993))

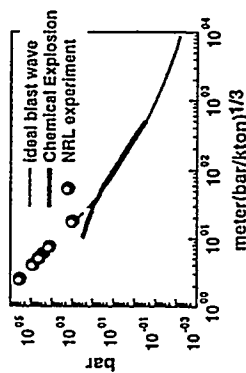
- filamentary structures in older supernovae
- Initial conditions for star formation
- formation of globular clusters

some theoretical work

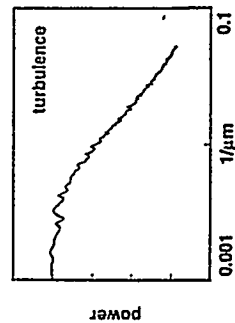
- Insenberg (1977), Cheng (1979), Book (1980)
- Newman (1980), Vishniak (1983), Gaffet (1984)
- Bertschinger (1986), Ryu and Vishniak (1987)
- Kohberg (1989), Mac Low and Norman (1993)

Typical scales

Naval Research Laboratory



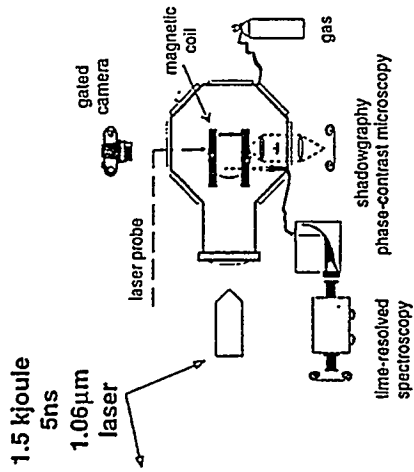
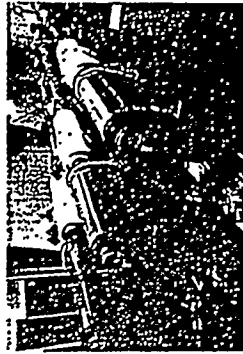
- blast radius: 1cm
- shock width: 100 microns
- Mach number: few hundred



- Kolmogoroff scaling
- flow speed: 10^5 cm/sec
- Reynolds number: 10^5

Setup of experiment

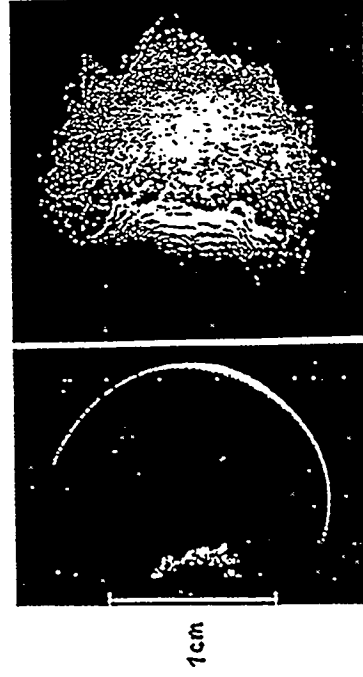
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1986, p. 1046, Fig. 1

Blast waves in a low γ gas are unstable

Naval Research Laboratory

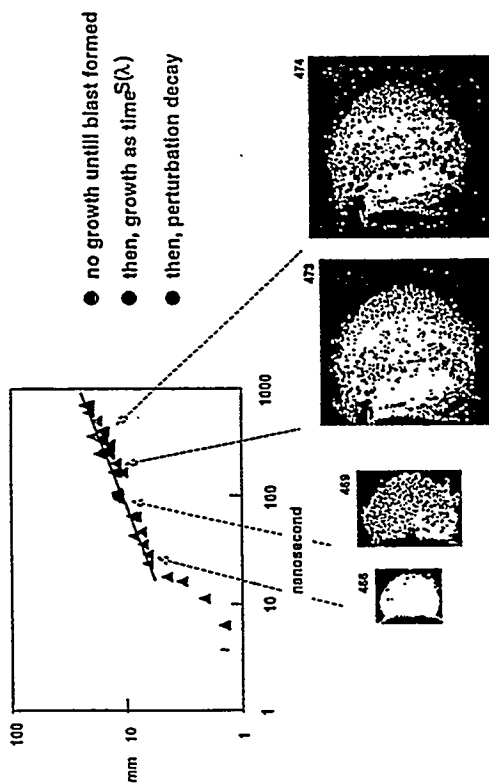


in nitrogen ($\gamma \approx 1.4$)

in xenon ($\gamma \approx 1.1$)

Progression of perturbation growth

Naval Research Laboratory

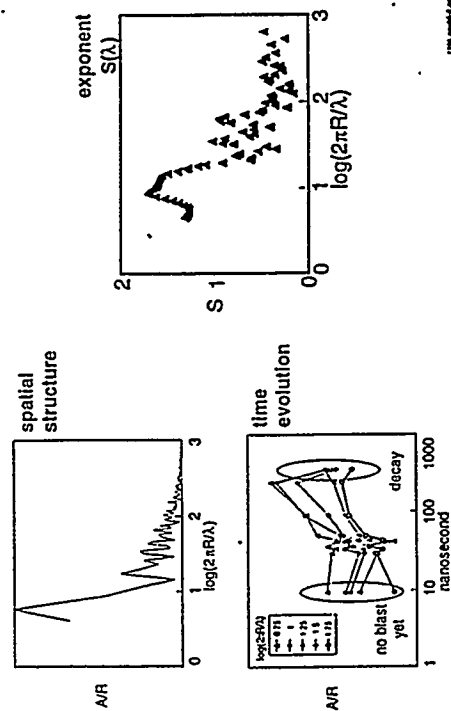


- no growth until blast formed
- then, growth as time $S(\lambda)$
- then, perturbation decay

$$A/R \propto \text{time } S(\lambda)$$



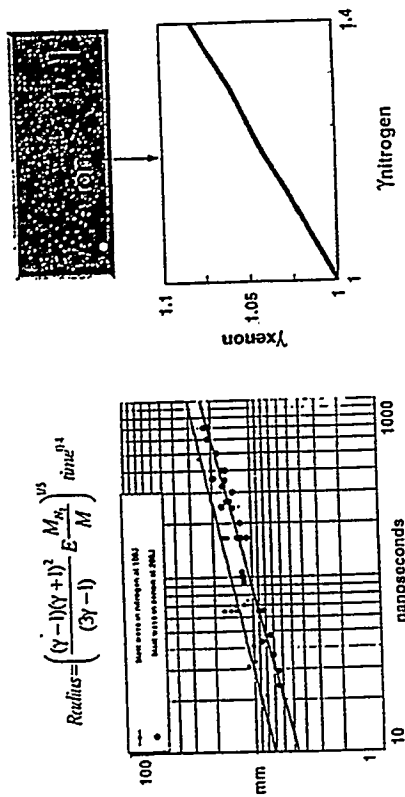
Naval Research Laboratory



1996-04-01

γ of Xenon inferred from Taylor-Sedov solution

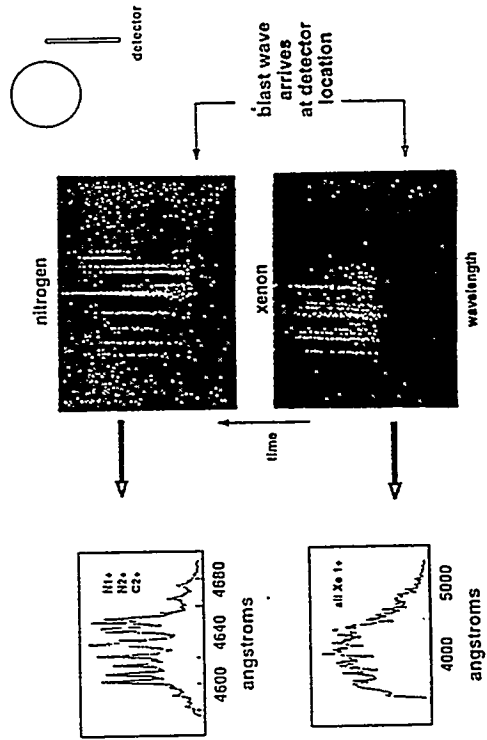
NAVAL RESEARCH LABORATORY



1998 10/10/98

γ of xenon lowered by copious emission

NAVAL RESEARCH LABORATORY



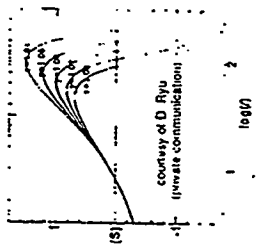
1998 10/10/98

Comparison to theory

Naval Research Laboratory

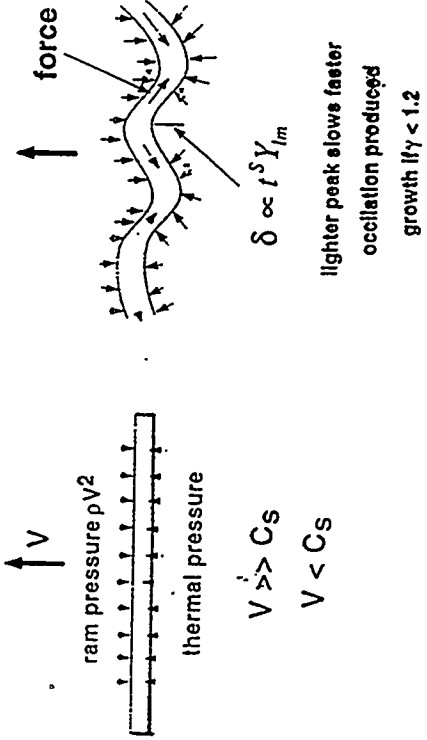
source
Linear: Ryu and Vishniac, Astrophys. J., 368, pg. 411 (1991)
Non-linear: Mac Low and Norman, Astrophys. J., 407, pg. 207 (1993)

- experiment confirms Vishniac's prediction of overstability when $\gamma < 1.2$
- time $S(\gamma)$ growth agrees with linear theory
- But, experimental $S(\gamma)$ is ~ 2 times larger than predicted
- observed saturation explained by nonlinear theory



Instability mechanism*

Naval Research Laboratory

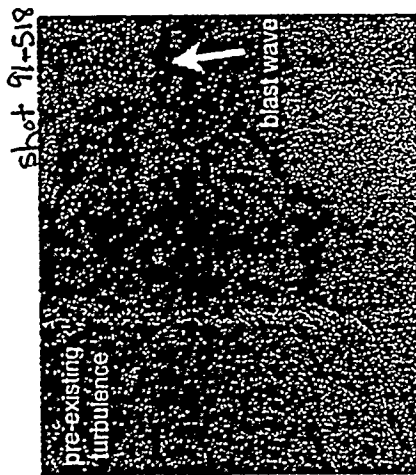


* from E.T. Vishniac, Astr. J. 274, pa. 152 (1983)

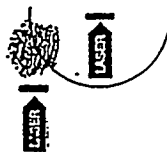
Turbulence appears altered by Blast-wave

Weak-shock theory predicts turbulence amplification & PSD changes

There is no strong-shock theory

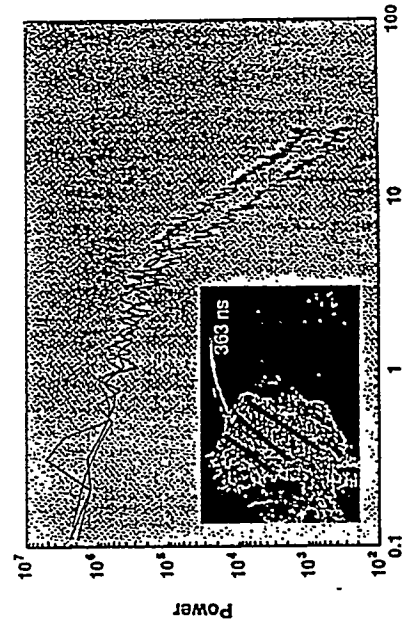
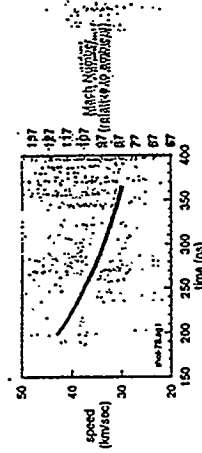


2cm



NIR

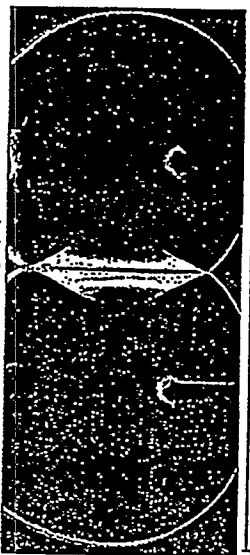
Turbulence amplification in nitrogen gas



Colliding blast-waves experiment

Scaling: two explosions, 45km apart,
100 kinetic kilotons each, at 150 km altitude

Shot 91-337 (dark-field shadowgraph)



7 cm

Measurements

visible emission (wide photography)
density gradients (darkfield shadowgraph)
density profiles (interferometry)
source temperatures (visible spectroscopy)
IR emission (1-100 spectroscopy)

NR ^{space} _{plasma}

Some Publications

- Spectroscopic Diagnostics in a Colliding-Blast-Wave Experiment
R.C. Eilon, D.M. Billings, C.K. Manka, H.R. Griem, J. Grun, B.H. Ripin,
and J. Resnick
Physical Review E, 49, pg. 1512 (1994)
- Space Plasma Physics in the Laboratory
B.H. Ripin, J. Grun, C.K. Manka, J. Resnick, and H.R. Burris
Research Trends in Physics: Nonlinear Space Plasma Physics, pg. 449-463,
H. Alven, R. Bingham, K. Quest, and R.Z. Sagdeev, editors (AIP Press, NY,
1993)
- Numerical Simulations and Experiments on Physics of High Mach Number
Shockwave-Turbulent Flow Interaction
A.C. Buckingham and Jacob Grun
Proc. 4th International Workshop on the Physics of Compressible Turbulent
Mixing, eds. P. Linden, D. Youngs, Cambridge Univ. Press (1993).
- Instability of Taylor-Sedov Blast Waves Propagating in a Uniform
Atmosphere.
J. Grun, J. Stamper, C. Manka, J. Resnick, R. Burris, J. Crawford, Phys. Rev
Lett. 66, pg. 2738 (1991)
- Laboratory Laser-Produced Astrophysical-Like Plasmas
B.H. Ripin, C.K. Manka, T.A. Peyser, E.A. McLean, J.A. Stamper, A.N.
Mostovych, J. Grun, K. Kearney, J.R. Crawford, J.D. Huba, Laser and
Particle beams, Vol. 8, pg. 183 (1990)
- Laboratory Laser-Produced Astrophysical-Like Plasmas
B.H. Ripin, C.K. Manka, T.A. Peyser, E.A. McLean, J. Stamper, A.N.
Mostovych, J. Grun, K. Kearney, J.R. Crawford, J.D. Huba, pg. 196-199,
Laser Interaction with Matter, G. Velarde, editor (World Scientific,
Singapore, 1989)

**Progress in Understanding and Modeling of
Hydro Instabilities and the Construction of a
Turbulent Mixing Model**

**Dov Shvarts
Nuclear Research Center Negev**

Progress in understanding and modeling of hydro instabilities and the construction of a turbulent mixing model

D. Shvarts, U. Alon, D. Ofer

Phys. department

MAAN

ISRAEL

- The basic physics of the mixing zone growth
→ large structures (bubbles)
inverse-cascade and dot turbulence
- Models to describe the late nonlinear evolution of the instability
→ bubble-merger model
• modal model
- Construction of an effective mix model based on the large

- Freed, Ofer, Shvarts, Orszag - Phys. Fluids A, 1991
- Ofer, Shvarts, Benamon, Orszag - Phys. Fluids B, 1992
- Alon, Mukamel, Shvarts - Phys. Rev E, 1993
- Alon, Hecht, Shvarts - Phys. Fluids, 1994
- Alon, Hecht, Mukamel, Shvarts - PRL, 1994
- Alon, Hecht, Ofer, Shvarts - PRL, 1995
- Shvarts, Alon, Ofer, McLaughlin, Verdon - Phys. Plasmas, 1995
- Hecht, Ofer, Alon, Shvarts, McLaughlin, Orszag - Laser & Particle Beams, 1995

Submitted:

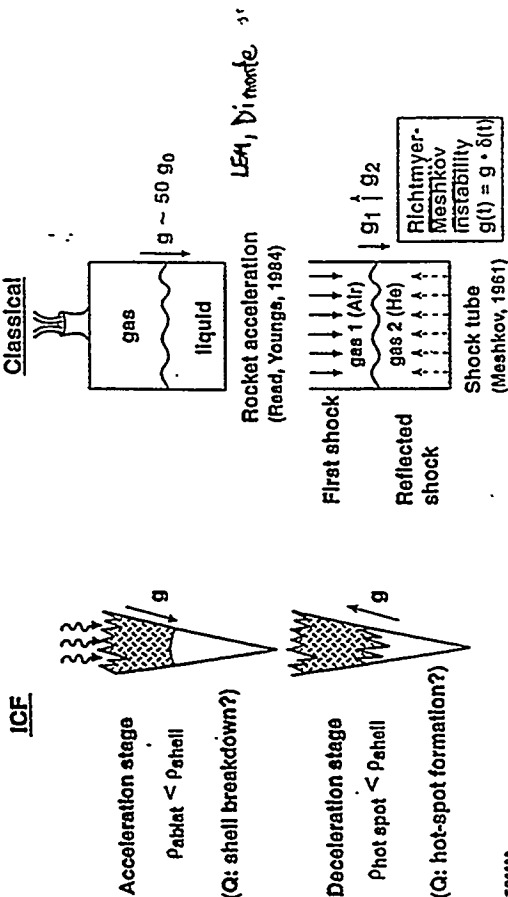
- Ofer, Alon, Shvarts, McLaughlin, Verdon - to Phys. Plasmas (1996)
- Alon, Shvarts - to Phys. of Fluids (1996)

In preparation:

- Ofer, Alon, Shvarts, McLaughlin, Verdon - 3D model

Classical experiments can be used to study aspects of the Rayleigh-Taylor and Richtmyer-Meshkov instabilities

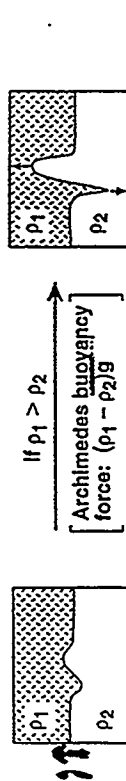
UR
LLB



TC3888

The Rayleigh-Taylor (RT) instability

UR
LLB



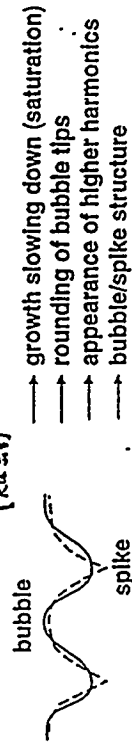
Linear theory: $a(x, t) = a_k(t) \cdot \cos(kx) \quad (k = 2\pi/\lambda)$

$\ddot{a}_k = \gamma_k^2 \cdot a_k$

with $\gamma_k = \sqrt{A \cdot k \cdot g}$ $\left(A = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}, \text{Atwood number} \right)$

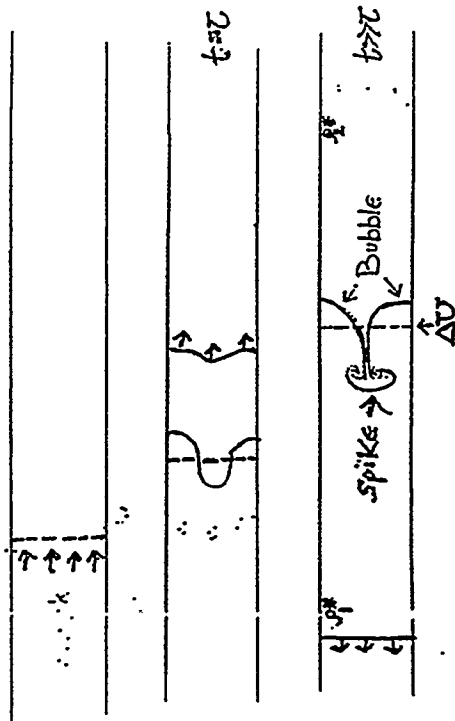
$\rightarrow a_k(t) = a_k(0) \cdot e^{\gamma_k \cdot t}$

Nonlinearity: when $a/\lambda \gtrsim 0.1$ - kinematic drag becomes important



TC3891

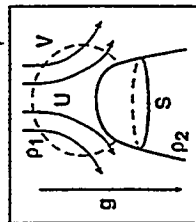
Richmyer-Meshkov Modeled by Initial Velocity and $g=0$



- Shocks don't interact with interface after $\tau \sim \lambda / \text{Shock Speed} \sim \lambda / \Delta U$
- Initial velocity from linear theory $u_0 = a_0 k \Delta U$ $a_0 k < 1$
(Richmyer (60), Meyer-Blewett (72), Holmes-Grove-Sharp (94), Yang-Zhang-Sharp (94))

Scaling from Simple Buoyancy and Drag Considerations

(Young (89), Takabe, Yamamoto (91), Alon, Hecht, Ofer, Shvarts (95))



$$S \sim \lambda^2, V \sim \lambda^3$$

- In the bubble frame:

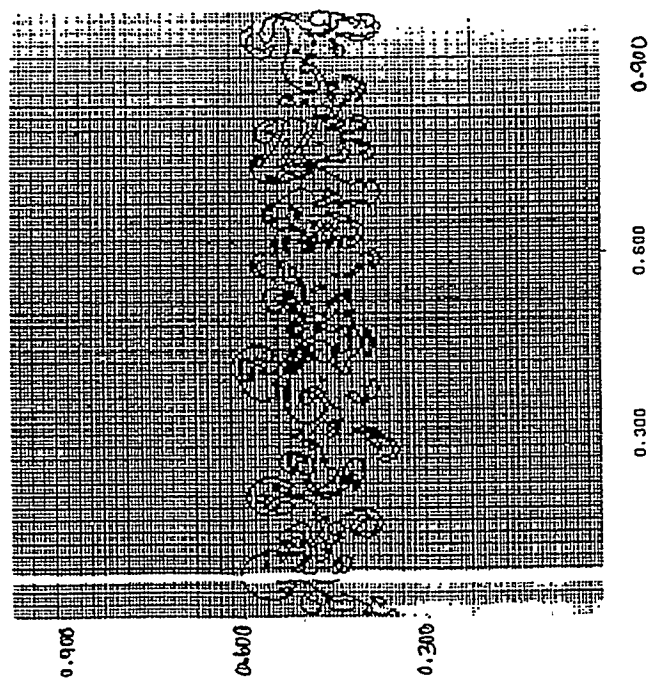
$$\rho_1 V \frac{dU}{dt} \sim \underbrace{-\rho_1 S U^2}_{\text{drag}} + \underbrace{(\rho_1 - \rho_2) g V}_{\text{buoyancy}}$$

- Drag/Buoyancy $\sim S / V \sim 1 / \lambda$
Large structures rise faster $\rightarrow$ Inverse cascade $\rightarrow$ $\lambda_{\text{outer}} \propto \lambda_{\text{inner}}^{-1/2}$
- RT (drag $\approx$ buoyancy): $U \sim \sqrt{g \lambda} \cdot \sqrt{\frac{\lambda}{1-\lambda}}$
 $\dot{U} = 0$
- RM (no buoyancy, only drag): $U \sim \lambda / t$
 $\dot{U} \sim \dot{U}^2 / \lambda$ No A dependence.

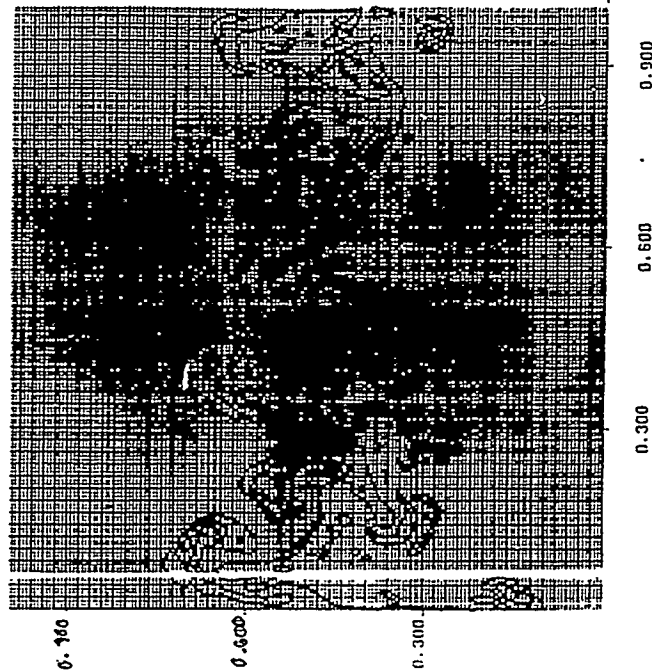
Late stage mixing zone structure for a
2-D random initial perturbation ($A=0.5$)

55

1. 2.000000 400 NCVG: 3776 random ray-len 200x200



1. 2.000000 400 NCVG: 5693 random ray-len 200x200



Rayleigh-Taylor growth at the ablation front is seen both from the surface finish and from laser imprinting

Indirect drive

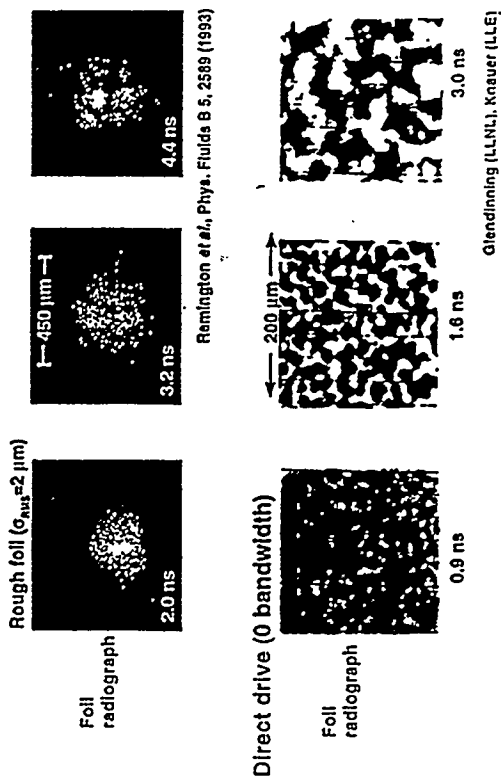
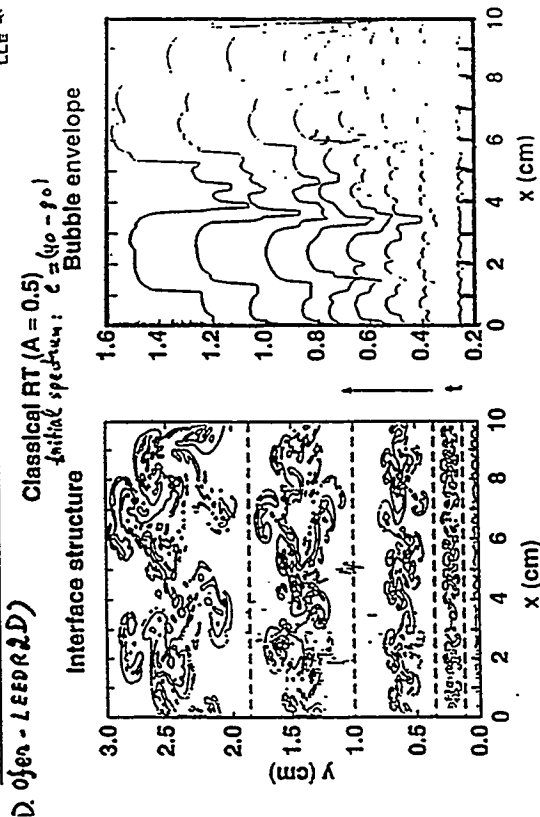


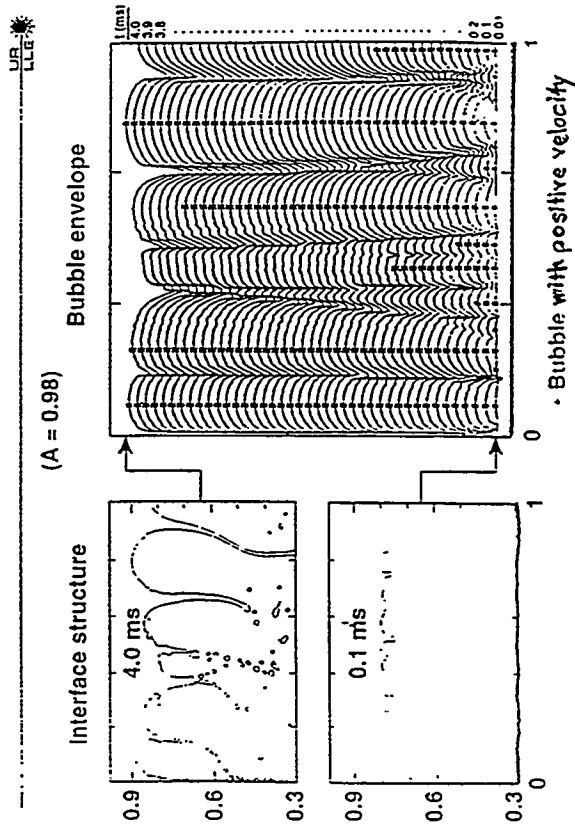
Figure 1. Iso-surfaces of $\rho = 0.99$ for the three-dimensional Rayleigh-Taylor calculation in the region $x < 0$. Gravity acts vertically downward.

D. Youngs (1995)

Large structure dominates the late time flow even with no initial long-wavelength perturbation



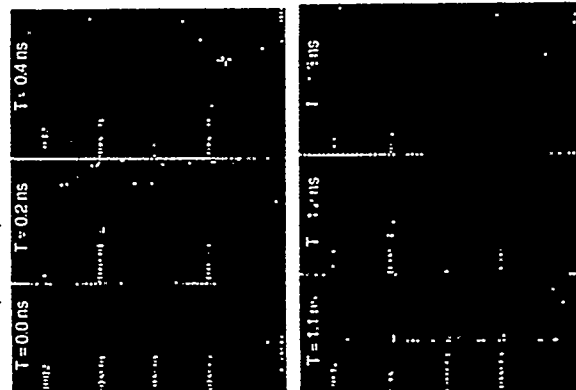
Simulation of multimode Richtmyer-Meshkov instability shows bubble competition



Early-stages evolution of a random initial mass perturbation ($\text{rms} = 2 \mu\text{m}$) under ablation condition ($I = 10^{14} \text{ W/cm}^2$, $\tau_{\text{rise}} = 1 \text{ ns}$, $\lambda_L = 0.53 \mu\text{m}$, $\Delta \text{CH}_2 = 20 \mu\text{m}$)

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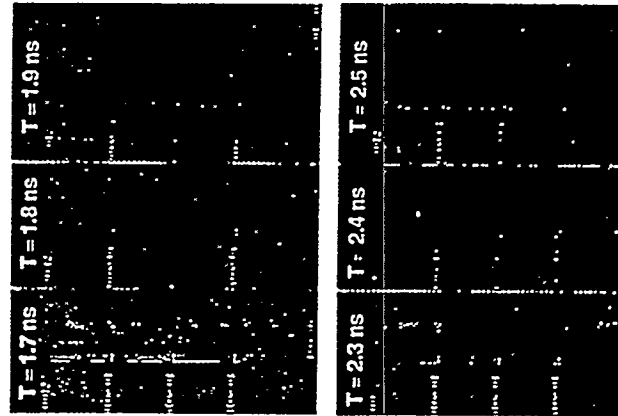
(Density contours)



← LASER

Bubble dynamics and competition are clearly seen while spikes are washed downstream

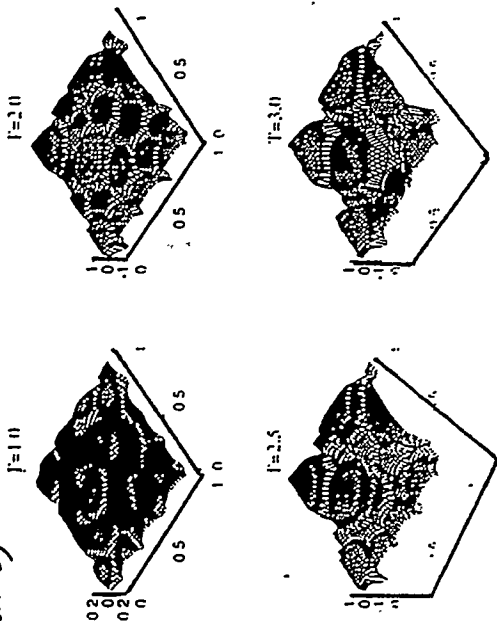
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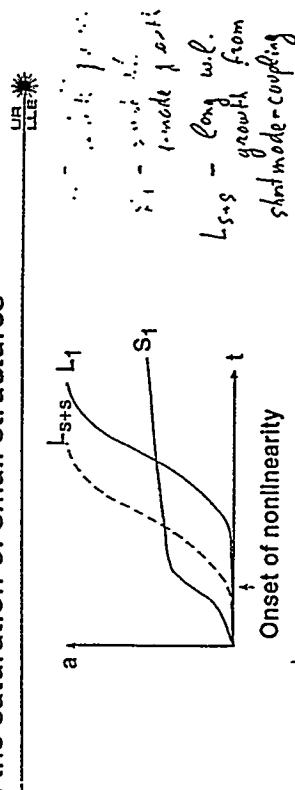
103701

3-D bubble competition is clearly seen for a 3-D isotropic short-wavelength initial perturbation

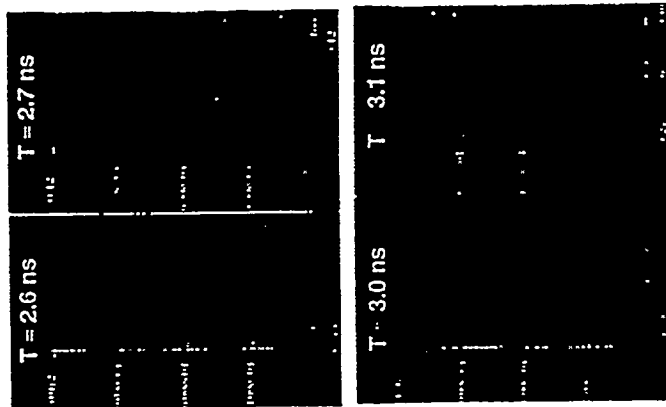
(D. Ofen - LEEOR3D)



In the multimode case nonlinearity is leading to the creation of large structures together with the saturation of small structures



At late stage, few bubbles are controlling the front evolution and punching the shell

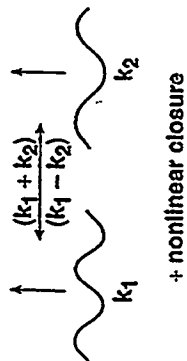


Two approaches to overcome the divergence problems

The Modal Approach

(K-space)

- Use the basic modes— $\cos(kx)$
- Take only 1,2 mode interaction into account
- Use a mean-field approach for all higher-order contributions — a nonlinear closure

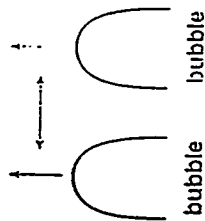


TC3995

The Bubble Approach

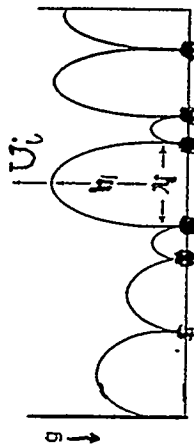
(Physical space)

- Use late-stage "dressed" nonlinear elements—Bubbles (harmonic information already included)
- Write an evolution equation for ensemble of bubbles with an effective 1,2 bubble interaction



Bubble-Merger Model Gives Multi-Mode Evolution from 1 and 2 bubble physics

Sharp and Wheeler (61), Glimm, Sharp, Zhang (88-91)
Alum, Shvarts, Mukamel (93)



- Single-Bubble Velocity

$$\text{RT: } U_i = c_1 \sqrt{g \lambda_i}$$

$$\text{RM: } U_i = c_1 \lambda_i / t$$

- Two-Bubble Merger, $\omega(\lambda_i, \lambda_{i+1})$

$$\lambda_i, \lambda_{i+1} \xrightarrow{\omega} \lambda_i + \lambda_{i+1}$$

Mean-field model equation (no correlations)
gives the main properties of the bubble
distribution time evolution

UR
LLS

$g(\lambda, t)$ - number of bubbles of size $(\lambda, \lambda + d\lambda)$

$N(t) = \int_0^\infty g(\lambda, t) d\lambda$ - total number of bubbles at time t

$$N(t) \cdot \frac{\partial g(\lambda, t)}{\partial t} = -2 \cdot g(\lambda, t) \cdot \int_0^\infty g(\lambda', t) \cdot \omega_m(\lambda, \lambda') d\lambda' \quad (\text{Death})$$

$$+ \int_0^\lambda g(\lambda - \lambda', t) \cdot g(\lambda', t) \cdot \omega_m(\lambda - \lambda', \lambda') d\lambda' \quad (\text{Birth})$$

Basic features:

$$\frac{dN(t)}{dt} = -\langle \omega \rangle \cdot N(t) \rightarrow N(t) \text{ decreases}$$

$$\rightarrow \langle \lambda(t) \rangle \text{ increases}$$

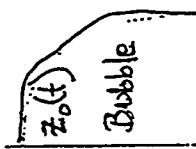
$$\rightarrow \langle v(t) \rangle \sim \sqrt{\lambda(t)} \text{ increases}$$

103574

Single-Model RM Bubble goes as
 $U \sim \lambda / t$

• At $A = 1$, Potential Flow model

[RT: I. Iyzer (55), RM - Hecht, Alon, Shvarts (94)]

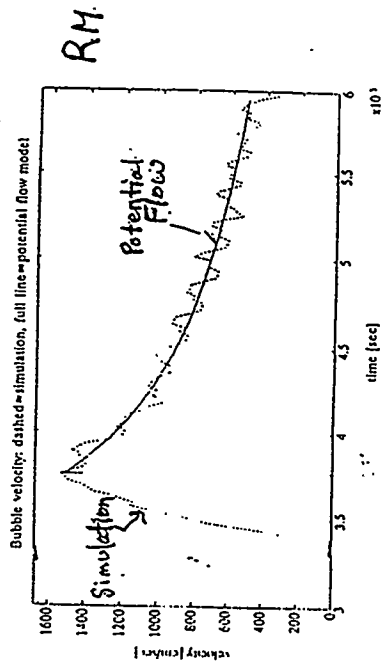


$$\nabla^2 \phi = 0$$

$$\phi = a(t) \cosh(\phi) e^{-k_3}$$

$$z_0(t)$$

$$RT: U = 0.23 \sqrt{g\lambda}$$



RM

Bubble competition is described by the potential flow model

UR
LLB

$$\phi(x, z, t) = \sum_{n=1}^3 a_n(t) \cdot \cos(n \cdot k \cdot x) \cdot e^{-n \cdot k \cdot z}$$

$$k = \frac{2\pi}{(\lambda_1 + \lambda_2)}$$

$$\left\{ \begin{array}{l} \phi + \frac{1}{2} v^2 + gz = \text{const} \\ v_z = \frac{DZ}{Dt} \Big|_{\text{interface}} \end{array} \right.$$

Linearizing the equations near the tip

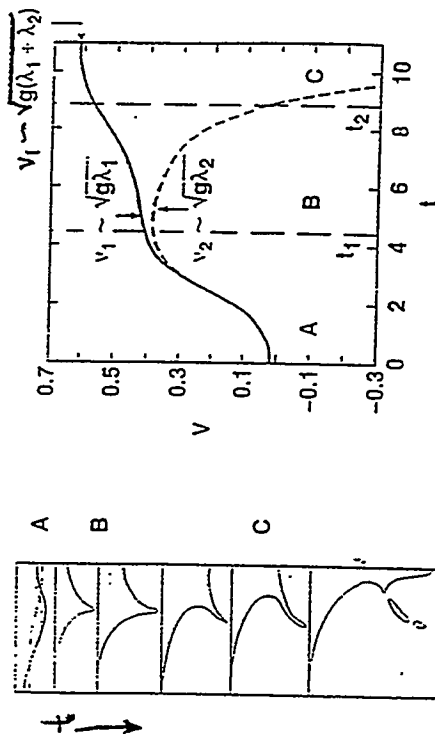
$\Downarrow$

7 ODE's for: $z_0^1, z_0^2, z_1^1, z_1^2$
 a_1, a_2, a_3

TC3577

Dynamics of two-bubble competition

UR
LLB



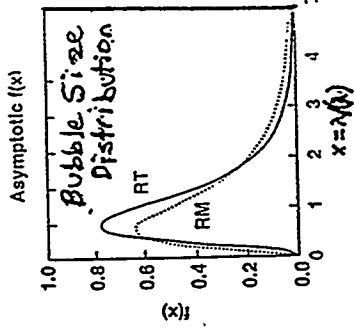
A. Exponential growth
B. Coexistence
C. Overtake

$$\Delta t_{\text{merge}} = t_2 - t_1$$

$$\omega(\lambda_1, \lambda_2) = \frac{1}{\Delta t_{\text{merge}}}$$

14.10.2017

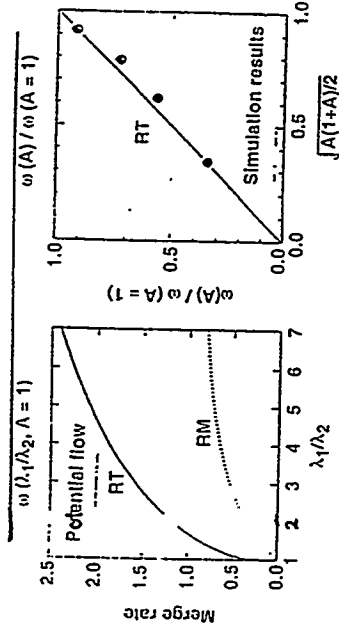
Bubble Front Reaches Scale Invariant Regime, where $h / \langle \lambda \rangle$ is Constant



$$\frac{dh_B}{dt} = \langle u(\lambda) \rangle_f$$

$f(\frac{\lambda}{\langle \lambda \rangle})$ independent of initial perturbation.

Using Single-Mode Velocities and Merger-Rates Yields Multi-Mode Scaling



• Bubble penetration from mean velocity

$$\frac{dh_B}{dt} = \langle U(\lambda) \rangle_f$$

RT Bubble Front:

$$h_B \approx 0.05 A g t^2$$

New Power-Law Scaling for the RM Bubble Front

- RM bubble-front penetration

$$h_B \equiv a_B (u_o t / \lambda_o)^{0.4}$$

- Power law - "no gt^2 "

- Depends on u_o, λ_o
 λ_o - initial mean wavelength

$$u_o \equiv \tilde{a}_o \frac{2\pi}{\lambda_o} \frac{\Delta U}{\lambda_o}$$

initial
amp.

1-bubble equation of motion:

$$V \rho_h \dot{U} = -\rho_h \cdot U^2 + V(\rho_h - \rho_e)g$$

$$V/S \sim \lambda$$

$$\rho_h \dot{U} = -c_D \rho_h U^2 / \lambda + c_B (\rho_h - \rho_e)g$$

Layzer 1955: in 2D, for $\rho_h \gg \rho_e$:

$$c_D = \frac{1}{2}, \quad c_B = 3\pi$$

asymptotic velocity:

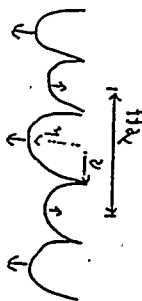
$$RT: U = \sqrt{\frac{1}{6\pi}} \sqrt{g\lambda}$$

$$RM: U = \frac{1}{3\pi} \sqrt{g\lambda}$$



The Multi-Bubble case.

from statistical model $h_B(t) \sim \frac{1}{4} \lambda_{eff}(t)$



• for min (S/V) : $h \approx R$ (round tip)

• bubble competition: $\lambda_{eff} \approx 4R$

$$\boxed{h_B \approx \frac{1}{4} \lambda_{eff}}$$

RT: $h_B(t) = V(t) = \sqrt{\frac{4}{\pi}} \cdot \sqrt{g \lambda_{eff}(t)} \approx \sqrt{\frac{4}{\pi}} \cdot g \cdot h_B$

$$h_B = \alpha g t^2$$

$$\boxed{\alpha \approx 0.06}$$

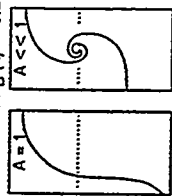
RM: $h_B(t) = V(t) = \frac{1}{3\pi} \cdot \frac{\gamma}{\ell} \approx \frac{4}{3\pi} \cdot h_B / \ell$

$$h_B \sim \ell$$

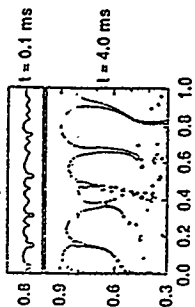
$$\boxed{\theta \approx 0.4}$$

The spike front evolution is determined by the dominant bubble structure at each time

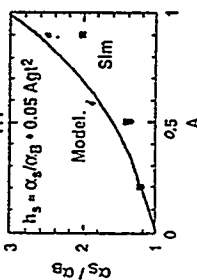
Single-mode spikes/bubble structure at $h_B/\lambda \approx 0.26$



Spikes have similar periodicity as bubbles



$\Rightarrow \frac{dh_B/dt}{RT} = \langle u_B(\lambda) \rangle$ when $h_B/\lambda \approx 0.26$

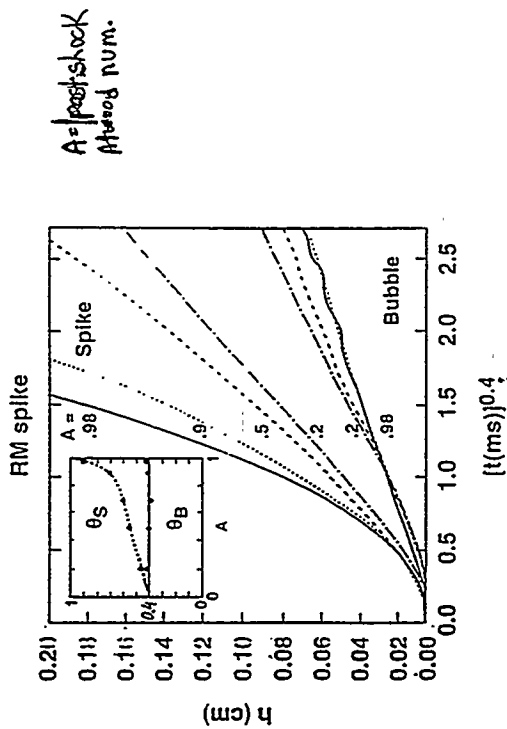


$$h_B, h_S \propto g t^2$$

$$\Downarrow$$

$$742 \sim g t^2$$

RM Spike and Bubble Fronts have Different Power Laws

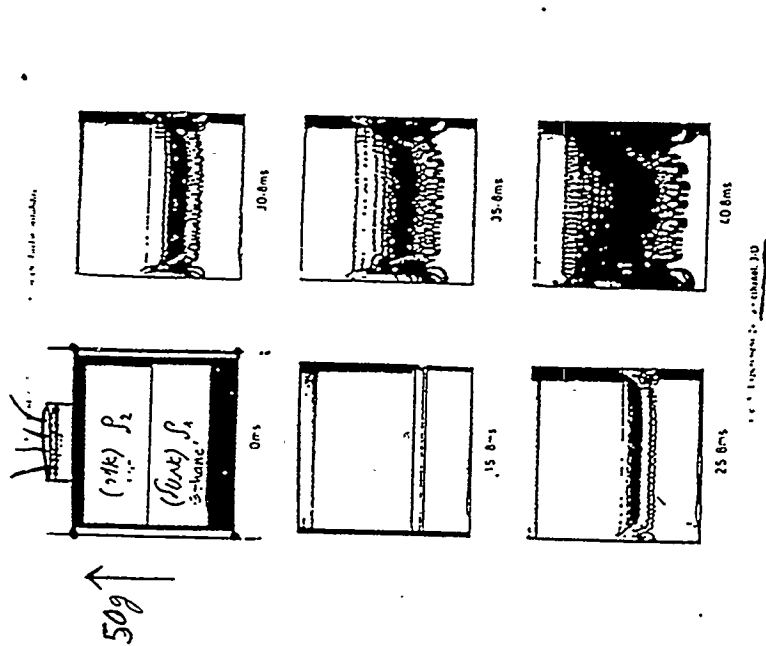


Experiments Welcome!

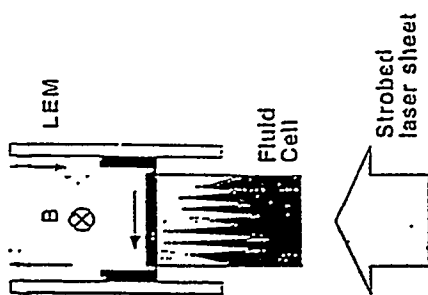
RM:

$$h_s \sim t^{\theta_s(A)} \Rightarrow TMZ = h_g + h_s \neq t^\beta$$

$$\theta_s = \begin{cases} 0.4 & A \rightarrow 0 \\ 1.0 & A \rightarrow 1 \end{cases} \quad (\text{free coast})$$



- **Linear electric motor (LEM)**
Variable acceleration
Deceleration for "de-mixing"
- **Laser Induced fluorescence (LIF)**
High resolution 2D images
No edge effects
- **Particle Imaging velocimetry (PIV)**
Measures turbulent energy
- **Radiography**
Turbulent mix distribution



Displacement (250 cm) >> Fluid size (10 cm) >> Shortest scale (.05 cm)

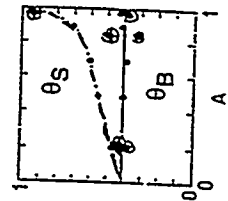
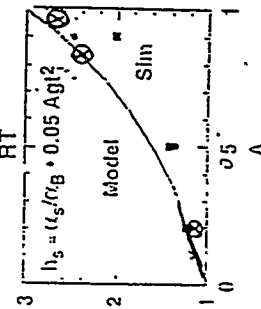
- **Multi-Mode Bubble Front Penetration**

$$RT \sim 0.05 Agt^2, \quad RM \sim (u_0 t / \lambda_0)^{0.4}$$

- **Multi-Mode Spike Front Penetration**

$$RT \sim \alpha_S(A) Agt^2, \quad RM \sim (u_0 t / \lambda_0)^{\theta(A)}$$

$$TM \sim g t^2, \quad TM \sim \lambda_0 \neq t^{\beta}$$

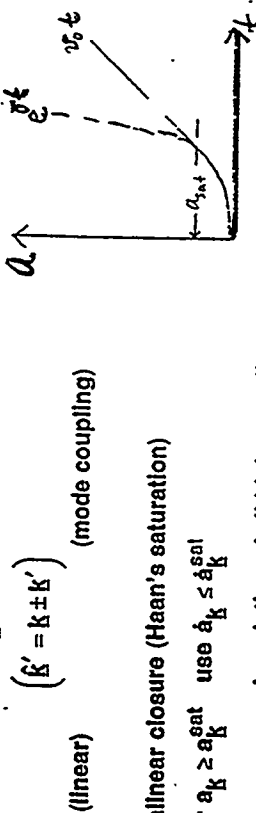


Simulation
model

New nonlinear model accounts for mode generation via two-mode coupling and for mode saturation

- One- and two-mode interaction

$$\ddot{a}_k = \gamma_k^2 \cdot a_k + A \cdot k \cdot \sum_{k'} \left(\alpha_{kk'} \cdot \dot{a}_{k'} \cdot \dot{a}_{k-k'} + \beta_{kk'} \cdot \ddot{a}_{k'} \cdot \ddot{a}_{k-k'} \right)$$



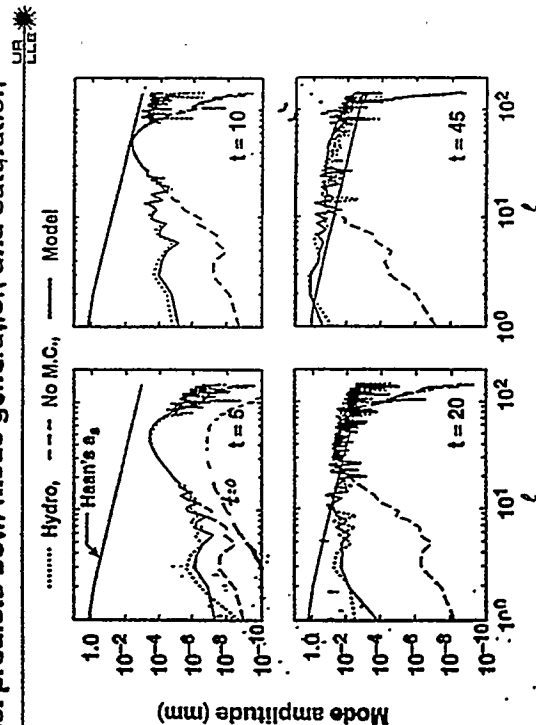
- Nonlinear closure (Haan's saturation)

$$\text{for } a_k \geq a_k^{sat} \text{ use } \dot{a}_k \leq \dot{a}_k^{sat}$$

as an average description of all higher nonlinear contributions.

TC3689

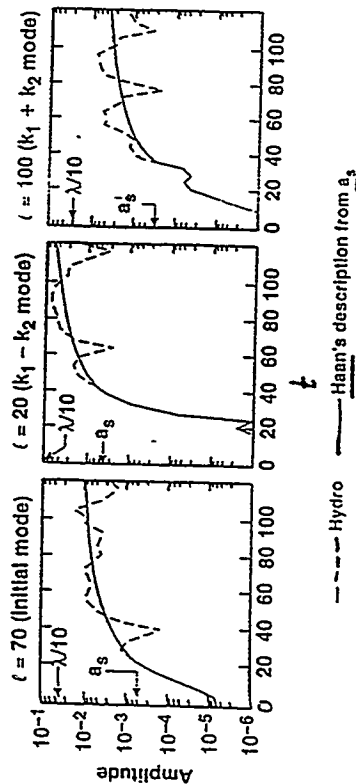
The classical Rayleigh-Taylor case (Read & Youngs) is a mode-coupling (M.C.) dominated case—new model predicts both mode generation and saturation



TC3678

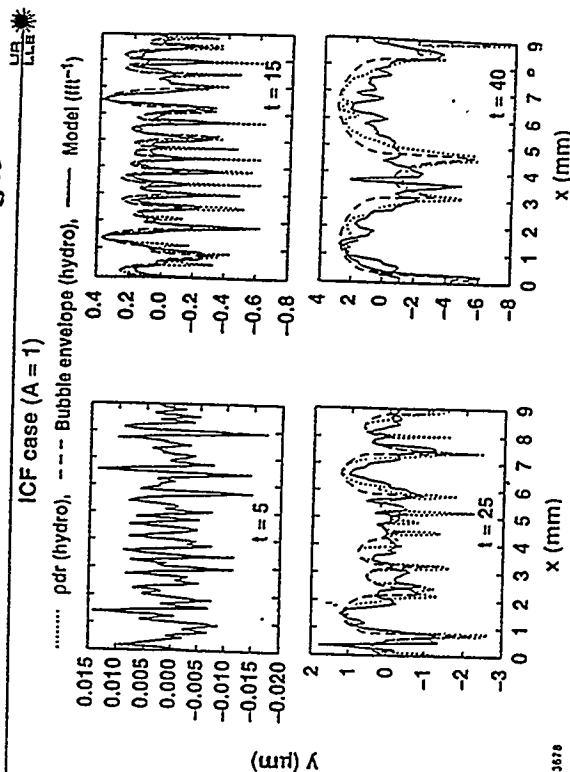
Haan's band saturation model is a nonlinear closure that represents the average effect of all higher-order contributions

Initial mode spectrum: $\ell = 40-80$ only



TC3680

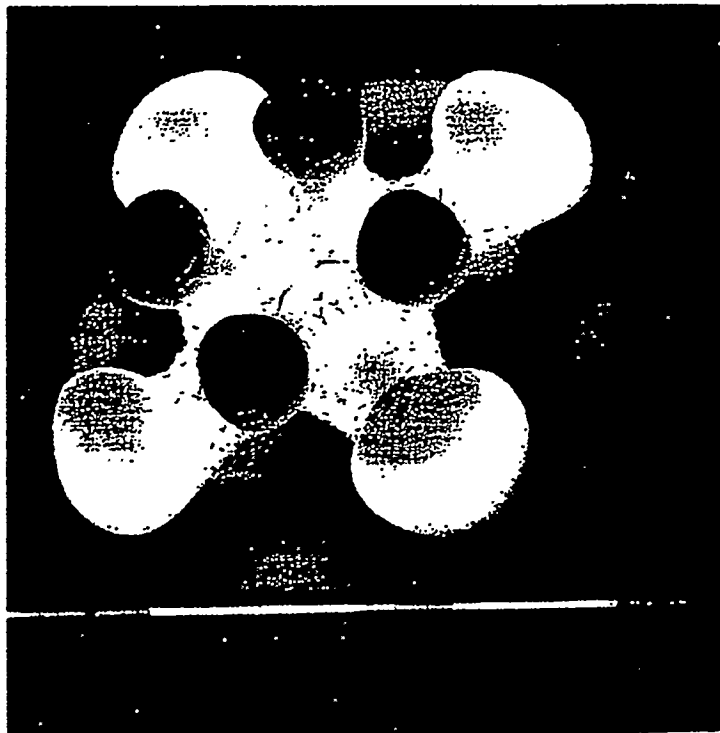
The new model can reasonably predict the interface structure in late nonlinear stages



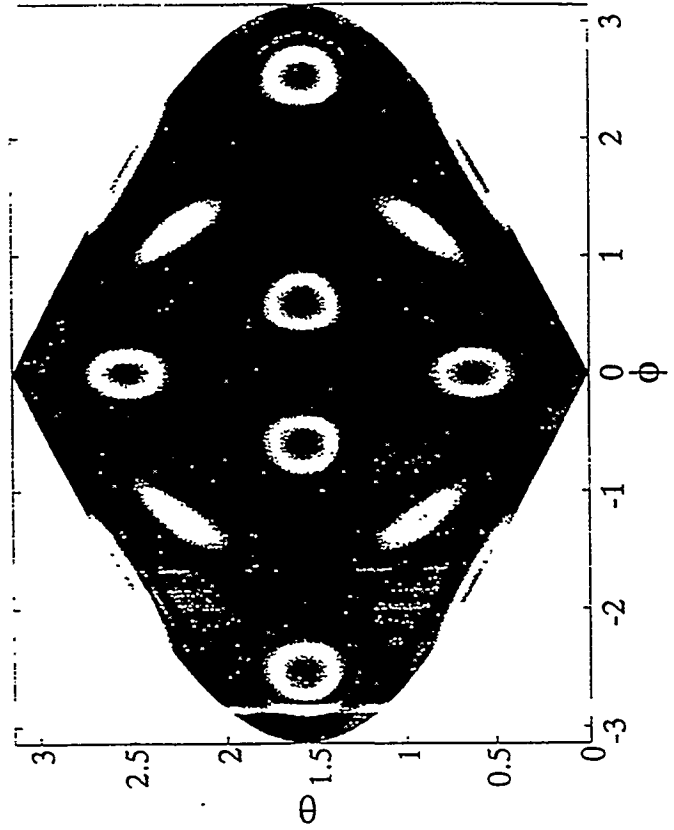
TC3679

Late time 3-D structure of an ICF Hot-Spot
 interface for a $(l=6, \cos(4\phi))$ 10%
 initial velocity perturbation

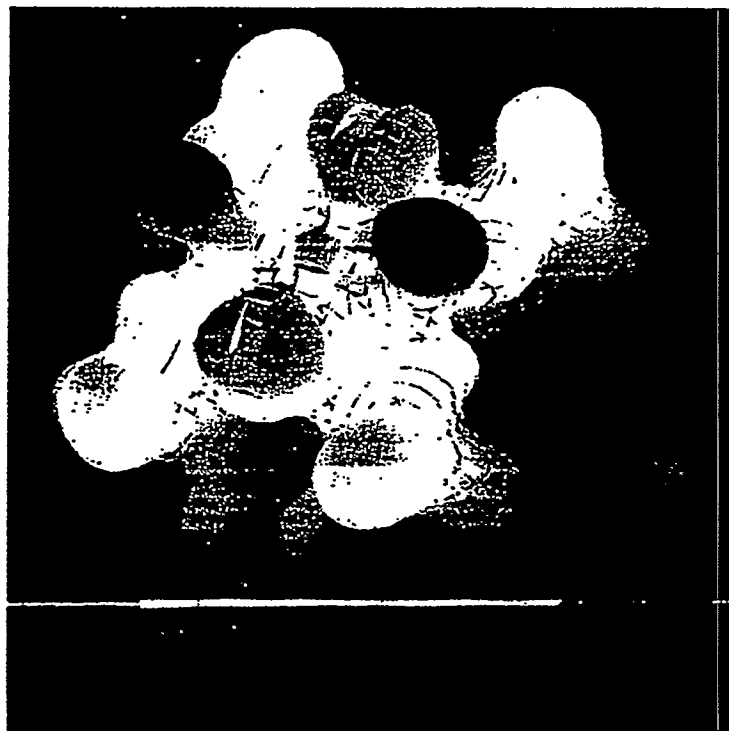
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Y60-Y62-Y64+Y66



Late time 3-D structure of an ICF Hot-Spot interface for a ($l=6$, random m's) 10% initial velocity perturbation



==

Bubble and Spike fronts:

Large structure physics.

- buoyancy
- drag
- bubble merging

a 2 phase - flow description

$$\frac{dU_i}{dt} = C_{B,i}(A) \cdot q(t) - C_{D,i}(A) \frac{U_i |U_i|}{L_i(t)} \quad (i = \text{bubble, spike})$$

use Layzer's parameters:

$$C_{B,6} = C_{B,5} = \frac{1}{2} \cdot A$$

$$C_{D,5} = 3\pi$$

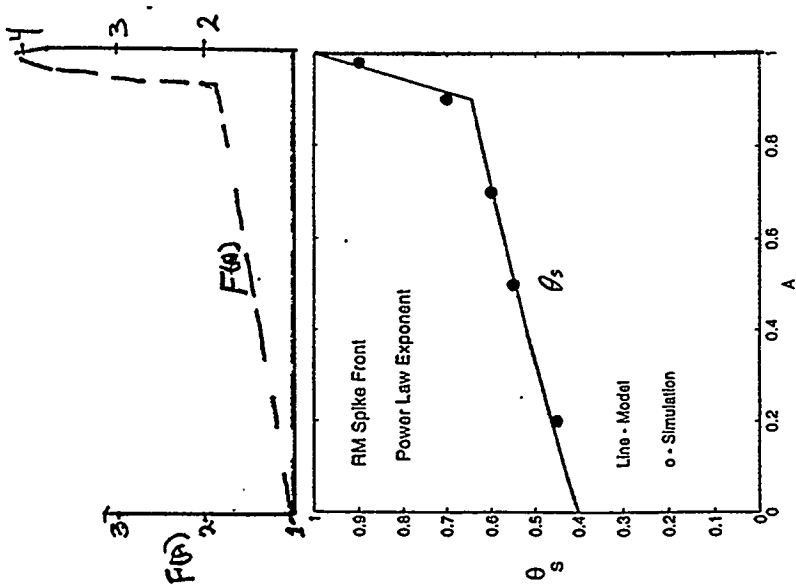
$$C_{D,6} = \pi \left[\frac{L^4}{F(t)} - 1 \right]$$

use 2 scale length
 $L_b(t), L_s(t)$

$$L_i = \beta U_i \quad \text{with } L_i(0) = \bar{\lambda}_0$$

$\beta=0$ - 1-mode
Layzer's result

$\beta \approx 2\pi$ - bubble-merger
scaling calls
for $RT + RM$
bubble + spike
fronts !!



Using $F(A) = \frac{\alpha_s}{\alpha_0} = \begin{cases} 1+A & A \leq 0.9 \\ 21(A-0.9)+1.9 & A > 0.9 \end{cases}$

$\theta_s \approx 0.4(1+A) \rightarrow 4$ for $A=1$

$(A \leq 0.9) \rightarrow 1.0$
 $(A > 0.9) \rightarrow 4$

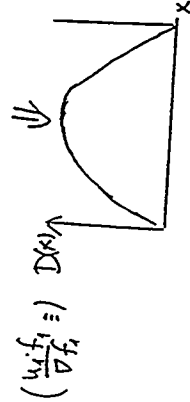
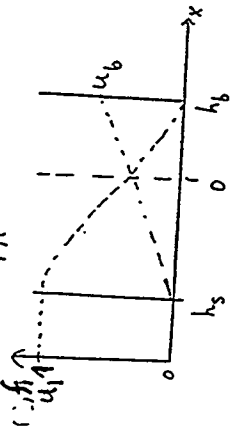
② Mixing Zone inner structure:

mass conservation eq:

$$\frac{\partial f_i}{\partial t} = \nabla(f_i u_i)$$

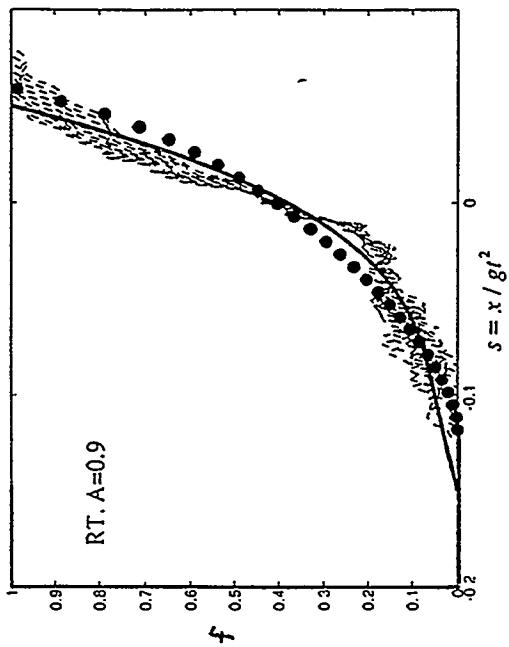
$$= \nabla(D \nabla f_i)$$

with $D \propto \frac{u_i f_i}{\nabla f_i}$

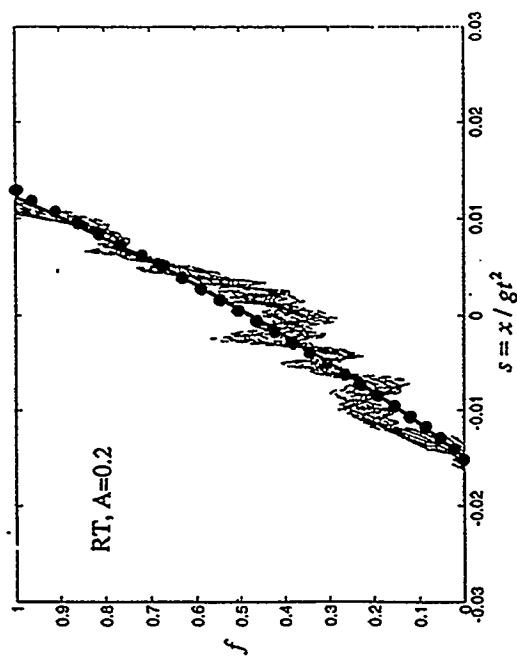
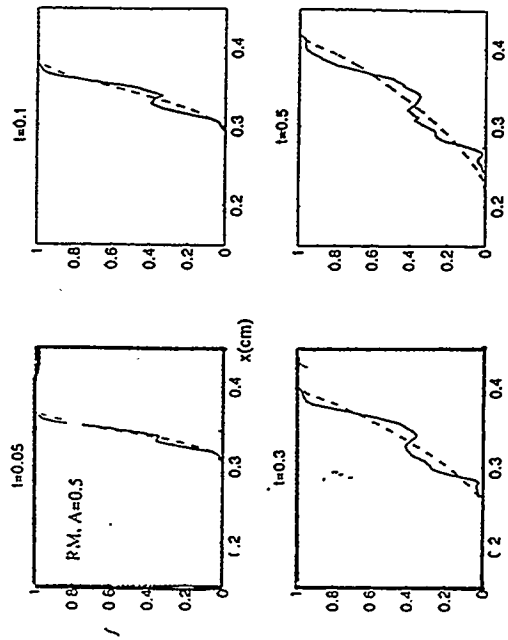


for $A \ll 1$: f_i, u_i are linear and $h_b \approx h_s$
 $\Rightarrow D(x)$ is parabolic.

we try to use parabolic (asymmetric).
 r... for all A 's and $q(t)$



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--- Simulation
 — self similar 2pF solution
 present model

What is still missing (work in progress)

- Compressibility effects

($C_{s,t}$ is an additional scale-length.)

- Non planar geometry

(R is an additional scale-length

and is important when:

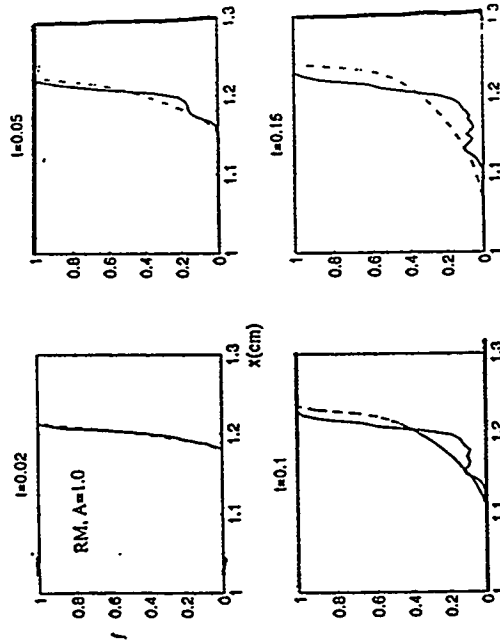
$$\lambda_{\text{dominant}} \sim L \sim TM2 \sim R$$

- Multiple shock treatment

(Is the $t^{0.4}$ ok. for a shock hitting a turbulent region?)

- The eq's for L_s and L_t in the mix model are good for early ($L \sim \lambda_t$) and late ($L \sim U$) stages. What happens at intermediate stages? (use of model-model to predict h_a, h_c, L_a, L_s)

- 2/3D effects - Lateral mixing - the transition from "ordered" to "disordered" flow



**Two Laser-Plasma Experiments of
Astrophysical Interest**

**Guy Dimonte
Lawrence Livermore National Laboratory**

Two laser-plasma experiments of astrophysical interest

Guy DImonte

Lawrence Livermore National Laboratory



Phys. Rev. Lett. 67, 1755 (1991)
Rev. Sci. Instr. 63, 5151 (1992)
Phys. Rev. Lett. 70, 1806 (1993)
Phys. Rev. Lett. 74, 4855 (1995)
Phys. Plasma 3, 614 (1996).

1440

Two laser-plasma experiments of astrophysical interest



- Dynamics of exploding plasma in a magnetic field
 - Model Very High Altitude Nuclear Explosions (VHANE)
 - Structure and size of diamagnetic cavity
 - Compare with dispersion relation of lower-hybrid drift instability
 - Janus laser - 100 J in 25 ns
- Richtmyer-Meshkov Instability with high Mach ~ 15 shocks
 - Radiatively driven shocks
 - Linear growth of single modes at high compression
 - Turbulent growth due to 3D random perturbations
 - Nova laser - 30 kJ in 3 ns

Basic Issues Associated with Exploding Magnetized Plasmas

- What is plasma containment radius ?

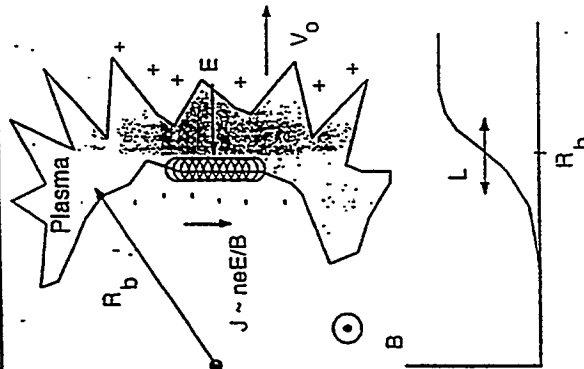
$$\frac{m V_o^2}{2} \sim \frac{B^2}{2\mu} \frac{4\pi}{3} R_b^3$$

- Is ion magnetization important ?

$$\frac{\rho_i}{R_b} \sim \frac{V_o}{\Omega_i R_b}$$

- What is instability and dominant scale of plasma structure ?

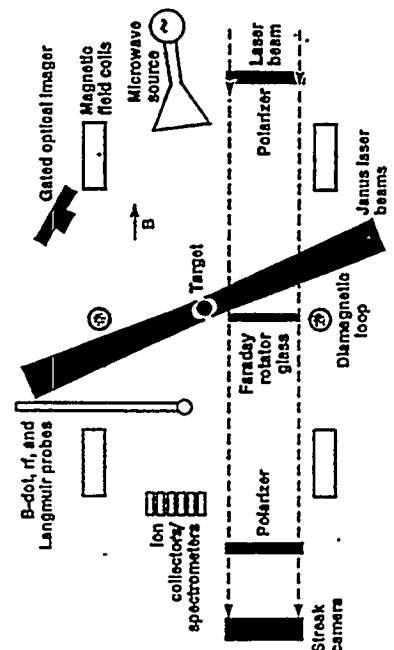
$$k_{\max} \sim \frac{\Omega_{LH}}{\sqrt{gL}} \quad g \sim \frac{V_o^2}{2R_b}$$



UNCLASSIFIED

Scaled laser experiments benchmark key physics

- 400 shots on Janus laser
 - Magnetic containment of plasma
 - Plasma instability structure
 - Multiple bursts
- Constructing "Space Chamber"
 - MHD-EMP generation
- Benchmark simulation codes
 - Collaborate with D-Division

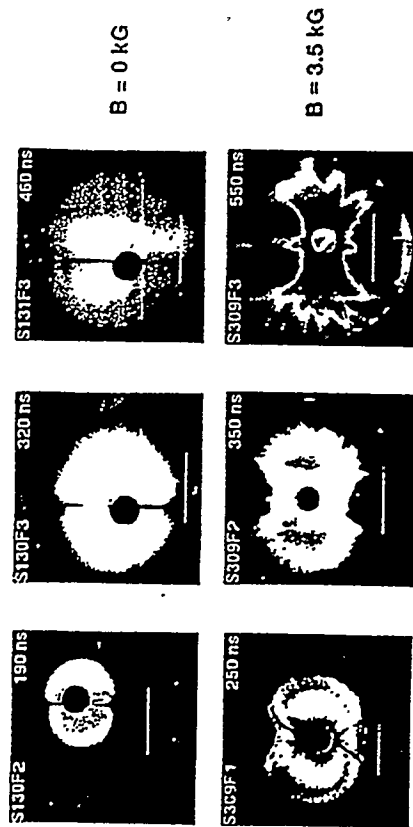


UNCLASSIFIED

UNCLASSIFIED
Lab experiments match scaled VHANE parameters

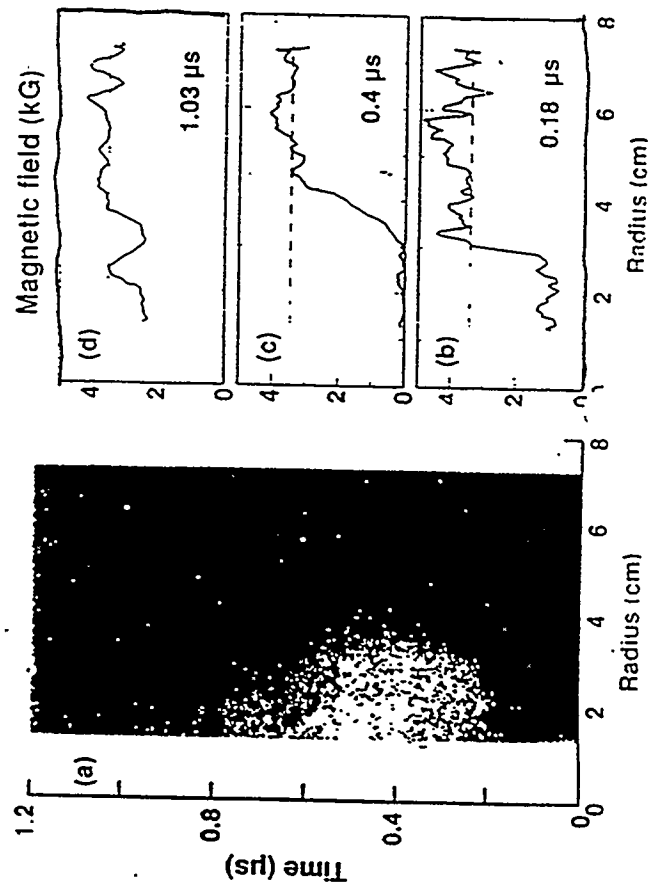
	STARFISH	LLNL
Total plasma energy (J)	$\sim 10^{15}$	~ 100
Altitude (km)	400	—
Number of ions	10^{28}	$\sim 2 \cdot 10^{17}$
Atomic mass	55	6
Directed speed-v (10^7 cm/s)	15	2-4
Magnetic field (G)	0.3	2000
Larmor radius ρ_L (cm)	$2 \cdot 10^6$	1
Bubble radius R_b (cm)	$3 \cdot 10^7$	5

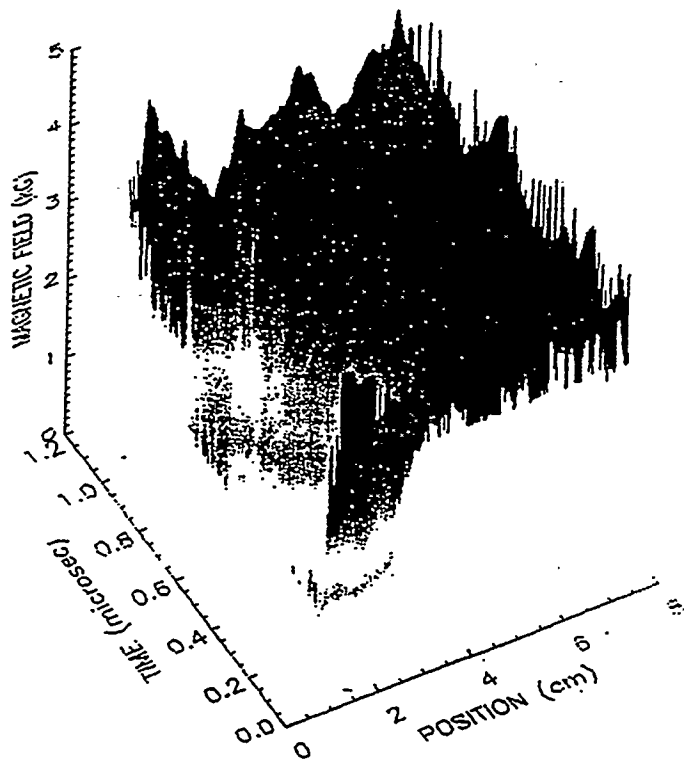
Plasma structure caused by magnetic field



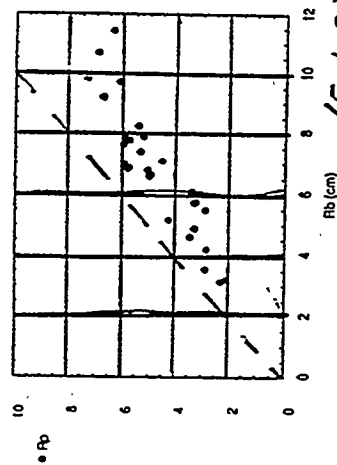
Magnetic compression magnifies small asymmetries
Instabilities evolve toward longer wavelengths

Magnetic Profile of Expanding Plasma Cavity

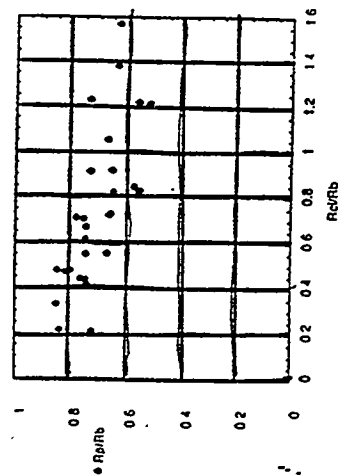




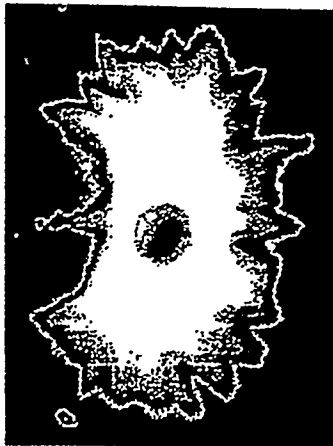
Plasma Radius Increases With Classical Bubble Radius



Plasma radius decreases weakly with ion magnetization

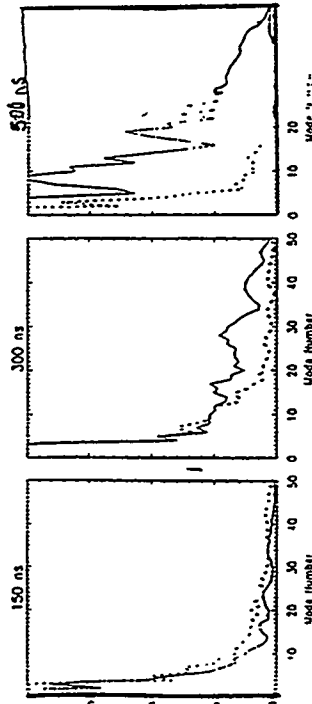


Plasma Structure Obtained by Fourier Analyzing
Edge Contour of Optical Plasma Image



B = 3.5 KG
E = 100 J
Dia = 3.2 mm
CH
500 ns

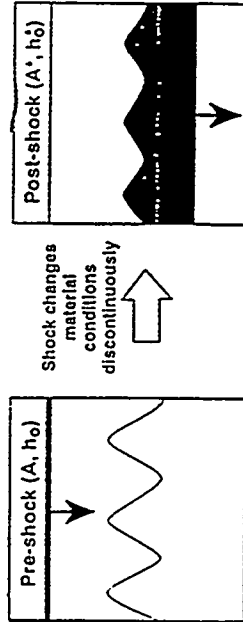
Spectral Amplitude (mm) vs Mode Number (N) B = 0



Linear theory predicts $N_{max} \sim 500$

$\lambda f = 200$

Nova laser produces strong shocks to investigate compression, but mainly in weakly nonlinear regime



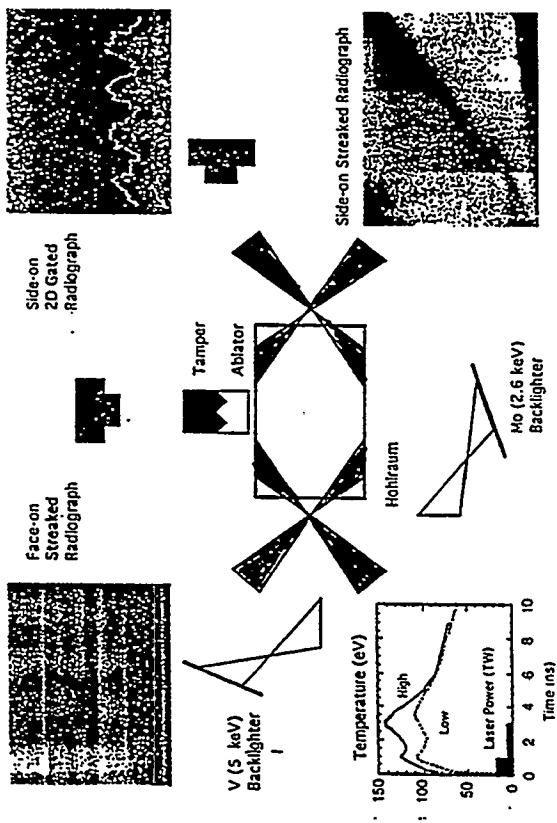
• Strong compression effects exhibited in linear regime

$$\frac{dh}{dt} \sim k U A_{eff} h_{eff} \quad h_{eff} = \begin{cases} h_0 \\ h_0^* \\ \frac{h_0 + h_0^*}{2} \end{cases}$$

- Compression makes A_{eff} and h_{eff} ambiguous
- Pre- and post-shock parameters are easily distinguishable on Nova experiments

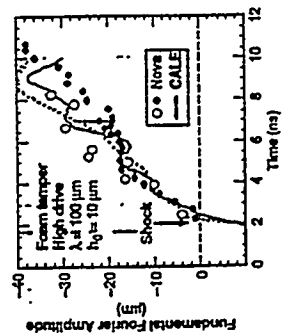
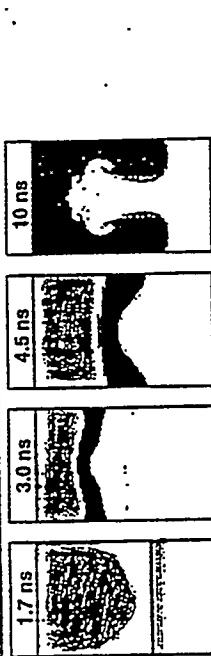
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Configuration for Nova Richtmyer-Meshkov Experiments



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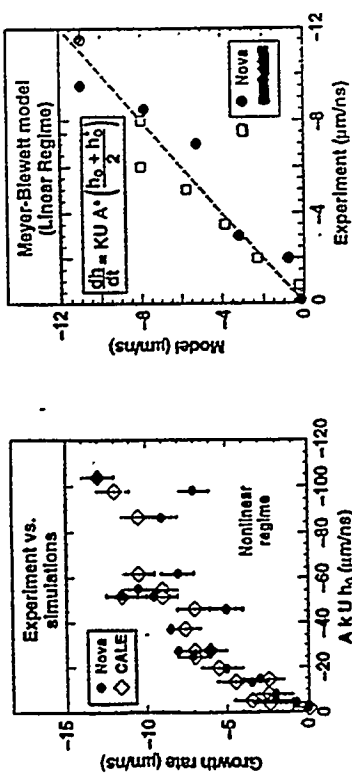
CALE simulations (2-D) reproduce measured growth of single mode



Physics of Plasma (in press)

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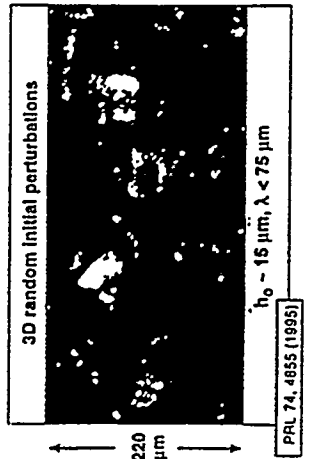
Growth rates from Nova single mode experiments agree with simulations and models over wide variation in A, k, U, h₀



- Linear and nonlinear growth rates agree with CALE simulations
- Compression described by average of pre- and post-shock parameters

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Compressible turbulence experiments performed on Nova with random 3D interfacial perturbations



- Experimental limitations
- Large initial amplitude required because experiment duration is short
 - Feature size not discernable with radiography

UNCLASSIFIED

Summary

• Dynamics of exploding plasmas (Janus laser)

- Maximum radius $\sim (E_k / B^2)^{1/3}$ Insensitive to ion magnetization
- Magnetic structure measured with Faraday rotation
- Observed wavelengths larger than most unstable lower hybrid drift modes
- Instability nonlinear - many e-foldings during stagnation

• Richtmyer-Meshkov Instability with high Mach shocks (Nova laser)

Single modes obey Mayer-Blewett model for $A < 0$

$$\frac{dh}{dt} \sim A^* k U \frac{\eta_0 + \eta_0^*}{2}$$

3D random modes obey power law

$$h \sim t^\beta \quad \beta \sim 0.6 \pm 0.1$$

Pair Production by Ultra-Intense Lasers

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PAIR PRODUCTION BY ULTRA-INTENSE LASERS

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ABSTRACT

We consider the production of electron-positron pairs by the interaction of relativistic superthermal electrons generated by ultra-intense laser pulses with high-Z material. We discuss the laser and target parameters required in order to optimize the pair production rate. We explore the regime when the pairs, if sufficiently confined, can start to exponentiate in number and the feasibility of ultimately achieving a pair-dominated plasma: a plasma in which the pairs outnumber the target background electrons.

PACS numbers: 52.40.Nk, 52.35.Nx, 52.60.+h

The pending development of ultra-intense laser pulses will allow the study of new regimes of laser-matter interaction¹. Experiments are now being designed² which will eventually lead to laser intensities such that $I_{\lambda} t^2 > 10^{19} \text{ W } \mu\text{m}^2/\text{cm}^2$. Here I is laser intensity and λ the wavelength in microns. At such intensities the electron jitter velocity in the laser electric field becomes relativistic: $p_0/mc > 1$ where p_0 is jitter momentum, m is electron rest mass, and c is light speed. When such lasers interact with an overdense plasma it is known to produce relativistic superthermal electrons. Numerical simulations with the Particle-In-Cell (PIC) codes³ show that as much as half of the absorbed laser energy goes into superthermal electrons whose characteristic kinetic energy E_{hot} is roughly given by:

$$E_{\text{hot}} \sim ((1 + I_{\lambda} t^2 / (1.4 \times 10^{18}))^{1/2} - 1) mc^2 \quad (1)$$

Hence $E_{\text{hot}} > mc^2$ for $I_{\lambda} t^2 > 4 \times 10^{18}$. In addition extremely intense magnetic fields with B up to 250 MG are observed to form in the overdense plasma. Such strong fields help to confine the superthermal electrons in the lateral directions. For even higher $I_{\lambda} t^2$ we expect E_{hot} to exceed the pair production threshold. It is the purpose of this letter to explore the physics of this regime and consider the prospects of creating a copious pair source and ultimately a pair-dominated plasma in the laboratory, in which the pair density outnumbers the background electron density.

Nonthermal electron-positron plasmas are known to be abundant in many astrophysical environments from pulsars to quasars. In the last few years discoveries of intense broadened 511 keV annihilation features lasting from days to weeks from several Galactic black hole candidates⁴ in our own Galaxy suggest that steady state thermal pair plasmas also exist. Since pairs annihilate on very short time scales, to maintain a steady state plasma over such long times the pairs need to be created prolifically to balance the annihilation rate. Such thermal plasmas represent a new state of matter with unique thermodynamic and radiative properties drastically different from ordinary plasmas⁵. If we define "compactness" roughly as the total plasma heating rate divided by its physical size, then for high compactness the pairs are primarily created by gamma ray (photon-photon)

collisions. For low compactness cases the pairs are primarily created by charged particle (lepton-ion) interactions whose cross section goes up as the square of Z , the ion nuclear charge. Whereas in the astrophysical contexts we are often dealing with the high compactness case⁶, in the laboratory simple estimates show that we will always be dealing with the low compactness case even for micron size laser spots. Hence in the following we will concentrate on pair production with high Z targets (e.g. Au, Z=79). For low compactness and a confined thermal plasma, Biskamp-Kogan, Zeldovich and Sunyaev (BKZS)⁷ first show that there exists a fundamental limiting temperature above which there is no pair equilibrium since the pair production rate will always exceed the annihilation rate. This limiting temperature was found to be about 20 mc^2 for pure hydrogen. For high Z or high B plasma⁷ it is expected to be lower but above the pair production threshold of $2mc^2$. If we use Eq. 1 as a measure of the superthermal electron temperature we find that formally, above a laser intensity of $\sim 10^{20} \text{ W/cm}^2$, the superthermal temperature would exceed the BKZS limit. In reality the BKZS limit does not apply due to the short duration of a laser pulse since it assumes a steady state. What all these mean is that above a certain laser intensity, pair processes must become important. We need to perform a time-dependent kinetic calculation to estimate the correct pair density development.

Consider a situation in which a significant fraction of the superthermal electrons and pairs are confined and reaccelerated to relativistic energies according to Eq. 1. In practice this can be accomplished by using a double-sided laser illumination so that the superthermal electrons and pairs are confined by the laser ponderomotive pressure in the front and back and by the strong magnetic fields on the side. In the limit of low annihilation rates the pair density grows according to:

$$n_t = n_{ei} + n_{ee} + n_{ey} + n_{yy} + n_{yt} \quad (2)$$

where the first term is the lepton-ion pair production rate, the second term the lepton-lepton pair production rate, the third term lepton-photon pair production rate, the fourth term the photon-photon pair production rate and the fifth term the photon-ion pair production rate (here photons include bremsstrahlung and Compton upscattered gamma rays). We have estimated in detail the relative magnitudes of the five terms in Eq. 2. It turns out that for typical laser target environments the first term is by far the dominant term, at least until the pair density starts to dominate the ion density. Hence in the pair deficient regime Eq. 2 reduces to:

$$n_t = n_{ei} = (n_e + n_i) \alpha_1 f(\alpha_1) \quad (3)$$

where n_i is ion density, $n_e = n_t + Z n_i$ is total electron density, v is relative velocity between ions and leptons and α_1 is cross-section for pair creation in the ion rest frame. The bracket denotes averaging over the normalized lepton distribution function f . At lepton energies much above threshold the cross section assumes the form⁸

$$\sigma_{ei} = 1.4 \times 10^{-30} Z^2 (\ln \gamma)^3 \quad (4)$$

where γ is the lepton Lorentz factor. Eq. 3 can be integrated to give the pair growth rate:

$$n_t = Z n_i [\exp(\Gamma t) - 1] / 2 \quad (5)$$

where the pair growth rate Γ is given by the integral:

$$\Gamma = 2 n_1 c \int dy \sigma_1 f(1 - \gamma^2)^{1/2} \quad (6)$$

As we will see below, Γ is of the order of $0.1(n_{Au})/ns$ where n_{Au} is the gold atomic density in units of normal solid density of 0.193 tons/cm^3 , for laser intensity exceeding a few times 10^{19} W/cm^2 .

Using the PIC codes we have run a number of 2-sided illumination of Au targets for various laser intensities. Fig. 1 shows the superthermal electron distributions for sample cases generated by such 2-sided laser heating. Using the superthermal electron distribution f generated by these PIC simulations in Eq. 6 we find the pair growth rate as a function of the laser intensity. This is plotted in Fig. 2. As we anticipated, Γ rises with laser intensity rapidly near threshold. But above a laser intensity of a few times 10^{19} W/cm^2 , Γ increases only slowly with laser intensity due to the log dependence of the cross-section. An important implication of this result is that for a laser of given total energy, to optimize the pair production one should make the laser pulse as long as possible provided the intensity stays above $\sim 10^{20} \text{ W/cm}^2$. A corollary is that the smaller the laser spot size the better. From Fig. 2 we see that for a 10^{20} W/cm^2 laser lasting 10 ps (such as that proposed for the faster ignitor at LLNL), $\Gamma \sim 2 \times 10^{-3}$ and the pair density can in principle reach $\sim 0.1\%$ of the target electron density. Since Γ is linearly proportional to n_1 one obvious way to increase the pair creation rate is to precompress the target to densities much higher than solid density (e.g. with another laser) prior to hitting it with the high intensity laser.

Another relevant issue is the maximum number of pairs one can hope to achieve for a given laser pulse energy and whether we can ever reach a pair-dominated state, as in the case of BKZ56. Assuming that a typical pair carries a total (rest plus kinetic) energy of $\sim 4mc^2$, we find that a kJ of laser energy, if 50% converted to superthermals and then a fraction p of that converted to pairs, will give rise to a total of $px \cdot 10^{14}$ pairs. This is to be compared to the total number of Au ions in a $10 \mu\text{m}$ diameter target spot of $1 \mu\text{m}$ thickness $\sim 5 \times 10^{12}$ and the total number of background electrons $\sim 4 \times 10^{14}$. Hence to reach a truly pair-dominated state we will need a laser energy of more than a kJ, independent of pulse duration and target density.

In addition to the confinement and reacceleration of the superthermal electrons and secondary pairs, we also need to consider their radiative cooling. These include bremsstrahlung and synchrotron cooling. If these are much shorter than the laser pulse then the above discussions on pair density evolution needs to be amended. For a typical field of a few hundred megagauss and Lorentz factor of 10, we find that the synchrotron cooling time⁹ is ~ 10 ns, whereas the bremsstrahlung cooling time⁹ is $\sim$ ns. Hence they are longer than the laser pulse if we are dealing with sub-ns pulse. But if we eventually go to a much longer laser pulse scheme then the radiative losses must be included in estimating the pair production. In any case we find that the energy loss by the superthermals to bremsstrahlung will always be at least a factor of 10 or more larger than the loss to pair production. Hence the factor p in the above paragraph will always be less than 0.1. However, at sufficiently high compactness (large photon density) some of the bremsstrahlung gamma rays will be reconverted back to pairs via gamma-gamma collisions. Accurate estimates can only be calculated via detailed numerical simulations.

How does one diagnose the pairs and superthermals? The direct method is to measure the prompt bremsstrahlung and annihilation gamma ray fluxes and spectra. However, many of the pairs will escape from the production region and annihilate in the surroundings (e.g. target chamber walls), likely after the laser pulse is over. Hence to estimate the total number of pairs produced we need to integrate the total 511 keV flux over

durations comparable to positron flight times to the target chamber walls. On the other hand, the prompt bremsstrahlung gamma rays from the superthermals provides diagnostics about the superthermal flux and energies during the laser irradiation. Hence together they will serve to calibrate the above estimates of the pair production efficiency.

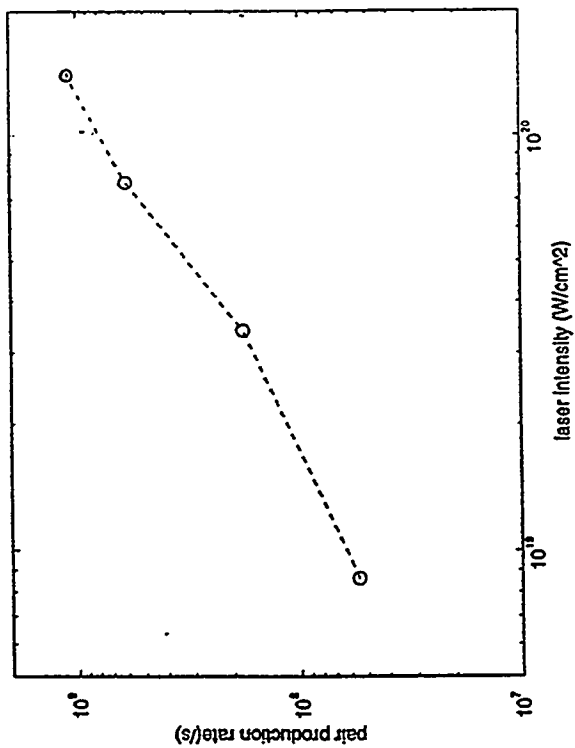
In summary, we expect that the next generation of ultra-intense lasers such as the one under development for the fast ignitor at LLNL, will be able to generate significant density of pairs under optimal conditions. A 10ps, 10^{20} W/cm^2 laser hitting solid-density gold foils on both sides can in principle produce peak pair density of the order of 10^{-3} of the target electron density. To go much beyond that we need to either consider much more powerful lasers with longer pulses, or precompressed targets with much higher than solid density or both.

We thank M. Tabak, W. Kruer, R. More and J. Woodworth for valuable discussions. This work is performed under the auspices of the US DOE by the Lawrence Livermore National Laboratory under contract W-7405-ENG-48. EPL is also supported in part by NASA NAG 5-1547.

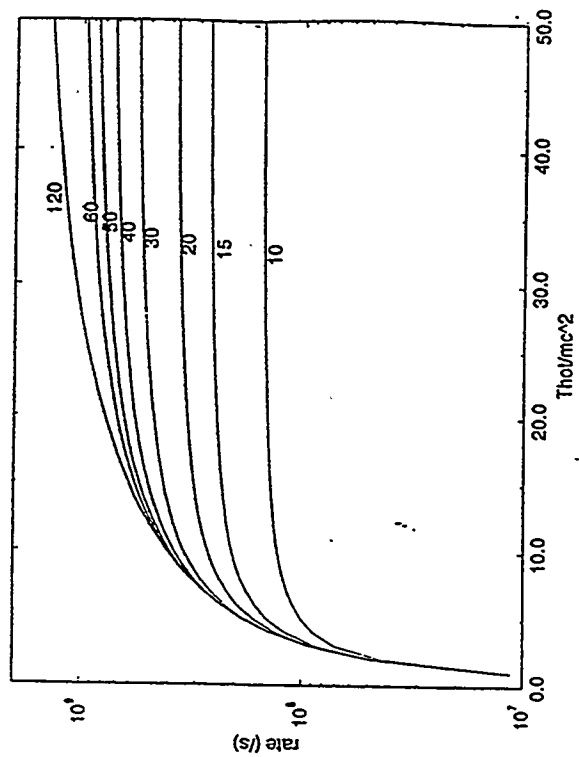
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pair rate vs laser intensity



pair production rate vs Thot



**Nova Experiments to Study the Interactions
of SN1987A with Circumstellar Matter**

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NOVA EXPERIMENTS TO STUDY THE INTERACTIONS OF SN1987A WITH CIRCUMSTELLAR MATTER

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ABSTRACT

This report summarizes the results of 1-dimensional numerical simulations of the interaction of NOVA laser target blowoffs with low density foams. Such experiments are explored to see if they can simulate some aspects of the interaction of Supernova (SN)1987A with circumstellar matter (CSM) and the anticipated x-ray emissions when the supernova shock wave reaches the high density circumstellar ring around the year 2000. We focus on (a) the most important astrophysics issues that may be addressed with such NOVA experiments; (b) the optimal experimental design parameters.

1. INTRODUCTION AND ASTROPHYSICS BACKGROUND

The supernova SN1987A was one of the most spectacular and important astronomical events of this century (see Chevalier 1992, McCray 1993 for reviews). At a distance of 55 kpc in the Large Magellanic cloud, a satellite of our own Milky Way, it was the nearest and brightest supernova in modern times. In addition, its progenitor star had the unusual property of going through both a red and blue supergiant phase before the final explosion, creating a multilayered circumstellar environment for the supernova ejecta to interact with. The earlier red supergiant progenitor had a slow, higher density stellar wind while the later blue supergiant had a faster, lower density stellar wind (see, e.g., Chevalier and Liang 1989). The interaction of the fast wind with the slow wind created a cocoon of high density shell, which is conjectured to have a peanut or hourglass shape (Fig. 1a, see Luo and McCray 1991, Panagia et al 1991, Wang and Mazzali 1992). When this peanut-shaped cocoon was lit up by the light of the supernova itself, it was observed as a spectacular triple ring system by the Hubble Space Telescope (Fig. 1b). The middle ring of the three rings likely defines the "neck" of the cocoon which is the part of the high density shell closest to the supernova. Based on current estimates of the SN shock wave velocity the forward shock should impact this equatorial high density ring sometime near the year 2000. At that point it will drive a shock into the high density material, resulting in strong x-ray and other frequency emissions for the next twenty years or more (Luo and McCray 1991, Suzuki et al 1993). The anticipated x-ray luminosity of $\sim 10^{38}$ erg/s, even at a distance of 55 kpc, should be easily detectable by the next generation of x-ray satellites, such as the NASA AXAF observatory to be launched in 1999.

There are however several important uncertainties with the predicted scenario. One is the density of the blue supergiant wind (BSW) and of the equatorial high density ring (HDR). They will affect the arrival time of the SN shock wave and the resultant evolution and x-ray emissivity of the shocked ring material. The other is the effective thermal conductivity (e.g., Liang and Chevalier 1984, Band 1988) of the circumstellar matter (CSM), which will greatly affect the strength and structure of the shock wave and the density and temperature of the post-shock material. The third is the possible effects of hydrodynamic instabilities and their growth rates (e.g., Chevalier and Blondin 1995). These are some of the uncertainties the effects of which we hope to address with NOVA laser target experiments.

The idea is to use laser target blowoff material (rarefaction wave) to simulate the SN ejecta, and foam layers of different densities to simulate the BSW and HDR. Of course most physical parameters such as the distance and time scales, densities and pressures of the laboratory experiments will be many orders of magnitude different from those of SN1987A (cf. Sec. 3). The key question is: there are many relevant parameters of the two phenomena which may have similar values. As we will demonstrate below, it turns out that the velocities and temperatures of the two cases can be quite similar. These are the similarities that we plan to exploit, and hope to learn something relevant to the actual astronomical scenarios with NOVA experiments.

We first briefly review the physics of SN interactions with its CSM. To highlight the basic physics of such interactions we first ignore the 2- and 3-dimensional nature of the SN ejecta and its CSM and idealize them as 1-dimensional spherical shells. Based on the works of Chevalier (1982), Dickey and Jones (1983), Liang and Chevalier (1984) and Band and Liang (1988), the evolution of the interaction zone of the SN ejecta with the low density BSW can be approximated by self-similar solutions. The contact surface is sandwiched between a forward shock propagating into the BSW material and a reverse shock propagating into the SN ejecta (Fig. 2). In the adiabatic limit (zero thermal conductivity) the density peaks at the two shock fronts and goes to zero at the contact surface, where the temperature profile has a sharp narrow spike. This whole interaction zone moves outward at the same rate as the expansion of the SN ejecta. The shocked ejecta layer is Rayleigh-Taylor (RT) unstable since the pressure and density gradients are pointing in opposite directions (Chevalier and Blondin 1995).

The adiabatic assumption is usually made in SN shocks since we know little about astrophysical thermal conductivity or the interstellar magnetic field topology. If, on the other hand, we assume as in laboratory laser plasmas that flux-limited Spitzer conductivity (Spitzer 1967, Max 1982, Fochner et al 1984) applies, then the SN-CSM interaction zone takes on a rather different structure (Liang and Chevalier 1984, Band 1988). The efficient thermal conduction makes the interaction zone close to be isothermal at all times. The shock interaction region then consists of only a single density plateau sandwiched between the forward and reverse shocks (Fig. 2). The profile is narrower and manifestly RT stable at all times. The shocks also propagate faster in this case due to thermal wave preheat. These differences potentially lead to rather different x-ray emission temperatures and profiles and arrival times at the HDR.

Based on the adiabatic simulations, the forward shock in the BSW is expected to reach the HDR around 1999 to 2002 (Luo and McCray 1991, Suzuki et al 1993), at which point the equatorial section of the front will drive a slower shock in the HDR, while the rest of the shock front in the BSW will continue to propagate at higher speed, gradually wrapping around the HDR and eventually evaporating it. These results are suggested by 2-dimensional numerical simulations (Fig. 3, Suzuki et al 1993). While such 2-dimensional details will be important in later phase studies, many of the critical questions can still be addressed in the context of 1-dimensional models. Moreover, since the size of the HDR is small compared to the curvature of the SN shock, to first order we can ignore the spherical divergence of the SN ejecta and approximate the interaction with planar SN ejecta and CSMs. Hence we will first explore 1-dimensional plane geometric laser experiments.

Since it is obviously impossible to reproduce the density and pressure of the SN ejecta or CSM (< 10 particles/cm³ for BSW and $\sim 10^4$ particles/cm³ for the HDR) in a laboratory laser experiment, we concentrate on exploring the temperature and velocity of the shock achievable in the laser experiments. Using standard NOVA laser intensities ($\sim 10^{14}$ W/cm²), we find that it is easy to achieve blowoff velocities $\sim 10^3$ km/s when the density rarefies to $\sim$ mg/cm³, a density that can be almost matched to the lowest density foams. The above velocity is only a factor of ~ 10 below that of the real SN forward shock velocity ($\sim 10^4$ km/s). Since in the SN case the density jump between the BSW and

the HDR is $\sim 10^3$ the velocity drop from the BSW to the HDR is ~ 30 , resulting in a shock in the HDR of only $\sim 10^2$ km/s and a temperature of ~ 1 keV. To achieve a similar shock velocity and temperature we therefore propose the use of two foam layers with a density jump of 10, so that the velocity drop is only ~ 3 . In the numerical simulations reported below, we will assume that the low density (LD) foam layer representing the BSW has a density of 1.5 mg/cm^3 and the high density (HD) foam layer representing the HDR has a density of $10\text{--}30 \text{ mg/cm}^3$.

2. PHYSICS OF LASER TARGET BLOWOFF INTERACTION WITH STANDOFF FOAM LAYERS.

To first order we can assume that the laser energy is deposited in a thin layer at the critical density surface (where laser frequency equals plasma frequency). From this layer outward temperature rises quickly to a constant asymptotic value via thermal conduction and the (planar) blowoff is adequately represented by an isothermal rarefaction wave with linear velocity and exponential density profiles. Inward from the critical density surface the density rises rapidly to solid density and temperature drops off quickly. The thermal diffusion front eventually drives a weak shock wave into the target whose momentum is balanced by that of the blowoff. In the isothermal limit the asymptotic blowoff at distance z is well described by a self-similar solution (e.g. Schmalz 1985):

$$v = z/(4c_s \text{ and } \rho = \rho_0 \exp(-2/c_4)) \quad (1)$$

where c_s is the isothermal sound speed and ρ_0 is an initial value somewhere between the critical density and quarter critical density. When the leading edge of this blowoff hits the low-density (LD) foam at a fixed standoff distance (the gap is needed for the laser beams to get in without preheating the foam layer), it generates a forward shock into the LD foam and a reverse shock in the blowoff material. The strength of the shocks depend on the velocity and density of the blowoff reaching the standoff distance. According to Eq. (1) we see that the higher c_s and ρ_0 the better. From the literature (e.g. Mux 1982) we have

$$c_s = (ZkT/m_e)^{1/2} \sim 730 \text{ km/s } (Z/A)^{1/2} (1/\lambda_D)^{1/2}; \quad \rho_0 \approx \rho_0 = 1.8 \times 10^{-3} \text{ g/cm}^3 (AZ)^{1/2} \lambda_D^{-2} \quad (2)$$

where Z is mean atomic number, A is mean atomic weight ($A/Z \sim 2$ for most materials), $\lambda_D = 1/(16\lambda_W \text{ cm}^{-2})$ and λ_W is laser wavelength in microns. Hence the higher the laser intensity the better. But c_s and ρ_0 have opposite dependences on laser wavelength. It turns out that the sound speed plays a more dominant role than the critical density since it sits in the exponent, and numerical simulations confirm that longer laser wavelength indeed generates stronger shocks in the foam layer.

Eqs (1) and (2) show that for NOVA laser pulse durations, wavelengths and intensities and realistic standoff distances, to get a good density match we need to use foams in the mg/cc range for the LD layer. One of the goals of our simulation is to see the effects of varying the foam density. Another goal is to see the effects of varying the thermal conductivity. In practice the thermal conductivity may be varied by doping with high Z material or applying strong transverse magnetic fields.

3. COMPARISON OF SN1987A AND NOVA EXPERIMENT PARAMETERS

In Table 1 we compare the physical parameters of SN1987A with that of the proposed NOVA experiments to illustrate the drastic differences of the scales. We see that the only similarity is in the shock velocity and temperature of the HD foam. Note

also that in both cases the Coulomb mean free path are $\gg$ the interaction region size but the cyclotron radius is $\ll$ the interaction region size.

Table 1.

	SN1987A	NOVA experiments
Distance to HD ring/foam	$6 \times 10^{17} \text{ cm}$	mm
Shock arrival time at HD ring/foam	12-15 yr	1.2-1.5 ns
Density of pre-shock BSW/LD foam	$\sim 10^{-10} \text{ atoms/cc}$	1-5 mg/cc
Density of pre-shock HD ring/foam	$\sim 10^{-14} \text{ atoms/cc}$	10-30 mg/cc
Pressure in shocked BSW/LD foam	$\sim 10^{-6} \text{ erg/cc}$	$\sim 10^{13} \text{ erg/cc}$
Pressure in shocked HD ring/foam	$\sim 10^{-3} \text{ erg/cc}$	$\sim 10^{13} \text{ erg/cc}$
B-field	$\sim \mu\text{G}$	10 MG
Electron cyclotron radius	$\sim 10^9 \text{ cm}$	10^{-6} cm
Coulomb mean free path in HD ring/foam	$\sim 1.5 \times 10^{18} \text{ cm}$	4.5 cm
Coulomb mean free path in LD ring/foam	~ 10	150
Shock velocity in BSW/LD foam	$\sim 6000 \text{ km/s}$	$\sim 500 \text{ km/s}$
Shock velocity in HD ring/foam	$\sim 200\text{--}400 \text{ km/s}$	$\sim 150\text{--}300 \text{ km/s}$
Shock electron temperature in BSW/LD foam	4-6 keV	2-3 keV
Shock electron temperature in HD ring/foam	0.7-1 keV	0.6-2 keV

4. 1-DIMENSIONAL NUMERICAL SIMULATION RESULTS

We have performed a large number of 1-dimensional (1-D) geometry numerical simulations with LASNEX to explore the interactions of laser target blowoffs with different density foams at a standoff distance realistic for actual laser experiments. The sample results reported here compare the runs of (a) 1 mg/cc LD plus 10 mg/cc HD foam densities versus 5 mg/cc LD plus 50 mg/cc HD foam densities; (b) thermal conductivity on versus off (adiabatic); (c) Z_{foam} (green) versus 30% (blue) laser light. Except for the above differences, the assumptions and parameter settings for everything else are the same for all runs and are summarized here:

- 1) The laser intensity is assumed to be 10^{14} W/cm^2 normal incidence, all absorbed at the critical surface; the laser is left on for the duration of the entire run ($\sim 3\text{--}5 \text{ ns}$).
- 2) The LD foam is located at 0.05 cm from the laser target. Its thickness is taken to be 0.06 cm in the low (1 mg/cc) density runs and 0.05 cm in the high (50 mg/cc) density runs.
- 3) The HD foam lying beyond the low density foam is taken to be ten times denser than the LD foam and its thickness is set to be 0.09 cm.
- 4) Both the laser target and the foams are assumed to be 50% C and 50% H in composition; the target is assumed to be at solid density (1.1 g/cm^3) initially.
- 5) Artificial linear and quadratic viscosities are turned on to their default values to control any numerical ringing from shock interactions.
- 6) When thermal conductivity is on, the flux limiter parameter f is always set equal to 0.03 as is customary in laser target calculations.

The initial geometry setup of the numerical runs is illustrated in Fig. 4. We now summarize the results of the different runs.

A. Benchmark run: 20% laser light, conduction on, low foam densities (1 mg/cc LD plus 10 mg/cc HD foams):

Fig. 5 gives the density profile snapshots at sample times. At 1 ns the forward shock in the LD foam has not yet reached the HD foam boundary, and the interaction region bounded by the forward and reverse shocks in the LD foam has a standard "plateau" structure similar to the conductive SN runs made by Liang and Chevalier (1984).

cf. Fig. 2). Notice the exponential density profile of the blowoff and the width of the interaction region (~0.15 cm, much larger than typical foam cell size). The forward shock hits the HD foam at around 1.2 ns. This produces a forward shock in the HD foam and a reflected shock in the LD foam. (see e.g. profile at 1.5 ns). Eventually, however, the reflected and reverse shocks merge into a single reflected shock in the blowoff material. There is no evidence of any "reverberation" of the reflected shock between the reverse shock and the forward shock as claimed by Luo et al (1994).

Fig. 6 gives the pressure profile snapshots at various times. The development of the forward and reflected shocks when the HD foam is first hit and the subsequent merging of the reflected and reverse shocks are more clearly illustrated in this picture. Fig. 7 gives the velocity profile snapshots and Fig. 8 gives the bremsstrahlung emissivity profile (~ $\pi^2/12$) snapshot. Note that the latter profile broadens with time as the shock advances. Note also that since the above emissivity function is dominated by the density peak and not the temperature, this profile need not represent the picture seen by x-ray detectors of a narrow band pass. Fig. 9 gives a sample temperature profile at $t=3.0$ ns. The temperature is in fact quite low near the forward shock where density peaks and rises slowly to a plateau of 2.8 keV only near the rear of the density profile. Hence the spectrum of x-ray emissivity is very soft at the shock front and gets harder only near the contact surface. Fig. 10 gives the transverse optically thin x-ray intensity spectrum just to the left of the density peak at $t=3$ ns. We see that even though the spectrum above ~2 keV is close to that of thermal bremsstrahlung, at lower frequencies it is still dominated by the bound-bound and bound-free opacities of carbon. Doping the foam with higher Z tracers will be very useful in mapping the density and temperature profiles of the shock interaction region.

Note also from the pressure and density profiles that since both of their gradients point in the same direction, the shock interaction regions are RT stable, thanks to the effects of thermal conduction. At 3 ns the shock has reached the outer edge of our HD foam at 0.2 cm.

B. High density run: the densities of both the LD and HD foams are 5 times higher than in A, all other parameters remain the same as in A; conduction is turned on.

Fig. 11-14 give the density, pressure, velocity and temperature profile snapshots. Note that the shocks are now propagating much more slowly than in case A. It does not reach the LD-HD foam interface until 1.5 ns. Even before the shocks reach the HD foam, the density profile is sharply forward peaked, unlike the flat plateau of the lower density run. When the shock hits the HD foam, it generates a very sharp forward density peak. This peak also propagates much more slowly than in the lower density case. The reflected shock also propagates more slowly. It has not yet caught up with the reverse shock by the end of the run at 3.6 ns. Note also that the density jump at the forward shock reaches a factor of ~30, much higher than the factor of ~3 reached in case A. Fig. 15 shows the late-time bremsstrahlung emissivity profiles which trace the density profiles. They are much narrower than those in case A. These results suggest that the width and amplitude of the x-ray emission profile may serve as a diagnostic of the density of the foam, and by analogy, the density of the CSM around SN 1987A.

In Fig. 16 we compare the forward shock trajectories of case A versus case B after the shock penetrates the HD foam. We see that A propagates much faster than B. In Fig. 17 we compare the forward shock peak density of case A versus case B. We see that B is shocked to much higher density than A. From the velocity profiles of runs A and B we see that the late time shock velocity employed in the HD foam are in the range of 150-300 km/s, similar to those expected when SN 1987A hits the high density ring.

C. Adiabatic run: conductivity is set equal to 0; all other parameters remain the same as in A.

Fig. 18-21 give the density, pressure, velocity and temperature profile snapshots of the shock interaction regions. Note that before the forward shock hits the HD foam (< 1.3 ns), the interaction region has the classical double density peak structure with a sharp temperature spike at the contact surface, well known in adiabatic SN runs (cf. Fig. 2). Despite the differences between our laser blowoff and SN ejecta cases (exponential instead of power-law density profile, and plane instead of spherical geometry), the shock interaction structures in both cases are almost identical. In the adiabatic limit, this gives us some confidence that the laser experiments can reproduce some of the important aspects of the SN interactions with the CSM.

After the shock hits the LD-HD foam interface, it generates a forward shock into the HD foam and a reflected shock in the LD foam which propagates toward the blowoff-LD foam contact surface. This reflected shock interacts with the contact surface and at late times produces a sharp density spike situated between the forward shock and the contact surface. Hence we see that the density is highest not at the forward or reflected shock but at somewhere in between. The overall density profile is clearly narrower than the conductive case. Whether the density peak here is caused by the reverberation effect discussed by Luo et al (1994) remains to be seen. Fig. 22 gives the thermal bremsstrahlung emissivity profile snapshots. Again it traces mainly the density profile. The sharp temperature spike at the target blowoff-LD foam contact surface does not lead to much x-ray emission since it coincides with a density dip. Note also that at all times the pressure and density gradients point in opposite directions in at least part of the forward shock interaction region, suggesting that it is RT unstable, similar to the adiabatic SN cases.

D. 300 run: laser frequency set equal to 300; all other parameters remain the same as in A. In Fig. 23-26 we compare the density, pressure, velocity and temperature profiles of the 200 versus 300 runs at 1 ns, just before the shock reaches the LD-HD foam interface. By integrating the density x velocity profile we find that in the 300 case the blowoff delivers to the foams only about 60% of the shock momentum of the 200 case. Hence from the point of view of generating the stronger shock, a 200 laser is definitely better than the 300 laser.

5. PROPOSED NOVA EXPERIMENTS

Based on the results of above numerical simulations, we propose a series of NOVA experiments using 5 NOVA 200 beams of 0.7 terawatt each incident at 50° from normal and a foam standoff distance of 0.5 mm. Based on the design calculations by Gail Glendon the 5 beams should be able to avoid the foams and produce an average projected intensity of 10^{14} W/cm² lasting about 3.5 ns. The footprint of the 5 beams is reproduced in Fig. 27. The circular region has a diameter of 0.15 cm which should deliver a plane target blowoff covering an effective area of at least 0.1 cm diameter. Even though the laser intensity in the footprint appears quite nonuniform over the circular region, based on past experience the resultant blowoff should quickly homogenize itself. For the first experiment we should start with the lowest density foam available since lower density should lead to higher shock velocity and temperature, and study the effects of increasing foam density in later shots. To simulate the transition from the BSW to the HDK in SN 1987A we suggest using a density jump of a factor of 10 between the LD and HD foams. But the thickness of the LD foam depends on the foam density. For an LD foam density of ~1 mg/cc a thickness of 0.6 mm is recommended but if the LD

foam density goes as high as 3mg/cc its thickness should be reduced to 0.5mm or even less, since the shock speed decreases with increasing density. We should try to observe the propagation of the shock profile in both x-ray emission and absorption. In particular, line- and space-resolved x-ray spectral measurements will be useful in studying the evolution of the output x-ray spectrum as a function of the foam densities. The use of laser probe beams and high-Z tracers in the foam should also be considered.

Once the above benchmark experiments prove successful, we should consider follow-up experiments aimed at (a) studying the effects of reduced thermal conductivity, (b) 2-dimensional effects. Two methods of inhibiting the plasma thermal conductivity should be explored: (a) doping the target and foam materials with high Z atoms (since Spitzer resistivity goes up as Z^2) and (b) application of transverse magnetic fields. In order to freeze the external magnetic flux into the blowoff and foams we may explore preheating the materials to ionizing temperatures for long enough so that the fields can fully diffuse into the plasma before the blowoff begins. To study 2-dimensional effects we may first try various rod or ring shaped HD foam geometries to simulate the HD ring or shell.

E.L. gratefully acknowledges the hospitality and support of X-Division, LLNL for this work. He also thanks Rich London, Bruce Remington and John Cantor for valuable discussions. The LASNEX generator decks are adapted from input decks provided by Rich London.

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Fig.1 (a) Artist conception of the peanut-shaped cocoon of low density BSW surrounded by a high density shell formed by the interaction of the BSW with the RSW. The ejecta of SN1987A is represented by the central sphere; (b) triple ring system observed by the NTT compared with a simulated image of the rings, which are formed by limb brightening when the cocoon of (a) is viewed at 43° from the symmetry axis (from Wang and Mazzali 1992).

Fig.2 Sample density and temperature profiles of the interaction zone between the SN ejecta and the CSM. NC denotes the adiabatic case and C denotes the conducting case with flux-limited Spitzer thermal conduction (from Liang and Chevalier 1984).

Fig.3 2-dimensional numerical simulation of the SN1987A shock interaction with the equatorial high density ring (from Suzuki et al 1993).

Fig.4 Sketch of the initial geometry of the laser target and the foam layer.

Fig.5 Density profile snapshots of the benchmark run (case A) with LASNEX.

Fig.6 Pressure profile snapshots of the benchmark run.

Fig.7 Velocity profile snapshots of the benchmark run.

Fig.8 Bremsstrahlung emissivity profile snapshots of the benchmark run.

Fig.9 Temperature profile of the benchmark run at 3.1 ns.

Fig.10 Transverse x-ray flux spectrum near the density peak at 3 ns for the benchmark run.

Fig.11-15 Density, pressure, velocity, temperature and bremsstrahlung emissivity profile snapshots of the high foam density run (case B).

Fig.16 Comparison of the forward shock trajectories after the shock hits the HD foam between (a) case A and (b) case B.

Fig.17 Comparison of the peak shock density as a function of time after the shock hits the HD foam between (a) case A and (b) case B.

Fig.18-22 Density, pressure, velocity, temperature and bremsstrahlung emissivity profile snapshots of the adiabatic run (case C).

Fig.23-26 Comparison of the density, pressure, velocity and temperature profiles at 1ns between the benchmark 2m, and the 3m, runs (case D).

Fig.27 Combined footprints of 5 NOVA beams incident at 50° from normal (from Glendinning 1995).

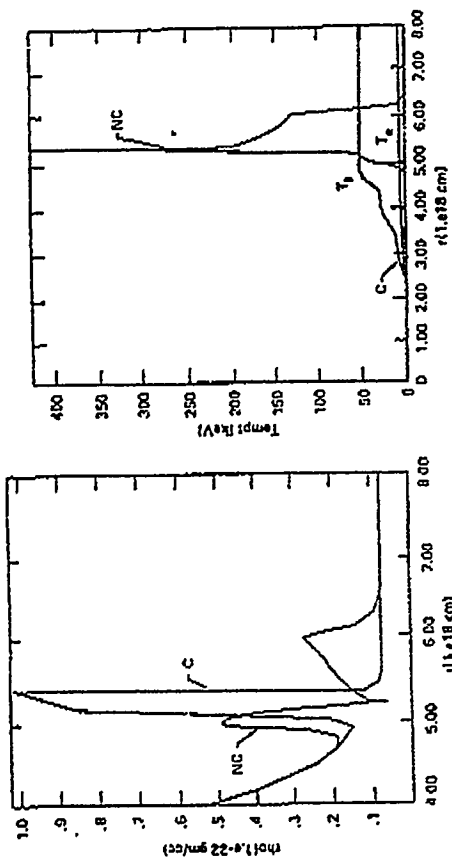


Fig. 2

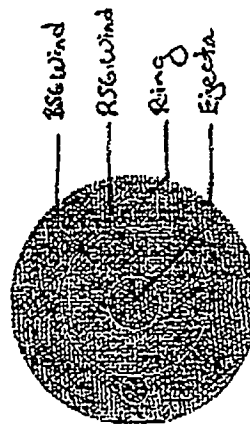


Figure 1: Point on the inner shell of the ring

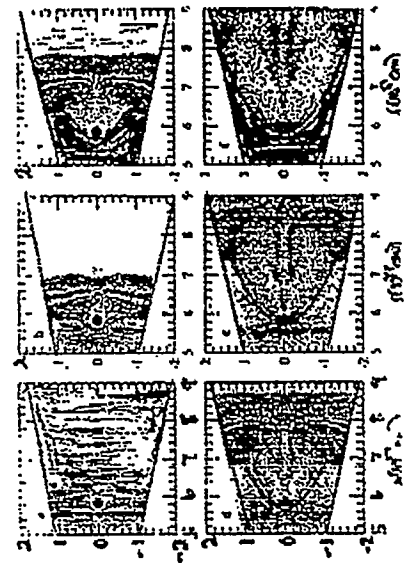


Fig. 3

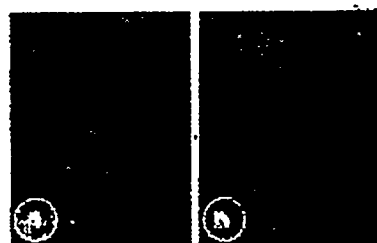
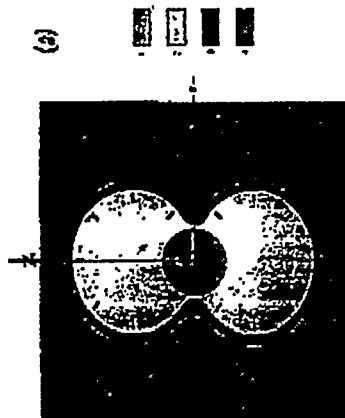


Fig. 1

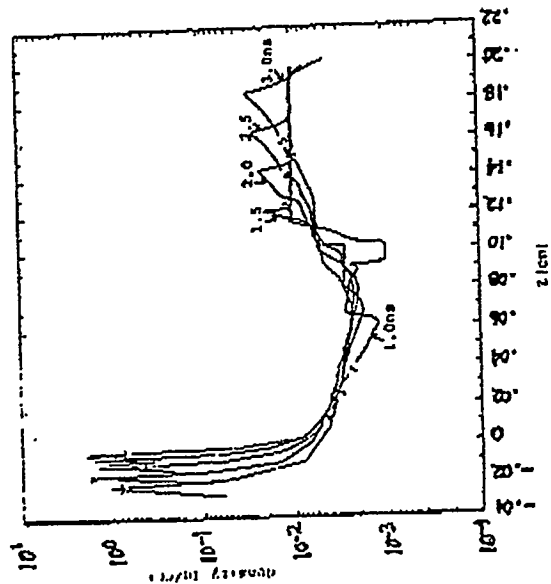


Fig. 5

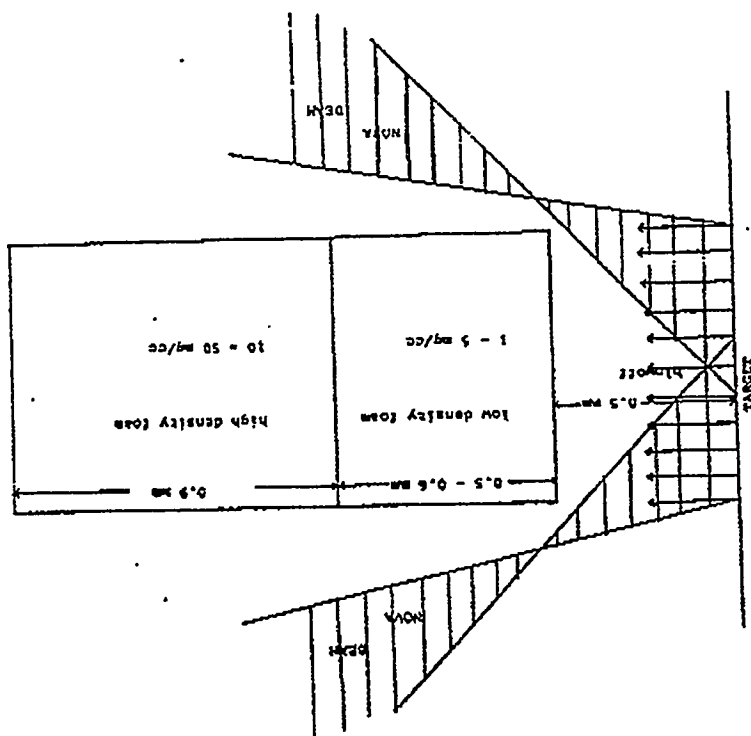


Fig. 4

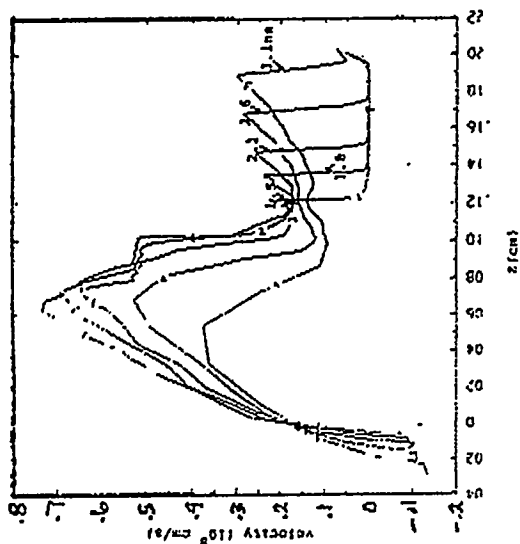


Fig. 7

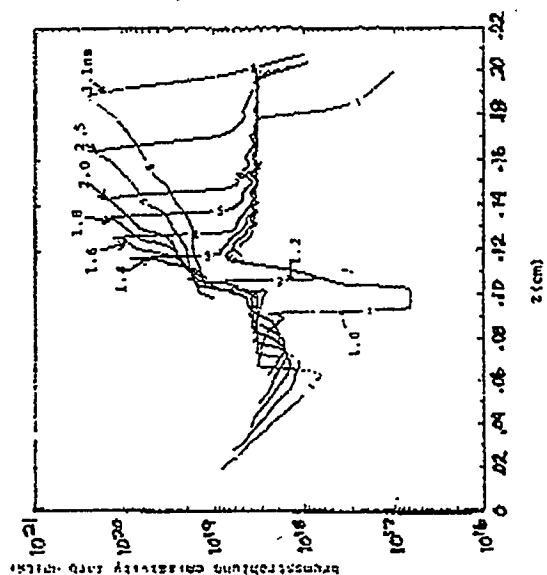


Fig. 8

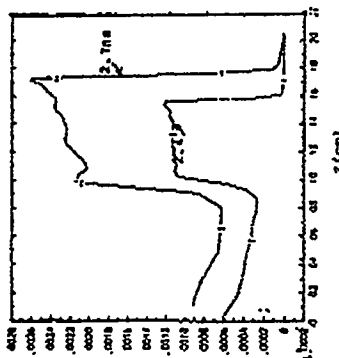
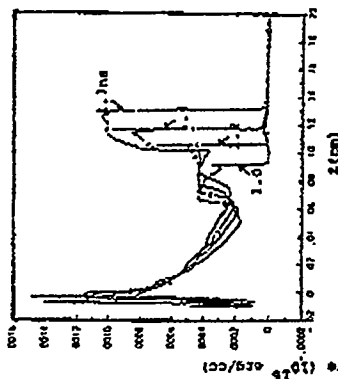


Fig. 9

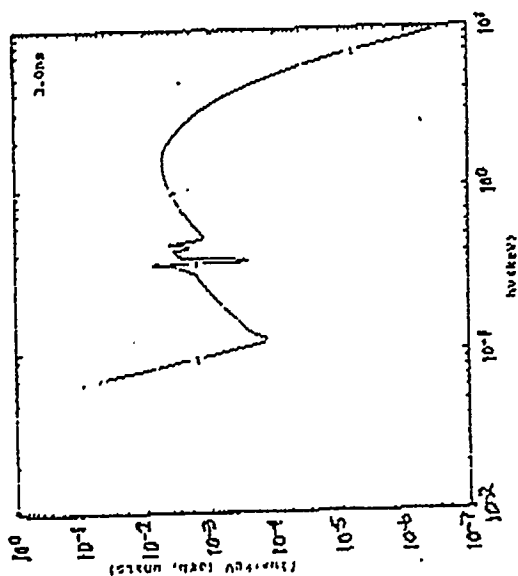


Fig. 10

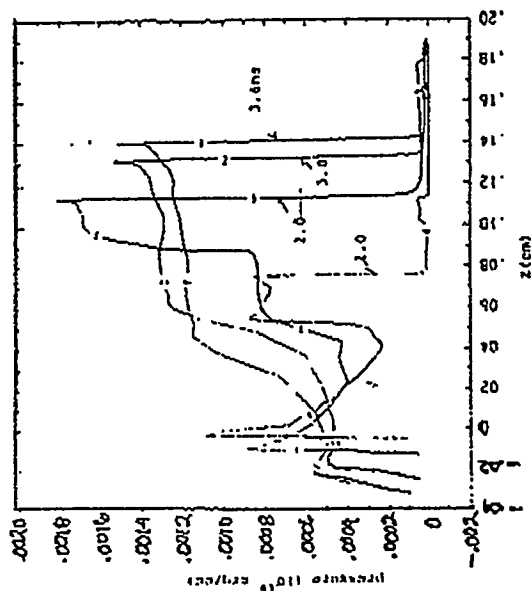


Fig. 12

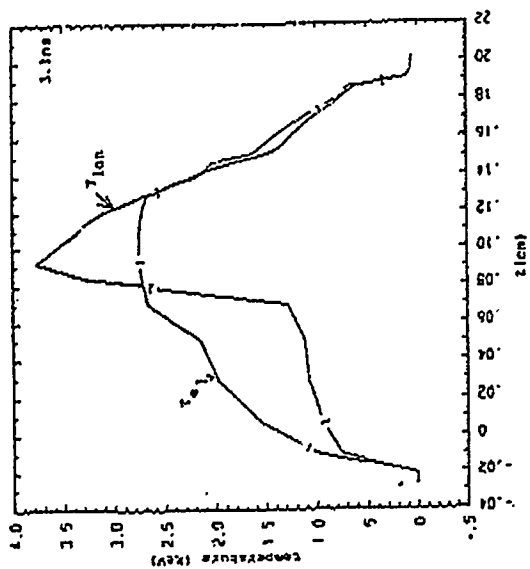


Fig. 9

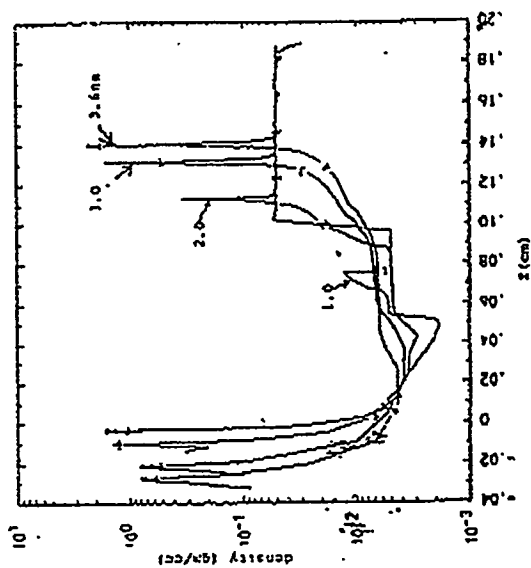


Fig. 11

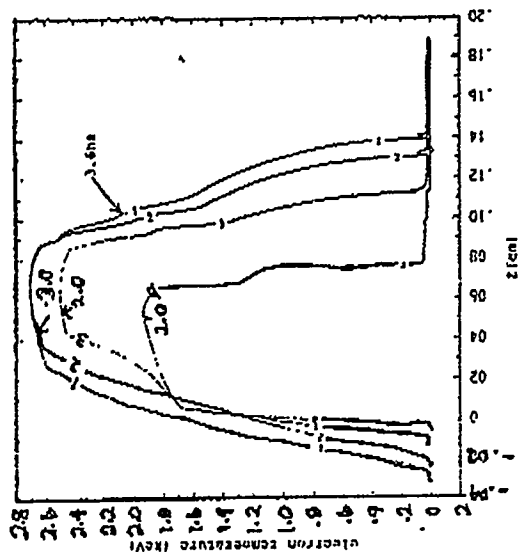


Fig. 14

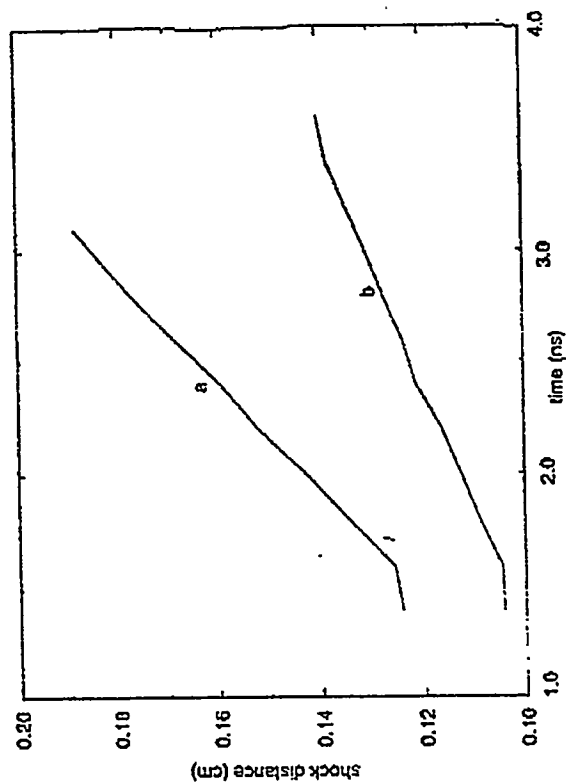


Fig. 16

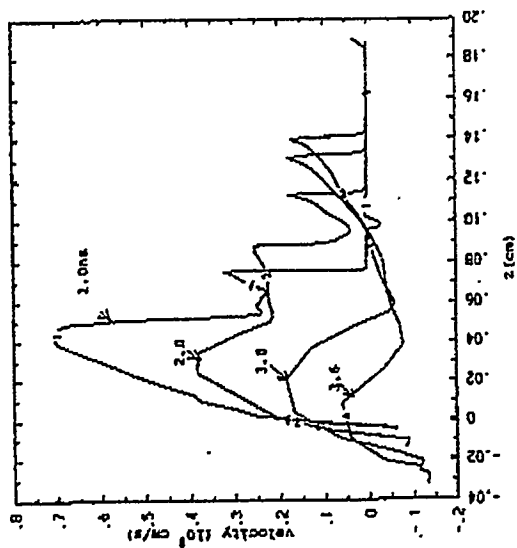


Fig. 13

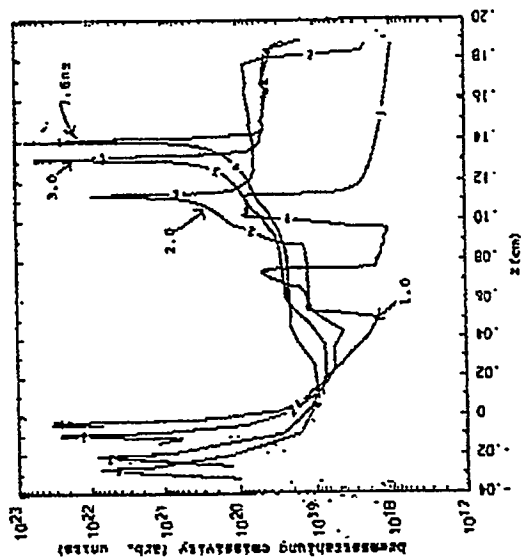


Fig. 15

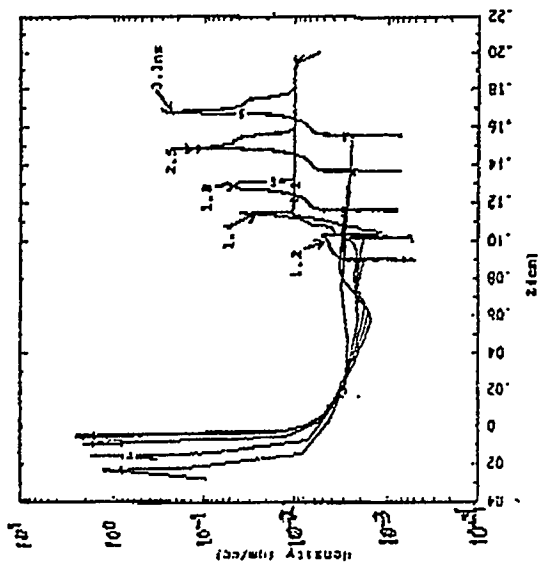


Fig. 18

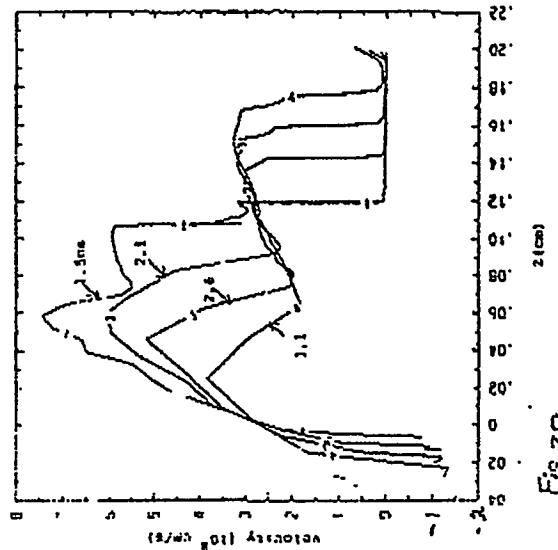


Fig. 20

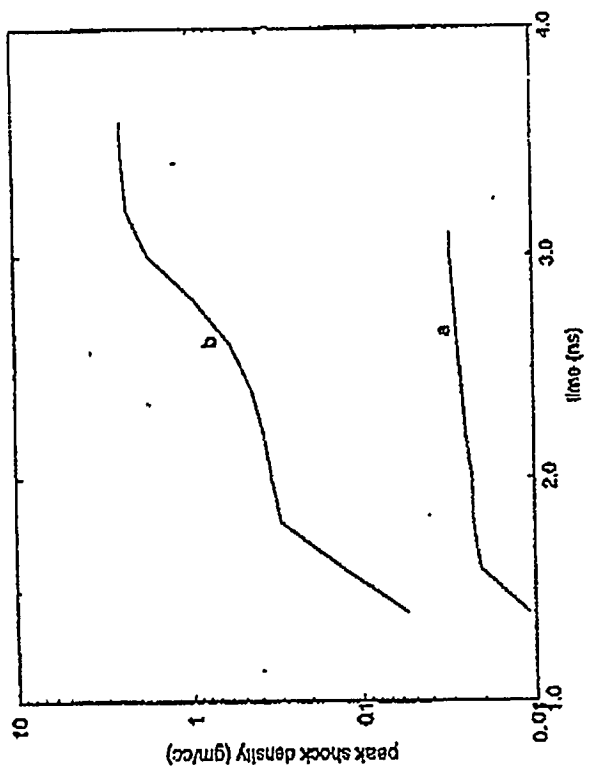


Fig. 17

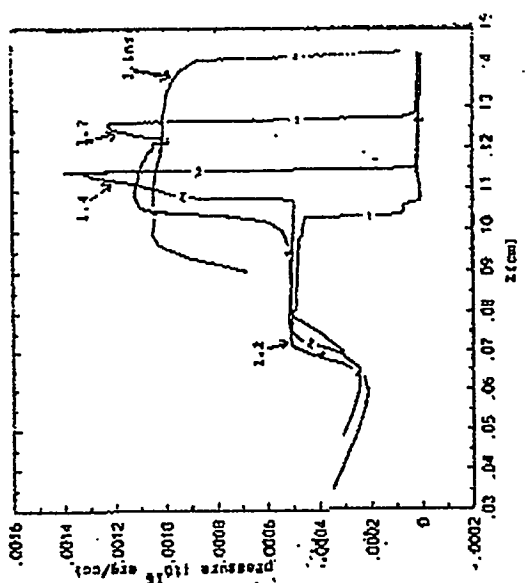


Fig. 19

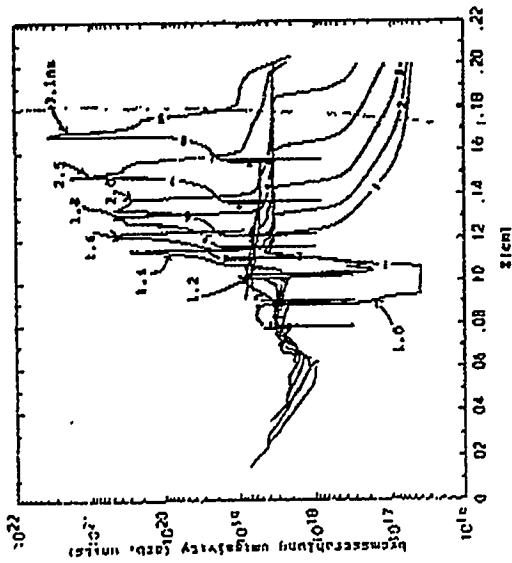


Fig. 22

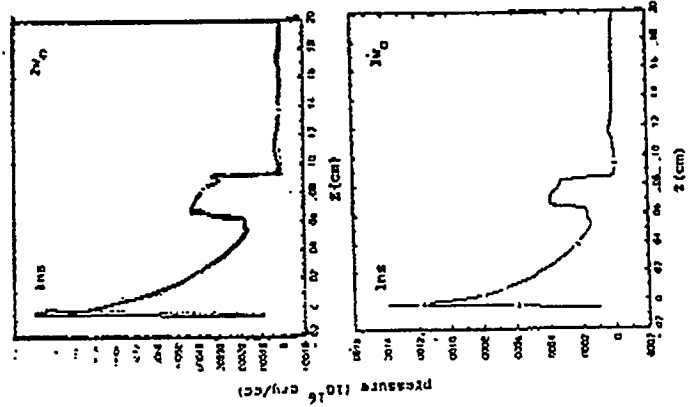


Fig. 24

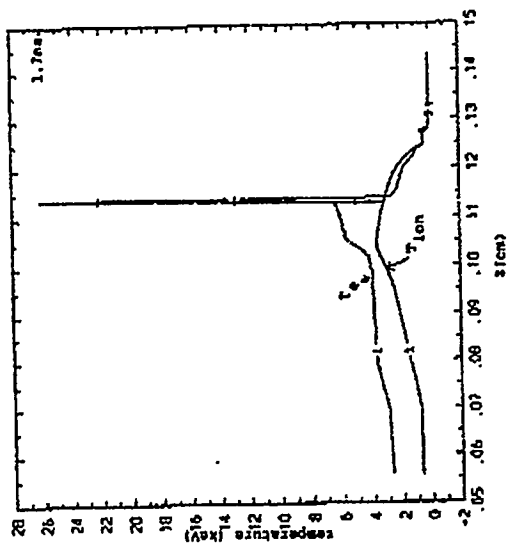


Fig. 21

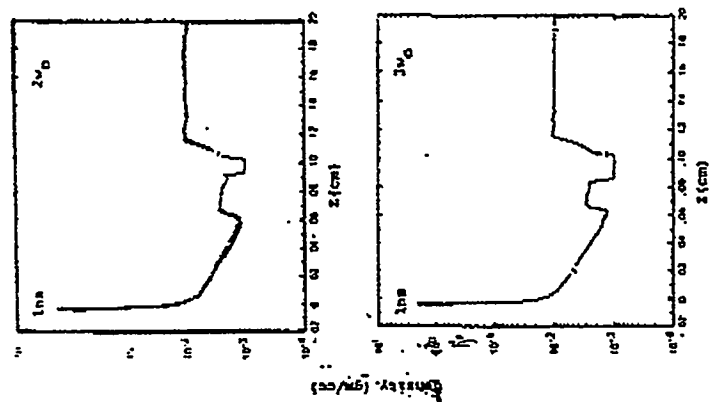
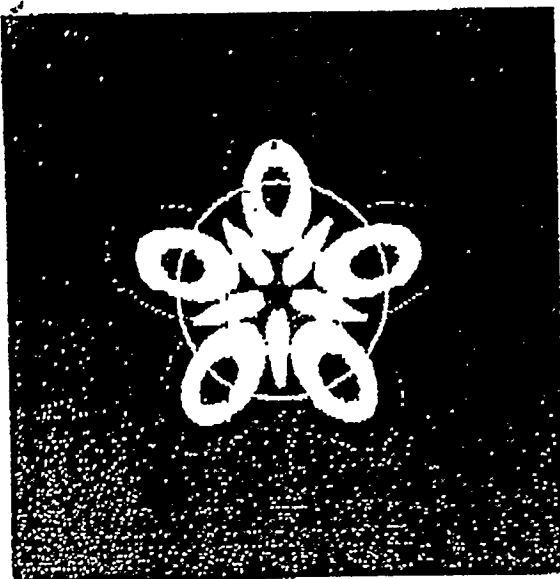


Fig. 23



The image is a 150 μ m diameter target, a thin amount of energy is outside the circle for to make the regions between the beams not go to 2.5 within the circle the average intensity is about 1.4×10^{14} W/cm² per input beam. The standard deviation is about 10^{14} W/cm² at 17. The beam size is 100 μ m and the standard deviation is about 3.5 μ m, about 4 μ m with a top

Fig 27

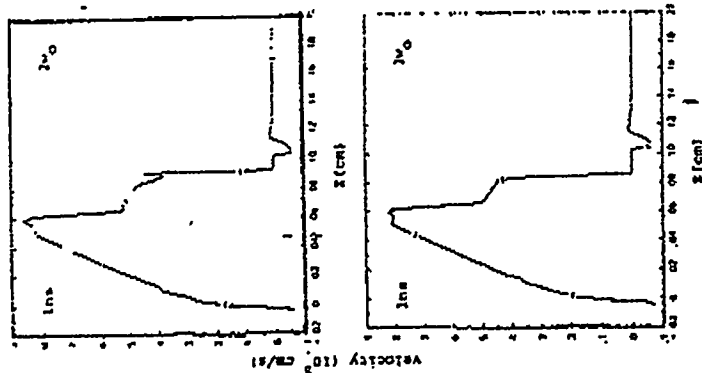


Fig 25

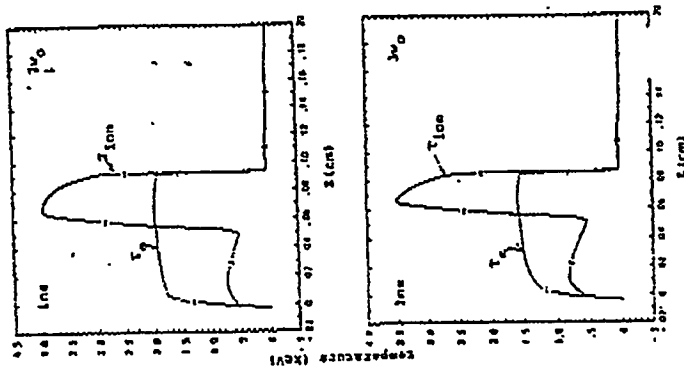


Fig 26

**Results from a Recent Shock Wave
Experiment on Trident**

**Gottfried Schappert
Los Alamos National Laboratory**

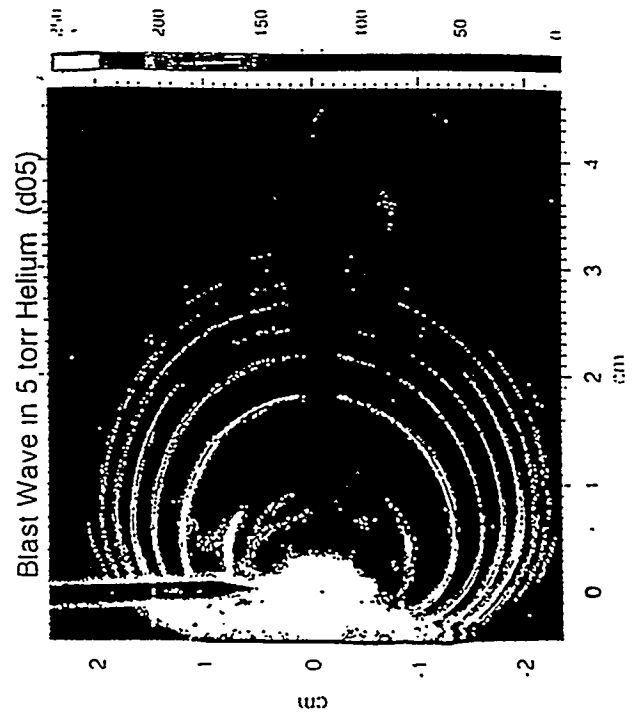
Results from a recent Shock Wave Experiment on Trident

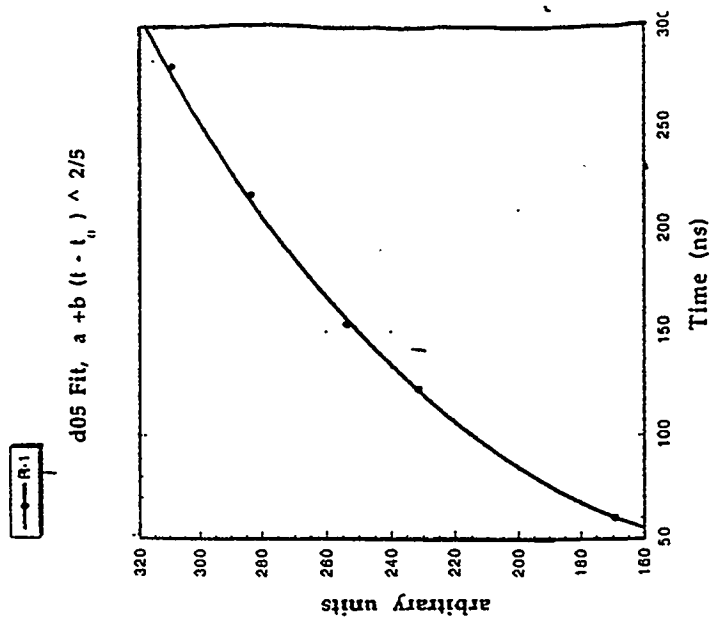
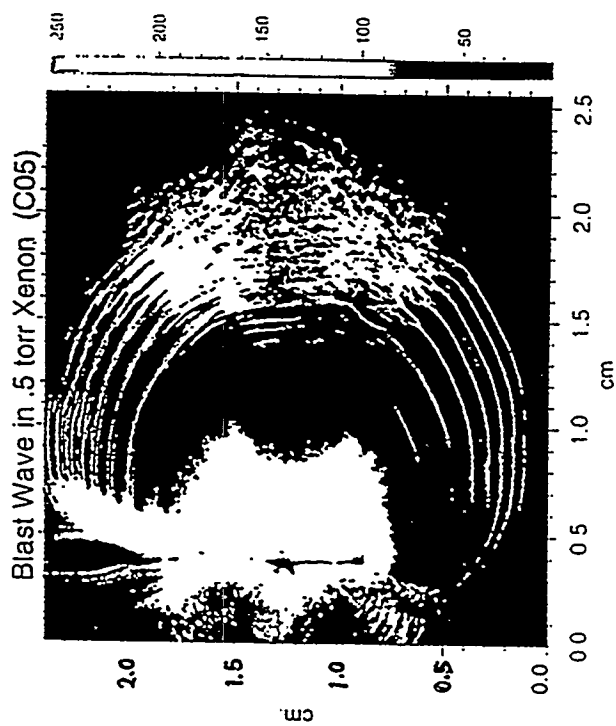
i.e.

the Vishniac Instability

Gottfried T. Schuppert, Robert D. Fulton and David M. Oro

Los Alamos





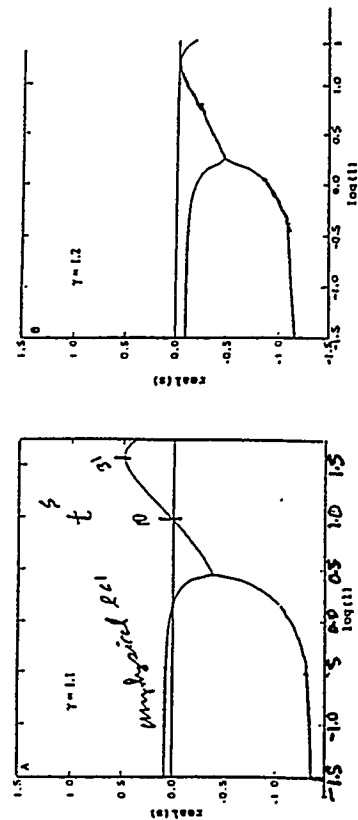
The Growth of Linear Perturbations of Adiabatic Shock Waves

D. Ryu and E. Vishniac, The Astrophysical Journal, 313: 820-841, Feb. 1987

The Perturbed radius of a spherical wave is

$$R \sim t^{2/5} (1 + b \times t^S \times Y''(\Theta, \Phi))$$

The growth rates S for various values of Γ are:



γ : the ratio of specific heats c_p / c_v

In statistical mechanics $\gamma = (\text{degrees of freedom} + 2) / (\text{degrees of freedom})$

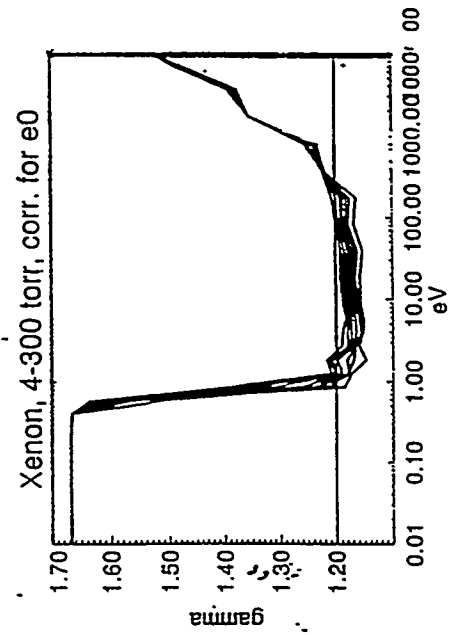
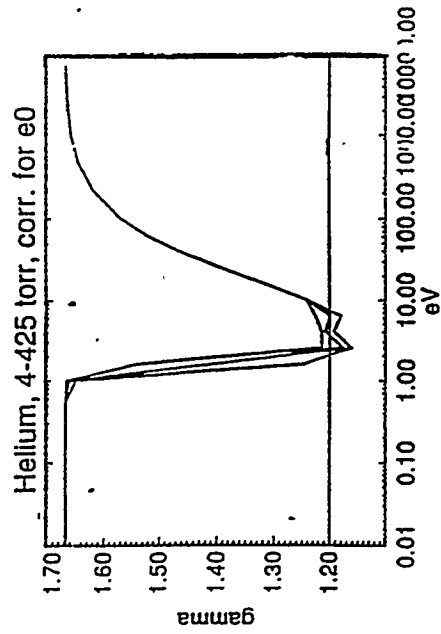
Xe: $\gamma = 5/3$

N_2 $\gamma = 7/5 - 9/7$

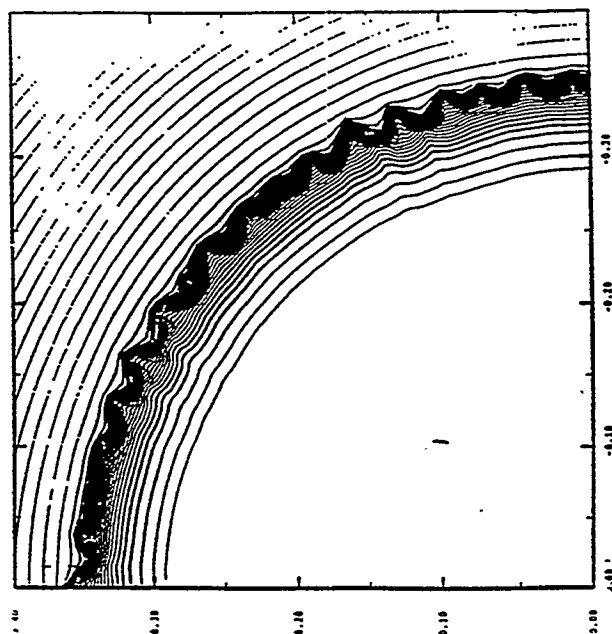
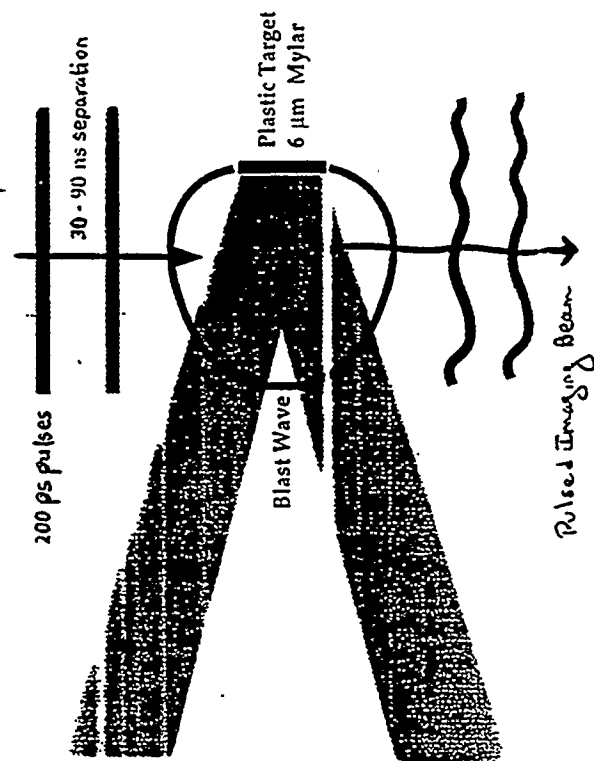
For non-ideal gases, under conditions of dissociation, excitation and ionization the blast wave model uses the relationship between pressure, energy density, and density

$$P = (\gamma - 1) E \rho$$

which we can get from equation of state tables.



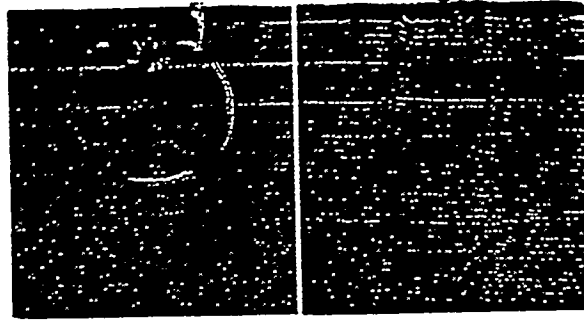
Top View of Layout for Trident Blast Wave Experiment



LASNEX calculation of a spherical Taylor-Sedov blast wave in a gas with a $\gamma = 1.06$ and a perturbation of 10^{-4} $P_{t=30}$

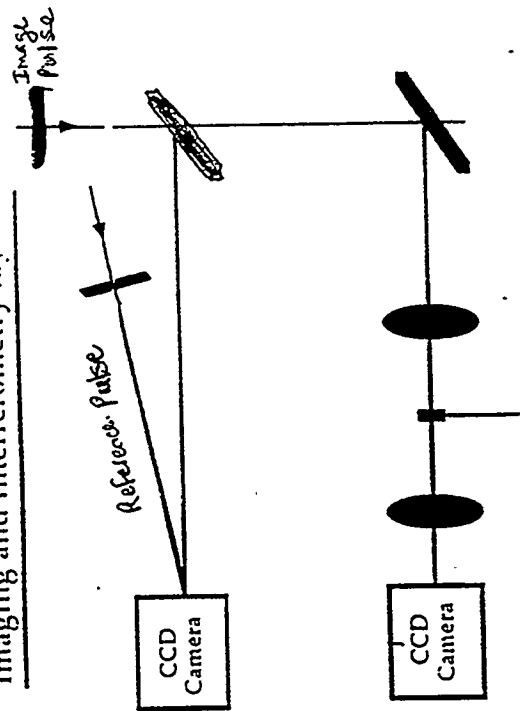
Image and Interferogram of Blast Wave in Helium

5 torr He
138 J
Time 52.6 ns



1402

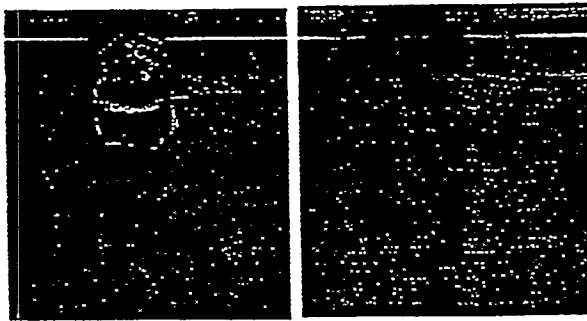
Imaging and Interferometry layout



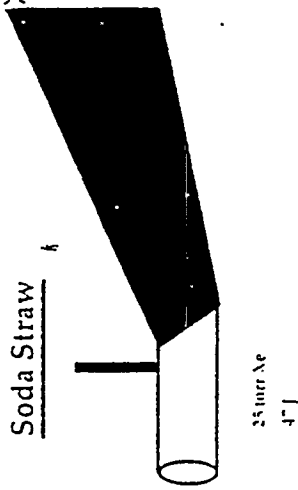
Los Alamos

Image and Interferogram of Blast Wave in Xenon

1 torr Xe
118 Joules
Time 52.9 ns.



Los Alamos



plus

Conclusion:

This is fun stuff

More modeling with complete hydro, atomic and radiation physics needs to be done

Even small laser systems can still contribute

Instabilities, Convection and Smoke Rings

Stirling Colgate
Los Alamos National Laboratory

INSTABILITIES, CONVECTION AND SMOKE RINGS

Stirling Colgate, T-6, LANL
2/26/96

Why a dynamo?

Why an accretion disk?

Why a sodium explosion?

Why a hurricane?

Why a supernova; 1A?

Why a supernova; II

Why a thunderstorm?

Why a tornado?

Why a plume? I

Why a mixing length?

Why a mixing layer?
Why a smoke ring?
in a non-smoking environment.

An answer to all, even a few of these would more than scratch the surface of the problem of instabilities, convection, and smoke rings, but such a big scratch deserves a big itch. : A unifying principle is needed:

The principle of maximal dissipation.

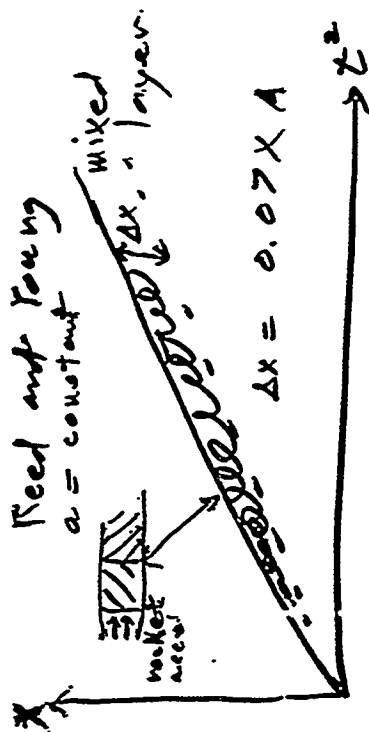
If it can, it will.

Or a scratch dissipates an itch.

Convection dissipates Free Energy
e.g., negative, gravity.

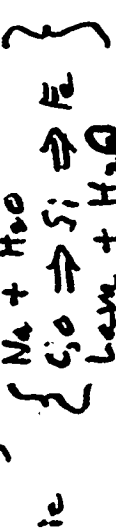
Entropy $\delta ds/d(z,R)$ negative

$\downarrow \rightarrow$ free energy



A = Atwood number - density contrast
 $\frac{\rho_1 \rho_2}{\rho_1 + \rho_2} \rightarrow 1$

$\Delta x/x$ independent of a , acceleration
 If gases are reactive



So original entropy?

Then $\Delta x = 0.07 X (S_i/S_o)$ flame
 if $(0.07 S_i/S_o) \geq 1$ then a flame
 if $() > 1 \Rightarrow$ explosion,

$$\Delta x = \Delta_0 \exp \left[(2\pi \sigma a / \lambda)^{1/2} t \right]$$

$$X = (1/2) a t^2$$

$$\Delta x = \Delta_0 \exp \left[(4\pi A \frac{x}{\lambda})^{1/2} \right]$$

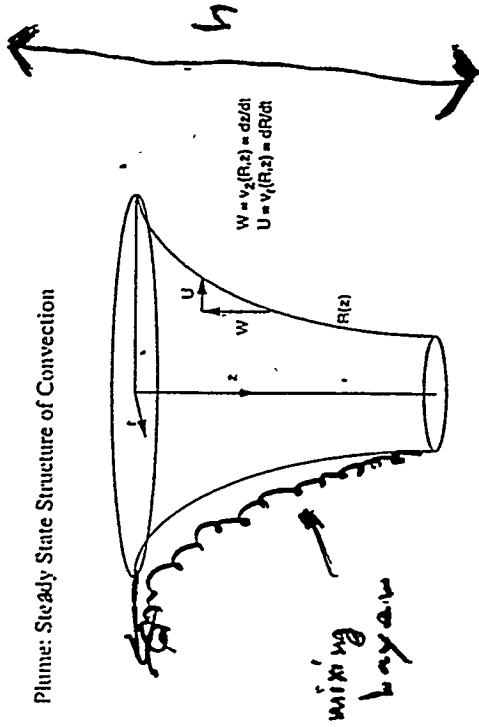


$$\Delta x = \lambda / 2^{1/2}$$

$$\text{Then } \exp \left(4\pi A \frac{x}{\lambda} \right)^{1/2}$$

$$\sim \exp \left[9 A^{1/2} \right]$$

Plume: Steady State Structure of Convection

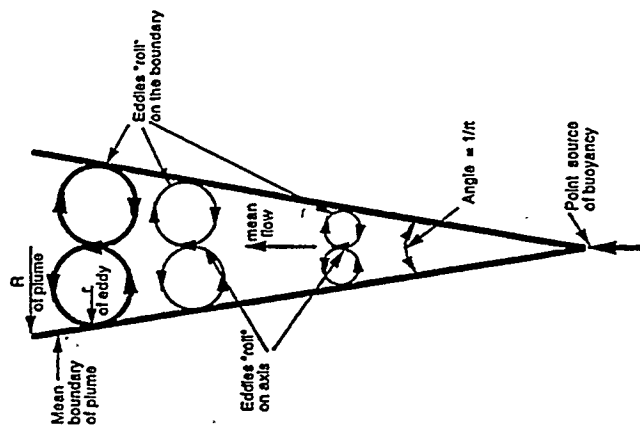


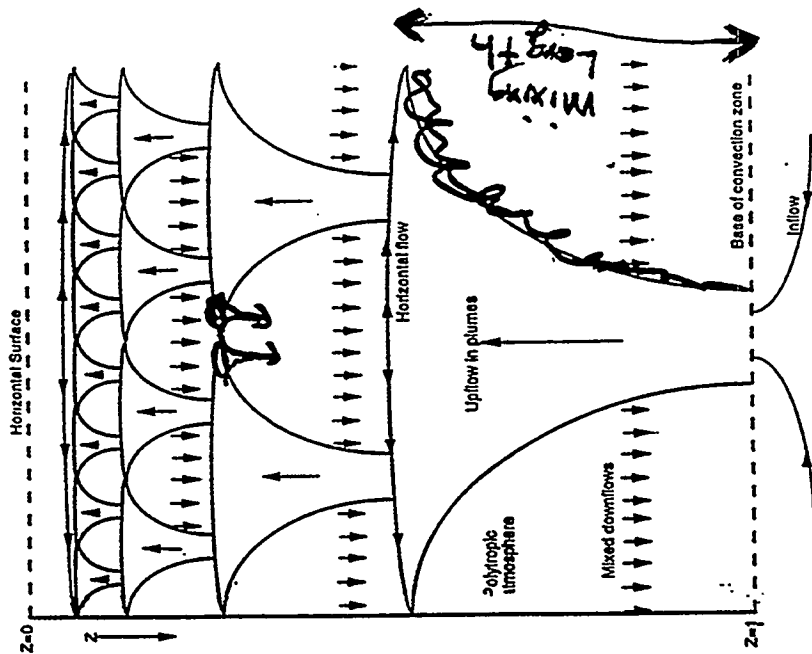
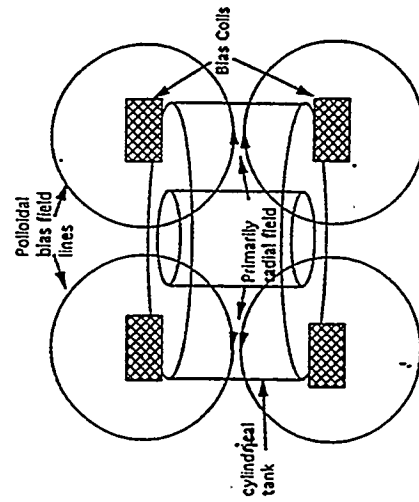
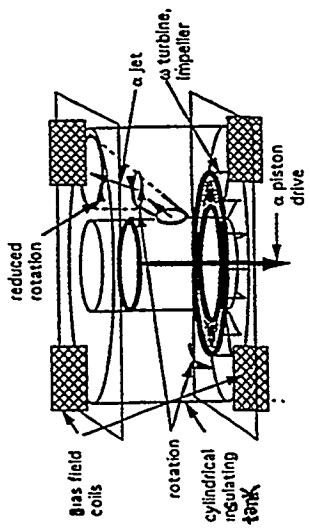
$h = \text{scale height}$

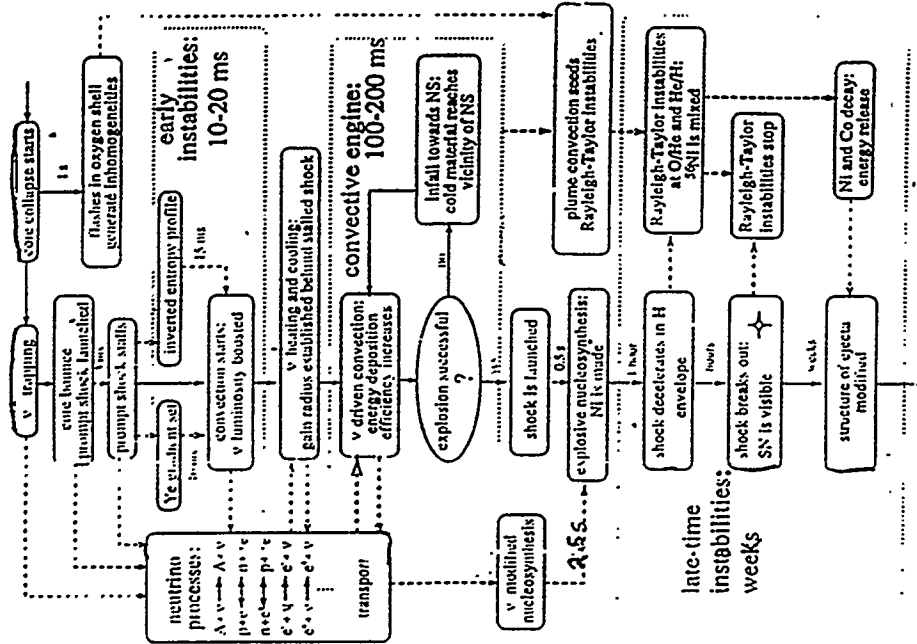
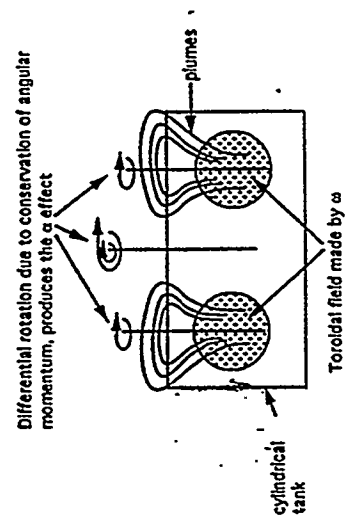
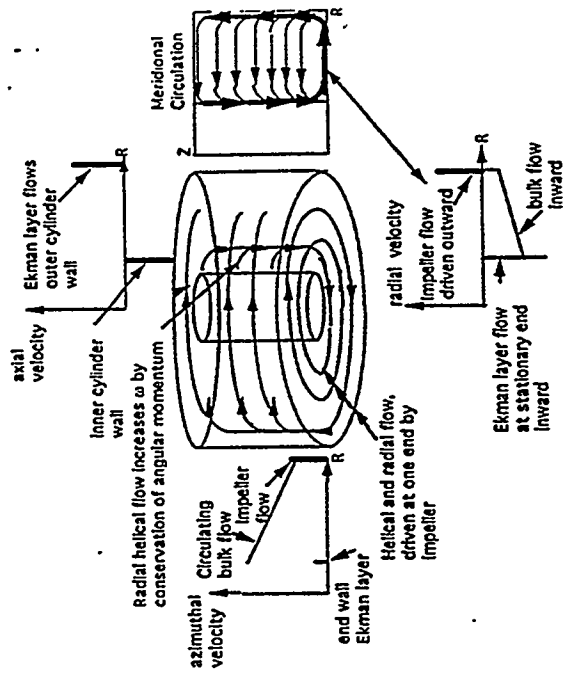
Greg Wille

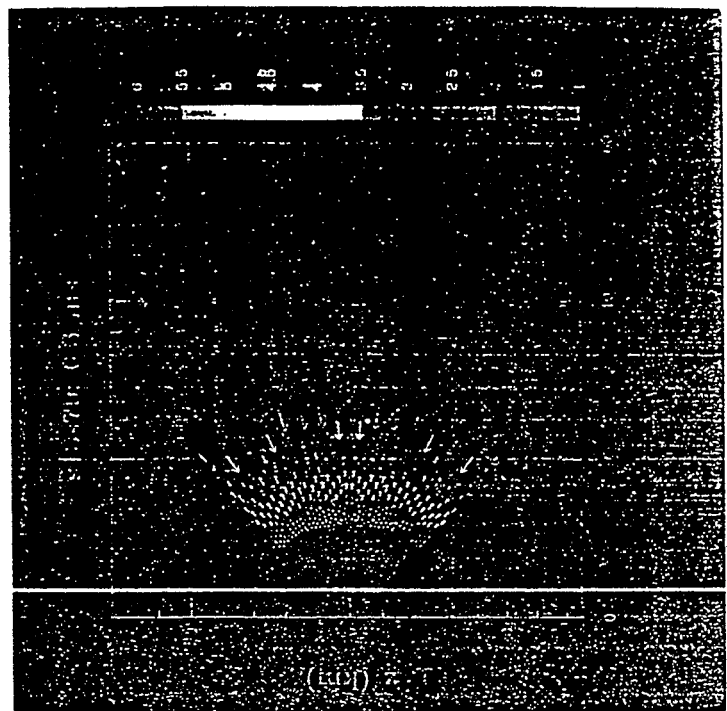
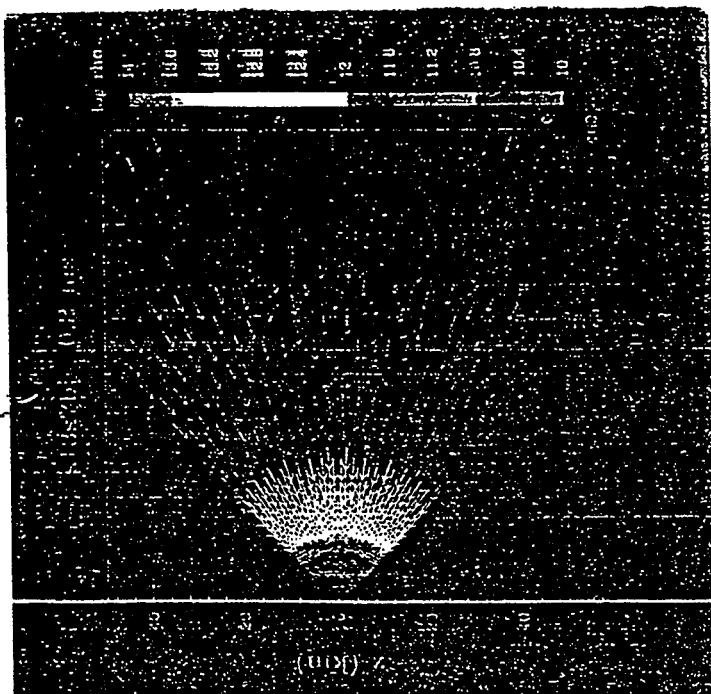
Plume Convection:
Equation for Radius w/o Entrainment

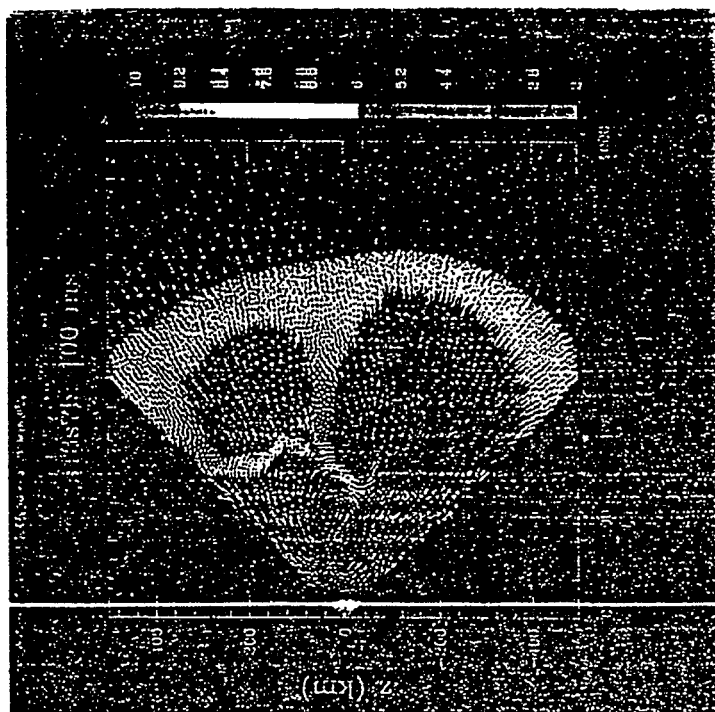
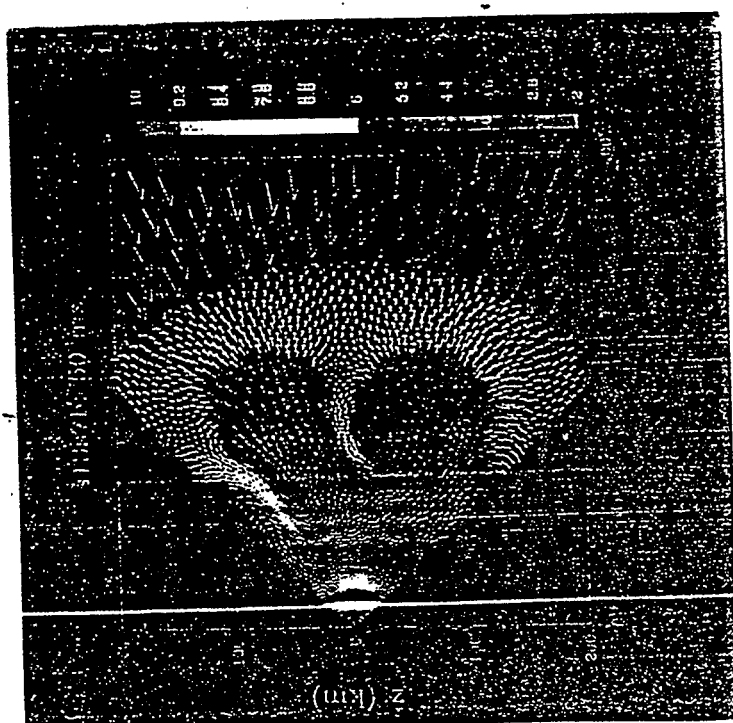
$$\frac{d^2 R}{dz^2} = \frac{1}{R} \left(\frac{z}{z_0} \right)^{2m} \left(\frac{R}{R_0} \right)^4 - \frac{1}{R} + \frac{2}{R} \left(\frac{z}{z_0} \right)^{2m} \left(\frac{R}{R_0} \right) \left(\frac{R}{R_0} \right)^4 (z_0 - z) + \frac{m}{z} \frac{dR}{dz} + \frac{2}{R} \left(\frac{dR}{dz} \right)^2 + \left(\frac{z}{z_0} \right)^{2m} \frac{\Omega_0^2 R}{3g z}$$

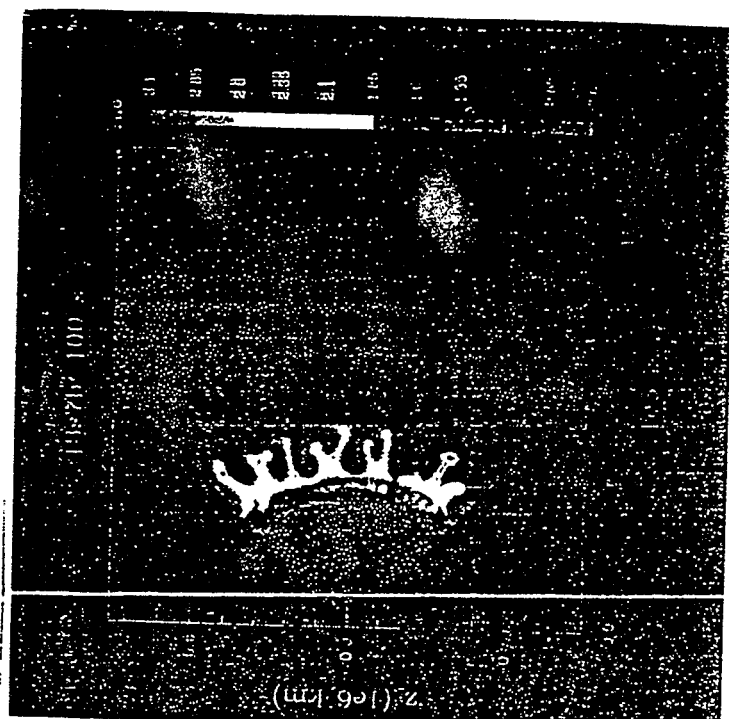
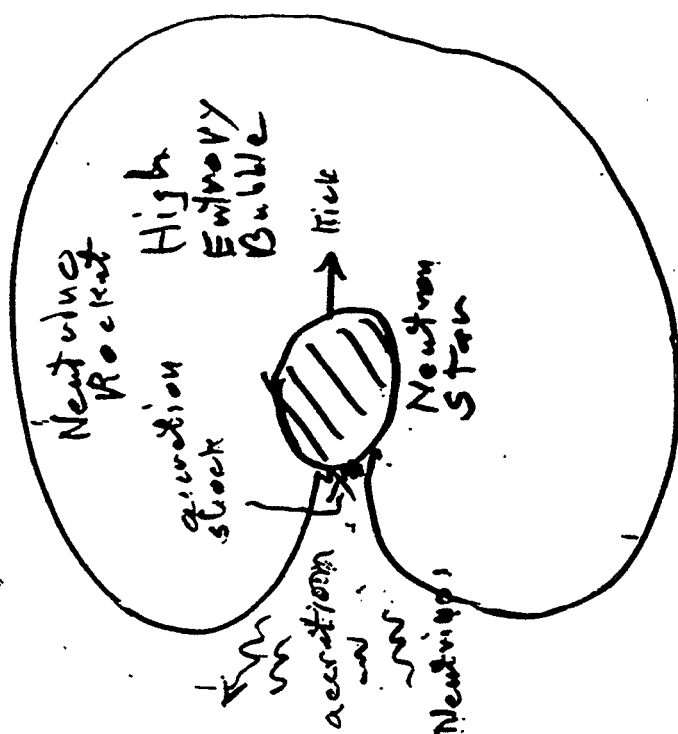


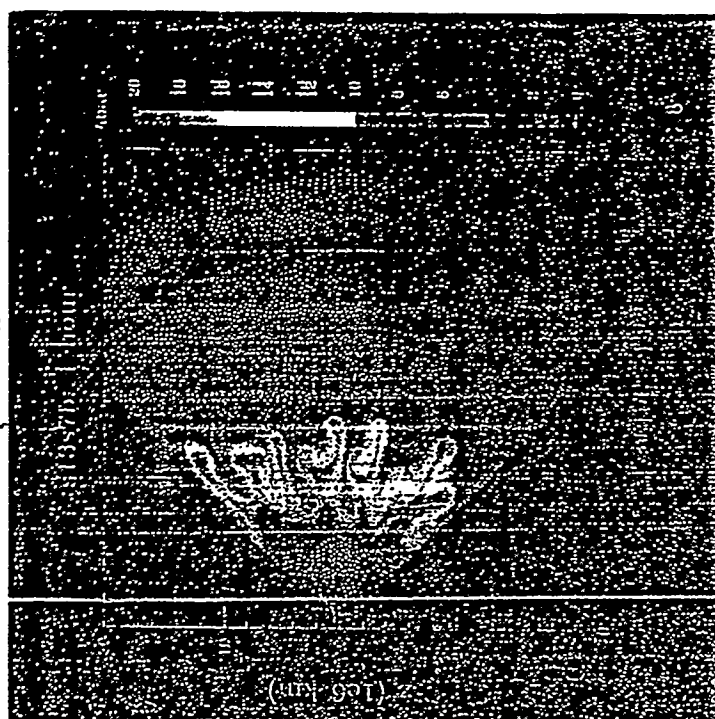
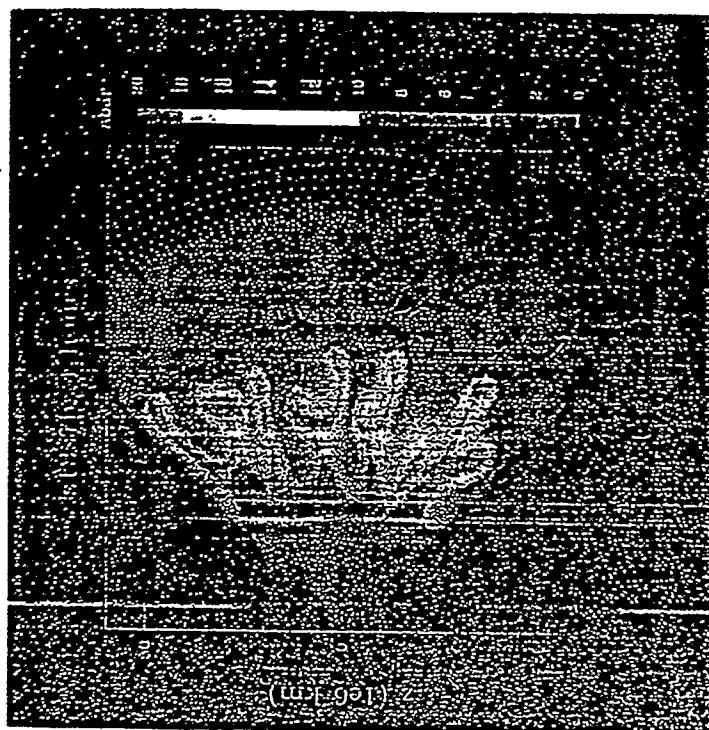


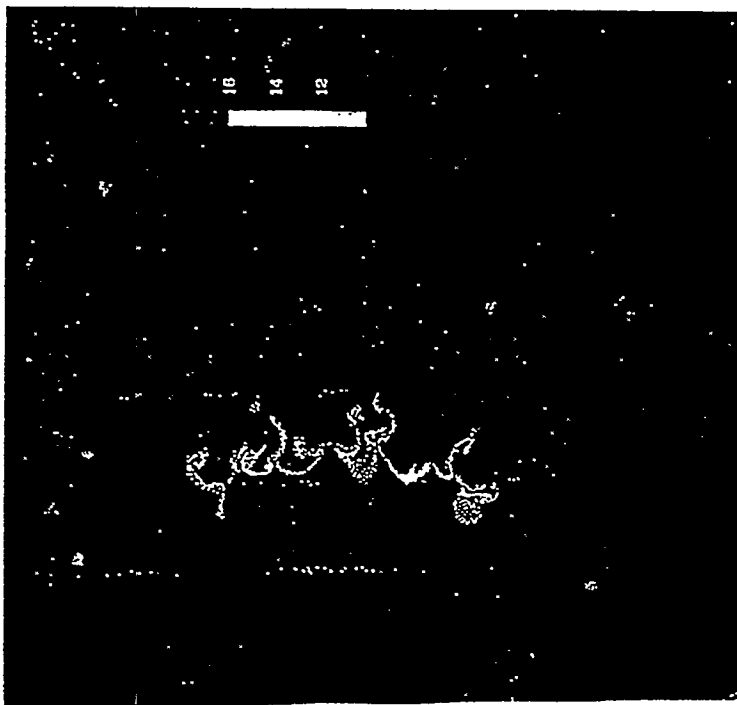
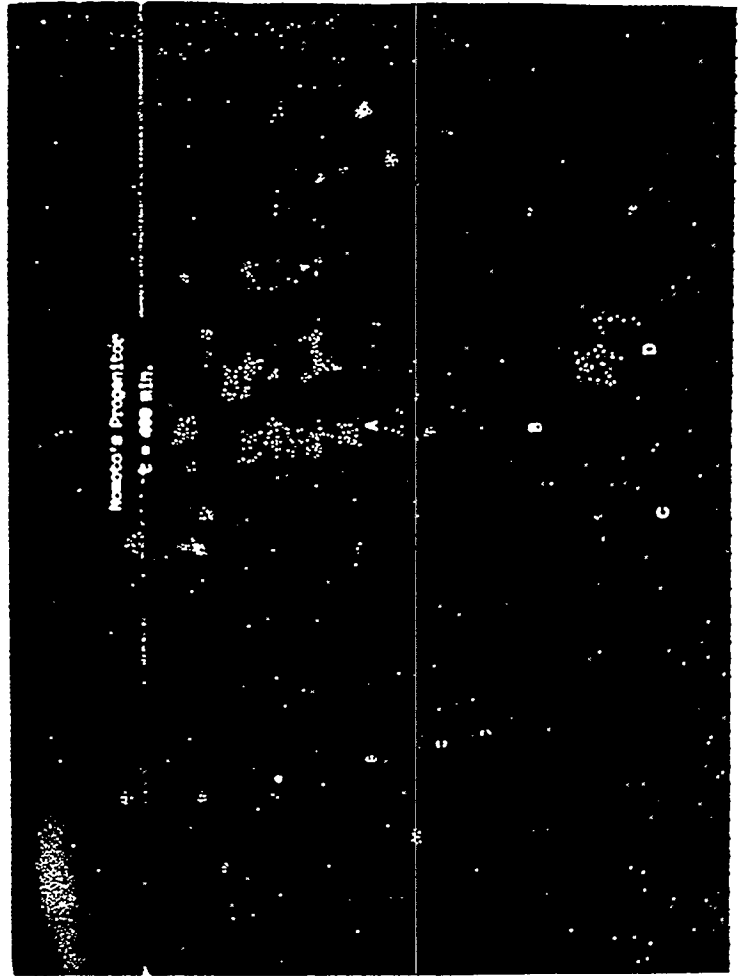


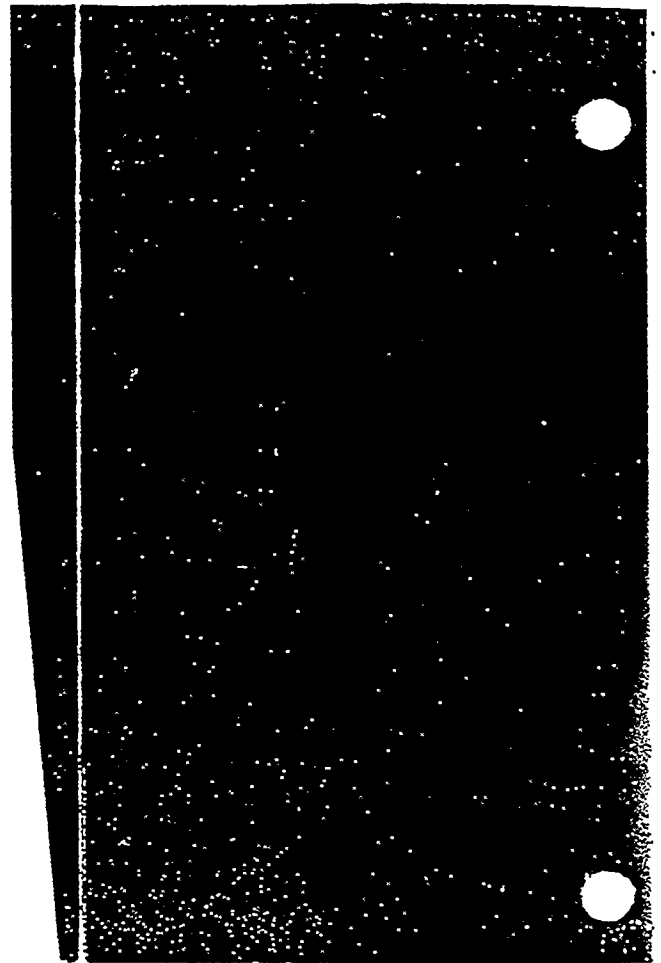
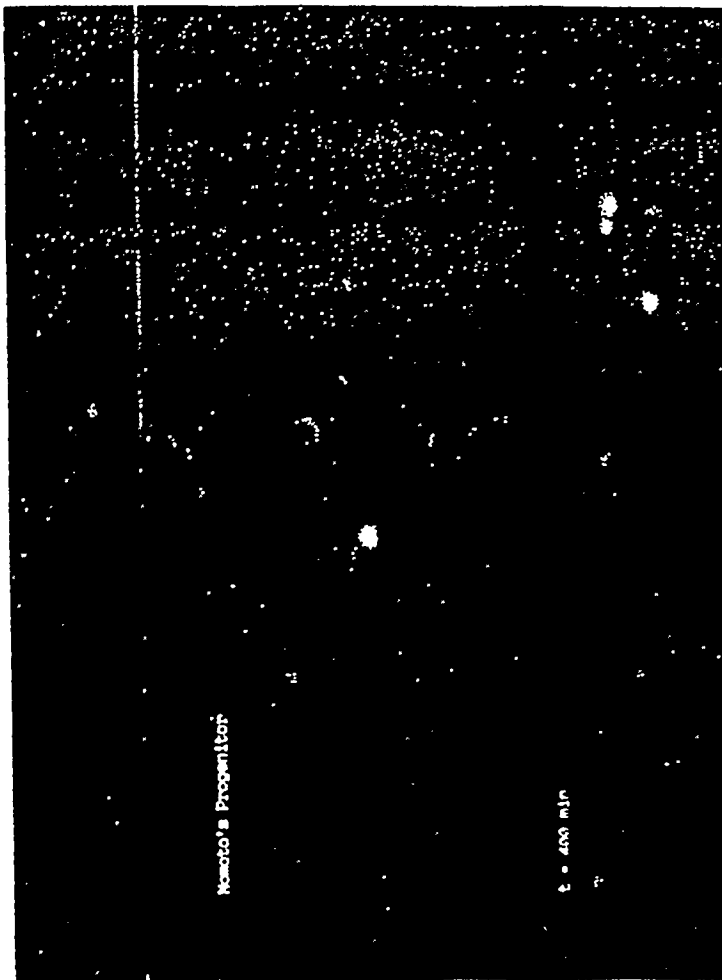


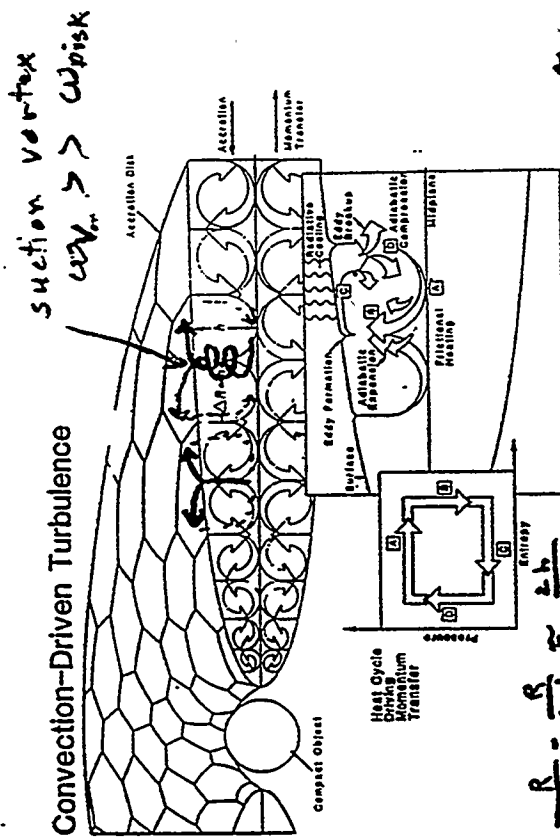












$$\Delta V_{in}^2 = \frac{R}{R+h} - \frac{R}{R+h} = \frac{2h}{R}$$

$$\Delta V_{in}^2 = \frac{R}{(R+h)} - \frac{R}{(R+h)} = \frac{4h}{R}$$

$$\Delta V_{in}^2 - \Delta V_{out}^2 = 2h/a = \Delta V_{Kuc}^2$$

$\therefore$ Requires 100% efficiency
cannot efficiency with $T_{amb} \rightarrow 0$

Car Engines, Hurricanes, suction vortex

Car Engine starts only for

$$\omega_{start} \approx \frac{1}{10} \omega_{run}$$

very non-linear instability

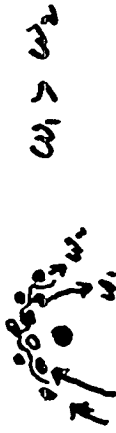
Hurricane = same starting condition

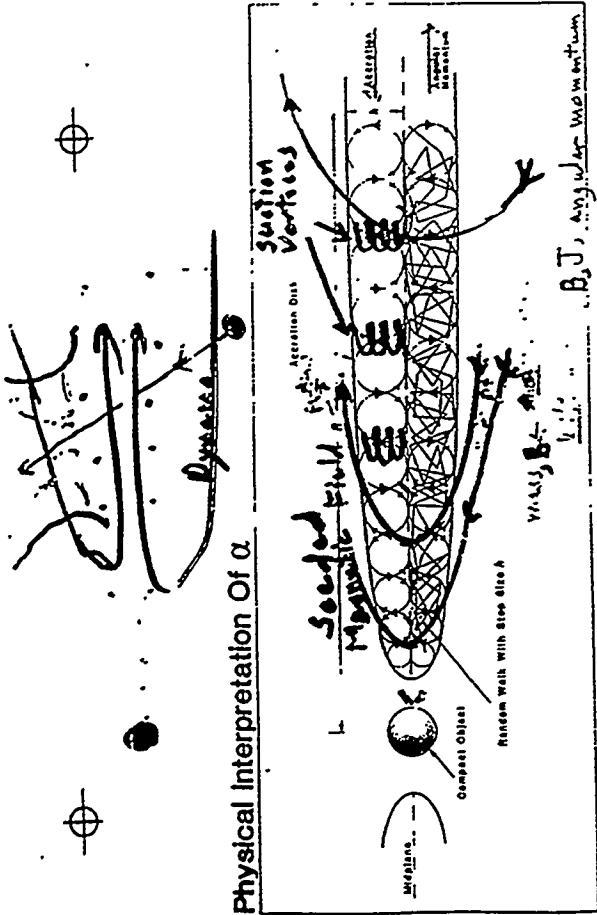
$$\omega_{run} \approx 100 \omega_{start}$$

suction Vortex same starting

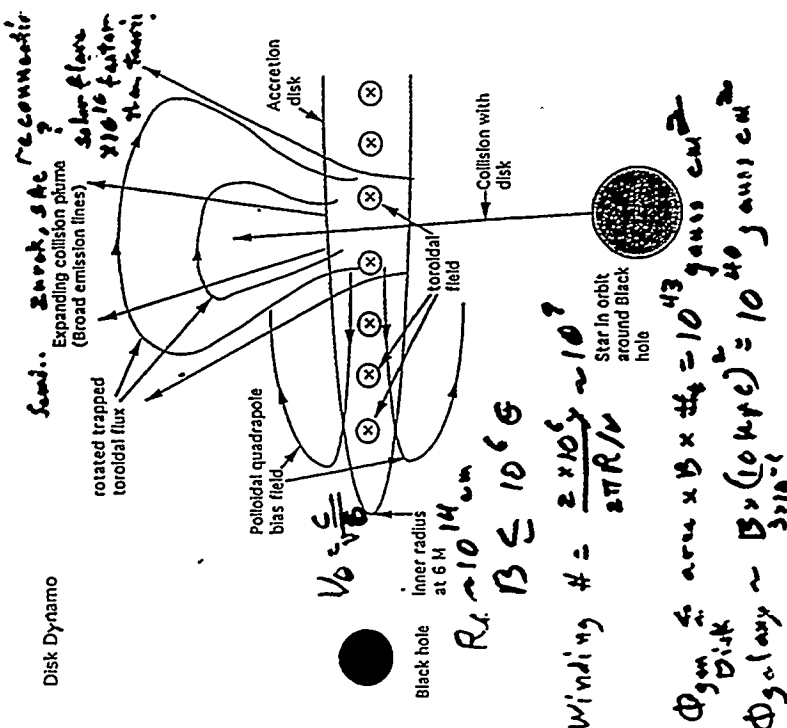
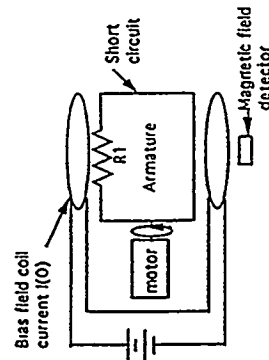
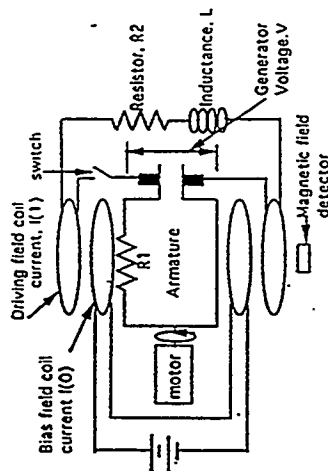
$$\omega_{run} \approx 10 \omega_{disk}$$

Multiple Vortices act like un-meshed gears





Diffusion of $B \Rightarrow$ Diffusion of J
 Angular momentum
 i, j, α



Recollections and Overview of Opacities for Stellar Astrophysics

**Arthur N. Cox
Los Alamos National Laboratory**

RECOLLECTIONS AND OVERVIEW

OF OPACITIES FOR STELLAR ASTROPHYSICS

ARTHUR N. COX

LOS ALAMOS NATIONAL LABORATORY

Los Alamos
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Useful Opacity Tables for Stellar Structure in 1964

Vitense, Erika, Der Aufbau der Sternatmosphären IV Teil: Kontinuierliche Absorption und Streuung als Funktion von Druck und Temperatur. 1951, ZAp, 28, 81

Stromgren, B., Unpublished hydrogen opacities including ionized H molecules.

Keller, G. and Meyerott, R. E., The Ionization of Gas Mixtures in Stellar Interiors.

1952, Argonne National Laboratory Report ANL-4771

Keller, G. and Meyerott, R. E., The Ionization of Gas Mixtures in Stellar Interiors. II. The Average Number of Electrons in Various Shells.

1952, Argonne National Laboratory Report ANL-4856

Keller, Geoffrey and Meyerott, Roland E., A Table of the Radiative Opacities of a Number of Gas Mixtures.

1955, ApJ, 122, 32

Zirin, Harold, The Calculation of Opacities for Stellar Interiors.

1958, ApJ, 128, 342

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Useful Opacity Tables for Stellar Structure in 1990

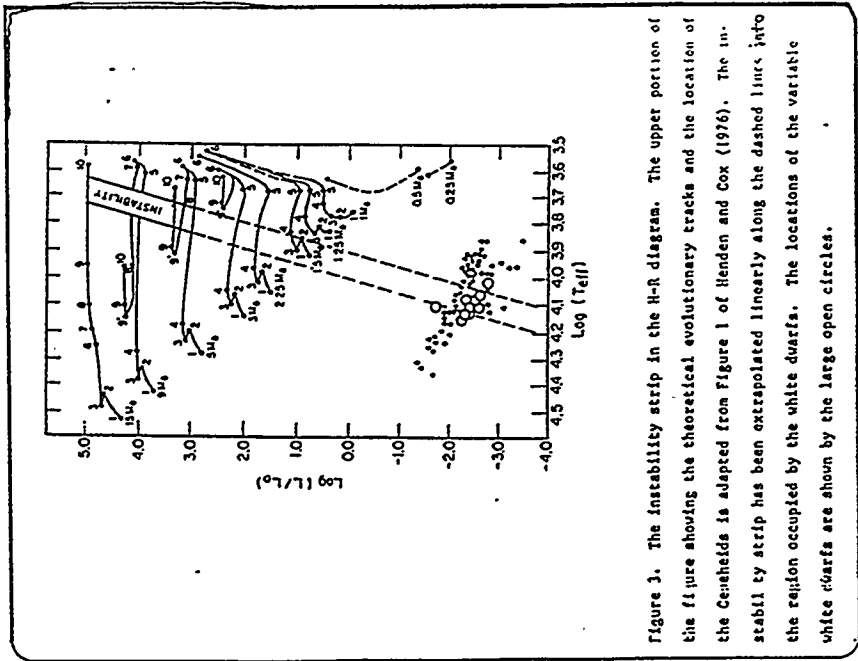
- Cox, A.N. and Stewart, J.N., Radiative and Conductive Opacities for Twenty Three Stellar Mixtures. 1969, Sci. Inform. Astron. Council USSR, 15, 1 and Nauch. Info. 15, 1
- Cox, A.N. and Stewart, J.N., Rosseland Opacity Tables for Population I Compositions. 1970, ApJS, 19, 243
- Cox, A.N. and Stewart, J.N., Rosseland opacity Tables for Population II Compositions. 1970, ApJS, 19, 243
- Cox, A.N. and Tabor, J.E., Radiative Opacity Tables for 40 Stellar Mixtures. 1976, ApJS, 31, 271
- Huebner, W. F., Atomic and Radiative Processes in the Solar Interior. Physics of the Sun, eds. P.A. Sturrock, T. E. Holtzer, D. Mihalas, and R.K. Ulrich (Dordrecht: D. Reidel) vol. 1, p. 33
- Weiss, Acham, Keady, J.J., and Magee, N.H., A Collection of Los Alamos Opacity Tables for all Temperatures. 1990, At. Data Nucl. Data Tables, 45, 209

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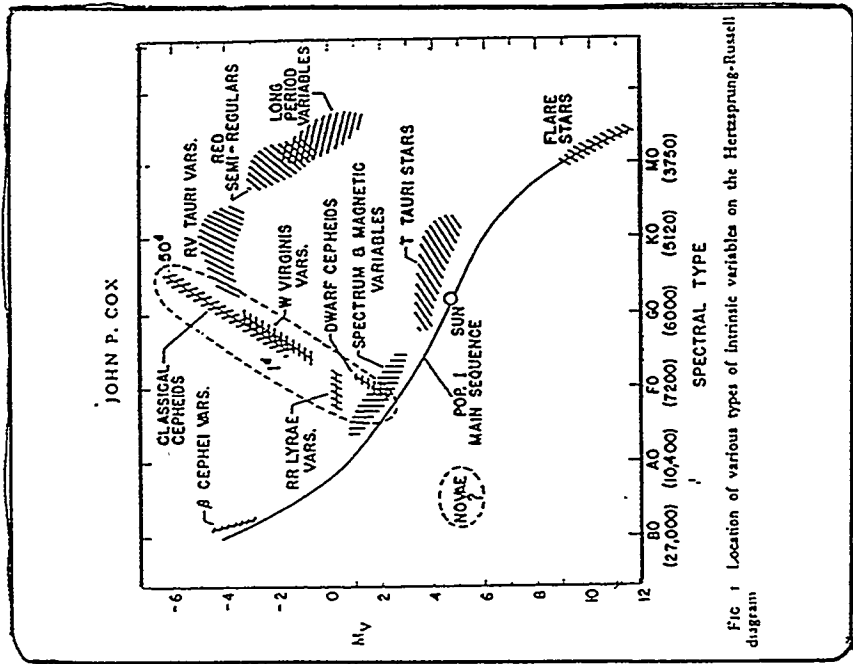
Current Useful Opacity Tables for Stellar Structure

- Iglesias, C. and Rogers, F.J., Opacities for the Solar Radiative Interior. 1991, ApJ, 371, 408
- Lenzuni, P., Chernoff, D.F. and Salpeter, E.E., Rosseland and Planck Mean Opacities of a Zero Metallicity Gas. 1991, ApJS, 76, 759
- Sharp, C.M., Molecular Opacities for Solar and Enhanced CNO Abundances: Relevance for Accretion Disks. 1992, AAS, 94, 1
- Rogers, F.J. and Iglesias, C., Radiative Atomic Rosseland Mean Opacity Tables. 1992, ApJS, 79, 507 (OPAL)
- Iglesias, C. and Rogers, F.J., Spin-Orbit Interaction Effects on the Rosseland Mean Opacity. 1992, ApJ, 397, 717 (OPAL)
- Iglesias, C. and Rogers, F.J., Radiative Opacities for Carbon and Oxygen Rich Mixtures. 1993, ApJ, 412, 752
- Seaton, M.J., Yan, Y., Mihalas, D., Pradhan, A.K., Opacities for Stellar Envelopes. 1994, MNRAS, 266, 805 (OP)
- Alexander, D.R. and Ferguson, J.W., Low Temperature Rosseland Opacities. 1994, ApJ, 417, 879

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Areas Recently Affected by Improved Opacities

Double-Mode Cepheid Masses

Double-Mode RR Lyrae Variable Masses

Delta Scuti Variable Period Ratios and Masses

Solar p-Mode Oscillation Frequencies

OB Star Pulsational Instability

Massive Star Instabilities and the Upper Mass Limit

Hyades G Star Lithium Depletion

Overshoot from Massive Star Convective Cores

Enhanced Mass Loss from Wolf-Rayet Stars

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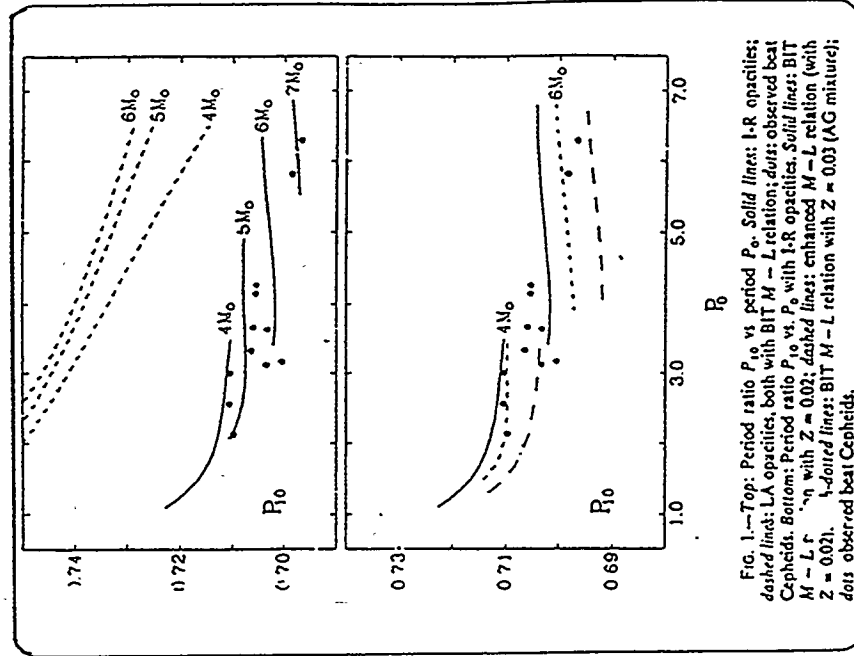


FIG. 1.—Top: Period ratio P_{10} vs. period P_0 . Solid lines: LA opacities; dashed lines: LA opacities, both with BIT $M-L$ relation; dots: observed beat Cepheids. Bottom: Period ratio P_{10} vs. P_0 with LA opacities. Solid lines: BIT $M-L$ relation with $Z = 0.02$; dashed lines: enhanced $M-L$ relation (with $Z = 0.02$). Dotted lines: BIT $M-L$ relation with $Z = 0.03$ (AG mixture); dots: observed beat Cepheids.

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Quantitatively our postulates of local thermodynamic equilibrium and almost equal matter and radiation temperature can be expressed by assuming an intensity given by the blackbody function reduced slightly on,

$$I_{\nu}(s) = B_{\nu}(T) - \frac{1}{\rho(\epsilon_1 + \epsilon_2)} \frac{\partial B_{\nu}(T)}{\partial s}, \quad (1)$$

The definition of the monochromatic radiative flux in direction s is given by

$$F_{\nu,s} = \int I_{\nu}(s) \cos \theta d\omega, \quad (11)$$

where $\cos \theta$ is now the projection factor for the intensity on to the direction s at angle θ from direction s . Insertion of the expansion of I_{ν} yields the expression

$$F_{\nu,s} = - \int \int \frac{1}{\rho(\epsilon_1 + \epsilon_2)} \frac{\partial B_{\nu}(T)}{\partial s} \cos \theta \sin \theta d\theta ds, \quad (12)$$

where the first isotropic term in the intensity vanished due to the symmetry of the integrand. The integral is thus

$$F_{\nu,s} = - \frac{4\pi}{3\rho(\epsilon_1 + \epsilon_2)} \frac{\partial B_{\nu}(T)}{\partial s}. \quad (13)$$

Now the total flux at all frequencies in direction s is

$$\begin{aligned} F_s &= \int F_{\nu,s} d\nu \\ &= - \frac{4\pi}{3\rho(\epsilon_1 + \epsilon_2)} \int \frac{1}{\rho(\epsilon_1 + \epsilon_2)} \frac{\partial B_{\nu}(T)}{\partial s} d\nu \\ &= - \frac{4\pi}{3\rho(\epsilon_1 + \epsilon_2)} \int \frac{\partial B_{\nu}(T)}{\partial s} d\nu, \end{aligned} \quad (14)$$

defining ϵ as a harmonic mean of $(\epsilon_1 + \epsilon_2)$ (see eq. (13)). Thus,

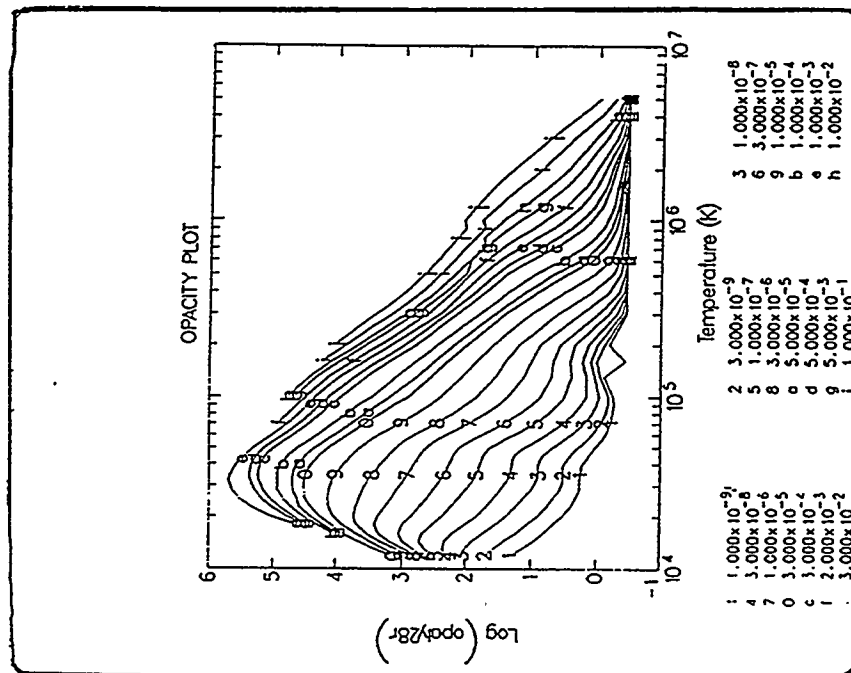
$$\begin{aligned} F_s &= - \frac{4\pi}{3\rho(\epsilon_1 + \epsilon_2)} \int \frac{\partial B_{\nu}(T)}{\partial s} d\nu \\ &= - \frac{4\pi}{3\rho(\epsilon_1 + \epsilon_2)} \frac{\partial}{\partial s} \int B_{\nu}(T) d\nu \\ &= - \frac{4\pi}{3\rho(\epsilon_1 + \epsilon_2)} \frac{\partial E}{\partial s}, \end{aligned} \quad (15)$$

which is our desired result. Here $\epsilon = \epsilon_1/\epsilon_2$, where ϵ and ϵ_2 are radiation constants and ϵ_1 is the velocity of light. The derivation is originally due to Rosseland (1924). Another early derivation was given by Eddington (1916, chap. V).

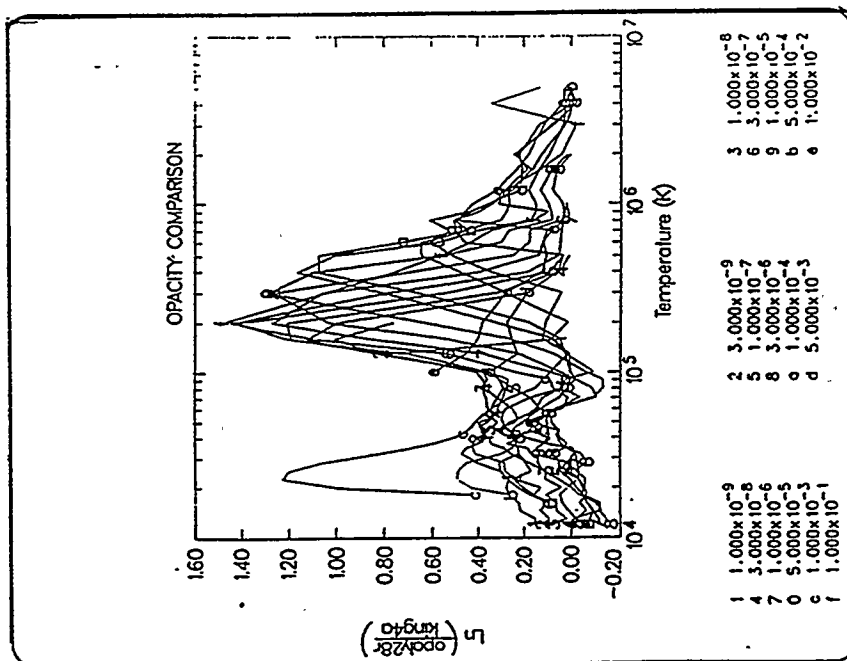
We have seen (eq. (14)) that the average absorption, according to Rószkano, is given by

$$\bar{\kappa} = \frac{\int \frac{1}{\rho(\epsilon_1 + \epsilon_2)} \frac{\partial B_{\nu}(T)}{\partial s} d\nu}{\int B_{\nu}(T) d\nu}. \quad (16)$$

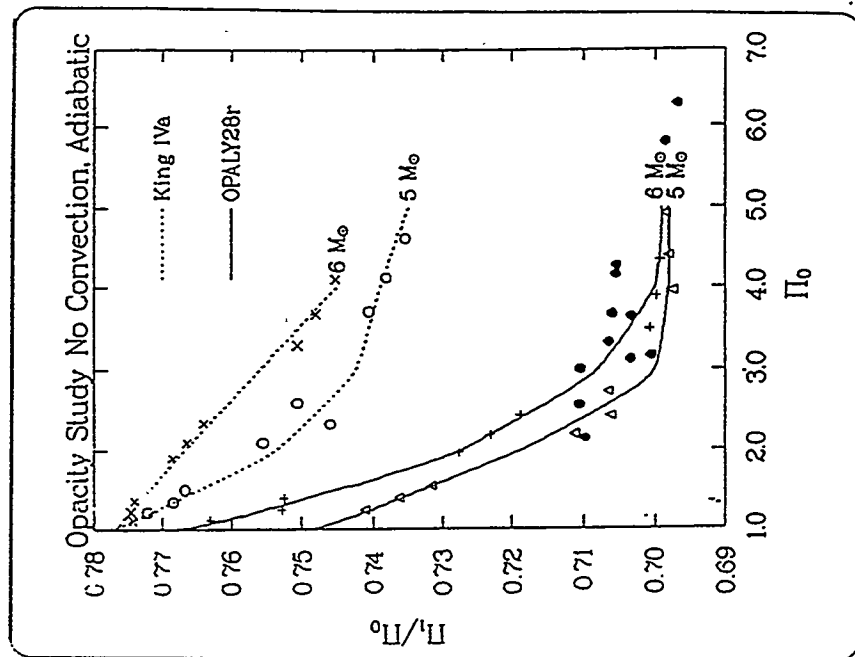
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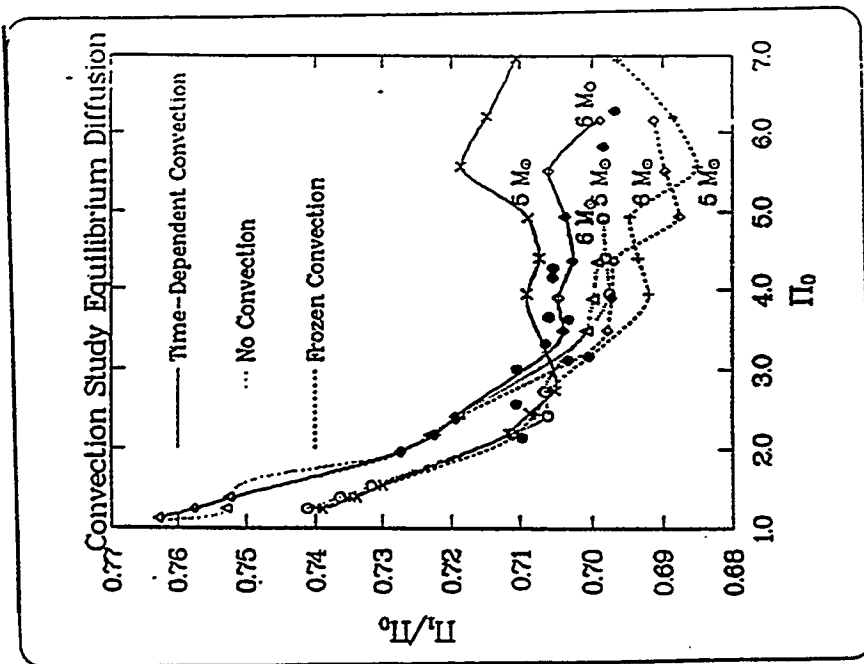
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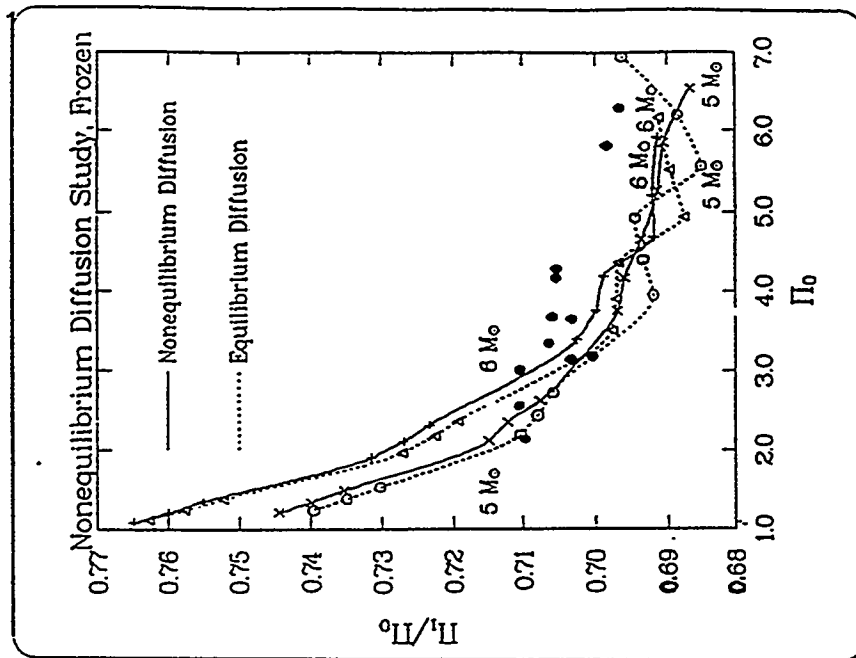
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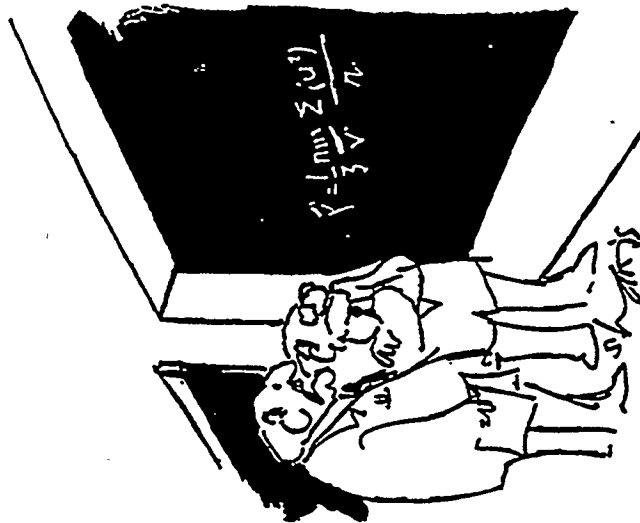
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"What's most depressing is the realization that everything we believe will be disproved in a few years."

CONCLUSIONS

1. The appearance of the Los Alamos opacities in 1965 to 1970 caused a great expansion of studies of stellar structure, evolution, and stability.
2. The appearance of the Livermore (OPAL) and United Kingdom (UK) opacities in 1969 to the present have allowed explanations of many previous problems, mostly in stellar pulsation theory.
3. The double-mode Cepheids can be interpreted with standard masses and luminosities from evolution theory, but the early simple interpretations with OPAL opacities did not reveal the whole complicated situation.

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**Opacity and Radiative Transfer Experiments
Using High-Power Lasers**

**Steven J. Rose
Rutherford Appleton Laboratory**

Opacity and radiative transfer experiments using high-power lasers

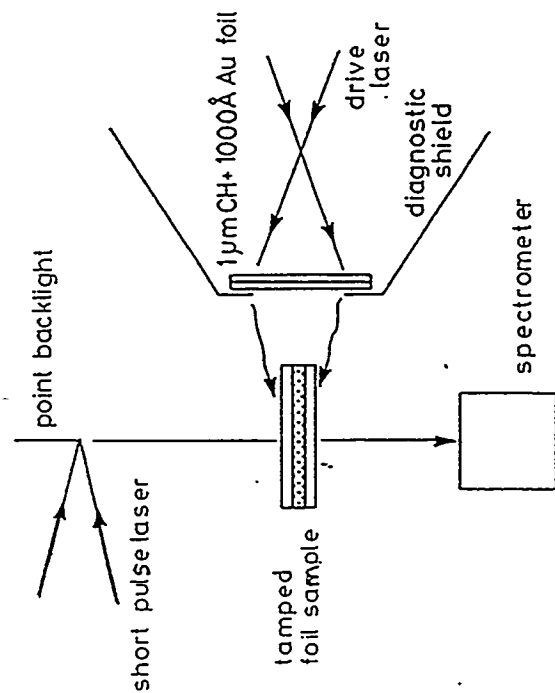
S J Rose

Rutherford Appleton Laboratory
and
Department of Physics and Space
Science, University of Birmingham,
U K

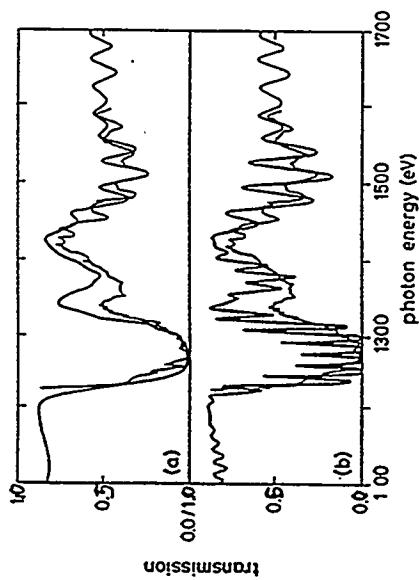
Outline

- Opacity experiments
- Dense plasma experiments
- Line transfer experiments
- Accretion plasmas
- Future opportunities

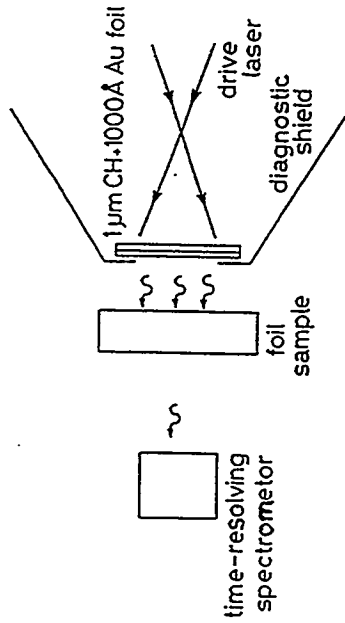
Absorption spectroscopy opacity experiment



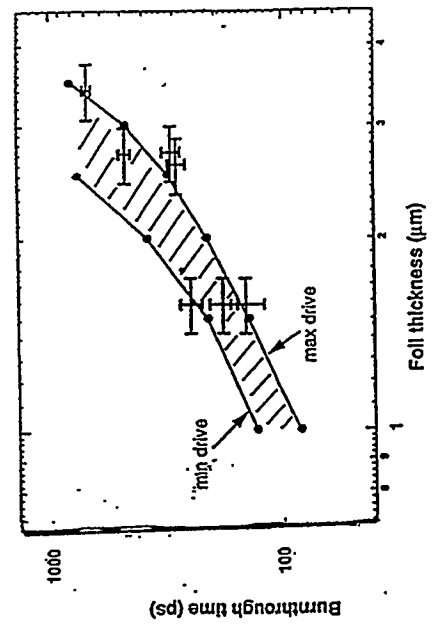
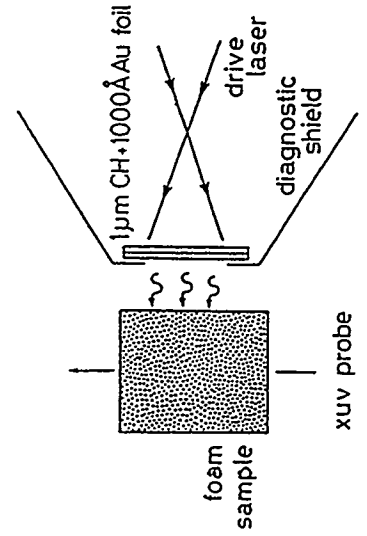
Comparison between IMP and experiment for germanium at 76eV and 0.054 gcm⁻³



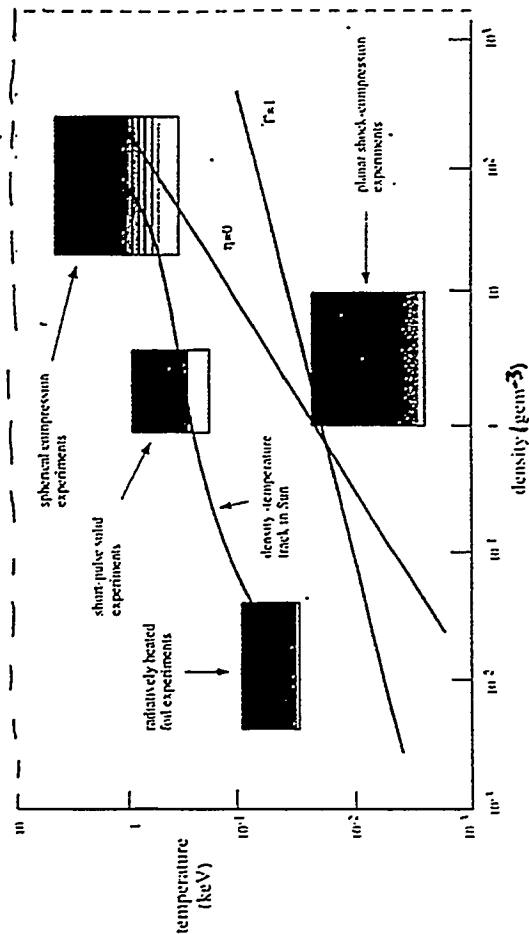
Radiation wave opacity experiment



Supersonic radiation wave opacity experiment

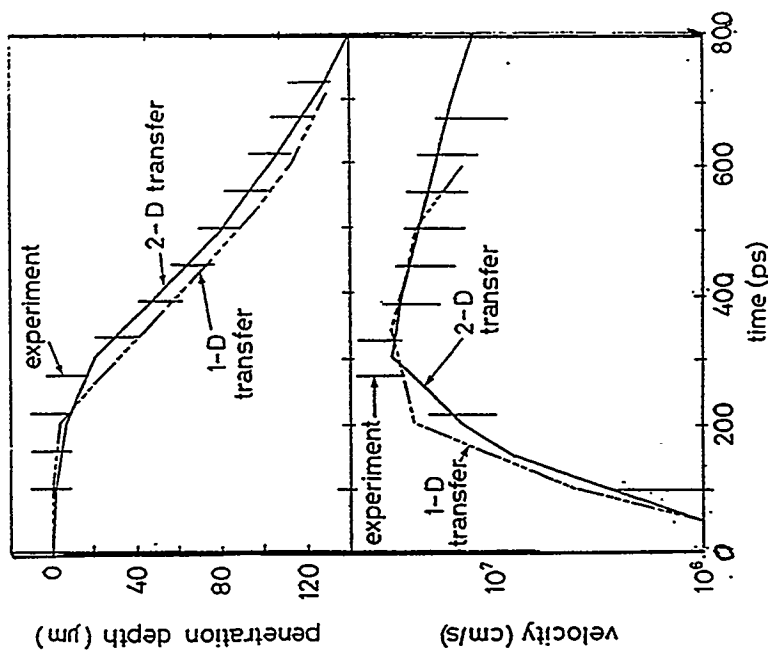


Opacity and dense plasma experiments

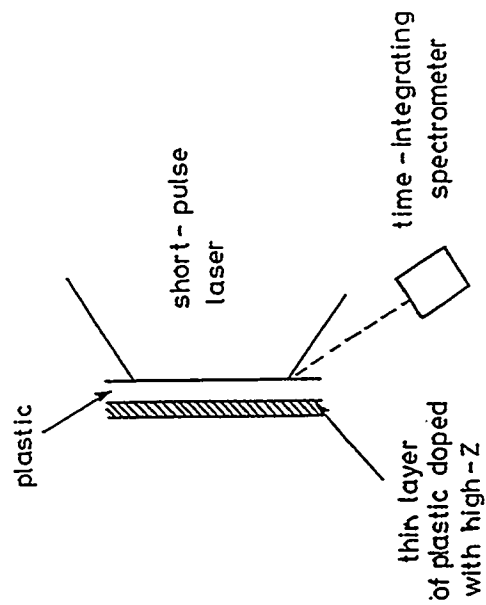


Short-pulse experiments

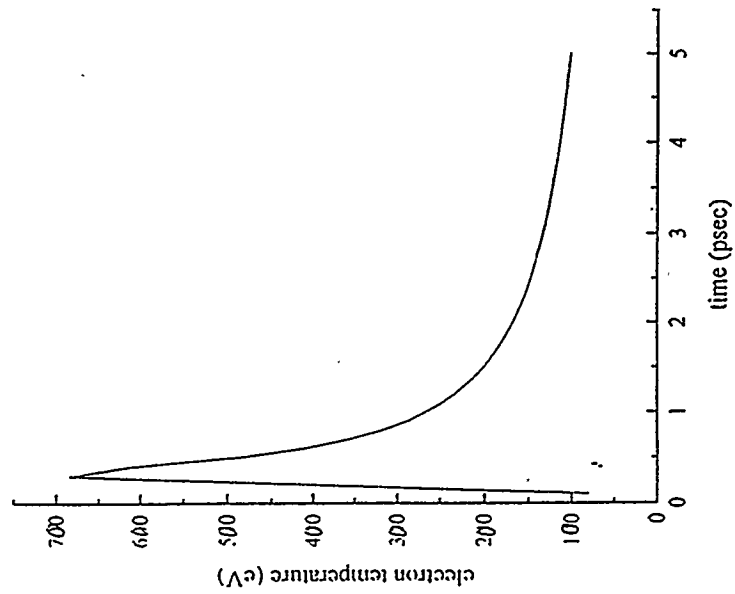
- Our understanding of the physics of short-pulse interaction with solid targets is still incomplete.
- Temperatures of a few hundred eV is possible with present lasers.



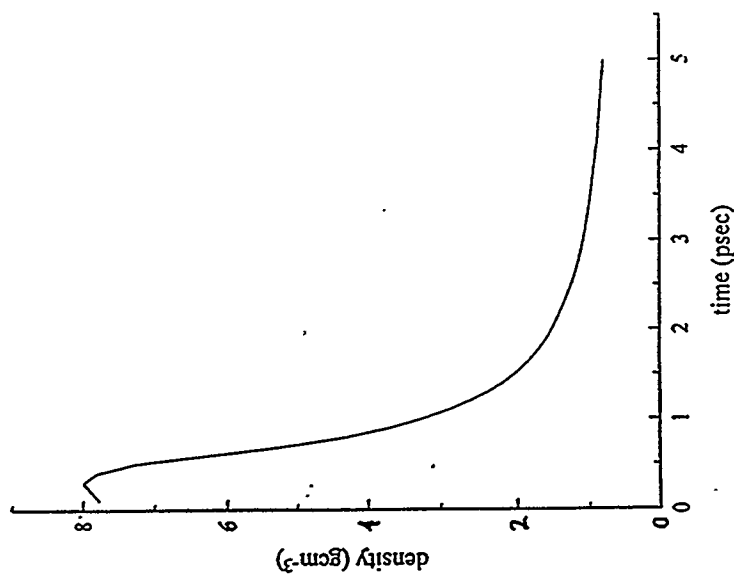
Short-pulse emission experiment to measure opacity



Variation with time of average electron temperature
over iron layer

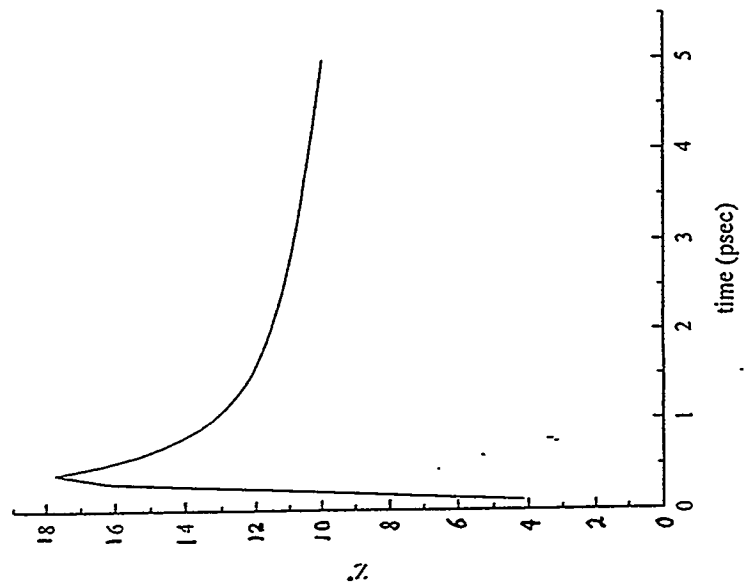


Variation with time of average density over iron layer



411

Variation with time of average Z^* over iron layer

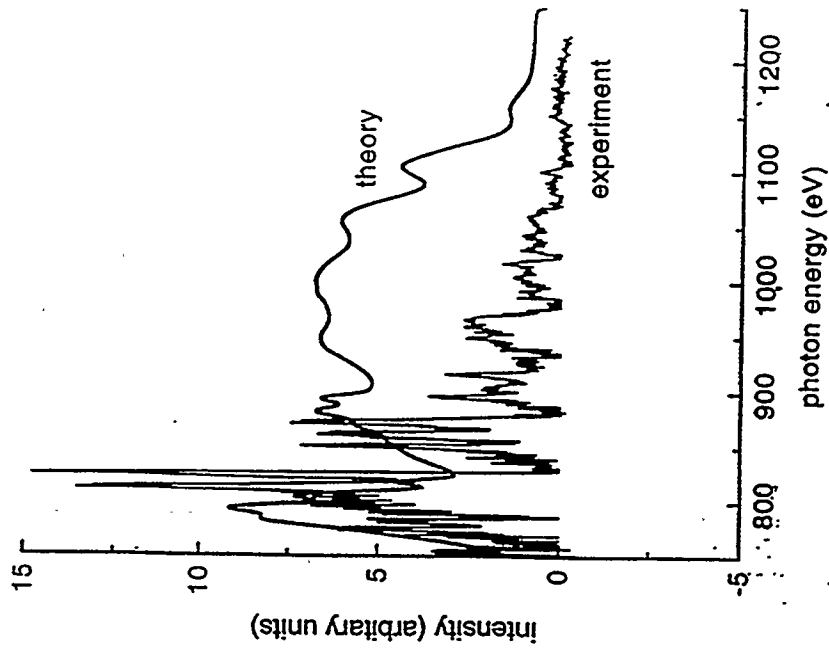


Line-transfer experiments

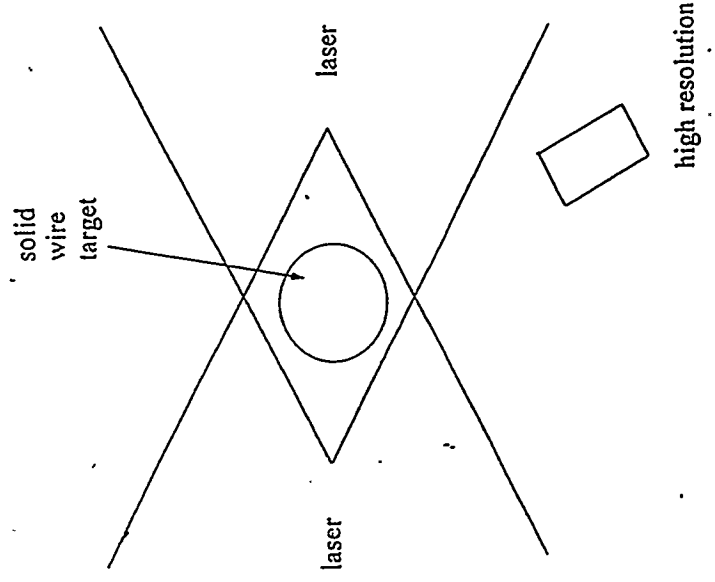
- Line radiation transfer in large velocity gradients is very important in certain astrophysical plasmas (Sobolev theory). Laser-plasma measurements have tested our understanding of this process.

- Resonance fluorescence is an important mechanism in planetary nebulae. Laser-plasma experiments test our understanding of radiation transport in overlapping lines.

Short-pulse iron opacity experiment



Measurement of line radiation in a velocity gradient



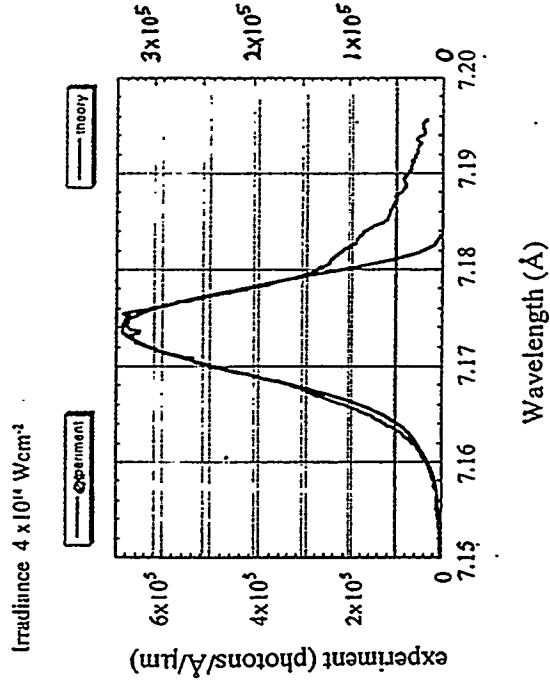
Accretion-powered objects



X-ray binaries, active galactic nuclei and cataclysmic variables are the dominant sources of energy in the observable universe

- Radiation domination of excitation and ionisation
- Inelastic Compton scattering

Line radiation transport in a velocity gradient - comparison of theory and experiment



Compton scattering energy exchange

- Compton scattering from a stationary electron moves energy from radiation to electrons. But scattering from moving electrons moves energy both ways.
- In a plasma with high T_e and low radiation field
electrons $\rightarrow$ radiation
- In a plasma with low T_e and high radiation field
radiation $\rightarrow$ electrons.

Future Opportunities

- High B-field physics studies
- Thermonuclear reaction rate measurements
- Electron-positron plasma studies
- Particle acceleration in plasmas

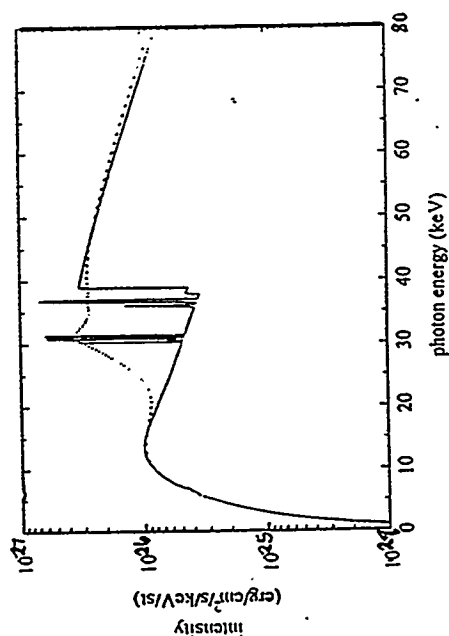
Conclusions

- The values of plasma temperature, density, radiation field, ionisation stage, velocity and velocity gradient etc. which can be achieved with high-power lasers are comparable to values found in certain astrophysical plasmas.
- Complex laser experiments are now being performed in which the plasma conditions can be controlled to investigate specific physical processes. Measurements are starting to be made.
- Further work is underway to investigate other effects and to produce more exotic plasmas.

The effect of Compton scattering on line radiation transport

$D0.495\text{To}.495\text{Xe}0.01$ ball, $R=0.005\text{cm}$, $\rho=500\text{gcm}^{-3}$

----- with Compton scattering
 ————— without Compton scattering



Opacity Measurements for Stellar Atmospheres

**Paul T. Springer
Lawrence Livermore National Laboratory**

Opacity Measurements for Stellar Atmospheres

Paul T. Springer, J.H. Hammer, A. Toor,
B.G. Wilson, C.A. Iglesias, W.H. Goldstein,
F.J. Rogers, and R.E. Stewart



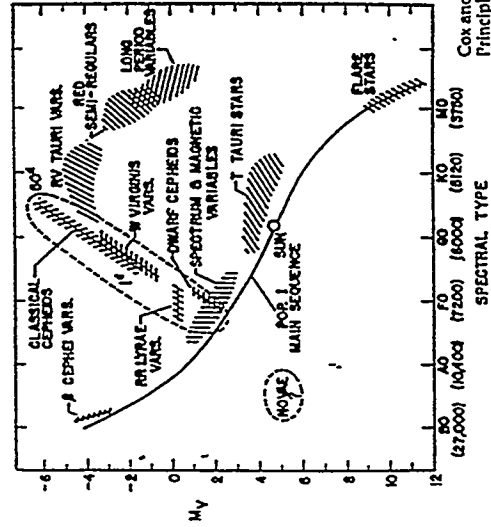
Workshop on Laboratory Astrophysics Experiments with Large Lasers

February 26-27, 1996

Modern opacity models solve long-standing puzzles in stellar pulsation: Experimental validation is required



Locations of types of variable stars on Hertzsprung-Russell diagram



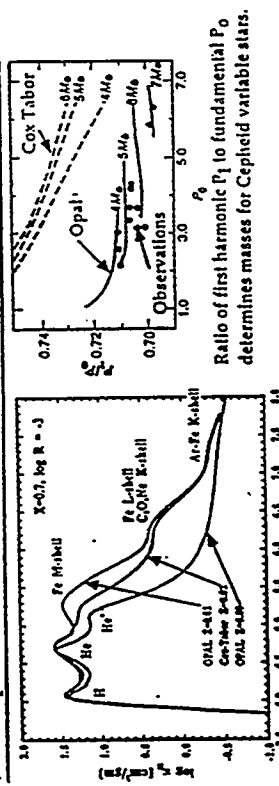
**Cox and Gull
Principles of Stellar Structure (1968)**

11: 11: 11

Problems:

- Cepheid Masses
 - Pulsation models
 - Evolution models
 - Blue loop excursions
- β Cepheid pulsation

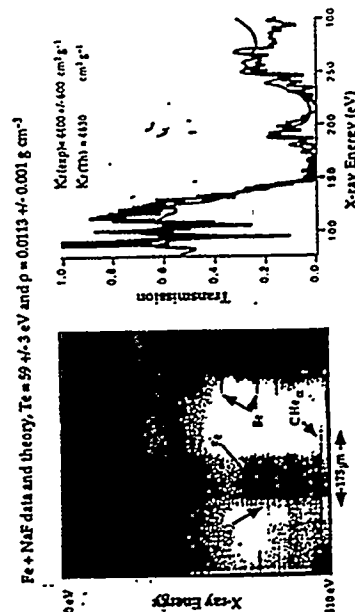
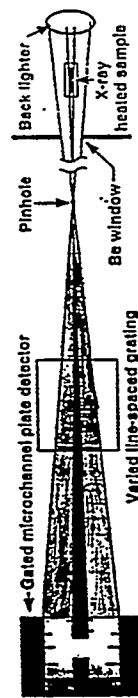
Modern opacity models solve long-standing puzzles in stellar pulsation



- Stellar mixture opacity versus temperature along track of constant $R \approx 10^{-3}$
- Fe M-shell bump due to $\delta n=0$ transitions
- Provides mechanism for β -Cephei pulsation

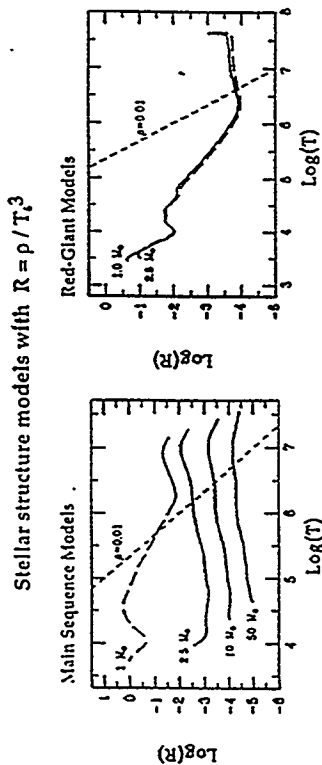
Opal is only indirectly tested by complex stellar models
Experimental benchmarking at relevant conditions is needed

Experimental setup and data



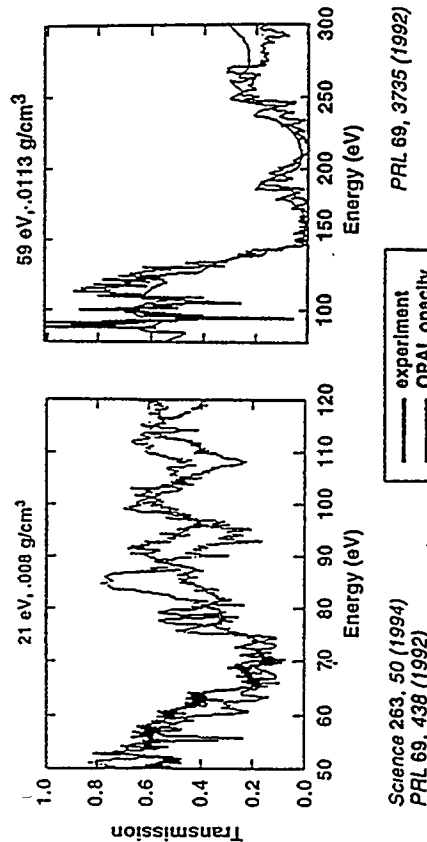
Spatially imaged transmission of Fe + NaF sample

Plasma conditions for stellar atmospheres can be achieved in the laboratory



Fe contribution maximized at $\text{Log}(T)=5.4$, $\text{Log}(R)=-3$
 $T = 20 \text{ eV}$, $\text{Rho} = 2 \times 10^{-6} \text{ g/cc}$

Iron opacity measurements at Nova have provided astrophysically relevant data at densities $\sim .01 \text{ g/cc}$

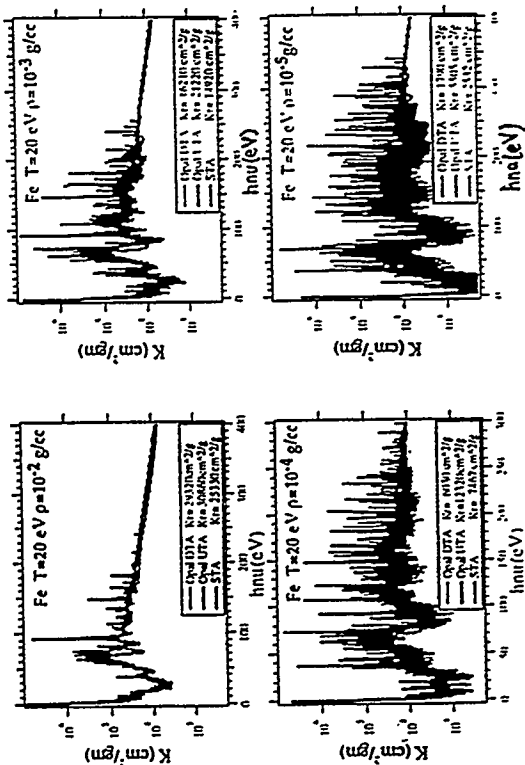


Science 263, 50 (1994)
PRL 69, 438 (1992)

PRL 69, 3735 (1992)

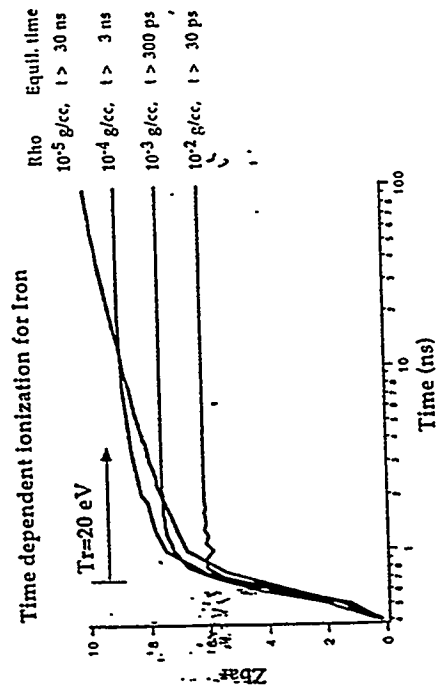
Rosseland mean opacities for iron are strongly model-dependent for $\rho < 10^{-2} \text{ g/cc}$

Tests of line shape theories and the accuracy of statistical methods are important for stellar opacities

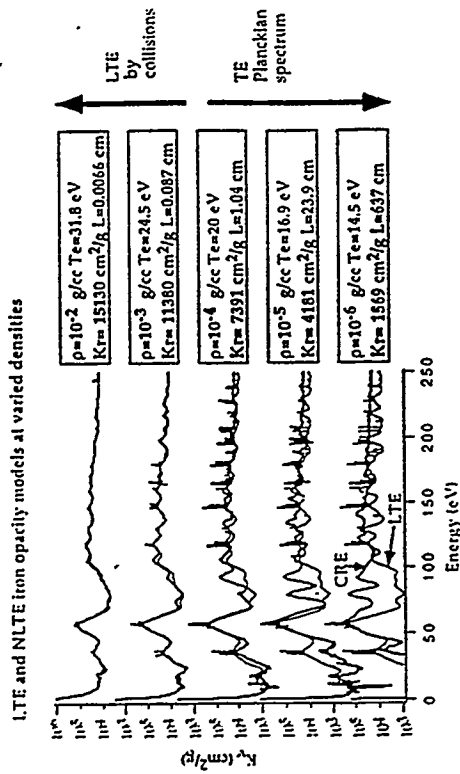


37448 01 v-12

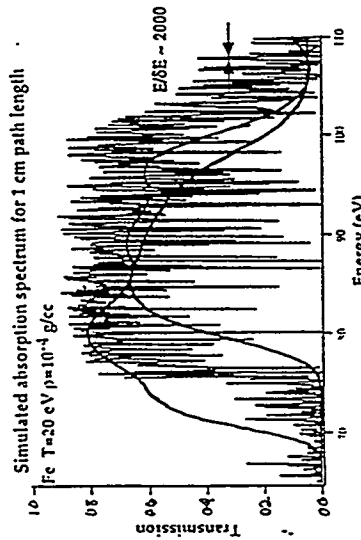
Long-lived hohlraums are required to establish equilibrium at low density



Low density experiments require radiative equilibrium, Planckian spectra, and large plasma volume



High spectral resolution is required to accurately measure UTA breakup



- Theories require accurate treatments of line shapes
- Natural width
 - Collisional broadening
 - Residual configuration and term broadening
 - Stark broadening
 - Doppler broadening
 - Line wings

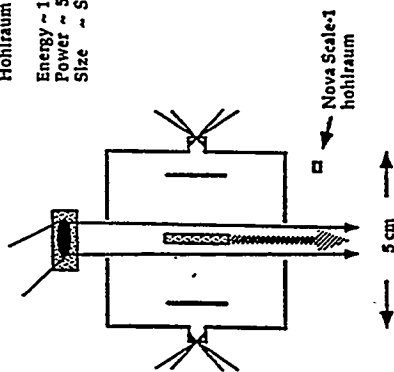
Qud DIA K= 1010 cm²/g
Qud UTA K= 1130 cm²/g
STA K= 146 cm²/g

Experimental setup for laser-driven hohlraum

Hohlraum Parameters

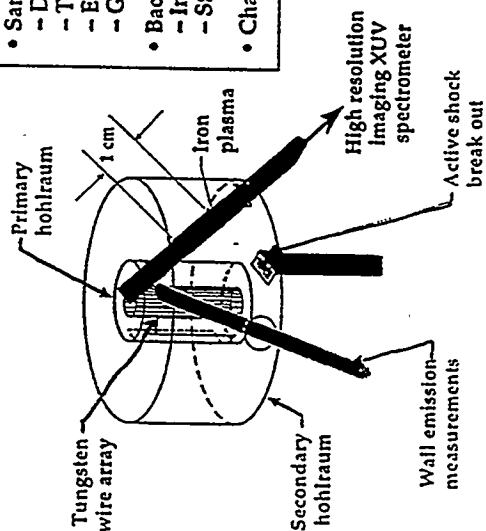
Energy ~ 100 kJ
Power ~ 5 TW
Size ~ Scale 30

- Issues:
- Sample conditions
 - Density $< 10^{-4}$
 - Temperature ~ 20 eV
 - Equilibrium rad-driven LTE
 - Gradients
 - Backlighting
 - Intensity
 - Sample emission
 - Characterization

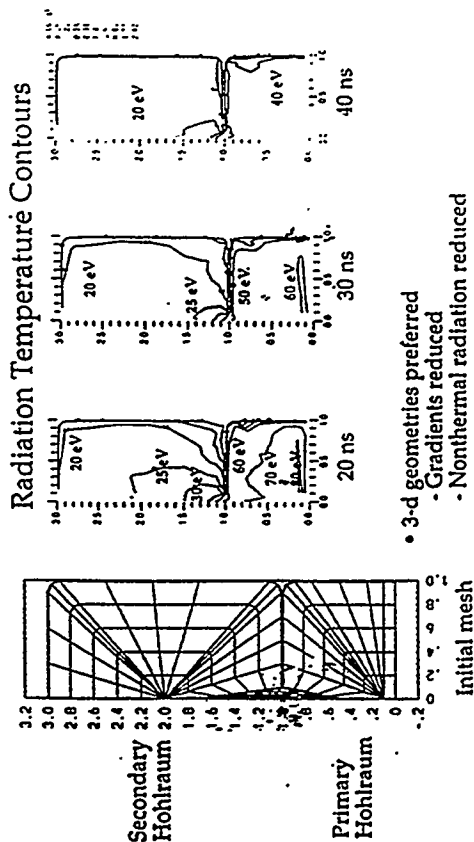


Experimental Setup

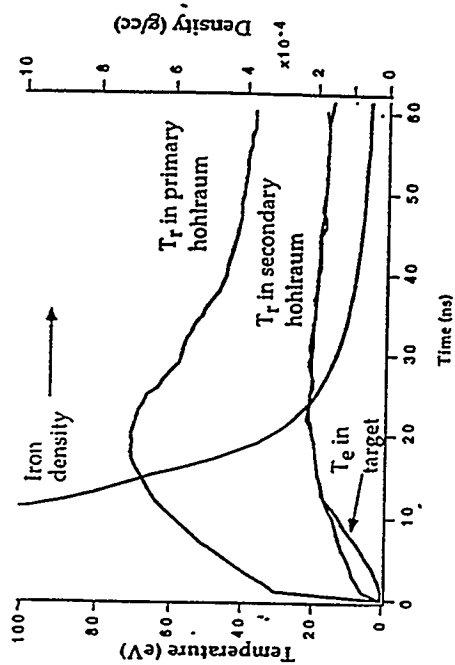
- Issues:
- Sample conditions
 - Density $< 10^{-4}$
 - Temperature ~ 20 eV
 - Equilibrium rad-driven LTE
 - Gradients
 - Backlighting
 - Intensity
 - Sample emission
 - Characterization



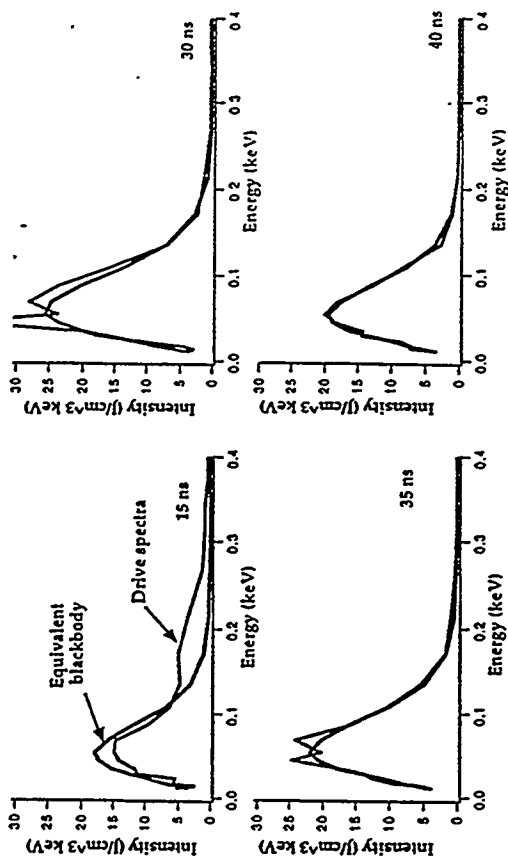
Experimental design has begun using 2d radiative hydrodynamic models



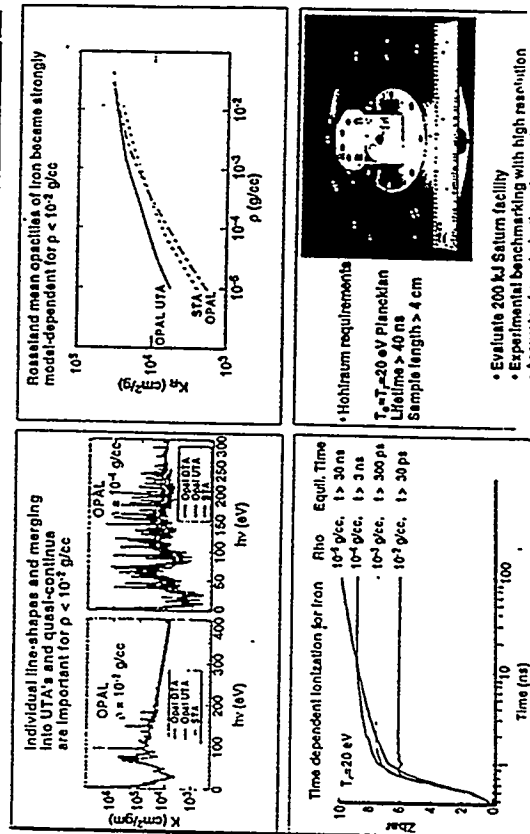
Primary hohlraum heats secondary target to desired conditions, and provides backlighting source



The required thermal radiation spectra are produced following initial heating



The crucial low density regime ($10^{-5} \lesssim \rho \lesssim 10^{-3} g/cc$) has not been experimentally explored



Uncertainties in Stellar Opacities

Carlos A. Iglesias
Lawrence Livermore National Laboratory

UNCERTAINTIES IN STELLAR OPACITIES

Carlos A. Iglesias
LLNL

1) Stellar Envelopes

2) Solar Radiative Interior

DEFINITIONS:

X = hydrogen mass fraction
Y = helium mass fraction
Z = metal mass fraction

[C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe]

$R = \rho / T_6^3$ where ρ = mass density [g/cm³]
 T_6 = million degrees [°K]

Typical Stellar Conditions:

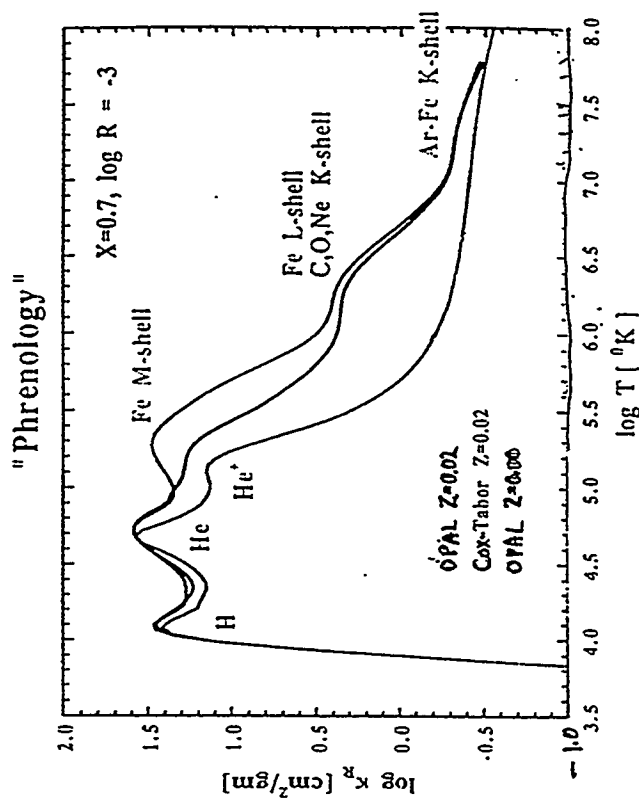
Solar radiative interior X=0.35-0.7, Z=0.02, logR=-1.5
Classical Cepheids X=0.7, Z=0.02, logR=-3.5
Hot variable stars X=0.7, Z=0.02, logR=-5.5
RR Lyrae X=0.7, Z=0.001, logR=-4

R & T as independent variables:

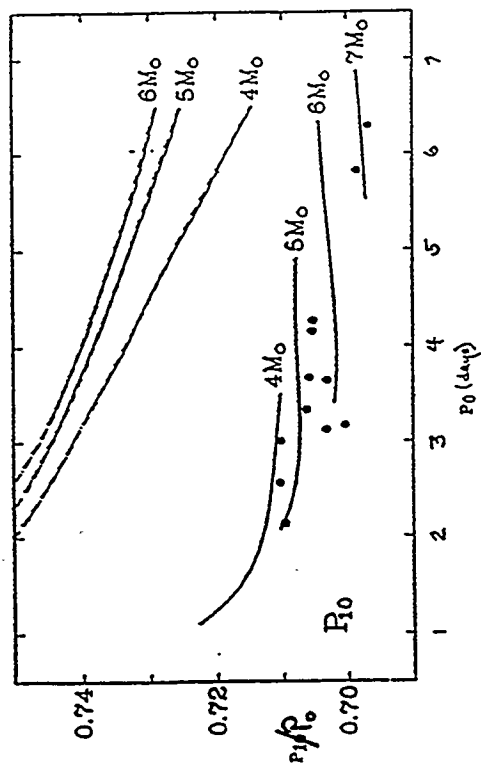
$R = \rho / T_6^3$ where ρ = mass density [g/cm³]
 T_6 = million degrees [°K]

Examples of Stellar Conditions:

Solar radiative interior X=0.35-0.7, Z=0.020, logR=-1.5
Classical Cepheids X=0.7, Z=0.020, logR=-3.5
Hot variable stars X=0.7, Z=0.020, logR=-5.5
RR Lyrae X=0.7, Z=0.001, logR=-4



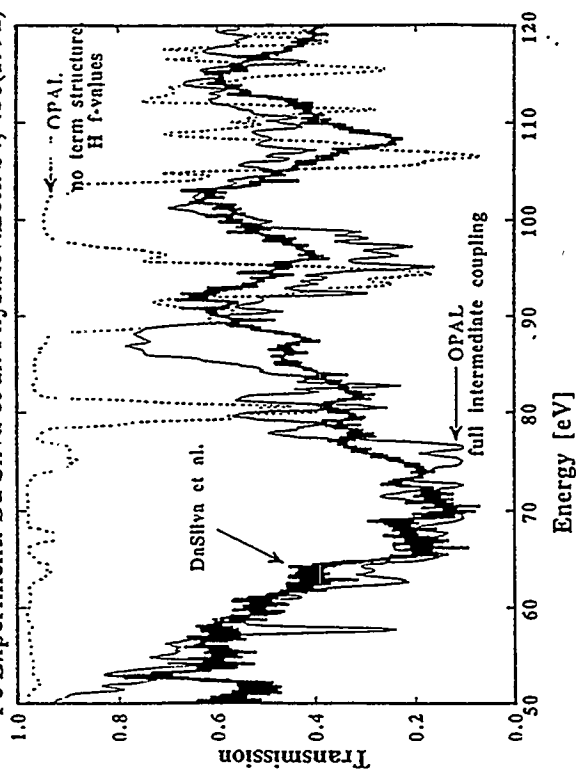
RESOLUTION OF BEAT MASS ANOMALIES WITH OPAL OPACITIES



- Observations (Szabados 1988)
- Cox & Tabor, *ApJS* 31, 271 (1976)
- Iglesias & Rogers, *ApJ* 371, L73 (1991)

From Moskalik et al., *ApJ* 385, 685 (1992)

Fe Experiment: Da Silva et al. Phys.Rev.Lett. 69, 438 (1992)



Third International Opacity Workshop
& Code Comparison Study

WorkOp-III:94

MPI für Quantenoptik, Garching
March 7-11, 1994

Final Report

edited by

A. RICKERT, K. EIDMANN AND J. MEYER-TEH-VEHN
Max-Planck-Institut für Quantenoptik
Hans-Kopfermann-Strasse 1, 85748 Garching, Germany

AND

F.J.D. SEBORG AND C.A. JOLZINS
Lawrence Livermore National Laboratory
P.O. Box 808, Livermore, CA 94550, U.S.A.

MPQ 201

August 1995

Fe K α COMPARISONS AT $T = 20$ eV ($\sim 230,000$ oK):

Code	$\rho = 0.01$ g/cm ³	$\rho = 0.0001$ g/cm ³
LANL'77	1.04×10^4 [cm ² /g]	0.15×10^3 [cm ² /g]
HOPE	1.37×10^4	1.40×10^3
STA	2.58×10^4	0.76×10^3
OPAL	2.93×10^4	6.03×10^3
LANL'94	3.07×10^4	6.75×10^3
IMP	3.14×10^4	10.80×10^3

KR COMPARISONS FOR ASTROPHYSICAL MIXTURE 'KING4a' AT
 $T = 20$ eV & $\rho = 1.2 \times 10^{-6}$ g/cm³:

Code	KR [cm ² /g]
LANL'77	1.76
HOPE	5.10
OPAL	5.47
STA	8.40

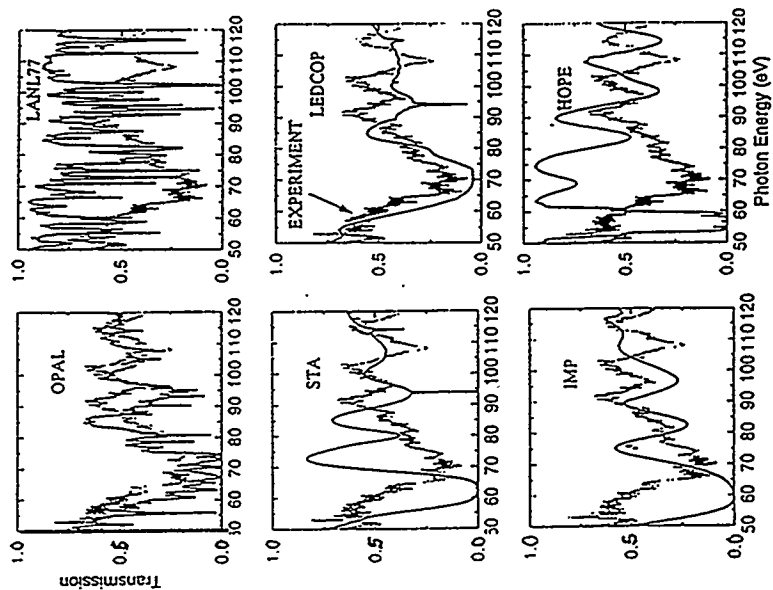
Fe K α COMPARISONS AT T = 20 eV (~230,000 °K):

Code	$\rho = 0.01 \text{ g/cm}^3$	$\rho = 0.0001 \text{ g/cm}^3$
LANL'77	1.04×10^4	$0.15 \times 10^3 \text{ cm}^2/\text{g}$
HOPE	1.37×10^4	1.40×10^3
STA	2.58×10^4	0.76×10^3
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LANL'94	3.07×10^4	6.75×10^3
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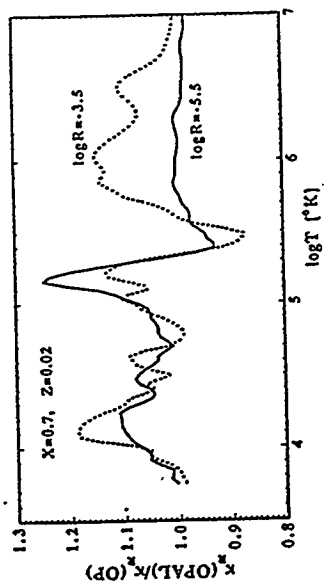
KR COMPARISONS FOR ASTROPHYSICAL MIXTURE 'KING4a' AT
T = 20eV & $\rho = 1.2 \times 10^{-6} \text{ g/cm}^3$:

Code	KR [cm ² /g]
LANL'77	1.76
HOPE	5.10
OPAL	5.47
STA	8.40

COMPARISONS TO Fe EXPERIMENT: T = 20 eV $\rho = 0.01 \text{ g/cm}^3$

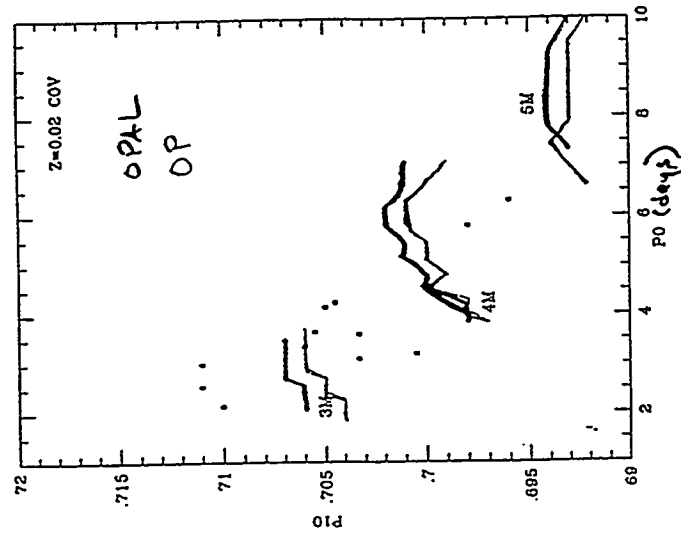


KR COMPARISONS OF OPAL & OPACITY PROJECT (OP):

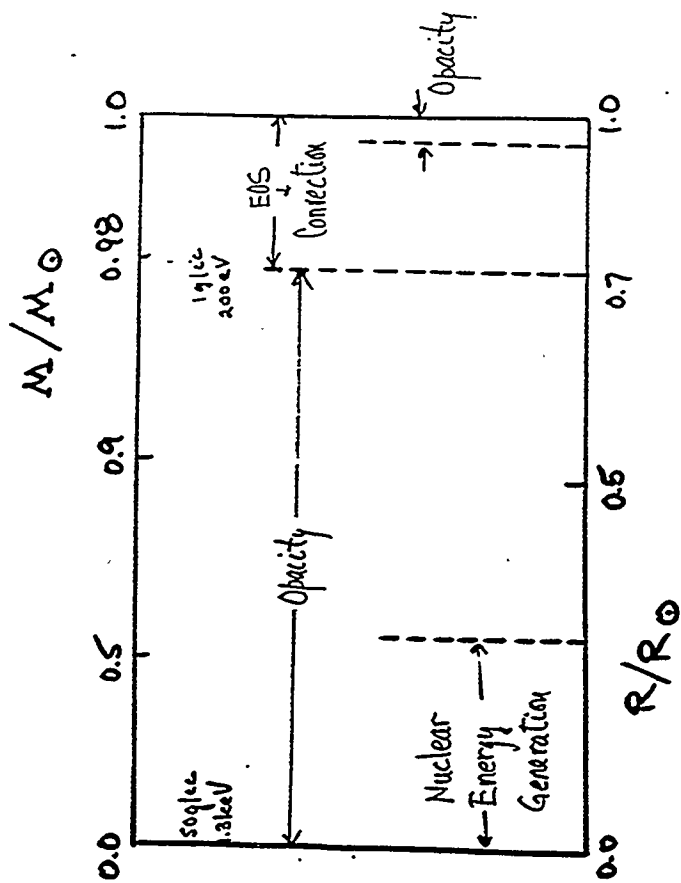


OP results from Seaton et al., *MNRAS* 266, 805(1994)

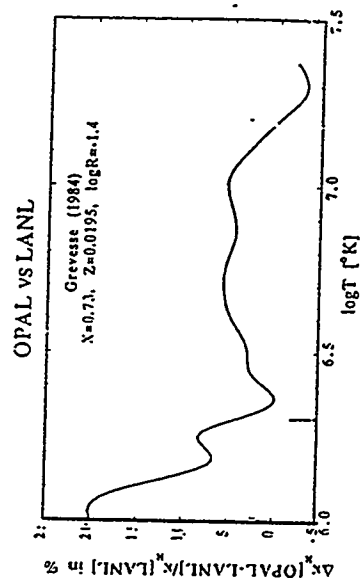
OPAL & OP COMPARISONS FOR DOUBLE-MODE CEPHEIDS:

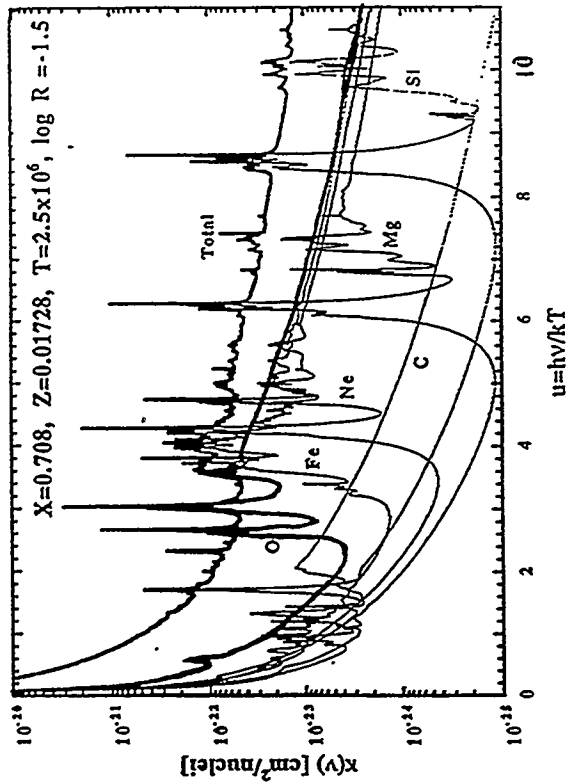


From Simon & Kanbur, *AJ* 429, 772 (1994)



COMPARISONS OF κ_R IN SOLAR RADIATIVE INTERIOR:





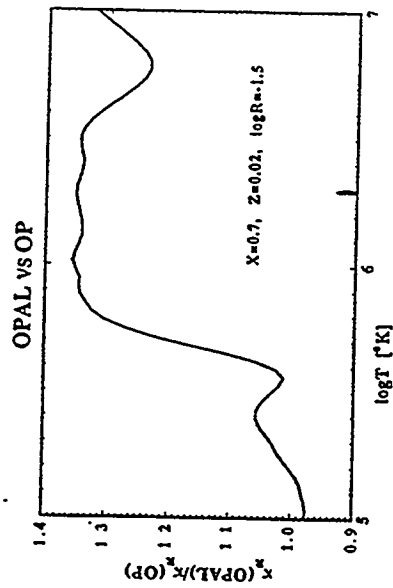
EOS COMPARISONS OPAL VS LANL:

Oxygen in an astrophysical mixture at
 $\rho = 1.38 \text{ g/cm}^3$, $T_6 = 3.264$, $X = 0.73$, $Z = 0.0195$

Element	LANL'77		OPAL		OPAL w/LANL EOS
	$\langle Z \rangle$	KR	$\langle Z \rangle$	KR	
O	7.406	7.14(-21)	7.187	8.69(-21)	7.04(-21)

From Iglesias & Rogers, *ApJ* 371, 408(1991)

COMPARISONS OF κ_R IN SOLAR RADIATIVE INTERIOR:



EOS COMPARISONS OPAL vs OP:

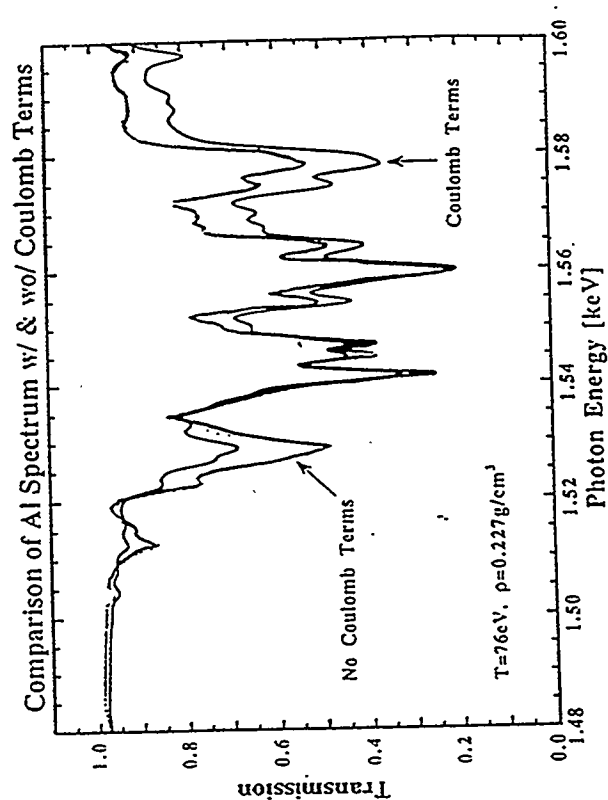
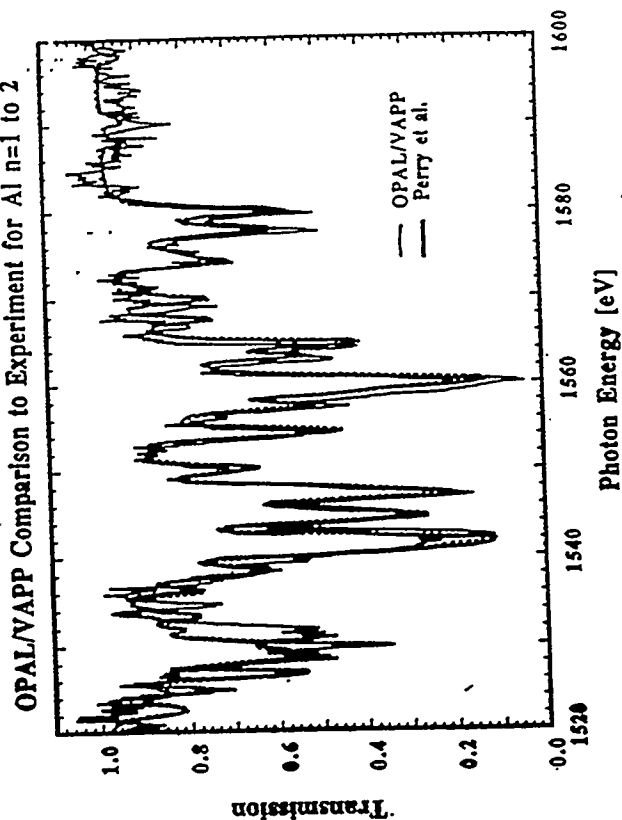
Hydrogenic Carbon "dissolution" in an astrophysical mixture at
 $\rho = 0.01 \text{ g/cm}^3$, $T_0=1$, $X=0.7$, $Z=0.02$

n	OP	OPAL
1	1.00	1.00
2	0.991	0.996
3	0.906	0.995
4	0.495	0.995
5	0.0362	0.914
6	6.33(-6)	0.527
7	2.96(-16)	0.162
8	4.76(-41)	0.0237
9	1.06(-94)	0.00223

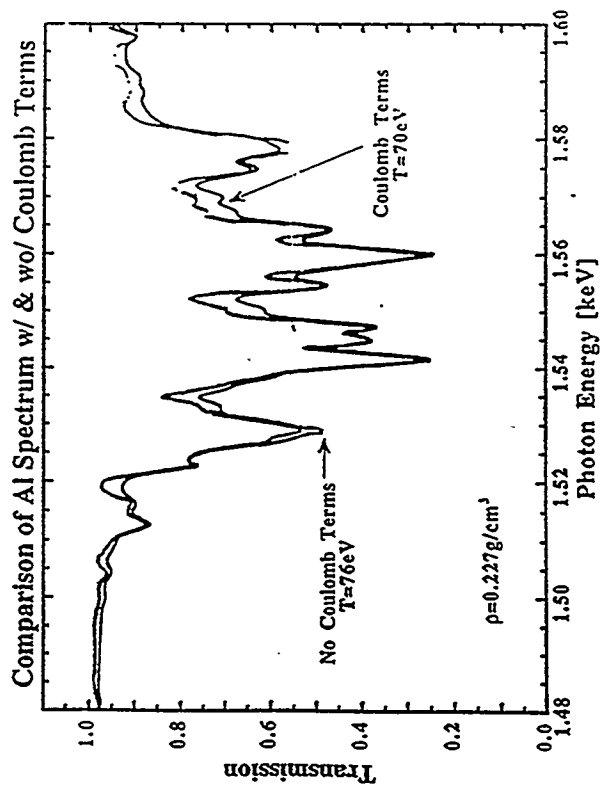
OP results from Seaton et al., *MNRAS* 266, 803(1994)

From Iglesias & Rogers, *ApJ* 443, 460(1995)

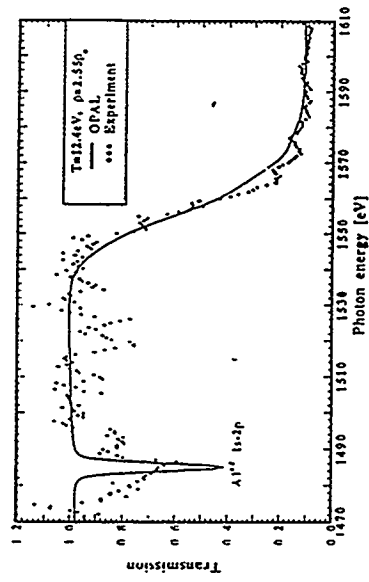
$T = 49 \text{ eV}$
 $\rho = 0.026 \text{ g/cm}^3$



From analysis of JOST-51, 125 (1991)

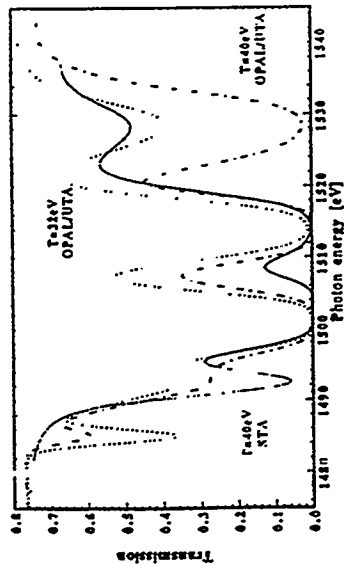


COMPARISONS OF OPAL & NOVA SHOCK EXPERIMENT:



Data from Celliers et al. (private communication)

$T = 40 \text{ eV}$
 $\rho = 3.7 \rho_0$
 COMPARISONS OF OPAL & STA:



Charge	Ionization Balance			
	T=40eV OPAL	T=40eV STA	T=40eV OPAL+TA	T=40eV OPAL+TA+TA
+7	0.056	0.005	0.011	0.011
+6	0.256	0.097	0.117	0.117
+5	0.406	0.418	0.377	0.377
+4	0.244	0.406	0.394	0.394
+3	0.037	0.073	0.101	0.101
<Z>	5.05	4.56	4.84	4.84

CONCLUSION:

- Experiments relevant to stellar envelopes are welcomed in order to study details in opacity calculations
- Ionization balance experiments are necessary to:
 - Reduce uncertainties in solar opacities
 - Fundamental issue in plasma physics!

Type Ia Supernova Lightcurves and Spectra

Phil A. Pinto
University of Arizona

Type Ia Supernovae

For our purposes here, they are explosions ~

$$E_{\text{inert}} \sim 10^{51} \text{ erg}, \quad M_{\text{tot}} \sim 0.8 \text{ to } 1.4 M_{\odot}$$

$$\langle v_{\text{exp}} \rangle \sim 7 \cdot 10^8 \text{ cm s}^{-1} \quad (v_{\text{max}} > 0.1c)$$

homologous expansion, $\rho(t) \propto e^{-4v/v_{\text{max}}}$

radioactivity-powered by $\sim 0.5 M_{\odot}$ of ^{56}Ni

$$L_{\text{peak}} \sim 10^{42} \text{ erg s}^{-1} \quad 15^{\text{d}} \text{ post explosion}$$

Type Ia Supernova Lightcurves & Spectra

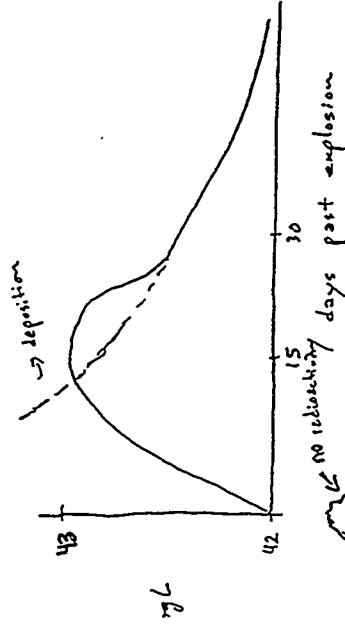
or

Radiation Transport in Flows with Large
Velocity Gradients & Dominated by Line Opacity

P.A. Pinto
Steward Observatory
U. of Arizona

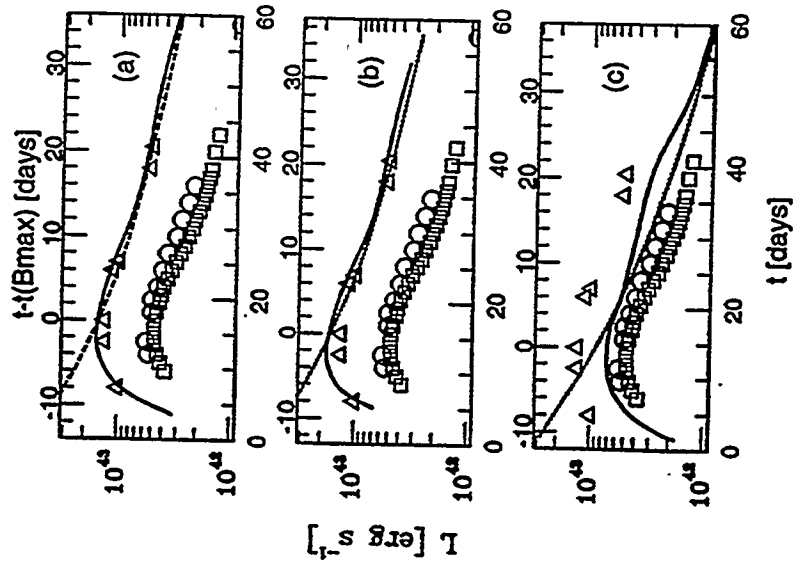
R.G. Eastman
LLNL

(... 2 couple of theorists in need of an experiment...)



Lightcurve is the most basic diagnostic & is
a competition between:

- Energy deposition by radioactive decay
 $^{56}\text{Ni} \xrightarrow{6.6\text{d}} ^{56}\text{Co} \xrightarrow{77\text{d}} ^{56}\text{Fe}$
- Adiabatic decompression (PJV work)
- Radiative transport to surface

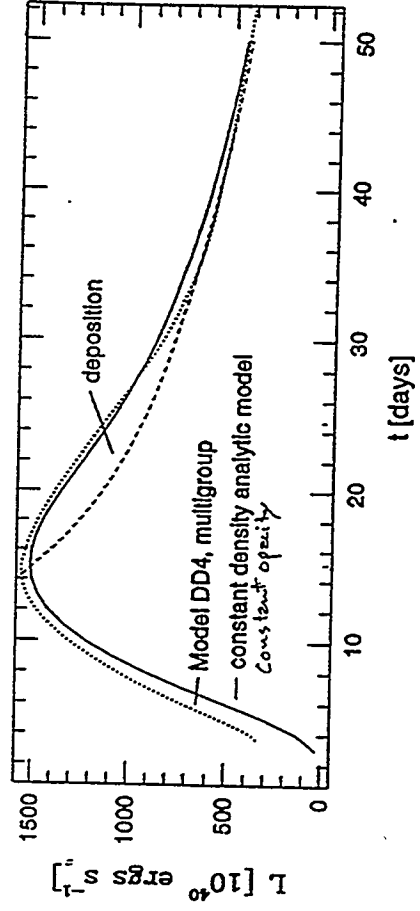


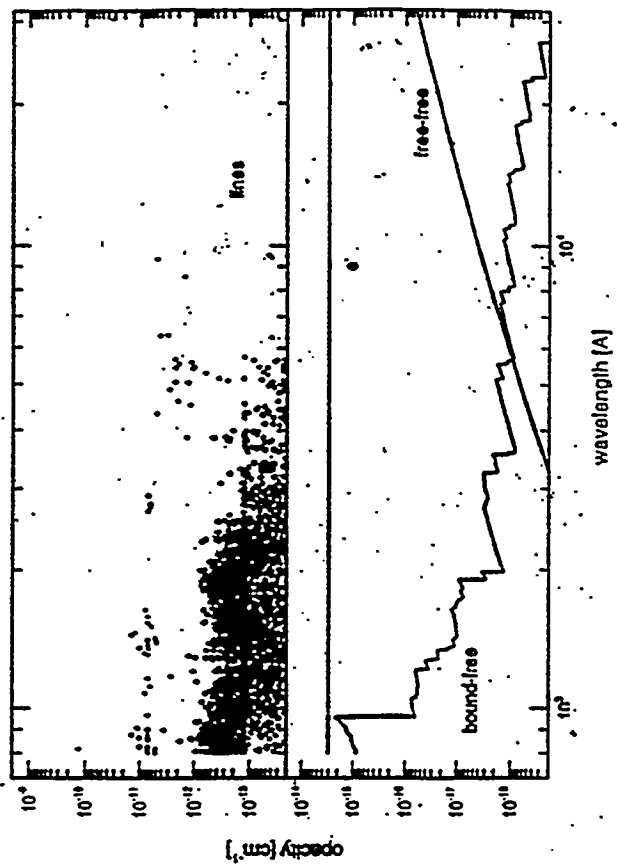
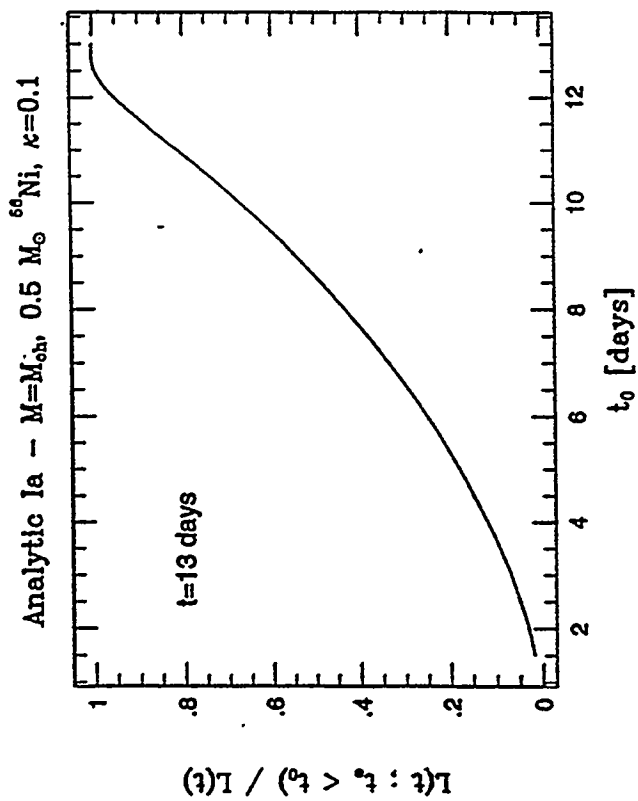
Exponentially-falling deposition rate $\Rightarrow$
 Peak luminosity occurs when radiation has half a
 chance to escape: $\tau_{\text{diff}} \approx \tau_{\text{exp}} = t_{\text{elapsed}}$

This is typically ~ 15 d

$$E_{\text{th}} = M_{\text{Ch}}, \langle v \rangle \sim 7500 \text{ km s}^{-1}$$

$$\Rightarrow K \sim 0.1 \text{ cm}^2 \text{ g}^{-1}$$





- Opacity is dominated by line transitions
- large $\sigma_{\text{tr}} \Rightarrow$ Sobolev theory appropriate
- distance a photon travels while trapped in a line resonance region is

$$\langle \ell \rangle_{\text{line}} \approx \frac{4 v_{\text{th}}}{v_{\text{res}}} \sim 10^{-3}$$

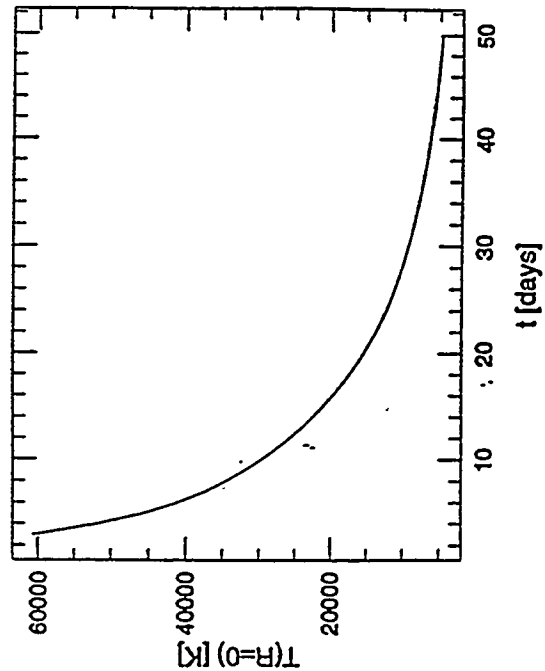
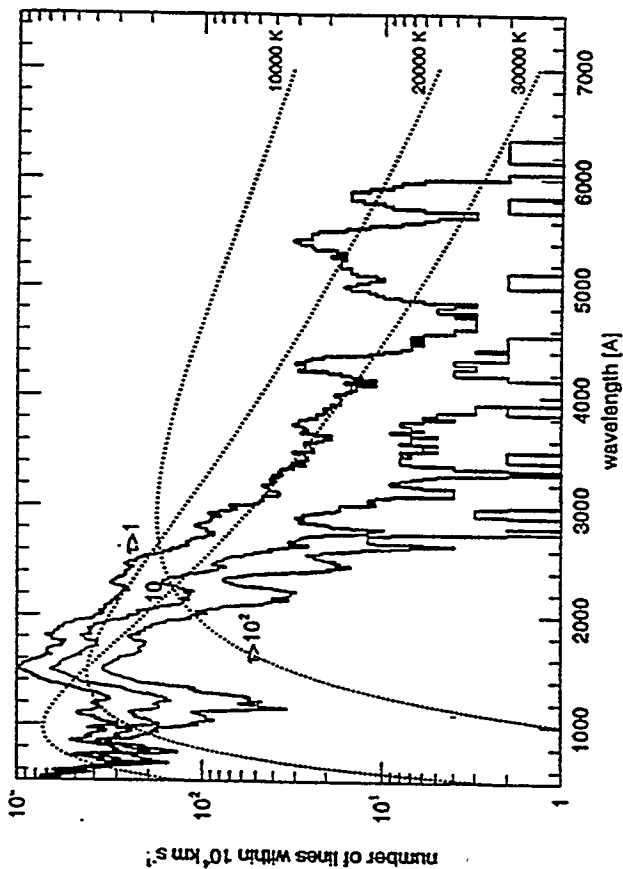
$\Rightarrow$ A photon spend virtually all of its time travelling between lines.

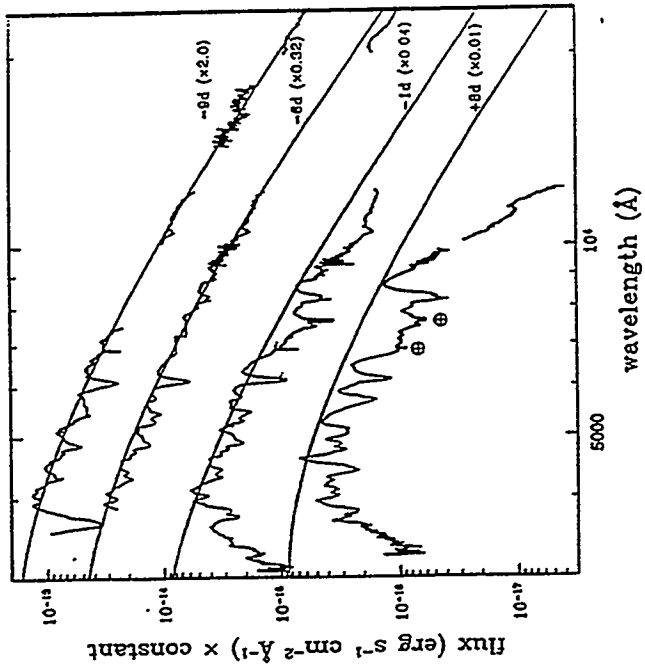
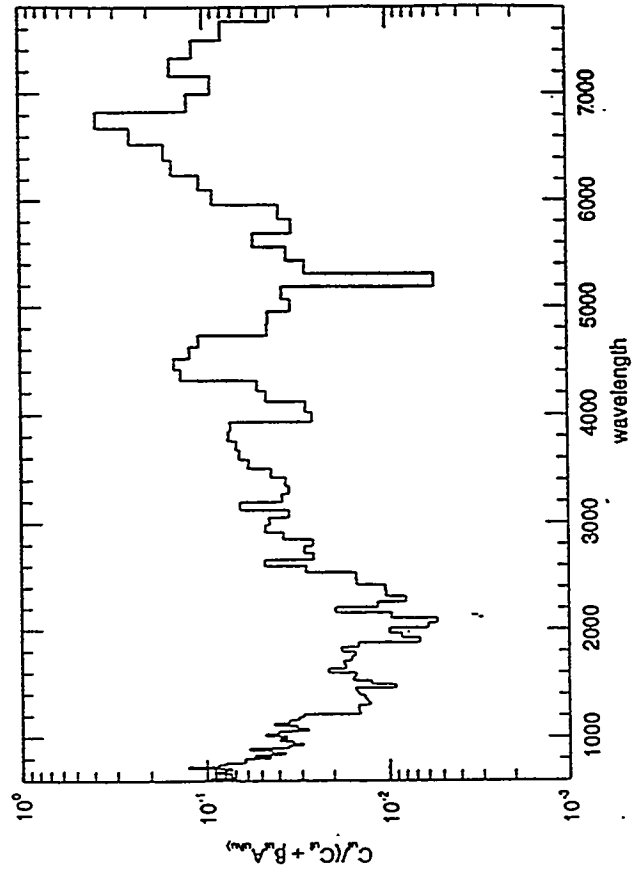
$\Rightarrow$ Each line acts as a single scattering event

The mean free path is thus the average distance between lines

$$\Rightarrow \tau_{\text{SN}} = \# \text{ of lines in } [\lambda, \lambda(1 + \frac{v_{\text{max}}}{c})]$$

$$\propto \rho_{\text{H}} \propto t^{-2}$$





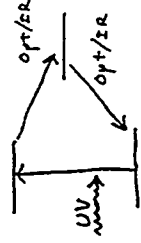
Energy Escape:

- As deposition falls faster than PDU,
T drops & thermal emission shifts to
longer λ . w/ lower $\tau \Rightarrow$ escape.

- Since $\tau_{10} = D \text{ (mas/10}^4 \text{ km s}^{-1})$, $wfp = \frac{R}{D}$
scatter τ^2 times to escape $\Rightarrow$ path length is DR
 $\Rightarrow$ total Doppler shift is $\frac{\Delta\lambda}{\lambda} \sim 1$.

Before this happens, photon falls in energy to
region of lower τ & escapes.

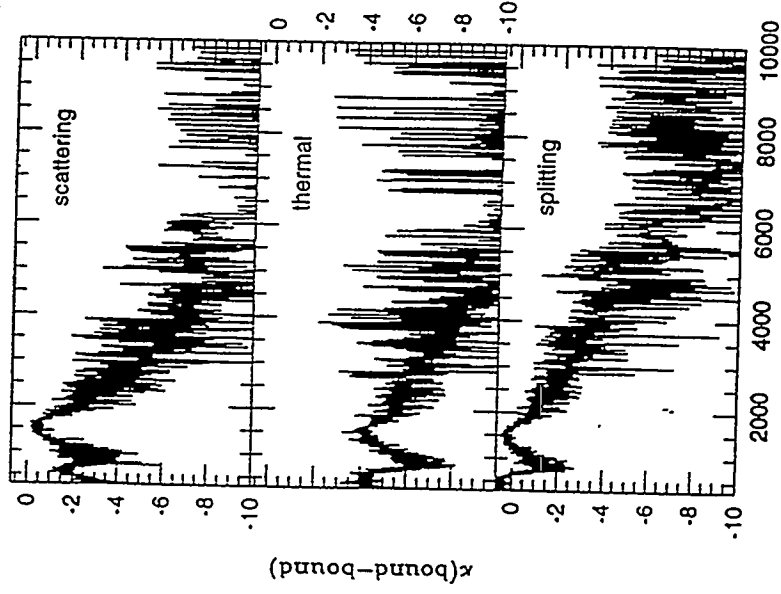
- Photon "Splitting":

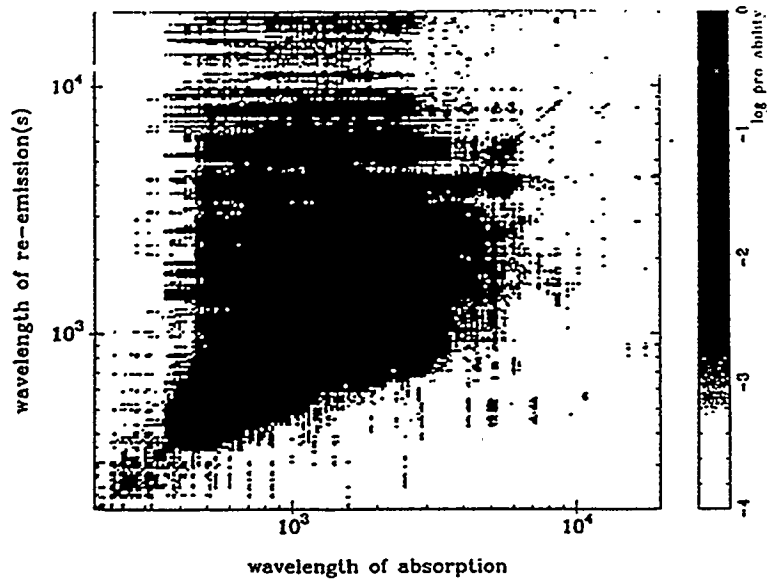


$$\sigma_{12} = (1 - e^{-\tau_i}) \frac{\rho_0 A_{12}}{\sum_i \rho_{0i} A_{1i}}$$

$\beta =$ escape probability

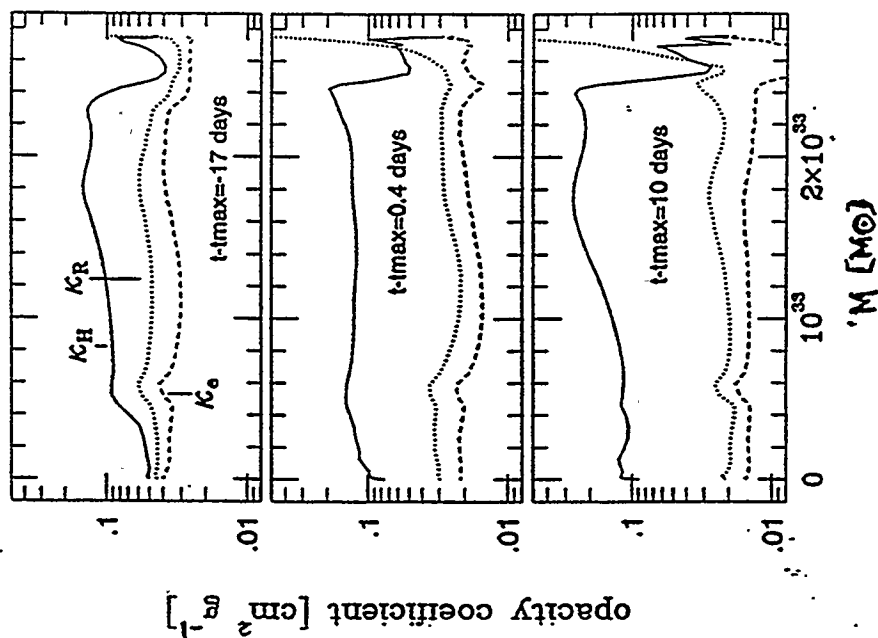
$\rho = 10^{-12} \text{ g cm}^{-3}$, $T_{\text{gas}} = 2.5 \times 10^4$, $X(\text{Co}) = 0.88$, $X(\text{Fe}) = 0.12$





Using a multigroup, time-dependent, LTE
calculation of Kurucz (see text),
 $\langle \kappa \rangle_F$ is nearly constant in time.

Model DD4



Help from Large Lasers

- "Expansion opacity" approximations
How to take $[(\ln \rho, P, T_{\text{gas}}, T_{\text{rad}})]$
+ get an appropriate $\langle n \rangle$
- Tests of more detailed transport physics
Model the experiment, don't try to
make a SM in the lab.
- Possible test of Fe group atomic physics
eg. mean splitting probability as function
of ρ, T

Photonization Modelling

Tim Kallman
NASA/Goddard Space Flight Center

i) Beckgrund

ii) Model ingredients

iii) Examples

with
O. Liedahl
S. Kahn
A. Osterheld
W. Goldstein
N. White
L. Angelini

and
S. Hatchett
R. McCune

$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{x}} \right) = \frac{\partial L}{\partial x}$

Why photoionization?

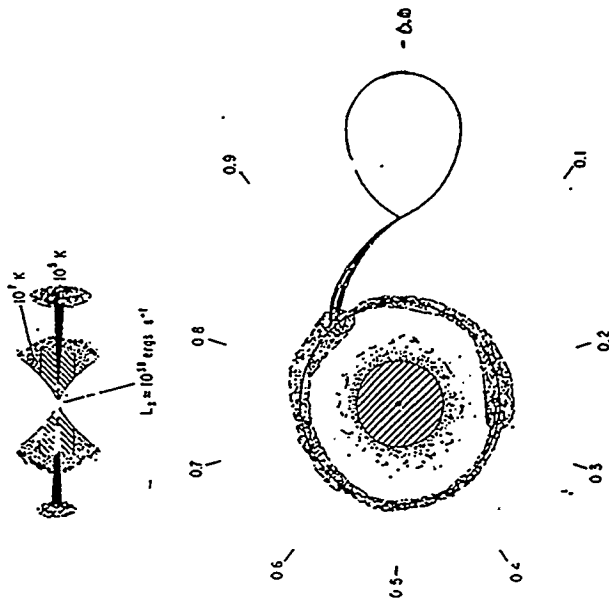
- "Compact" astrophysical X-ray sources are among the brightest objects in the X-ray sky
- Also enigmatic: X-ray binaries, AGN
- Variability + huge luminosities imply compact source

$$\frac{\Delta t}{L} \sim \frac{R}{c} \sim \frac{0.5 \text{ msec}}{10^{18} \text{ erg s}^{-1}}$$
- Lines & bound-free features formed in surrounding gas

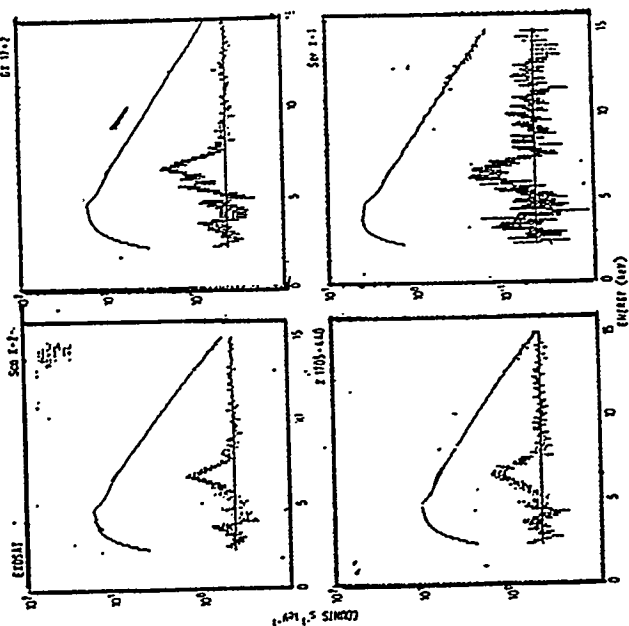
$$\tau_{\text{var}} \gg \Delta t_{\text{cont}} ??$$
- Continuum provides limited information about the conditions in the source

• What would we like to learn?

abundances processed material?
 geometry heated disk? wind?
 mass motions inflow? outflow?
 temperature heat source?
 luminosity std. candles?
 density

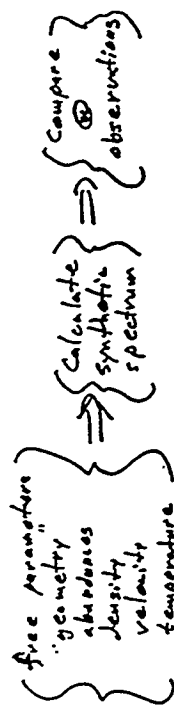


White 8th/17/1992



White et al. 1986

Modelling:



But this too hard

X-ray opacity dominated by metals

Strategy: ignore geometry, velocity, other parameters, time dependence

Details: assume simple geometry (sphere or slab)

all heating & ionization from observed continuum

steady state

"corona" excitation

simple R.T. (e.g. escape probability)

Try to treat the atomic microphysics

as accurately as possible

More details

Assume "solar" abundances to start
 Z is most abundant elements

solve:

ionization
 $PI \quad CI$

= recombination
 $RR \quad DI$

heating
 $PI \quad comp$

= cooling
 $RR \quad DI \quad CX \quad comp \quad brems$

excitation

= deexcitation
 $RR \quad DI \quad CX \quad RX \quad AD \quad CX \quad PI \quad CI$

"Collisional Radiative model"

"Radiation transfer

escape probability, 1 or 2 stream

Results

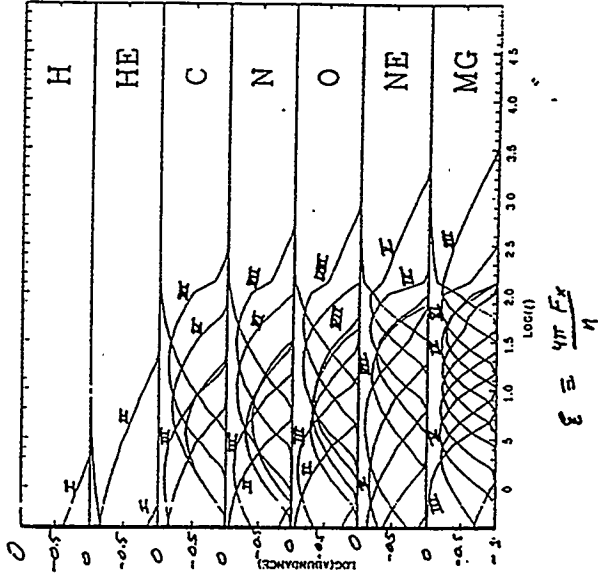
Scaling parameter:

"Ionization parameter"

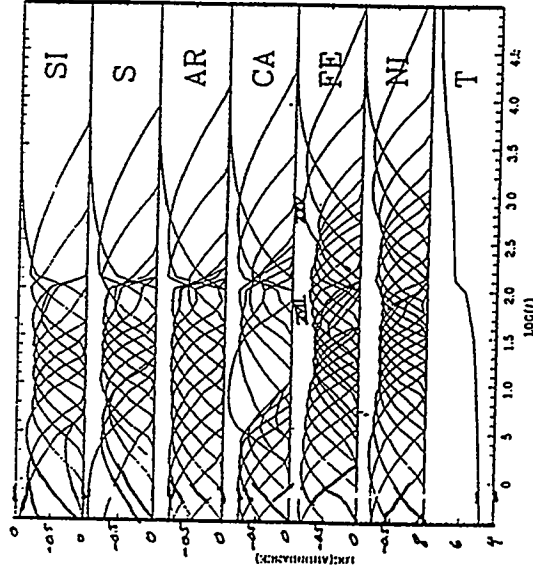
$$\xi \sim \frac{\text{Radiation flux}}{\text{gas density}}$$

$$\xi \sim \frac{\text{heating}}{\text{cooling}}$$

$$\xi \sim \frac{\text{Photoionization}}{\text{recombination}}$$



$$\xi \equiv \frac{4\pi F_{\gamma}}{n}$$



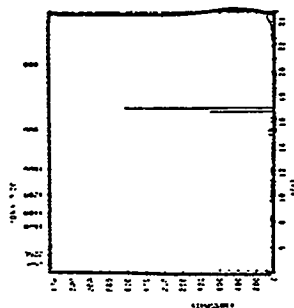
$$\xi \equiv \frac{4\pi F_{\gamma}}{n}$$

Low (w/keV) energy line modelling

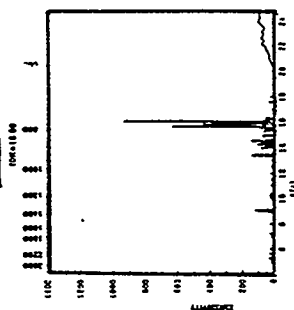
- K lines of medium Z elements (e.g. O, Ne, Mg) mostly from H&He-like ions (Si, S)
atomic physics is "simple": H-like scaling
 1 $\Rightarrow$ Ly, L α , continuum
 lines are strongest due to abundances (n.b. O, Si, S)
 wide range of E for recombination
- L lines of iron ($n=2 \rightarrow n=3$) from Li - Ne like ions
 atomic physics is complicated:
 hundreds of levels thru $n=2$
 need good model to do rec. cascade
 lines are weaker, tend to broad blends
 narrow range of E
 strongest are $4p-3s$ not $4p-3d$.

Iron L Line Spectrum:

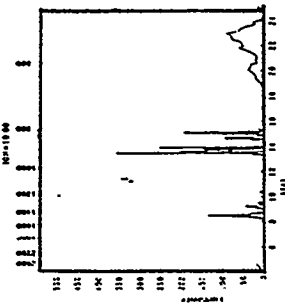
XVII



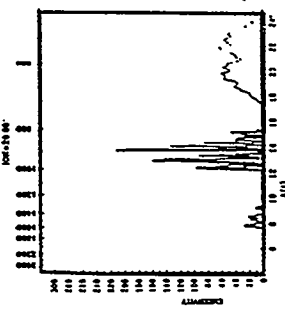
XVIII



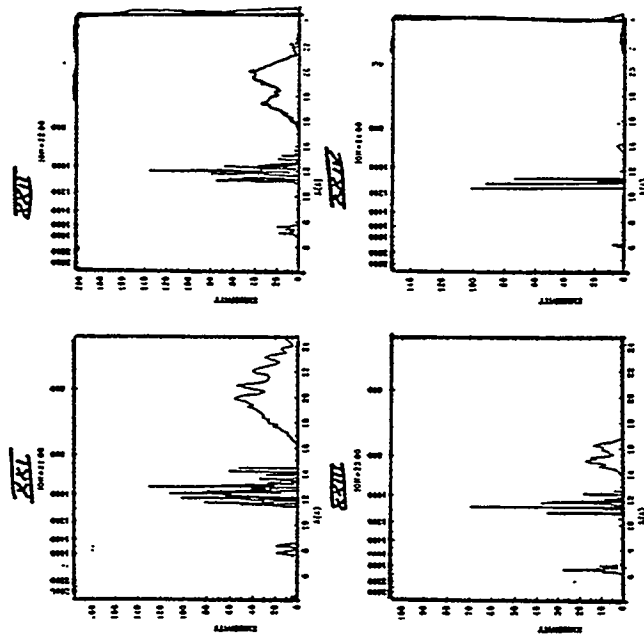
XIX



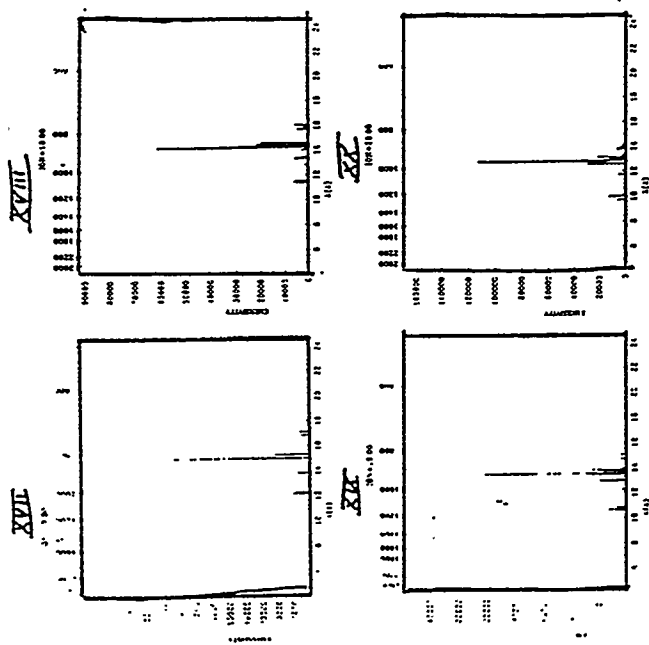
XX



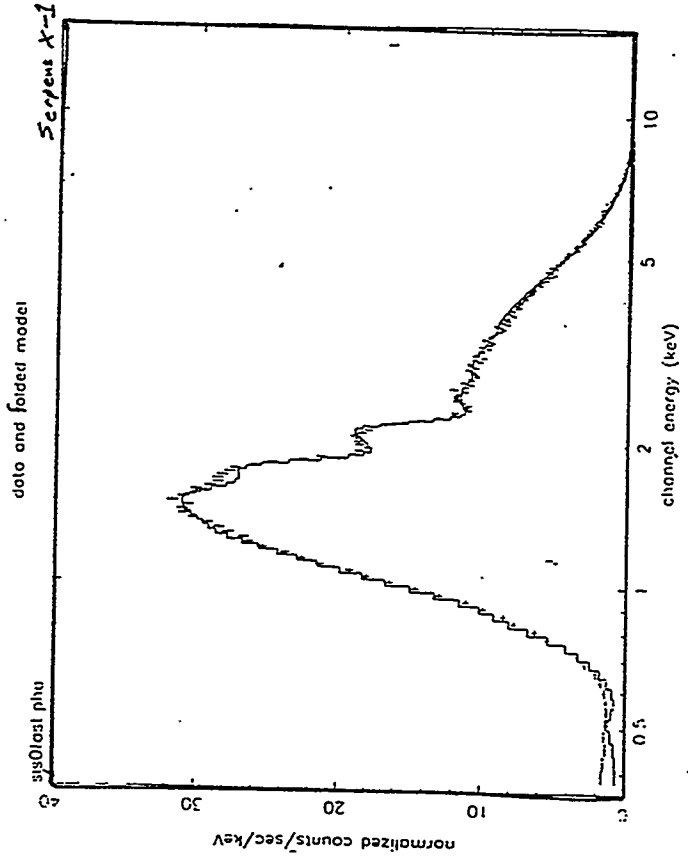
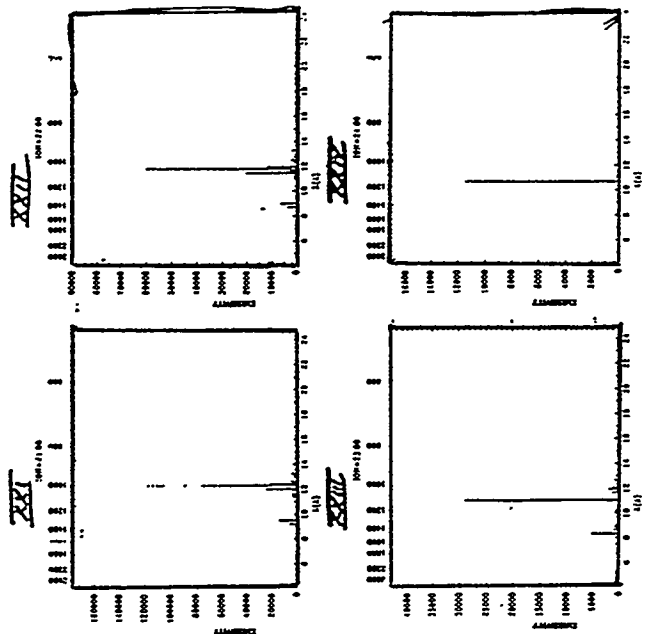
*Iron L line spectra
Recombination*



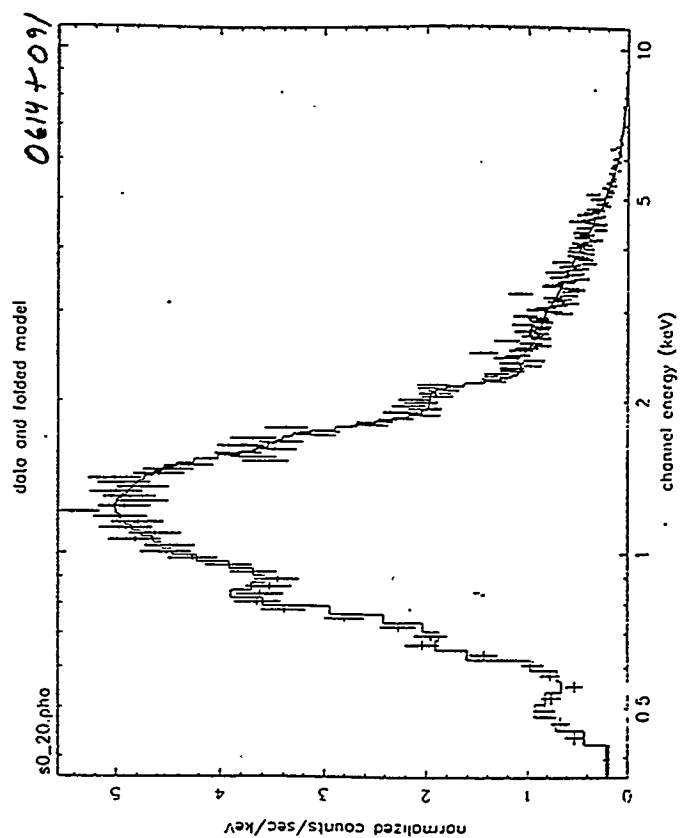
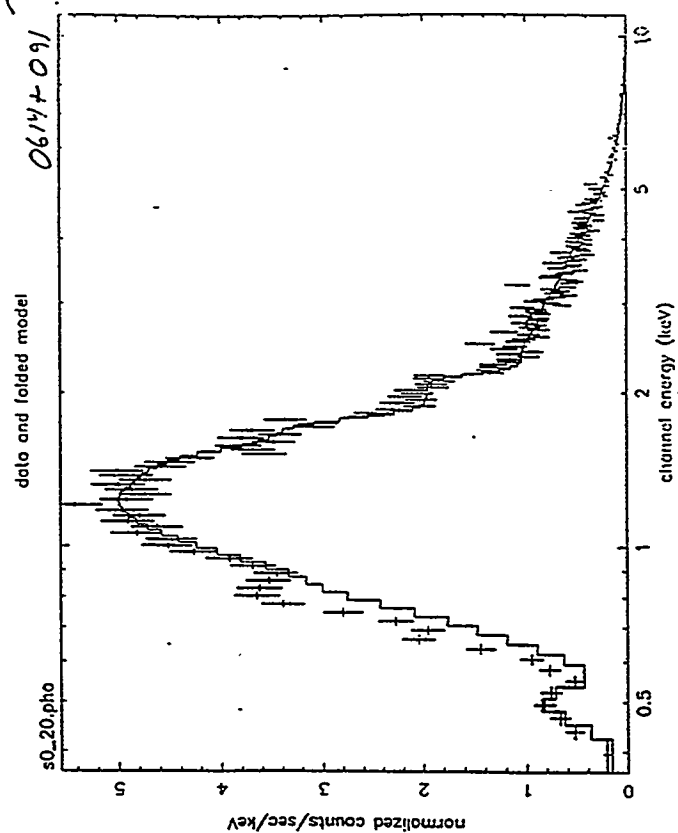
*Iron L line spectra
Resonance scattering*

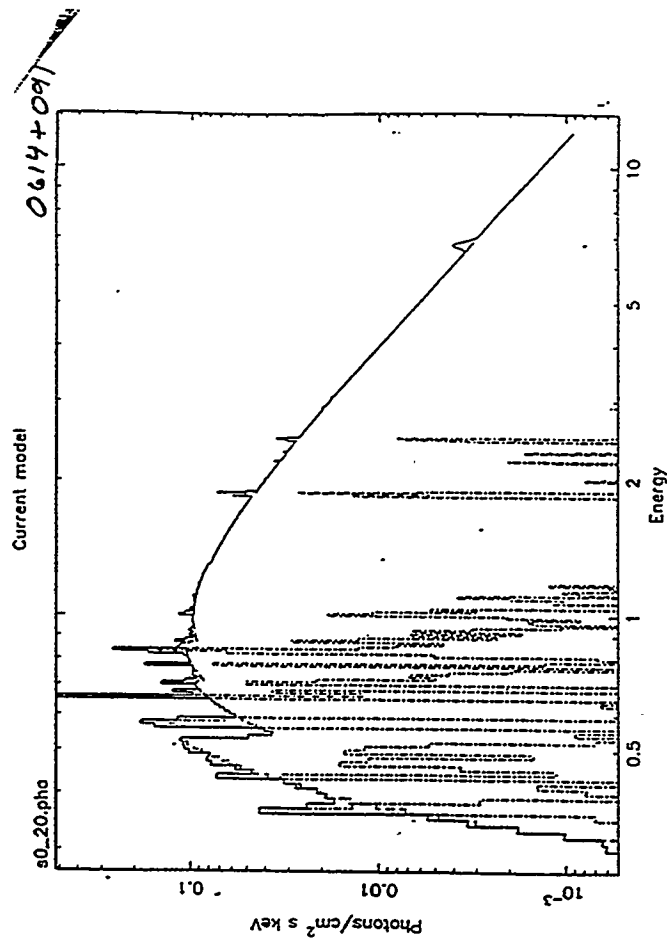


Iron L line spectrum
Resonance scattering



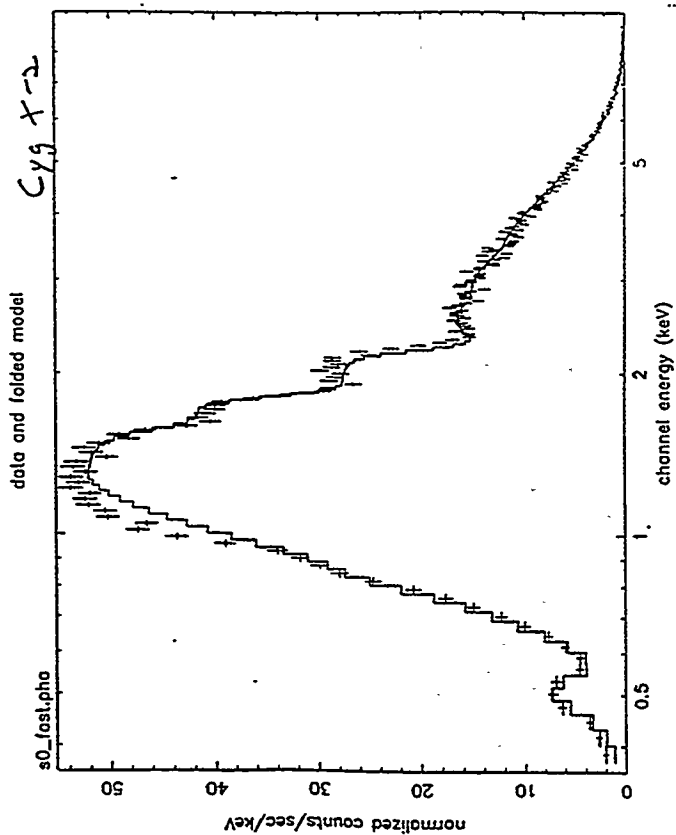
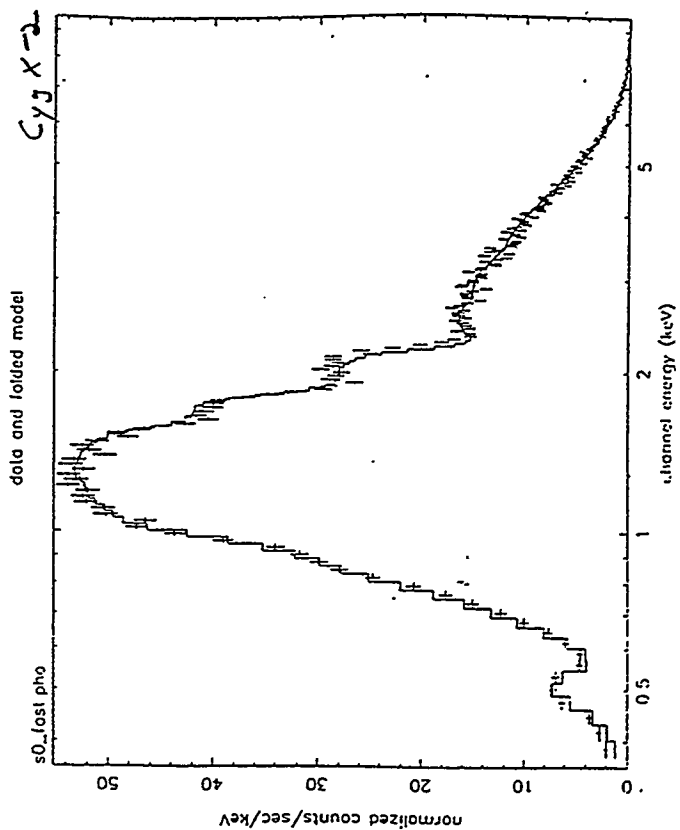
Jan 2-01-1995 11:07

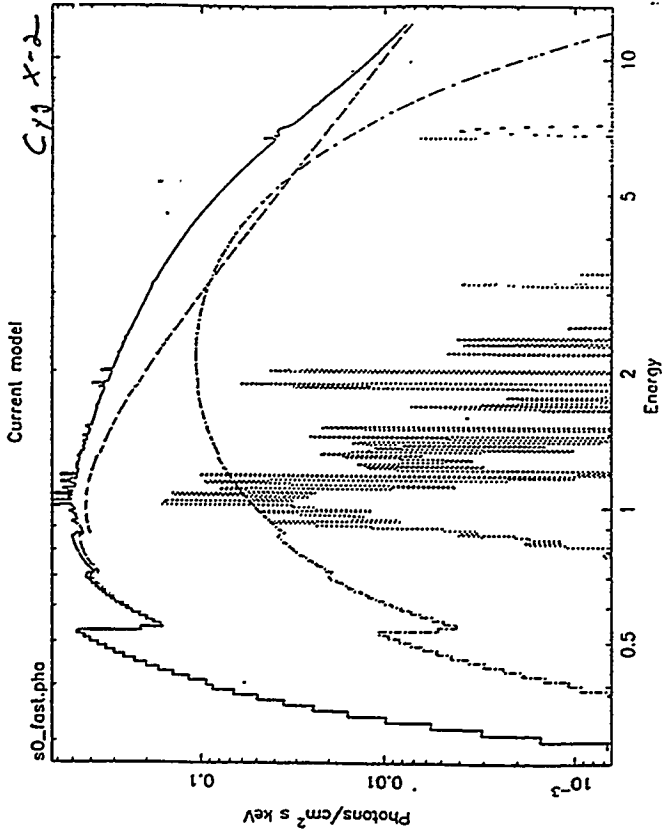




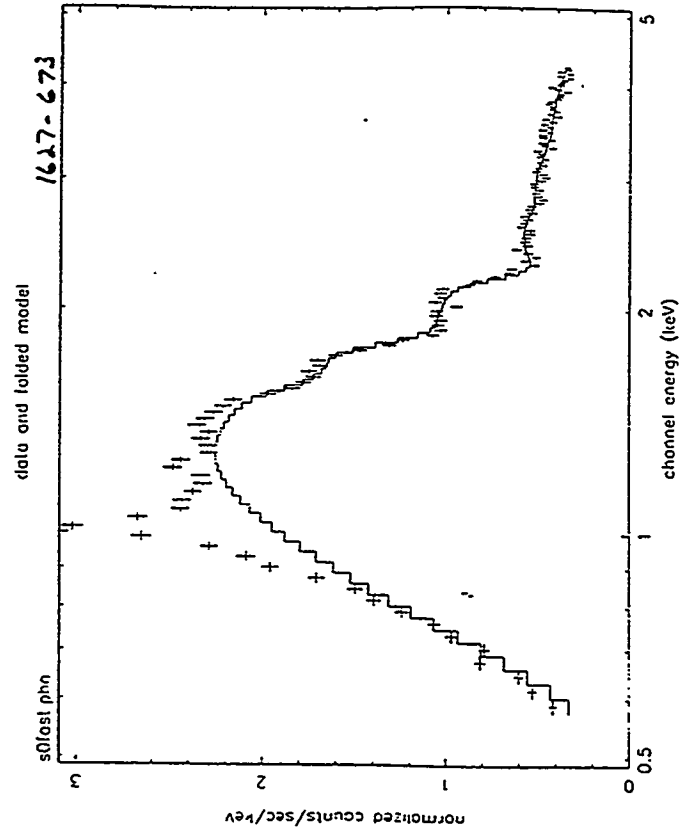
The ASCA spectrum 4U0614+091

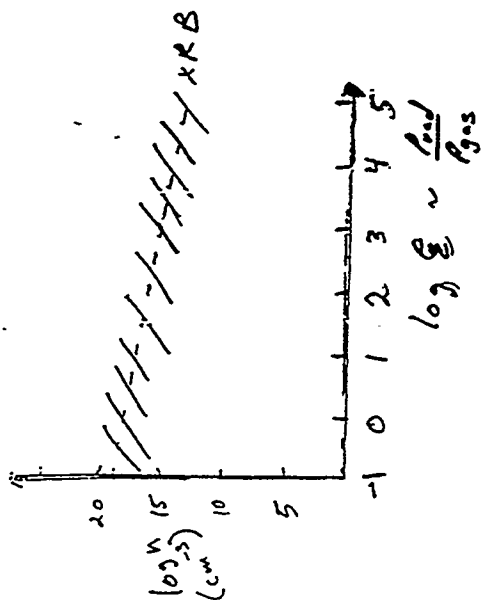
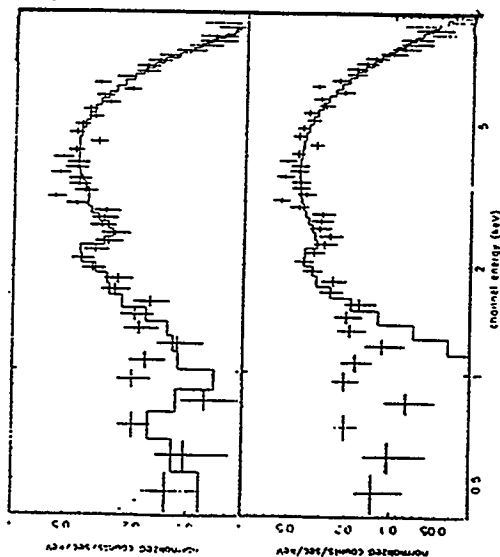
- X-ray Burst source
 - Continuum fits to absorbed power law
 - Iron K line $\varepsilon = 6.75 \text{ keV}$ $\text{EW} \approx 60 \text{ eV}$.
 - Low energy line emission near 0.65 keV , 0.8 keV , $\text{EW} \approx 125 \text{ eV}$.
 - Best fit to ~~model~~ ^{recomb.} model, $\log(\xi) \approx 2.8$, Abundances not strongly constrained.
- $\Rightarrow$ solar abundances OK.





- The ASCA spectrum of Cyg X-2*
- well-known Z source, studied by all previous satellites.
 - Continuum fits to absorbed power law.
 - Iron K line $\epsilon = 6.75 \text{ keV}$ $\text{EW} \approx \text{xx}$.
 - Low energy line emission near 1 keV
 - Best fit to scattered model, $\log(\xi) \approx 2.8$, $\text{O}/\text{Fe} \approx \text{xx} \times \text{solar}$.





Issues

1) Atomic processes:

OR, PI

2) Time dep. $\frac{F(E)}{F(E)} \approx \frac{F(E)}{F(E)}$?

3) Other physics

.. e.g. protons, non-Maxwellian

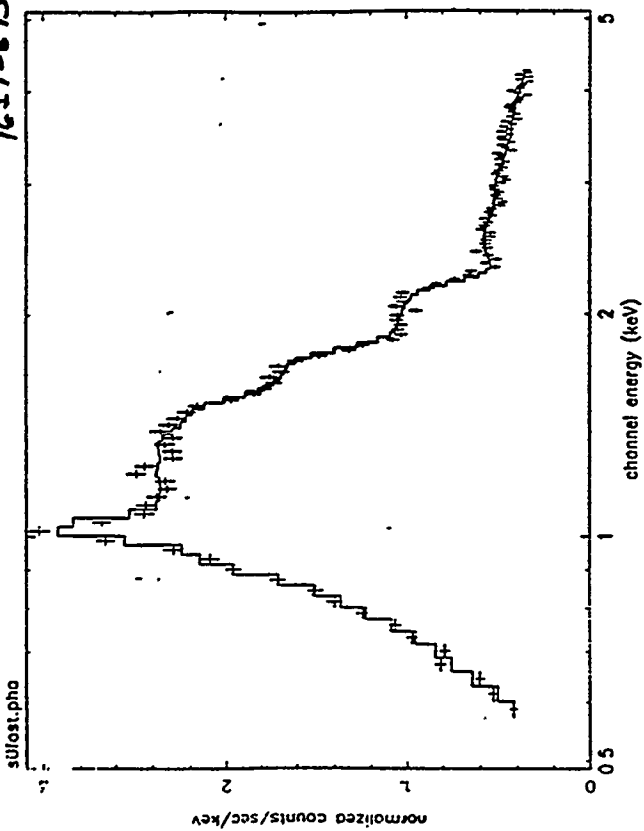
4) Modelling (atomic model) & RT

5) Assumptions

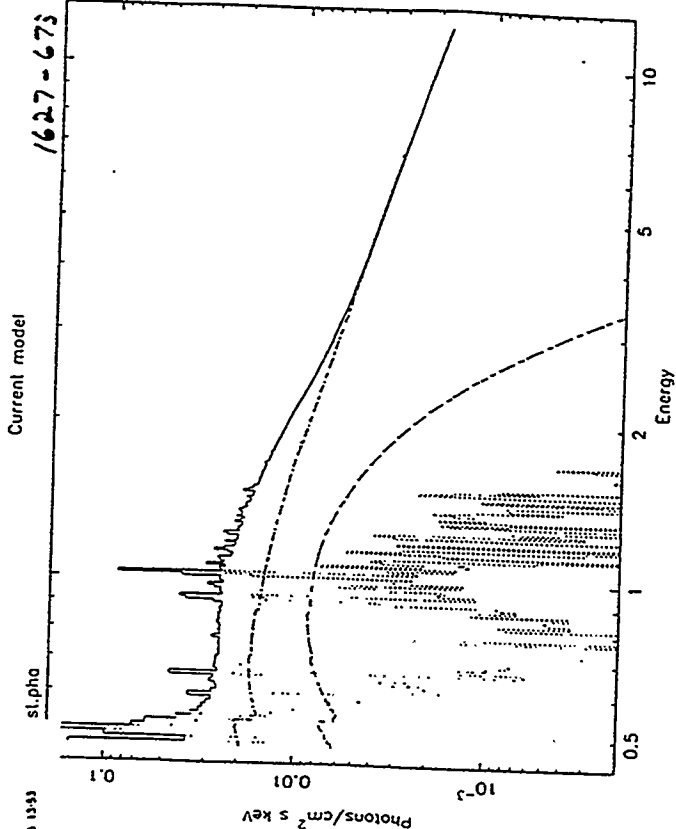
e.g. static

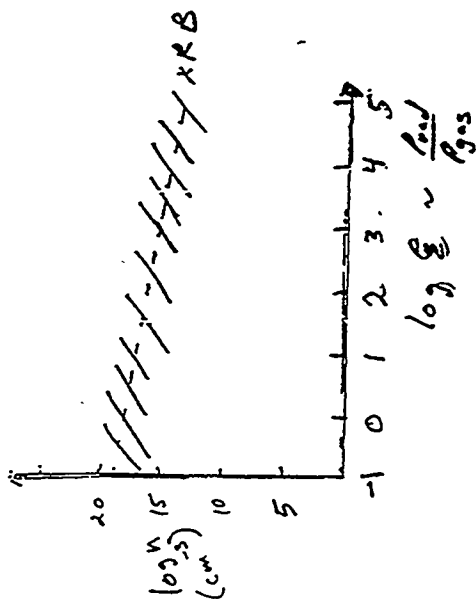
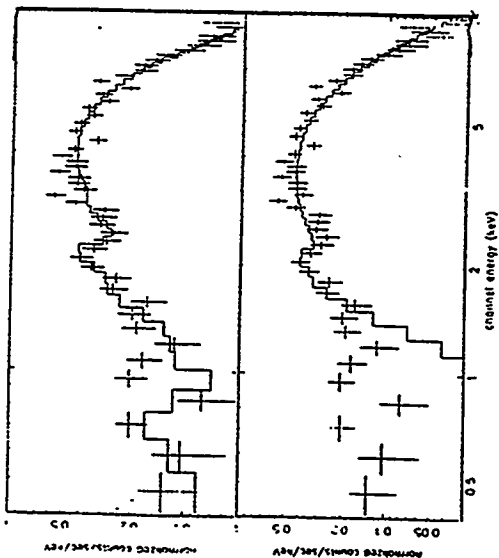
1627-673

data and folded model



242





Issues

1) Atomic processes:

$OR, PI \dots$

2) Time dep: $\frac{1}{S} F(\bar{E}) \approx \frac{F(E)}{F(E)}$?

3) Other physics

e.g. protons, non-Maxwellian

4) Modelling (atomic model)
& RT

5) Assumptions

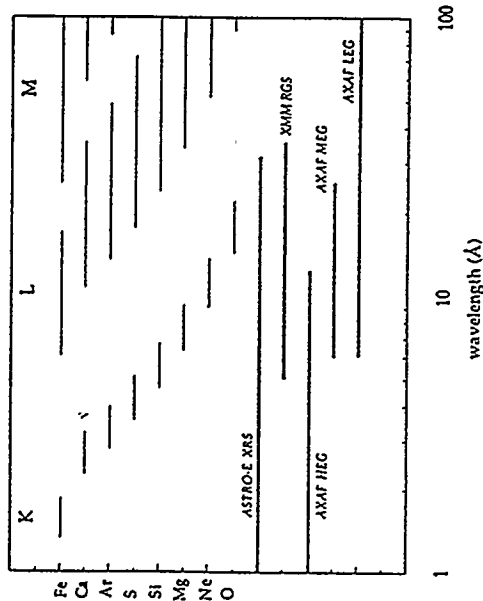
e.g. static

Spectroscopy of X-ray Photonized Nebulae

Duane Liedahl
Lawrence Livermore National Laboratory

X-ray Spectral Bands for Cosmically Abundant Elements

Spectral Coverage of Future X-ray Observatories



Spectroscopy of X-ray Photoionized Nebulae

Duane Liedahl
V-Division, LLNL

Collaborators:

James Dunn
William Goldstein
Albert Osterheld
Rosemary Walling

Tim Kallman - NASA/GSFC

Basic concept: create X-ray heated, photoionization-dominated plasmas in the laboratory that will allow the study of ionization/recombination, heating/cooling, and X-ray line formation as functions of ionization parameter ($\xi \sim F/n$), spectral shape, chemical composition, and density.

Motivation: launch of three facility-class X-ray satellite observatories with high-resolution spectrometers by 2000; complexity (micro & macro) of modeling spectra from X-ray photoionized plasmas; existence of suitable experimental facilities.

Contrast of Physical Processes in X-ray Emission-Line Regions

stellar coronae
supernova remnants
clusters of galaxies
interstellar medium
active galactic nuclei
X-ray binaries
cathodysmic variables(?)

hot, collisionally ionized

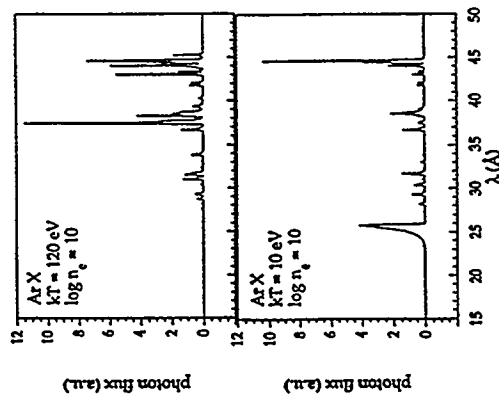
cool, photoionized

	Collisional equilibrium	Photoionization equilibrium
Ionization	electron-impact ionization	photoionization
Recombination	$\Delta n > 0$ DR	RR and $\Delta n = 0$ DR
Excitation	electron-ion impact	recombination, photoexcitation
Heating	mechanical	thermalization of photoelectrons
Characteristic temperatures	$10^6 - 10^7$ K	$10^3 - 10^6$ K
Radiative transfer	no	yes
Spectral quality	line-dominated	continuum-dominated
Fundamental parameter	T_e	ξ

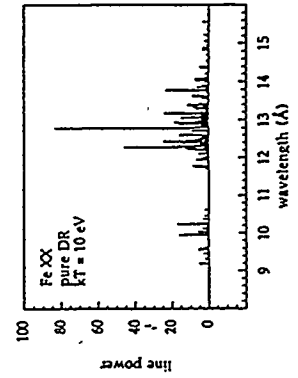
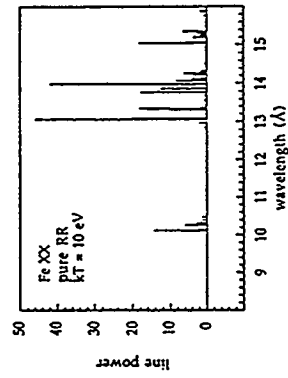
Presented at Workshop on Laboratory Astrophysics Experiments With Large Lasers 2021/94, Pittsburgh, CA

Presented at Workshop on Laboratory Astrophysics Experiments With Large Lasers 2021/94, Pittsburgh, CA

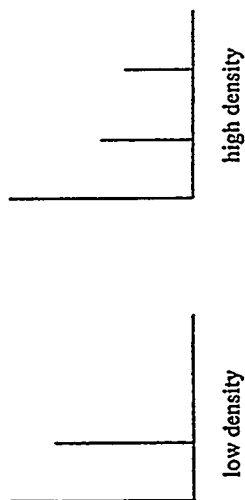
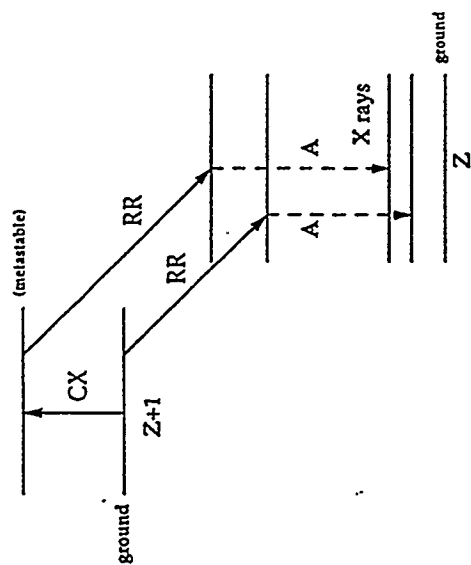
Differences in the underlying population kinetics mechanisms leads to obvious differences in the resulting emission spectra. (Top) F-like Ar X as it would appear in coronal ionization equilibrium. (Bottom) Ar X in photoionization equilibrium.



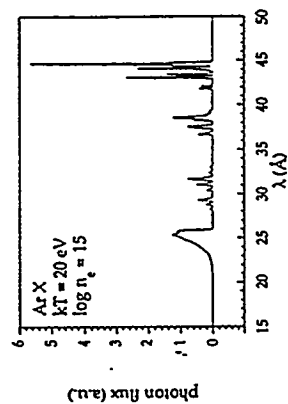
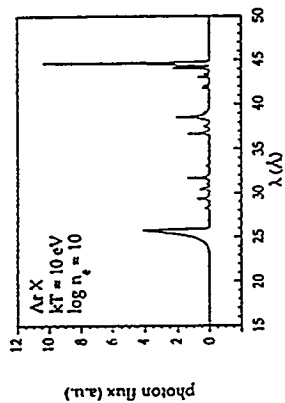
Different temperature dependences of RR and DR ($\Delta T = 0$) provide temperature diagnostics in L-shell ions. Shown here is the N-like Fe XX recombination spectrum, decomposed by process.



Mechanism providing density sensitivity in L-shell ions in X-ray photoionized plasmas

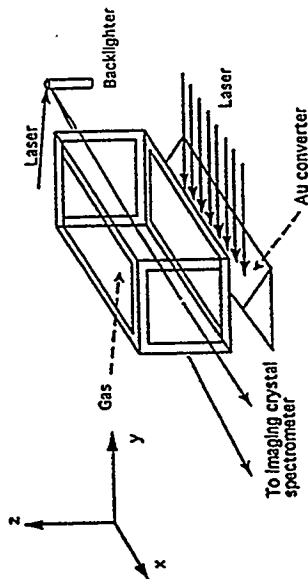


X-ray spectra of L-shell ions are sensitive to temperature and density. Shown here is Fe-like Ar X at two temperatures and two densities. Lines are from 3-2, 4-2, and 5-2 transitions. Features near 25 Å are radiative recombination continua, indicative of the low temperatures.

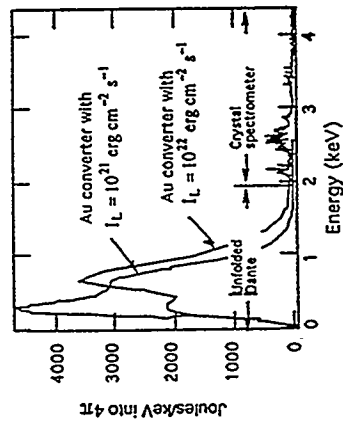


The gas cell experiment allows exceptional control over the target sample characteristics.

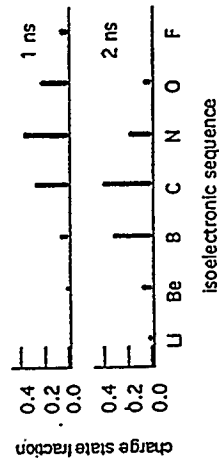
- Total ion density known *a priori*.
- Large range of ionization parameters are accessible
- Elemental mixtures
- No hydrodynamics



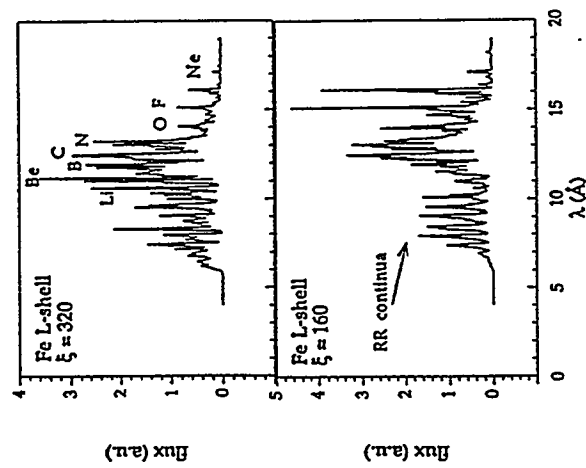
Gold converter spectra for two laser intensities (Carter *et al.* 1991).



The converter flux has sufficient ionizing X rays to drive Ar ($Z = 18$) into the L shell, as shown here in a LASNEX simulation of the charge state distribution vs. time.

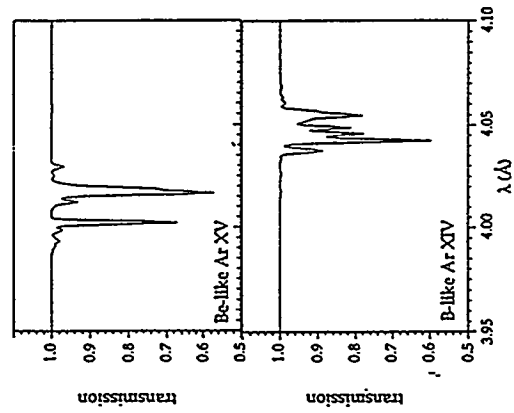


Ionization equilibrium in X-ray photoionized plasmas is characterized by the simultaneous presence of several charge states. Below is the Fe L-shell emission spectrum at two values of the ionization parameter, folded through the XMM ROS Instrument response. Some of the brighter lines are labeled by their isoelectronic sequence. (Charge state distribution from Kallman & McCray 1982.)

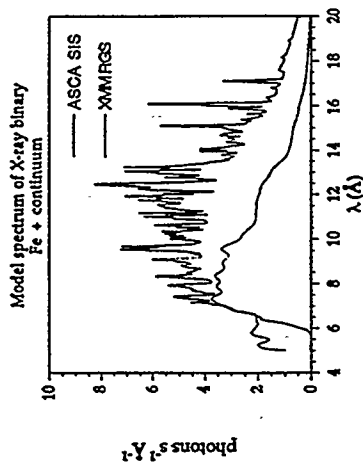


Presented at Workshop on Laboratory Astrophysics Experiments With Large Lasers 22/27th, Pleasanton, CA

Model transmission spectra for two Ar ions, with column density $N_{\text{col}} = 10^{16} \text{ cm}^{-2}$. Absorption structure results from K α transitions ($1s \rightarrow 2p$). Adjacent charge states throughout the L shell can be easily separated. Assumed resolving power $\lambda/\Delta\lambda = 2000$. Models generated with ILLUAC.



Future observations will allow high-resolution studies of accretion-powered X-ray sources. Shown here is a toy spectrum of a typical X-ray binary, convolved with the effective area and resolution of the ASCA Solid State Imaging Spectrometer (red) and the *XMM* Reflection Grating Spectrometer (blue). Spectral model includes Fe L-shell ions overlying a central continuum. Assumed interstellar column density is $N_H = 4 \times 10^{21} \text{ cm}^{-2}$.



Concluding Remarks

Availability of high-quality spectroscopic data from hundreds of extragalactic X-ray sources provides major challenge to nebular modeling and atomic modeling.

X-ray spectra formed in photoionized plasmas are relevant to active galactic nuclei, X-ray binaries, and cataclysmic variables. Taken together these objects comprise >40% of pointed observations.

X-ray drives currently available on Nova are sufficient to study K-shell and L-shell physics of low-to-intermediate Z elements.

Spectral diagnostics in this regime have never been tested in the laboratory.

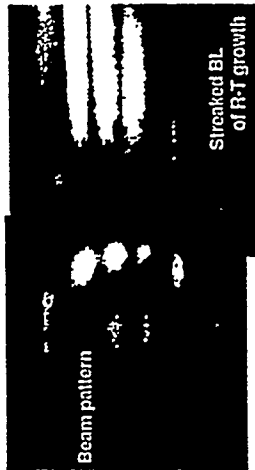
Effectiveness of point-projection backscatter technique has been demonstrated in other experiments.

Experiments on Nova can also help to lay the groundwork for larger scale experiments with NIF.

Hydrodynamic Instability Experiments at ILE

**Hiroshi Azechi
Osaka University**

Hydrodynamic Instability Experiments at ILE



H. Azechi, K. Shigemori, M. Nakai, N. Miyanaga, H. Shiraga, K. Meguro, R. Kodama, M. Honda, H. Takabe, K. Mima

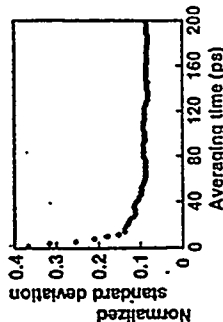


Institute of Laser Engineering, Osaka University

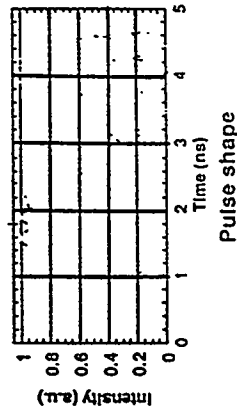
Experimentals

Targets were irradiated by fiber-generated partially-coherent light.

- Wavelength $\lambda = 0.53 \mu\text{m}$
- Bandwidth $\Delta\lambda = 0.2\text{nm}$ (x470 transform limit)
- Beam divergence $\Delta\theta = 1.31 \times 10^{-4} \text{ rad. (64TDL)}$
- Angular dispersion (1D) $\Delta\theta / \Delta\lambda = 478 \mu\text{rad. / nm}$
- Smoothing characteristics

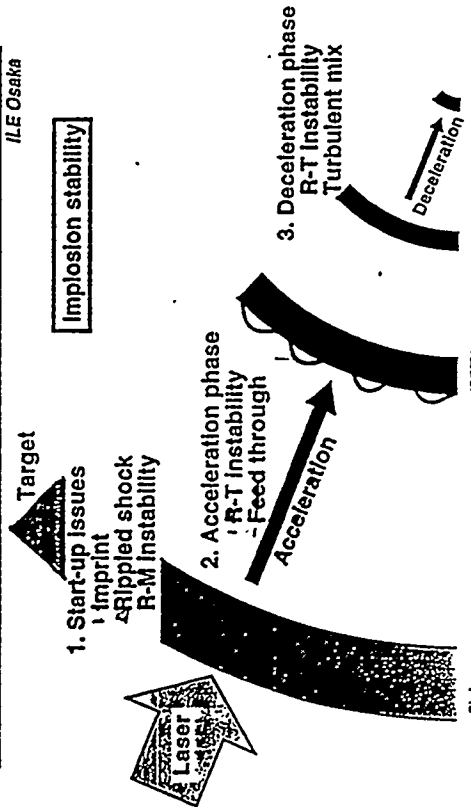


Time-integrated, beam pattern



Introduction

Perturbation growth before the first-shock breakout gives initial conditions to the following Rayleigh-Taylor instability



Experimental

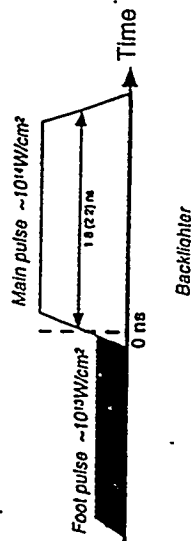
Experimental conditions on Rayleigh-Taylor / Imprint experiments

Target

Flat CH (polystyrene) $16 \mu\text{m}^1$
Initial perturbation (R-T experiment)
wavelength : $60 \mu\text{m}$
amplitude : 0.1, 0.3, 1 μm

Laser

PCL : flat top pulse (FWHM: 1.8 or 2.2 ns)
Intensity modulation (Imprint experiment)
wavelength (on target) : $100 \mu\text{m}$
amplitude ($\Delta I / I_0$) : 10%, 40%



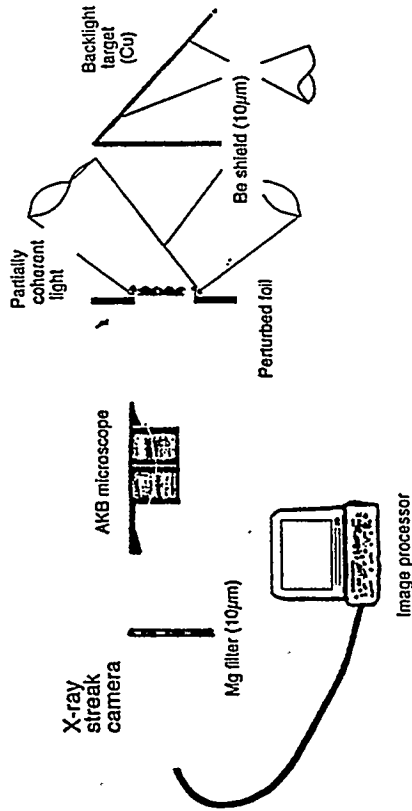
Fool pulse intensity was spatially modulated at the imprint experiment

Experimental

Perturbation growth was measured by face-on x-ray backlighting method.



ILE Osaka



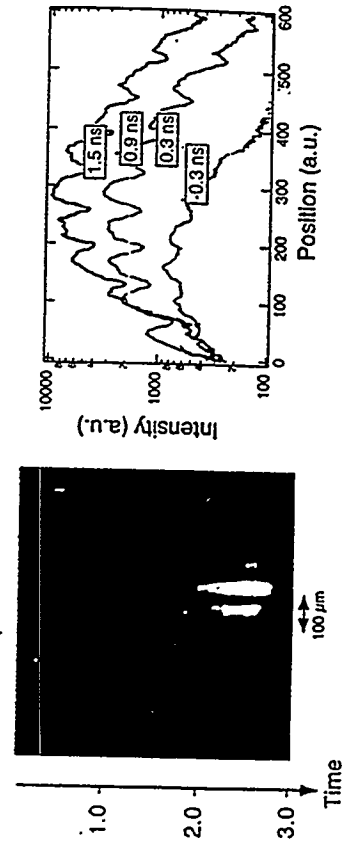
KS95A012 (APS)

Temporal evolution of backlit images due to R-T instability were obtained.



ILE Osaka

#17590 Initial amplitude : 1 μm

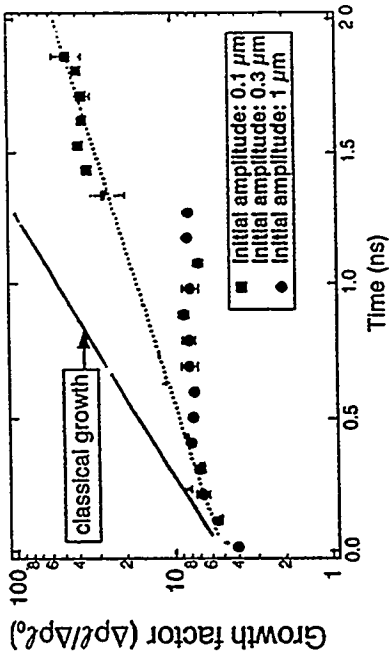


Results

Growth rate of R-T instability was evaluated from three target shots.



ILE Osaka

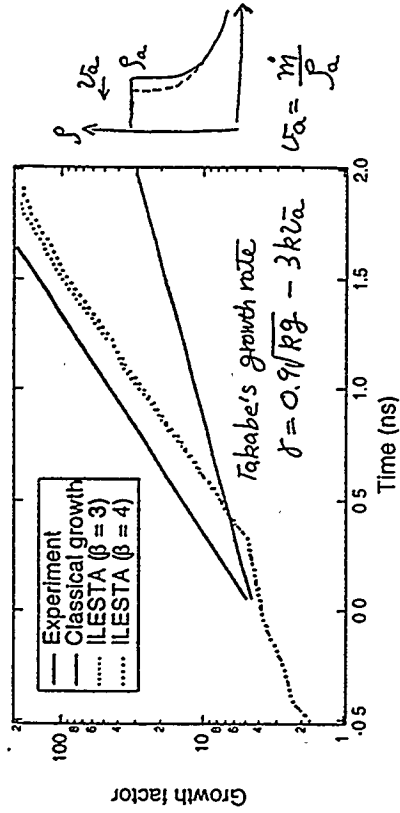


Simulation

Experimental results were compared to calculations by ILESTA 1-D simulation.



ILE Osaka

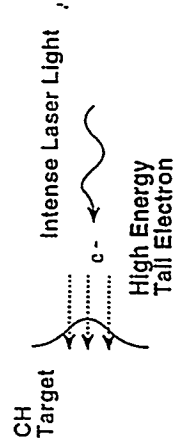


Fokker-Planck simulations show that target preheating due to nonlocal electron thermal transport suppresses Rayleigh-Taylor instability.



ILE Osaka

R-T Inst. is suppressed by precursor thermal wave?



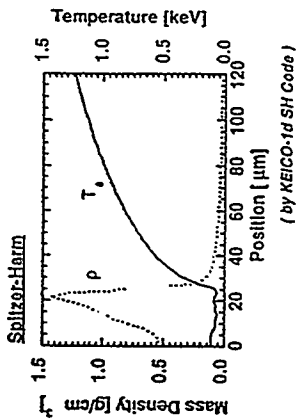
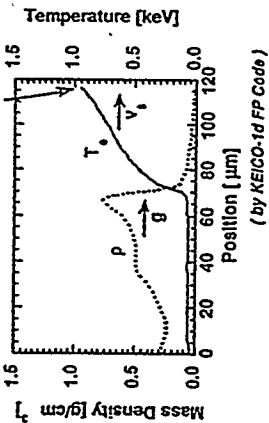
$$\ell_{\text{inf. p. ant. eff.}} \approx 180 \left(\frac{\lambda_{\text{nm}}}{0.53} \right)^{1/3} \left(\frac{I_{\text{W/cm}^2}}{10^{15}} \right)^{4/3}$$

R-T Insta. by FP 2d

Initial Temperature and Density Profiles for 2D Fokker-Planck Simulations

Target Thickness : 32 [micron]
Laser Intensity : 1×10^{14} [w/cm²]

$g = 4.56 \times 10^{-15}$ cm/sec²
Fokker-Planck
Chapmann-Jugel
Diffraction Point



ILE OSAKA

R-T Insta. by FP 2d

Preheating due to nonlocal electron heat transport suppresses the Rayleigh-Taylor instability

RESULTS :

$$\gamma_{\text{classical}} = 2.19 \times 10^{-9} \text{ [s]}$$

$$\gamma_{\text{SH}} = 2.04 \times 10^{-9} \text{ [s]}$$

$$\gamma_{\text{FP}} = 0.886 \times 10^{-9} \text{ [s]}$$

$$V_{\text{abl SH}} = (\rho v)_{\text{C-J}} / \rho_{\text{abl}}$$

$$= 2.17 \times 10^{-5} \text{ [cm/s]}$$

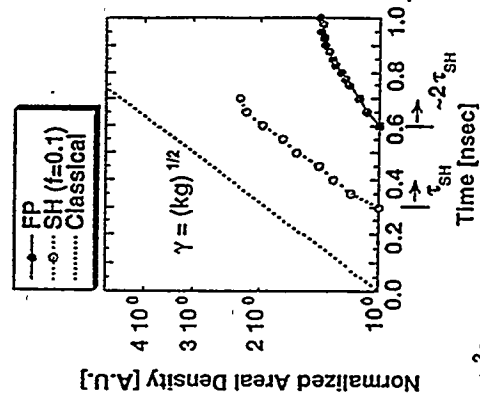
$$V_{\text{abl FP}} = 3.22 \times 10^{-5} \text{ [cm/s]}$$

$$\beta_{\text{SH}} = ?$$

$$\beta_{\text{FP}} = 3.51$$

for Wave Length : 60 micron,
Gravity Force : 4.56×10^{15} [cm/s²]

ILE OSAKA

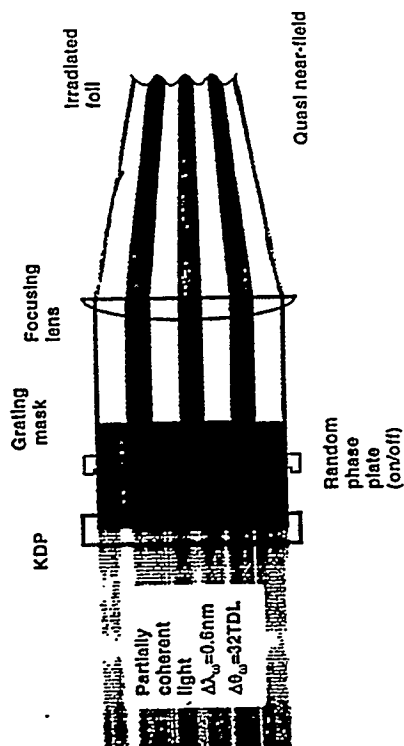


(by KEIOX 'Code)

Sinusoidal intensity modulation was imposed by a opaque grating mask



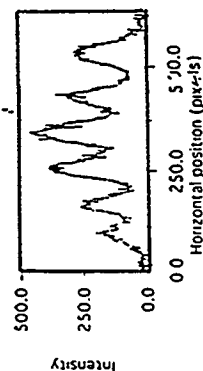
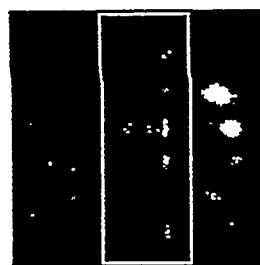
ILE Osaka



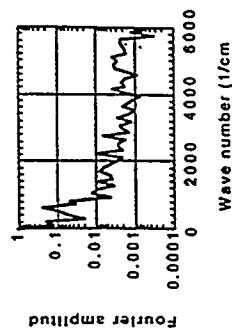
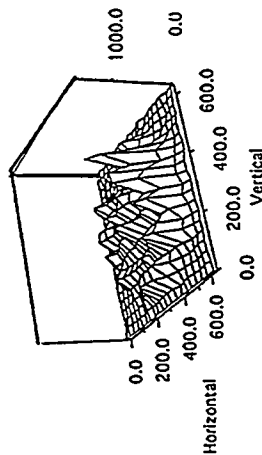
Intensity profile of the modulated prepulse on the target (without RPP)



ILE OSAKA



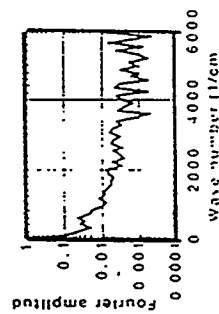
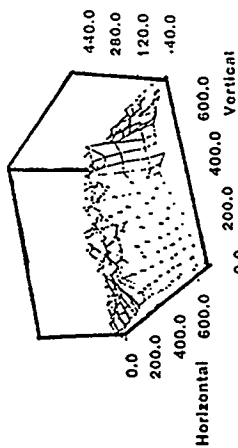
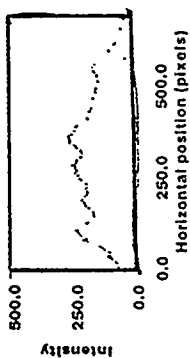
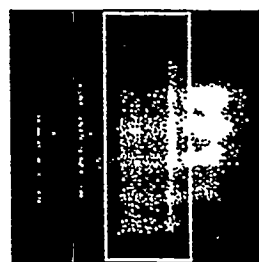
(Scale: 1 15 $\mu\text{m}/\text{pixel}$)



Intensity profile of the modulated prepulse on the target (with RPP)



ILE OSAKA



Areal density perturbation seeded by the initial imprinting increases with increasing imposed intensity modulation

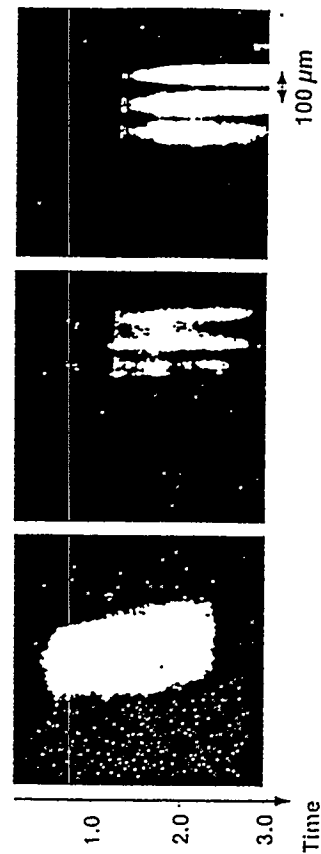


ILE OSAKA

#17596
 $\Delta I/I \sim 0\%$

#17562
 $\Delta I/I \sim 10\%$

#17560
 $\Delta I/I \sim 40\%$

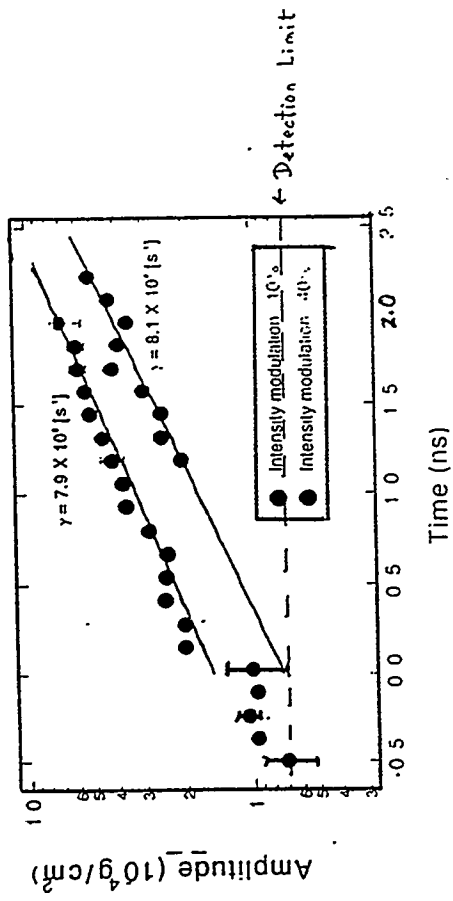


$\Delta I/I$: modulation amplitude

Initial Imprinting perturbation is amplified by Rayleigh-Taylor instability

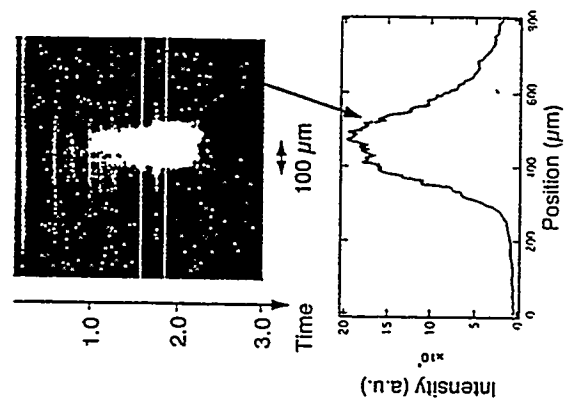


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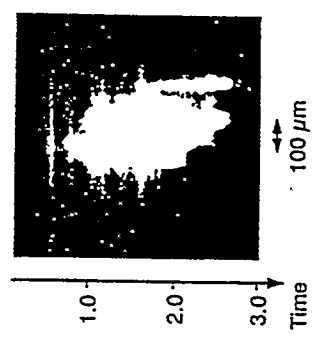


260

#17596 Intensity modulation
:-0% $\Delta\lambda = 6\text{\AA}$ 327DL



#17634 $\Delta\lambda : 3.5\text{\AA}$, 10TDL at ω_0

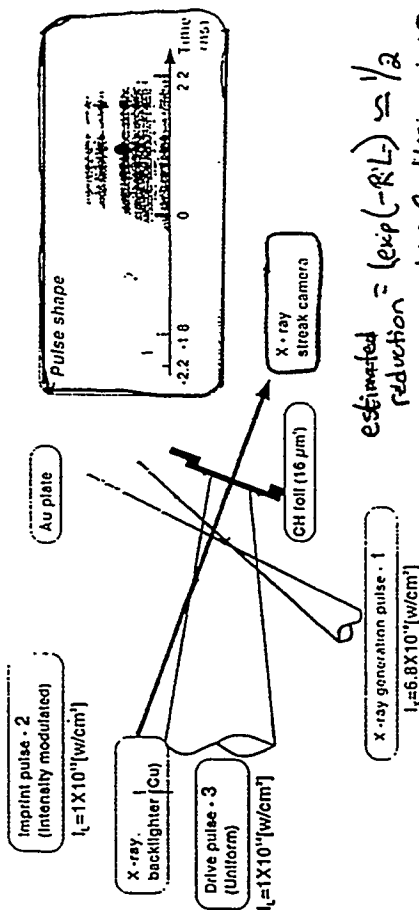


We used external x-ray source
to suppress the initial imprinting



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Top view



$$\text{estimated reduction} = \exp(-R/L) \approx 1/2$$

$$L \approx 400 \text{ ps} \approx 15 \mu\text{m}$$

$$R = 2\pi / 100 \mu\text{m}$$

Significant reduction of perturbation growth
due to x-ray pre-irradiation was observed
by face-on backlighting method



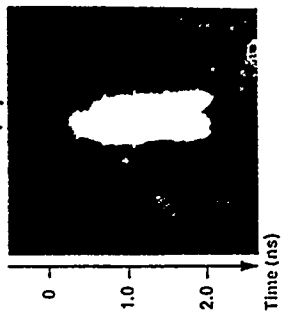
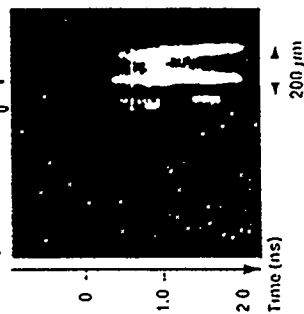
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S.N. J7562

S.N. J7562

Intensity modulation $\sim 10^{-3}$
Without x-ray pre-irradiation

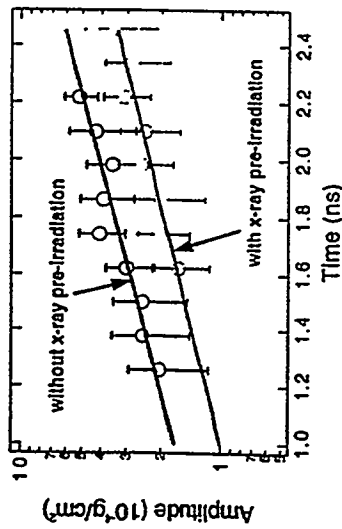
Intensity modulation $\sim 10^{-3}$
With x-ray pre-irradiation



Perturbation growth was reduced to 65%
of no x-ray pre-irradiation



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summary

A number of hydrodynamic perturbation growth crucial to ignition/burn has been clarified.

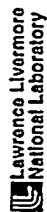
- **Ripple shock**
Finding of damped oscillation.
Areal-density-perturbations grow by a factor of ~4.
- **Initial imprinting**
First observation of single-mode Initial Imprinting.
~~First~~ observation of laser coherency dependence.
Initial imprinting is reduced by soft x-ray pre-irradiation.
- **Rayleigh-Taylor Instability**
~~First~~ observation of linear growth rate in direct-drive

**Spectroscopy of Compressed High Energy
Density Matter**

**Nigel Woolsey
Lawrence Livermore National Laboratory**

Spectroscopy of Compressed High Energy Density Matter

N. C. Woolsey, B. A. Hammel, C. J. Keane,
A. Asfaw, C. A. Back, S. Glenzer,
B. Talin, R. Stamm, L. Godbert, C. Mossé,
L. S. Klein, J. S. Wark,
R. W. Lee



Collaborations

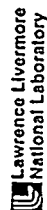
N. C. Woolsey, B. A. Hammel, A. Asfaw, C. A. Back,
S. Glenzer, D. Kalantar, C. Keane, J. Koch, J. Moreno
LLNL, University of California, P.O. Box 808, Livermore, CA 94551, USA

B. Talin, R. Stamm, L. Godbert, C. Mossé
PIIMA, Centre St. Jerome Université of Provence, Marseille, Cedex 20 France

L. S. Klein
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J.S. Wark
Clarendon Laboratory, Department of Physics, University of Oxford, Parks Rd, Oxford OX1 3PU, UK

R. W. Lee
Department of Physics, University of California, Berkeley, CA 94720, USA



Reasons to Develop Spectroscopy at High Energy Density

- Basic physics:
 - 1) Test physical models of the bound-bound and bound-free spectroscopy
 - 2) Investigate ion dynamic effects on the Ar XVII $1s^2-1s3p^1P$ emission line
- Radiation Transfer
- Reveals details of nature of the imploded core, e.g., gradients
- Applications
Mechanisms involved are the same as those in ignition targets

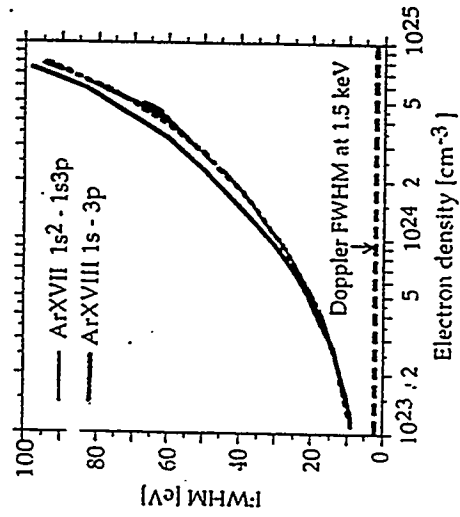
Three points will be emphasized

- FWHM of the Ar K-shell 1-3 lines are a robust N_e diagnostic
- Central region of the 1-3 lines are effected by ion-field fluctuations
- Dielectronic satellites of the 1-3 lines provide a T_e diagnostic

N_e Diagnostic

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The FWHM of the 1 - 3 k-shell transitions shows
it is a good density diagnostic



- Widths extracted from FLY
- Robust diagnostic since $N_e \propto FWHM^{2/3}$ (relatively independent of T_e)

Details of the shape of the ArXVII 1 - 3 transition
provide insight into the nature of the line formation

- The central part of the line could be affected by various effects
 - Density gradient in the implosion core
 - Optical depth effects
 - Au emission
 - Ion dynamics
 - Satellite line transitions
- To find the intrinsic line profile, test the effect of low versus high Z ion perturbations

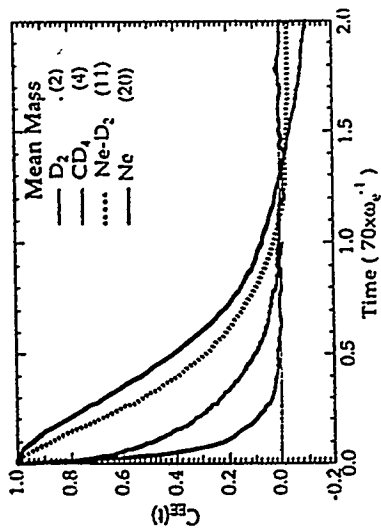
2.5 Ion Dynamics Effects

The ion dynamics can be investigated with
 different fill gases

- Investigate ion dynamics on the ArXVII $1s^2 - 1s3p$ 1P lineshape by varying the fill gas in the microsphere
- Keep N_e constant and try to ensure the hydrodynamics of the implosion is similar
- Fill gases:

D_2	-	50 atmospheres
CD_4	-	10 atmospheres
N_2	-	7 atmospheres
Ne	-	10 atmospheres
- Argon is introduced in trace amounts to ensure ArXVII 1-3 line remains optically thin and the argon does not effect the implosion
- Ion motion is greater for lighter ions
 - ion dynamics is most prominent for D_2

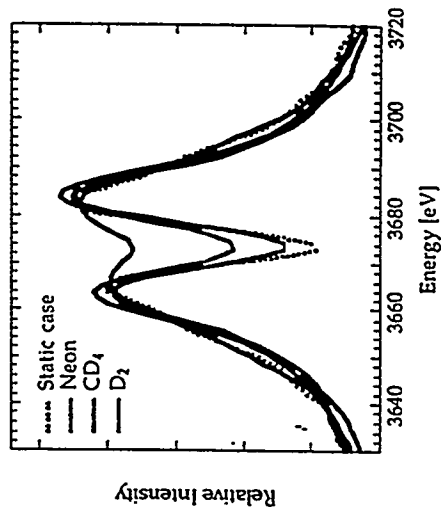
The electric field autocorrelation function is the key to ion dynamics



- $C_{EE}(t)$ for 4 gas fills at $N_e = 1.2 \times 10^{21} \text{ cm}^{-3}$ and $T_e = 1.55 \text{ keV}$
- By the fluctuation-dissipation theorem we can find, from the decay of $C_{EE}(t)$ ion microfield fluctuation rate ν

21-0

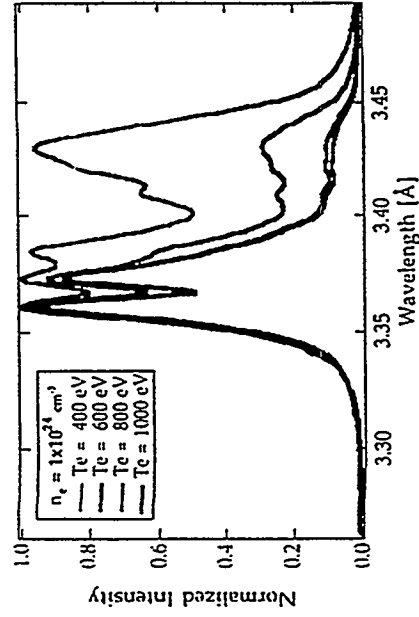
Ion dynamics alters the central part of the Ar XVII $1s^2 - 1s3p^1P$ lineshape -- but not FWHM!



- Central dip in the lineshape is significantly altered through ion dynamics. Different fill gases may enable the effect of ion motion to be determined

Dielectronic Satellites

Li-like satellites to the He-like resonance transitions effect the width of the resonance at low T_e .

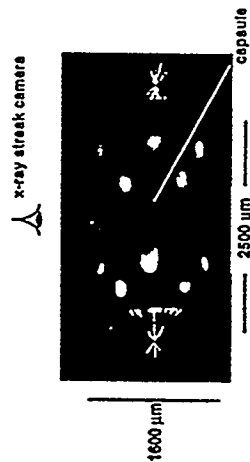


- Spectrum synthesis requires compatible kinetics and line shape calculations; atomic model contains all the $213l'$, $313l'$ and $314l'$ states
- At high T_e (< 1000 eV) satellites do not fill in the dip
- Shape and intensity of the Li-like Ar satellites to the He-like Ar 1-3 line provides a T_e diagnostic

ICF implosions provide extreme conditions. Illustrates diagnostics, ion dynamics, and large-scale calculations for line shapes

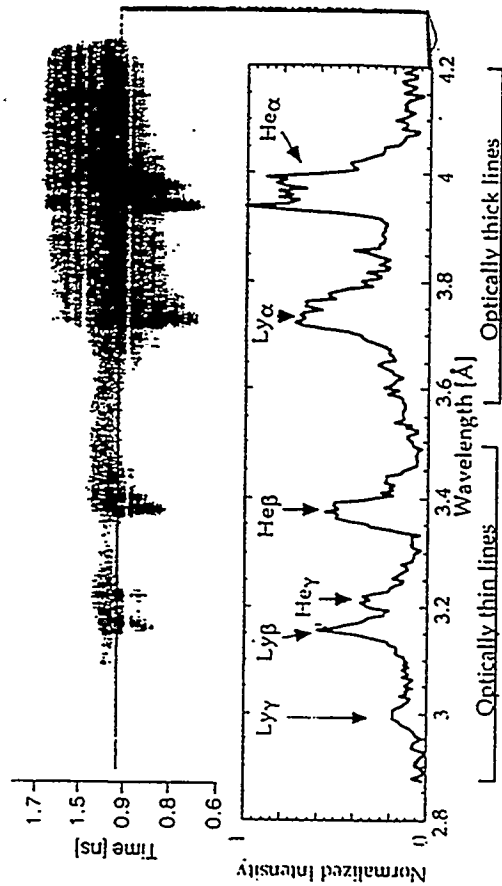
- Experiments are performed at Nova using laser produced x-rays to implode a plastic capsule filled with a test gas.

- Capsules are $\sim 270 \mu\text{m}$ radius, with 50 atm of D_2 and 0.1 atm of Ar
- Optical depth and emissivity of ArXVII 1 to 3 lines controlled
- Implosion compresses core plasma to high N_e & T_e , $\geq 10^{24} \text{ cm}^{-3}$ & 1 keV
- Time resolved imaging measures implosion core
- Spectroscopy performed with x-ray crystal coupled streak camera



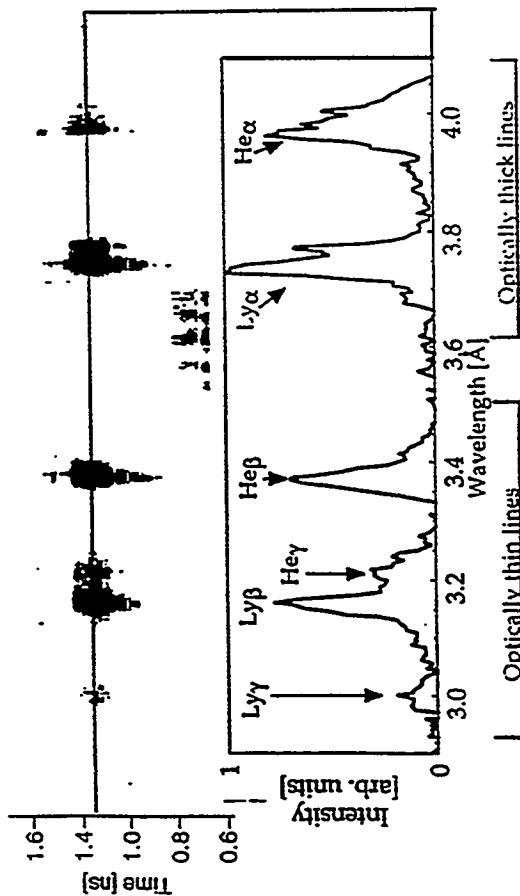
270

Argon emission spectrum from an imploding CD_4 filled capsule driven at 17 kJ



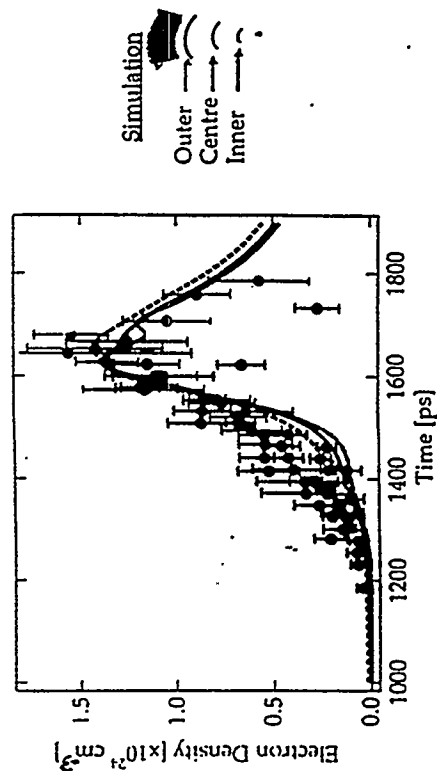
note: dip in ArXVII 1-3 is not observed

Argon emission spectrum from an imploding D₂ filled capsule driven at 17 kJ



14

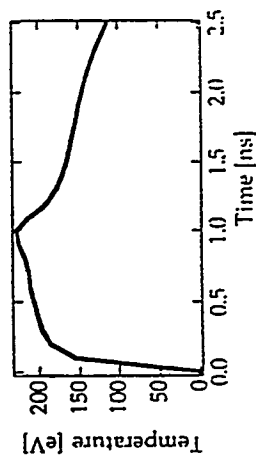
Ne(t) determined using the ArXVII 1s²-1s3p
emission from an imploding D₂ microsphere



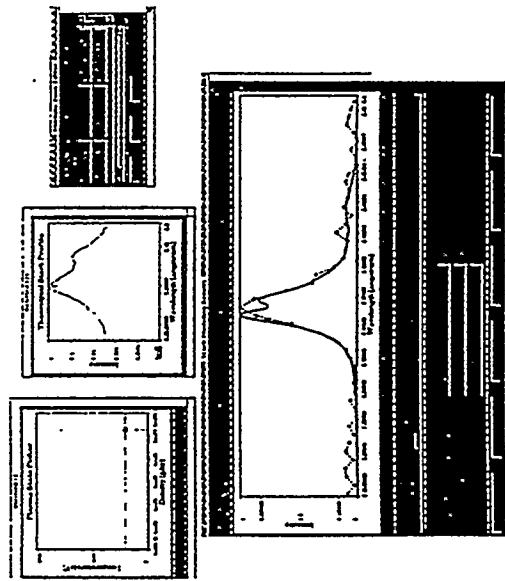
• 4 shots at ~19 kJ are represented
HYADES simulation using a 16 kJ Planckian drive

Radiation-hydrodynamic simulations are used to understand the details of these implosions

- HYADES 1-D radiation hydrodynamics code
- SESAME EOS of state library
- Average atom atomic physics
- Multigroup radiation transport
- The radiation drive we used in the simulations is a Planckian source measured from a $2500\text{ }\mu\text{m} \times 1600\text{ }\mu\text{m}$ diameter hohlraum irradiated with 16 kJ in a 1 ns temporally square laser pulse

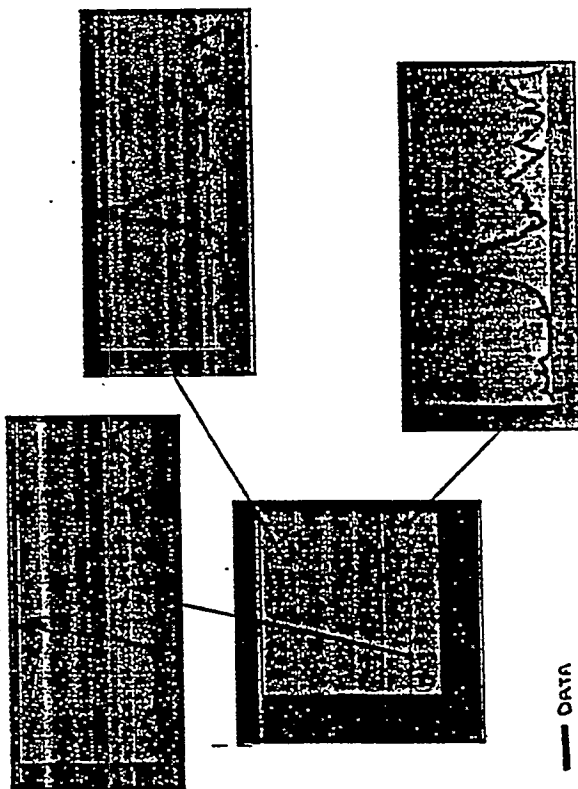


Interactive database / analysis software aids ArXVII n_e and T_e modelling



- Modelling software written by J. K. Nash
- Data base generated using TOTAL by J. C. Moreau

An interactive, database - driven application
simplifies data analysis for Ar XII He / Te diagnostics



Summary: Density Diagnostics

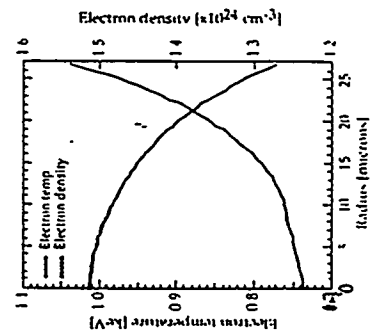
- ArXVII 1s²-1s3p¹P is a T_e , N_e diagnostic for hot dense systems
- Implosion cores provide a testbed for hydrodynamic simulations
- Implosion cores provide a testbed for theoretical lineshapes
- Implosion cores provide an excellent test of complex kinetics

Summary: Experiments

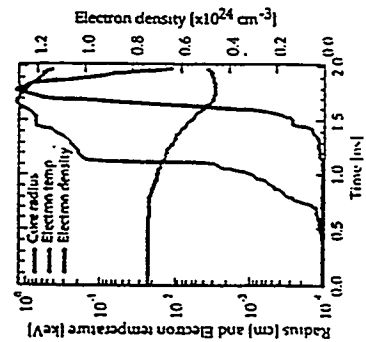
- Spectroscopic measurements have been made of indirectly driven implosions
- Dip in the ArXVII 1 - 3 with D_2 , CD_4 , and N_2 fills not observed
- The absence of the dip may be due to N_e , T_e gradients in core.
 - This is supported by hydro-simulations
- Argon emission spectra not observed with neon filled targets
 - Predicted due to mismatch of T_e and N_e peaks
- $N_e(t)$ a test of hydrodynamics is determined from line widths
- Time histories are reproducible

Simulations of an imploding D_2 microsphere

Time history of the outer core radius cell and central core T_e and N_e



Spatial density and temperature profiles at peak density



**Ultra-Short Pulse Laser for High
Energy-Density Science**

**Richard More
Lawrence Livermore National Laboratory**



Experiment:

R. Stewart
D. Gold
G. Guethlein
D. Price
R. Shepherd
B. Young

Theory:

R. More
E. Alley
M. Foord
A. Osterheld
R. Walling
(Z. Zinamon)

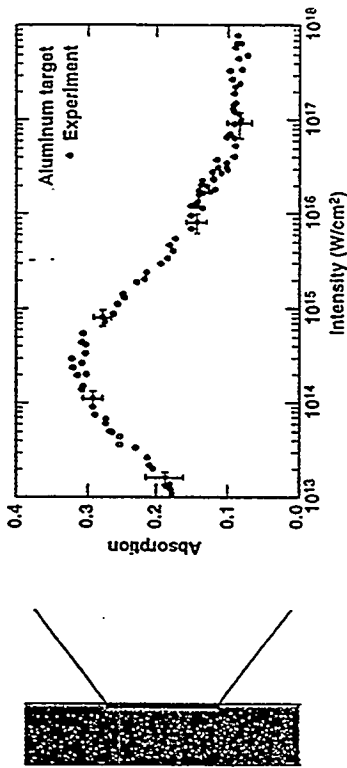
From the beginning, the LLNL USP Laser
was aimed at *High Energy-Density Science*

- Chirped-pulse amplification, recompression, harmonic conversion produce

0.3 Joules of 400 nm light in 100 fs
Prepulse intensity kept below 10^{-9}

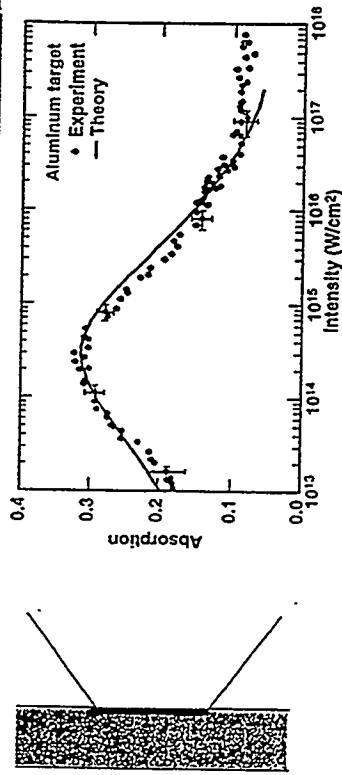
- Diagnostics from LLNL test program
 - Reflected, scattered and transmitted light
 - Hydro expansion at small distance
 - Hydro expansion at large distance
 - Time-resolved x-ray emission
 - X-ray absorption
- Close contact with theory

Absorption is a first question—
we measure it carefully



- Low prepulse
- Always irradiate fresh target material
- Measure pulse autocorrelation and spatial profile
- Measure incident, reflected and scattered energies

We understand the absorption



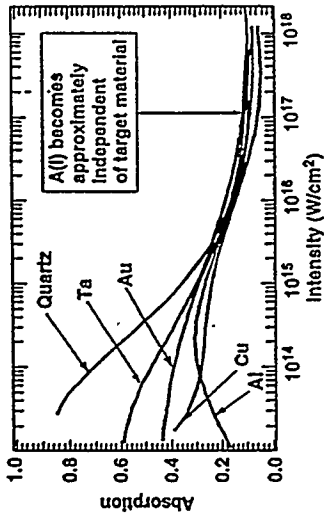
LASNEX MODEL

- Gaussian beam profile
- Realistic time-history
- Maxwell equations with correct AC conductivity
- 2T EOS and conductivity
- Hydrodynamic expansion
- Nominal heat flow

This excellent agreement is obtained for aluminum targets

Absorption depends on the target material

At high intensity, observe *Universal Plasma Mirror* reflection



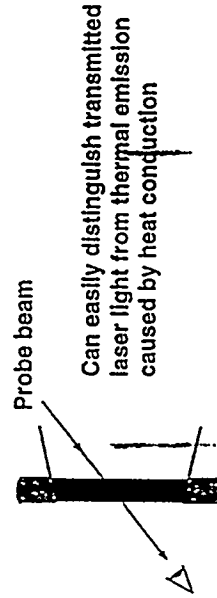
Low Intensities:

- Conduction electron inverse bremsstrahlung
- Intra-atomic line absorption (interband transitions)

High Intensities:

- Free electron/ion inverse bremsstrahlung
- Novel mechanisms above about $10^{18} \text{ Watts/cm}^2$

We can test our understanding of absorption by future experiments on thin targets



Electromagnetic skin depth $\delta = c / \sqrt{4\pi Z^* n} e^2 / m$

Penetration is proportional to $\exp(-x/\delta)$

Transmission measurements will give us a direct measure of the ionization state $Z^*(T)$

EOS is the linkage of thermodynamic variables specific to a given material

Thermodynamic variables:

$$\rho, T, p, E, S$$

Thermodynamic functions which define an EOS:

$$F(\rho, T), E(\rho, S), G(p, T), H(p, S)$$

— must know these in a 2-D region to form the derivatives...e.g.,

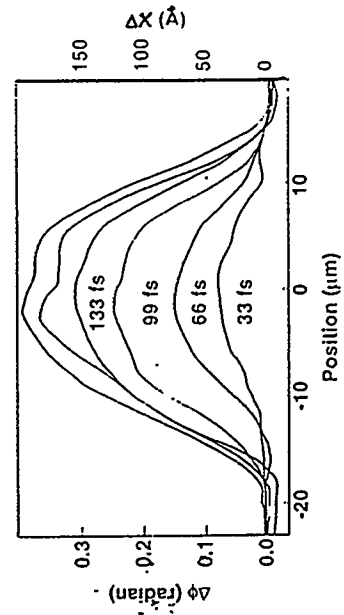
$$p = \rho^2 \frac{\partial F}{\partial \rho} \quad S = \frac{\partial F}{\partial T}$$

Incomplete or partial EOS:

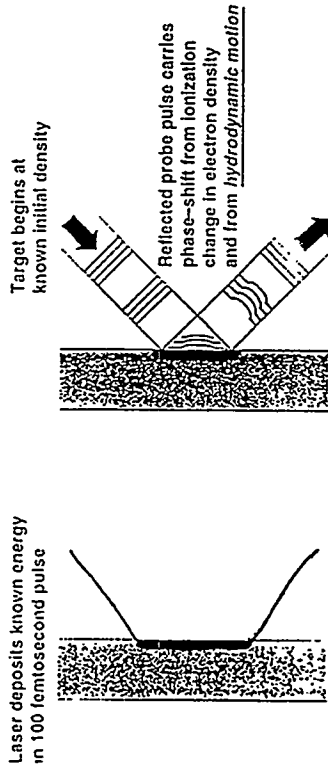
$$p(\rho, T), E(\rho, T), p(\rho, T)$$

Variation of the phase with time in Aluminium

Gauthier et al., Ecole Polytechnique



An Important Goal: to measure EOS using the USP Laser

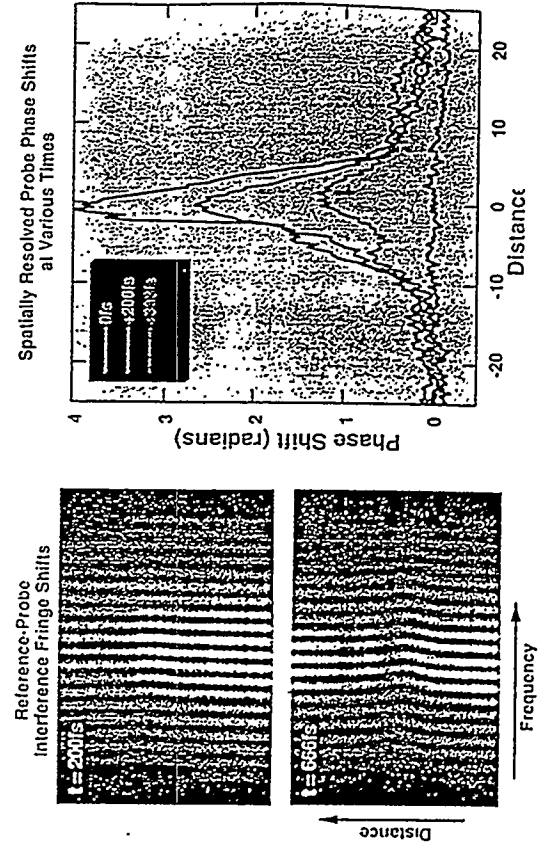


Analysis of spectroscopic Interferometry:

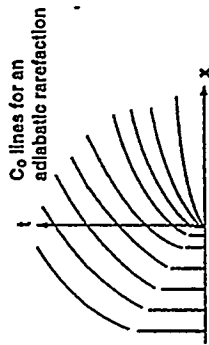
- Measure phase shifts at various delays
- Separate ionization effect from hydrodynamic effect
- Determine expansion velocity vs time delay
- Extrapolate to early times

Frequency-Domain Interferometry

Accurate measurement of short pulse plasma expansion with femtosecond time resolution has been demonstrated.



Ideal gas release velocity is 3 times the sound speed



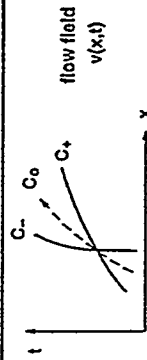
γ -law gas has $p \propto \rho^\gamma$ and $V(\infty) = \frac{2c}{\gamma-1}$

In fact, $v(x,t) + \frac{2c(x,t)}{\gamma-1} = \text{constant}$

Can these equations be generalized to an arbitrary equation of state?

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Expansion velocity is related to $dp/d\rho$ for arbitrary EOS



$C_0 = \text{particle track}$ $\frac{dx}{dt} = v(x,t)$

$C_{\pm} = \text{sound wave path}$ $\frac{dx}{dt} = v(x,t) \pm c(x,t)$

Theorem (Bernhard Riemann):

$$J_{\pm}(x,t) = v(x,t) \pm \int \frac{1}{c} \frac{dp}{\rho}$$

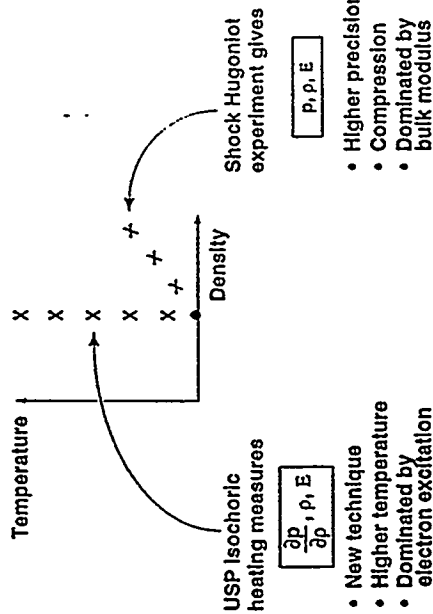
Is constant along $C_{\pm}$ path

$$c^2 = \frac{dp}{d\rho}$$

Application:

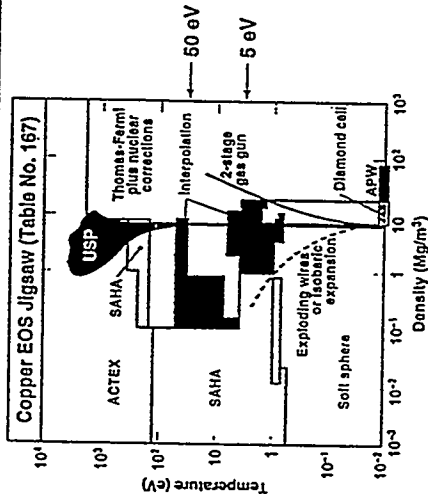
- Know Initial value of $J_{\pm}(x, 0)$
- Measure $v(x,t)$ from phase-shift data
- Then determine EOS integral by subtraction.

The EOS information is very much like that given by shock-wave experiments



Neither technique gives a complete equation of state, but the measured numbers serve to test theoretical EOS models

USP experiments can test EOS where it is most uncertain



- No complete or conclusive theory (quantum + many-atom + disorder)
- No quantitative experiments (especially not above 10 eV temperature)
- Previous "high-quality" data-bases handled this region by Interpolation

Do USP targets reach LTE in 100 fsec?

For this question we use codes and analytic formulas

- We expect to find

$$T_{\text{rad}} \ll T_{\text{ion}} \ll T_e$$

- Radiation is only a small part of the energy at conditions of our EOS experiments.
- Ion EOS can be 10% of the total, but only 1/2 of that is due to interactions and only about 1/4 (i.e., 2%) is uncertain
- However when $T_{\text{ion}} \ll T_e$, the ion contribution is much less

$$p = \frac{Z^2 k T_e}{V} + \frac{k T_i}{V} + \text{Ion Gr\"unisen part}$$

electrons 90%
ideal 5%
ion Interactions 5%

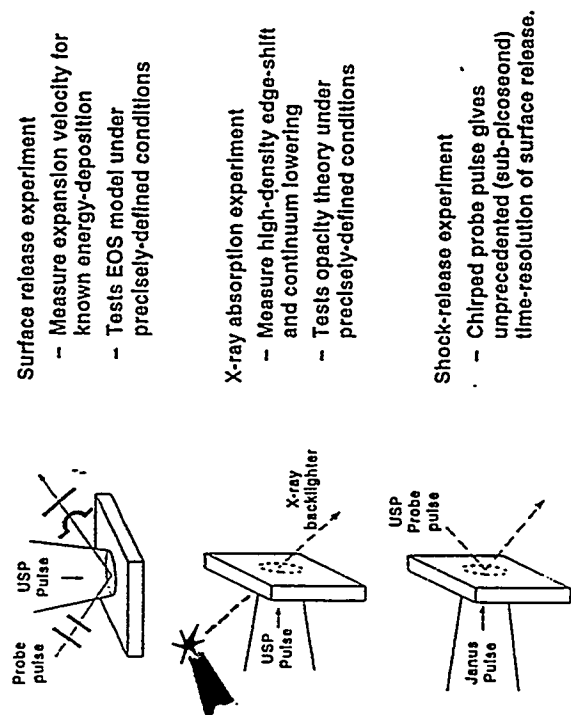
Are USP targets close enough to LTE to provide meaningful equation of state data? Evidently so, in the range where the EOS is most uncertain

- Electron-electron collision times are short enough that free electrons have an equilibrium (Maxwellian or Fermi-Dirac) distribution.
(Typically τ_{ee} is 1 fsec)
- Impact ionization rates are large enough to ionize all but inner shell electrons in 10-20 fsec at 100 eV temperatures. Stepwise ionization leads to a steady-state. At solid density, impact ionization and three-body recombination are more rapid than radiative processes, producing approximately LTE populations.
- Numerical calculations agree.
New X-ray spectra look like LTE emission.

How can we determine the temperature?

- X-ray emission spectrum
- Absorption of optical probe (Ng et al., UBC)
- Optical emission for known emissivity
- Ion velocities in TOF spectrum (Guethlein and Foord, LLNL)
- Emitted electron spectrum (Downer, U. Texas, Austin)
- Thin target calorimetry with known absorption

Near-term USP experiments test key physics of high energy-density



**Femtosecond-Laser Driven Heat Waves
in Solid**

**Andrew Ng
University of British Columbia**

FEMTOSECOND-LASER DRIVEN HEAT WAVES IN SOLID

- Inspired by the experiment of Vu *et al.*, Phys. Rev. Lett. (1994)

Andrew Ng, Andrew Forsman
University of British Columbia, Canada

Peter Celliers

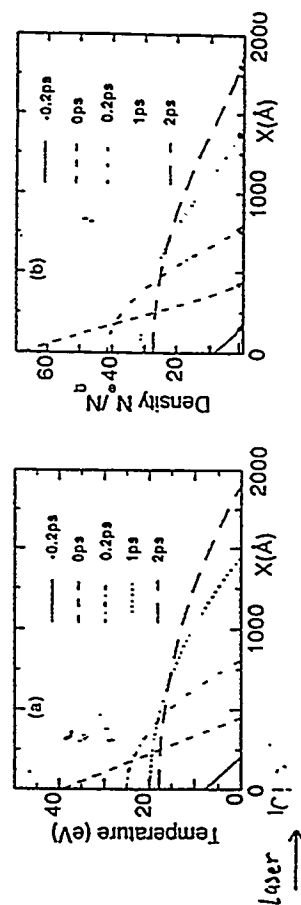
Lawrence Livermore National Laboratory, U.S.A.

- 1-D hydrodynamic simulation
 - Examine roles of laser deposition, thermal conduction and hydrodynamics

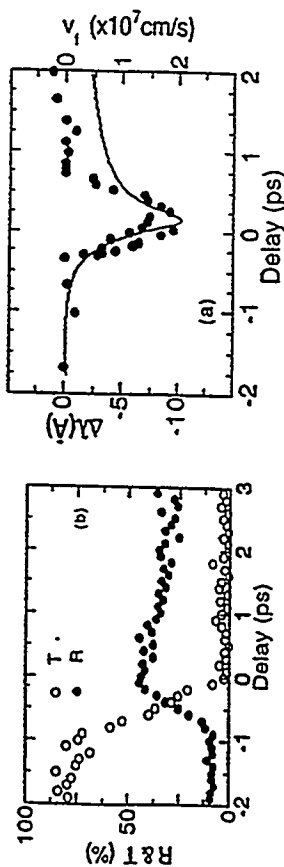
PROBING THERMAL CONDUCTIVITY OF DENSE PLASMAS

UNC

- Propagation of heat front governed by thermal conductivity
- Experiment of Vu, Szoke and Landen [PRL 72, 3823 (1994)]
 - Glass target with top layer of 300 Å carbon irradiated with 100 fs, 616 nm pulse at 5×10^{14} W/cm²
 - Laser deposition in carbon leads to heating of carbon-glass interface
 - Thermal conduction drives an ionization front into the glass



- Ionization front probed by 100 fs pulse at different time delays through target rear side
- Doppler shift in reflected probe pulse yields velocity of heat front
- Results in agreement with diffusion calculations using Spitzer conductivity



Difficulties with the study

- Experimental issues
 - Initial transmission of pump laser into glass due to finite opacity of 300 Å carbon
 - Plasma formation at extremely early times (~ 1 ps) of pump pulse at $\sim 10^9$ W/cm² might cause decoupling of laser from carbon-glass interface
 - Laser deposition at interface leads to laser heating of glass
- Modelling issues
 - Ionization in glass given by Saha equilibrium did not account for interband transitions
 - Laser deposition in carbon or glass, and plasma hydrodynamics not treated in thermal diffusion model
 - Use of Spitzer-type thermal conductivity might not be valid for dense plasmas

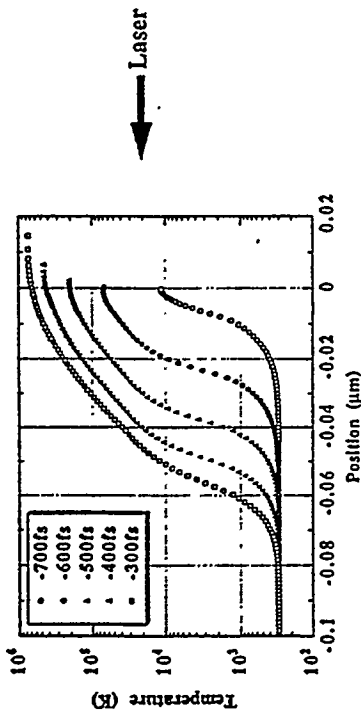
MODELLING OF LASER-DRIVEN HEAT FRONT

- Attempt to understand the phenomenon in a simple metal
- 1-dimensional hydrodynamic code
 - Laser-matter interactions treated with an EM wave solver (Helmholtz equations and dielectric function description)
 - Normal incidence for probing high densities
 - Examine effects of plasma conductivities on heat front propagation
 - Radiation transport, non-equilibrium effects of temperature and ionization not treated
- Aluminum irradiated with laser radiation of 400 nm, 100 - 500 fs (FWHM) at 10^{13} - 10^{15} W/cm² show similar features
 - EOS and conductivity data available for aluminum
 - Present 500 fs case for plausible time-resolved measurements

SNAP-SHOTS OF HEAT FRONTS AT EARLY TIMES

UBC

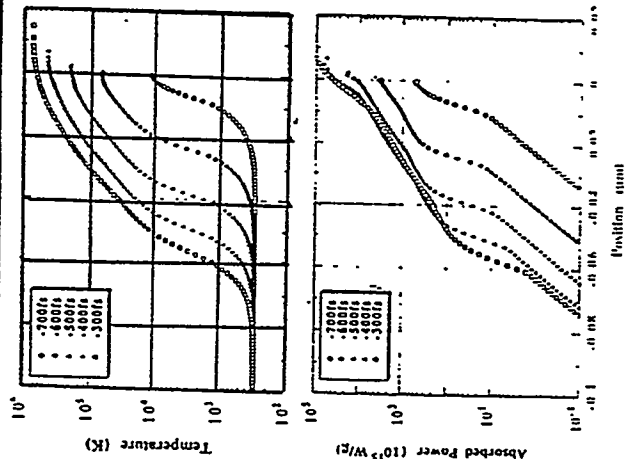
- Aluminum irradiated with 400 nm, 500 fs laser at 10^{15} W/cm² QEOS; Lee & More conductivities; screened hydrogenic model
- Laser peak at $t = 0$; initial target front surface at $x = 0$



Dominated by laser penetration process

Temperature and laser absorption profiles

UBC



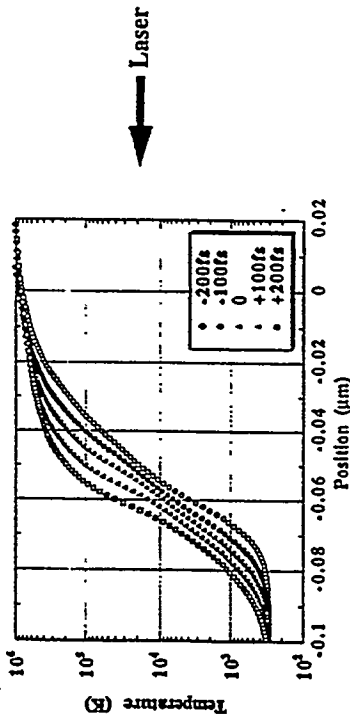
- At very early times, the heat front appears to move at similar speed as deposition front

SNAP-SHOTS OF HEAT FRONTS NEAR PEAK INTENSITY

UBC

- Aluminum irradiated with 400 nm, 500 fs laser at 10^{15} W/cm²
- QEOS; Lee & More conductivities; screened hydrogenic model

- Laser peak at $t = 0$; Initial target front surface at $x = 0$

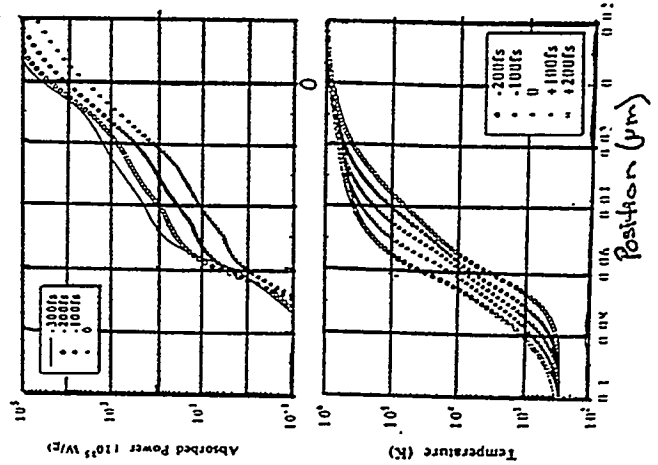


Steepening of temperature profile by nonlinear heat flow

Decoupling of laser deposition from heat front

UBC

- As an expanding plasma forms, laser deposition begins to decouple from heat front
- As temperature rises, non-linear thermal conduction leads to steepening of heat front

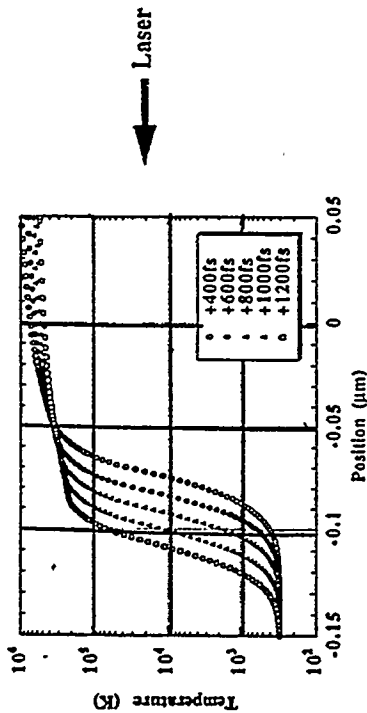


SNAP-SHOTS OF HEAT FRONTS AT LATE TIMES

UBC

- Aluminum irradiated with 400 nm, 500 fs laser at 10^{15} W/cm² QEOS; Lee & More conductivities; screened hydrogenic model

- Laser peak at $t = 0$; Initial target front surface at $x = 0$

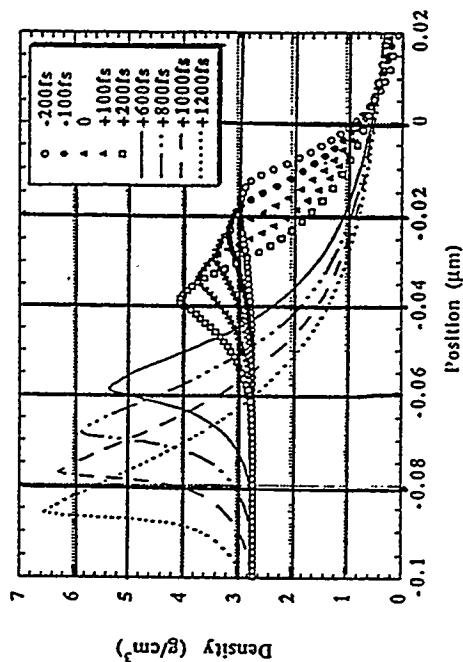


Plasma hydrodynamics producing shock waves

DEVELOPMENT OF SHOCK WAVES

UBC

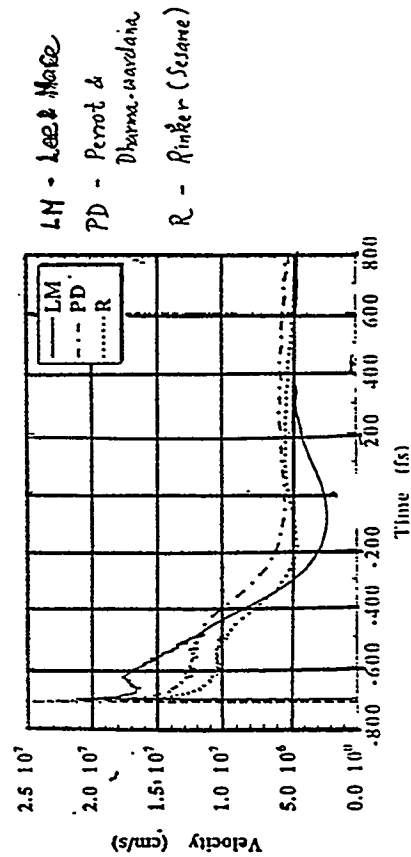
- Significant compression occurs only after end of laser pulse



VELOCITY OF HEAT FRONT

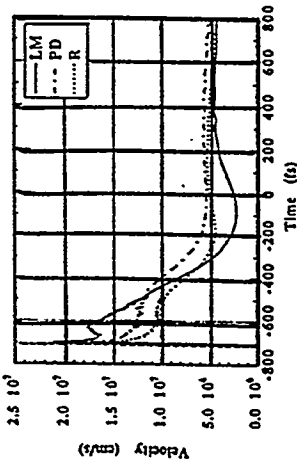
UBC

- Consider the 10^4 K (sufficient to produce critical electron density in a solid) point on heat front for different conductivity models
 - At early times, velocity spike exceeding 10^7 cm/s
 - Before peak intensity, increase in velocity after minimum
 - At late times, steady but lower velocities

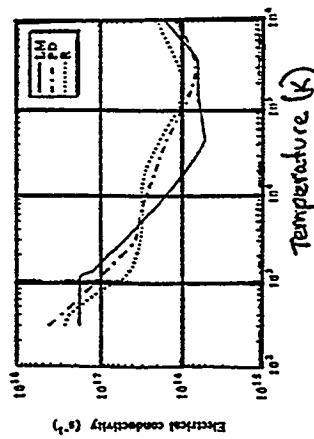


10⁴ K heat front speed and electrical conductivity

UBC.

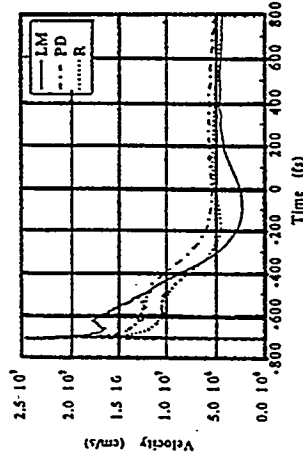


- At very early times, models with lower electrical conductivity allow deeper penetration of laser as an evanescent wave, leading to higher heat front speeds

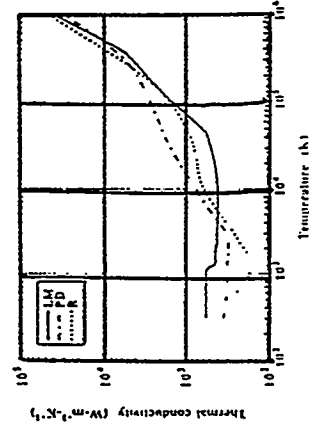


10⁴ K heat front speed and thermal conductivity

UBC



- When thermal conduction dominates, models with lower thermal conductivity yield slower heat front speeds



Conclusions on fs-laser driven heat waves

UBC

- Heat fronts produced in fs-laser heated solids characterized by three phases

- Skin-depth deposition
- Thermal conduction
- Shock compression

- The high velocity ($>10^7$ cm/s) observed by Vu et al. might be due to laser penetration and not a measure of thermal conduction
- Caveat : glass might behave very differently from aluminum

- Accurate measurements of heat front velocity may allow a complete test of models in electrical and thermal conductivities
- New diagnostics required to provide sufficient sensitivity, accuracy and temporal resolution

- Details described in Phys. Rev. E. 51, R5208 (1995)

Asteroseismology of White Dwarf Stars

Paul Bradley
Los Alamos National Laboratory

by

Presented at
 "Laboratory Astrophysics Experiments
 With Large Lasers"
 Workshop held at Lawrence Livermore National Laboratory
 Feb. 26-27, 1996

1. Physics Regimes
2. Introduction and Motivation
3. Seismological Results
4. Astrophysical Implications
5. Comparison to Laser Plasmas



What Are White Dwarfs?

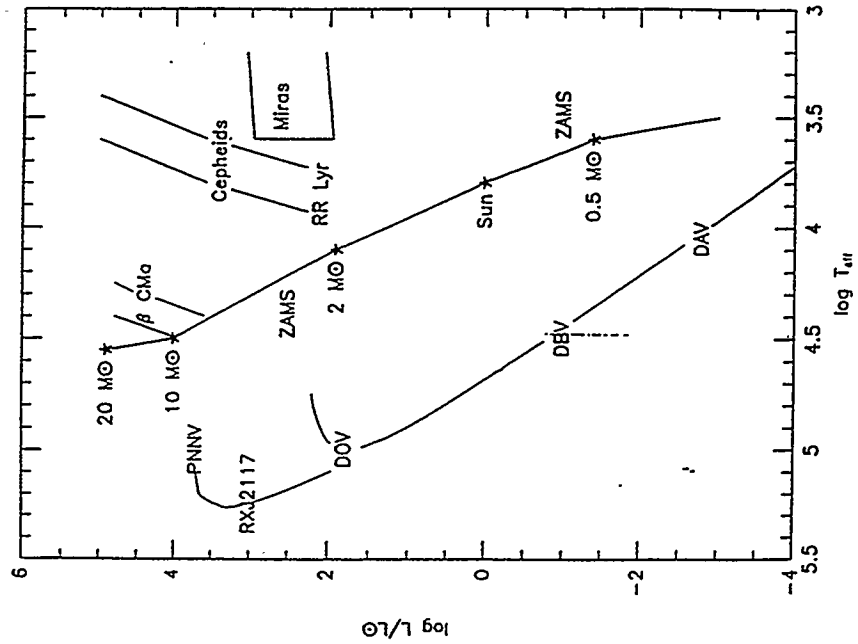
• General Properties

1. White dwarfs are the end result of stellar evolution for most stars. ($M_* \sim 1M_\odot$ to $5 - 8M_\odot$)
2. The average mass for planetary nebulae, PG1159 stars, and white dwarfs is $0.5 - 0.6M_\odot$ (Weidemann 1990; Bergeron, Safer, & Liebert 1992; Werner 1992; Bergeron et al. 1995).
3. We believe the internal structure consists of a C/O core overlain by a thin surface layer. The composition of the surface layer and effective temperature determines what we call it.

PG1159 stars are pre-white dwarfs. We see helium, carbon, and oxygen in their spectra and occasionally nitrogen is also present (see Driezler et al. 1995). The surface temperatures ($\geq 100,000\text{K}$) are too hot for hydrogen lines to appear in their spectra.

DB white dwarfs have a modest helium layer at the surface and we only see lines of helium in their spectra.

DA white dwarfs have only hydrogen lines in their spectra as a result of the thin hydrogen layer at the surface. The helium layer lies underneath due to gravitational settling because $\log g \sim 8$.



• Pulsators

1. All 3 white dwarf classes mentioned above have a function of their members pulsating in nonradial g -modes. They are called DOV stars in the PG1159 domain, DBV stars in the DB region, and DAV stars in the DA region.
2. Pulsation driving comes from the α , γ mechanism (heavily modified by convection/pulsation interactions) operating in the partial ionization zone (Winget 1981; Winget et al. 1982; Starrfield et al. 1983, 1984; Bradley & Dzielonowski 1996). The different ionization potentials of the dominant element are responsible for the location of the instability strips.
3. The observed light variations are due to changes in the surface temperature distribution (Robinson, Kepler, & Nather 1982).
4. Various studies suggest the pulsators are otherwise normal white dwarfs that happen to be passing through an instability strip (Fontaine et al. 1985; Bergeron et al. 1995). What we learn about the pulsators should apply to white dwarfs in general.
5. To resolve their complicated light curves into individual pulsation modes, we use multi-site observing campaigns with the Whole Earth Telescope.
6. The multi-site nature of the Whole Earth Telescope allows us to minimize confusion in our data analysis due to daily gaps in the data one gets from sunrises at a single site.

Why Mess With White Dwarf Stars?

- The strong gravity of white dwarfs gives them a relatively simple "onion" structure.
- We do not have complicating effects like nuclear burning, heavy element (metal) enhancement, rapid rotation, or strong magnetic fields in most white dwarfs.
- The work of Bradley & Winget (1994) for GD 358 and Knauer & Bradley (1994) for PG 1159-035 show that detailed seismology of white dwarfs is possible.

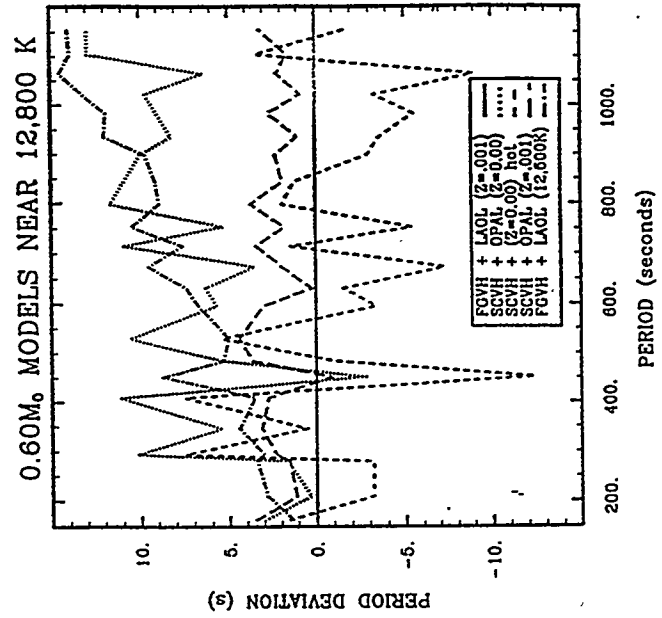
White dwarf seismology can help us with the following:

1. We can determine the total stellar mass, surface layer mass, depth and steepness of the chemical composition gradients, along with rotation rates and/or magnetic field strengths.
2. We can learn more about the properties of matter under extremes of density and temperature. This will help us with problems in the Equation-of-State (EOS), conductive+radiative opacities, viscosities, neutrino emission, and convection.
3. We can constrain the previous phases of stellar evolution in terms of what kind of progenitor gives rise to a particular class of white dwarf.
4. We can probe the previous history of star formation in the Galactic Disk and—eventually—the Halo.

Evolutionary Models

1. I use the White Dwarf Evolution Code (Lamb 1974; Lamb & Van Horn 1975; Wood 1990) to construct models of cooling white dwarfs
2. I do not include nuclear burnings, but do include neutrino emission by dense matter (Itoh et al. 1996).
3. In my older models, I use the H, He, C, and O EOS for dense plasmas computed by Fontaine, Graboske, & Van Horn (1977) along with the Lamb (1974) C and O EOS for the strongly coupled plasma in the core.
4. I recently incorporated the OPAL opacities into WDEC, and use the conductive opacities of Itoh et al. (1983, 1984).
5. I also incorporated the new H and He EOS of Saumon, Chabrier, & Van Horn (1995). For now, I recast them onto a ρ, T grid for computational convenience.

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DBV stars: • The helium layer masses of GD 358 is $2 \times 10^{-4} M_{\odot}$, and our limit for PG 1115+158 is $M_{He} \leq 10^{-4} M_{\odot}$.

- These are thinner than expected from stellar evolution theory ($M_{He} \leq 10^{-2} M_{\odot}$).
- However, Dehner & Kawaler (1995) show that if one allows diffusion to modify the composition profile of PG 1159-035, the main He/C composition transition occurs at $\sim 2 \times 10^{-6} M_{\odot}$, consistent with what we see for GD 358.

- The total amount of helium in Dehner & Kawaler's models is about $6 \times 10^{-4} M_{\odot}$, consistent with what Pelletier et al. require to duplicate the carbon abundance trends in the DQ stars.

DAV stars: • The hotter DAV stars have common trends in their periods that are consistent with their having a small range of hydrogen layer masses.

- These common pulsation spectra are consistent with their having hydrogen layer masses near $10^{-4} M_{\odot}$ to $10^{-5} M_{\odot}$.
- This is reasonably close to what stellar evolution theory predicts (Iben & MacDonald (1985, 1986)).

Conclusions

- We are now able to perform seismology on white dwarfs, and have results for several DOV, DBV, and DAV white dwarfs.

- Seismology suggests that the DA and DB white dwarfs arise from different progenitors.

- We have suggestive evidence that DBs descend from Hotter PNN via the PG 1159 phase.

- Most DA white dwarfs are descendants of H-rich PNN.

- White Dwarf models with the new OPAL opacities and new SCVH equation of state are not very different from previous models with older opacities and EOS.

- The previous two points say that previous seismological results are sound, and that we expect at most slight changes to earlier seismologically determined structural parameters.

- The biggest difference comes from using (more realistic) $Z = 0.0$ opacities, which were not available before.

- The $Z=0.0$ DA and DB models give the similar periods as before, but at about 500 K hotter temperatures.

Comparison of Seismology Results to Other Results

1. Stellar Masses

- PG 1159-035 and PG 2131+066 has masses of 0.50 $M_{\odot}$ and 0.61 $M_{\odot}$.

- These masses are consistent with the mean mass $\sim 0.6 M_{\odot}$ for PNN (Weidmann 1990). It is larger than the masses ($\sim 0.5 M_{\odot}$) suggested for extended horizontal branch objects (Heber 1992).

- GD 358 has a mass of $0.58 M_{\odot}$, while PG 1115+158 is $\sim 0.62 M_{\odot}$, consistent with the mean mass of other DBs and the PG 1159 stars. (Oke, Weidmann, & Koester 1984).

- Our masses for the DAV stars are similar to the spectroscopically determined masses of Bergeron et al. (1995).

2. Surface Layer Mass

DOV stars: • The surface layer mass of PG1159-035 is $4 \times 10^{-3} M_{\odot}$, thinner than the maximum allowed layer of $10^{-2} M_{\odot}$, (see Iben 1984 for example).

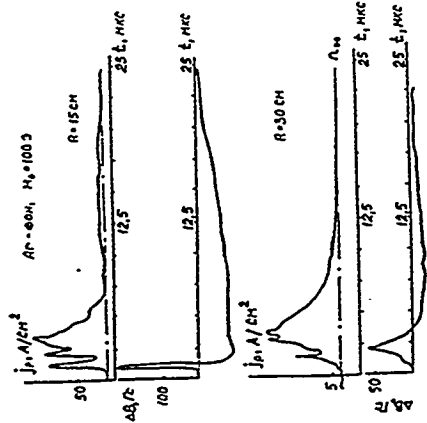
- PG 2131+066 has a similar surface layer mass of $6 \times 10^{-3} M_{\odot}$.

- However, it is similar to D'Antona & Mazzitelli's (1991) minimum surface layer mass of $2 \times 10^{-3} M_{\odot}$.
- Stellar evolution models are not yet able to duplicate the observed abundance patterns of the PG1159 type stars.

Interaction Processes Between Exploding Plasmas and Media in Space

**Anatolle Orishich
Novosibirsk State University**

Finality Orisueh



Oscillograms of electric E and magnetic B probes at the cloud expansion in Ar-background at $R_0 = 100$ O.
 $R_H < R^*$, $R_H^* \Rightarrow R^*$, $R_H R_H^* \Rightarrow R^*$
 $M_0 \approx 2.5$

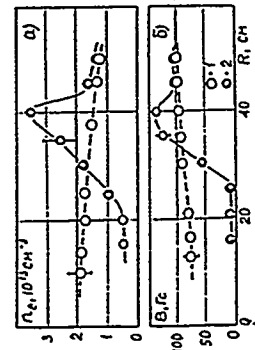
The first investigation problem

Collisionless deceleration of exploding plasmas in the conditions:

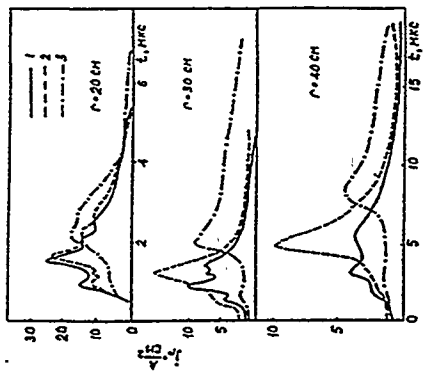
- Alfvén-Mach number $M_A \gg 1$;
- $\lambda \gg R^*$, where λ - scale of collisional free-path of exploding plasmas ions, R^* - gas dynamic scale, $R^* = \frac{3M_A}{4\rho_0}$, where ρ_0 - background plasma density;
- magnetic Reynolds number $Re_m \gg 1$;
- $\eta \approx \frac{8\pi T}{E_0} \ll 1$ - cold plasma.

Processes of interaction:

- For a cold background plasma and $M_A \gg 5$ the interaction between interpenetrating plasma flows due to charge-induced electric fields, both laminar and turbulent, is unlikely take place.
- The influence of the magnetic pressure upon to the deceleration of the cloud may be negligible, as it is M_A -times less than the dynamic pressure of the ambient plasma.
- Magnetic Laminar Mechanism (MLM) of interaction may be strong enough at $M_A \gg 1$. It is based on the action of a curl electric field E_{θ} . An expanding diamagnetic cavity created by spherical cloud should effectively generate this field though $rot E_{\theta} = -\frac{1}{c} \frac{dB}{dt}$. The necessary condition of this MLM interaction is the strong enough magnetization of ions. Larmor radius R_L and R_H^* for cloud and background plasmas (calculation for cloud velocity) should be less than R^* ($R_L R_H^* < R^*$).



The structure of plasma (a) and magnetic (b) cavities with the moving layer of compressed n and B_0 in the front, formed at the interaction of the cloud with H^+ -background at $M_A = 5$ and $R_H R_H^* < R^*$.
Dotted lines - initial distributions of n and B_0 .



The influence of magnetic field $B_0 = 100$ G on the dynamics of radial flow of cloud ions in H^+ -background at $R_0 R_0 < R^0$:

- 1 - $n_0 = 2 \times 10^{11} \text{ cm}^{-3}$, $B_0 = 0$;
- 2 - $n_0 = 2 \times 10^{11} \text{ cm}^{-3}$, $B_0 = 75$ G, $M_0 = 6$;
- 3 - $n_0 = 4 \times 10^{11} \text{ cm}^{-3}$, $B_0 = 65$ G, $M_0 = 8$.

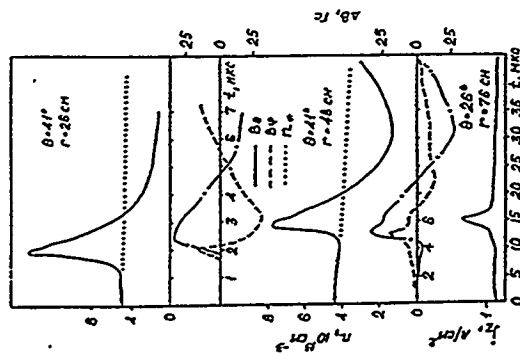


Dynamics of the radial flow of the ion cloud without magnetic field. ($B = 0$):
1 - $n_0 = 0$; 2 - $n_0 = 2 \times 10^{11} \text{ cm}^{-3}$. $H^+ - \text{ions}$

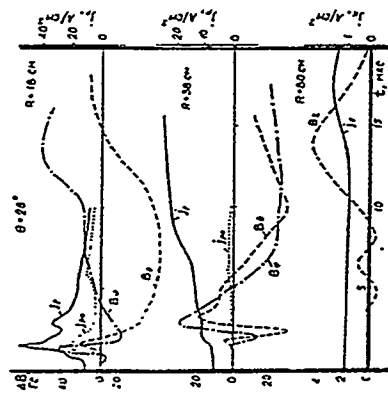


Plasma density distribution after the expansion of the cloud at $B = 0$. Light points - initial distribution.

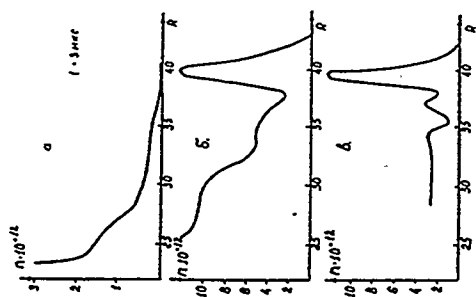
Mach number $M_0 = v_0/c \approx 3$
 c_s - sound speed



The structure of cloud-generated disturbances of H^+ background on the stage of their forming ($R = 26$ cm) and propagation ($R = 48$ and 76 cm) at various angles $\theta < 90^\circ$ at $M_s > 3$ and $R_H R_s < R^2$.



Dynamics of "quasi-parallel" disturbances of plasma and field at $M_s = 2$ ($R = 40$ cm).
 j_z, B_z - currents of the double probe at $n = 0$, and $n_1 = 4 \times 10^{11} \text{ cm}^{-3}$,
 j_A - current of the collector.



Typical radius distribution of concentration in laser plasma cloud.



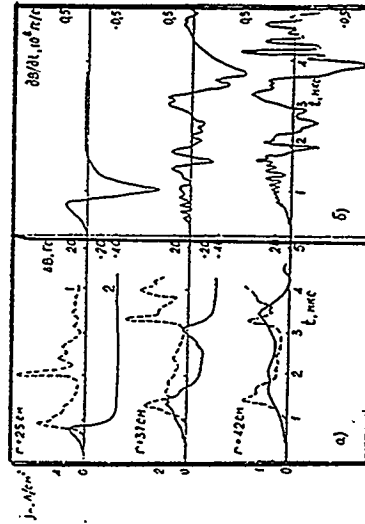
The second investigation problem:

The plasma cloud interaction with the vacuum magnetic field in the conditions:

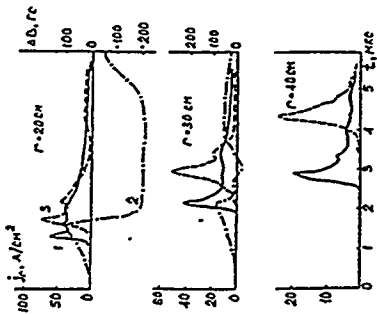
- Alfvén-Mach number $M_A \ll 1$;
- magnetic Reynolds $Re_m \gg 1$, according to Coulomb collisions.

Processes of interaction:

- Deceleration scale must be $R_p \approx (c^2 E_p / B_0^2)^{1/2}$, and its criteria must be ω_p / R_p .
- Diffusion processes of $\vec{B}$ into the cloud may be turbulent.



Dynamics of interaction of laser plasma cloud with the magnetic field $B = 40$ G in vacuum at $R_p / R_0 > 1$.
the case of strong turbulent diffusion connected with the development of instability on lower hybrid frequency:
1 - n , at $R_0 \approx 40$ G;
2 - change of the perturbation of magnetic field ΔB .



Dynamics of deceleration and following departure to $R > R_s$ of the cloud with $R_p/R_s < 1$ at its interaction with magnetic field in vacuum:
1 - J_z at $B_0 = 0$; 2 - ΔB ; 3 - J_z at $B = 260$ G.

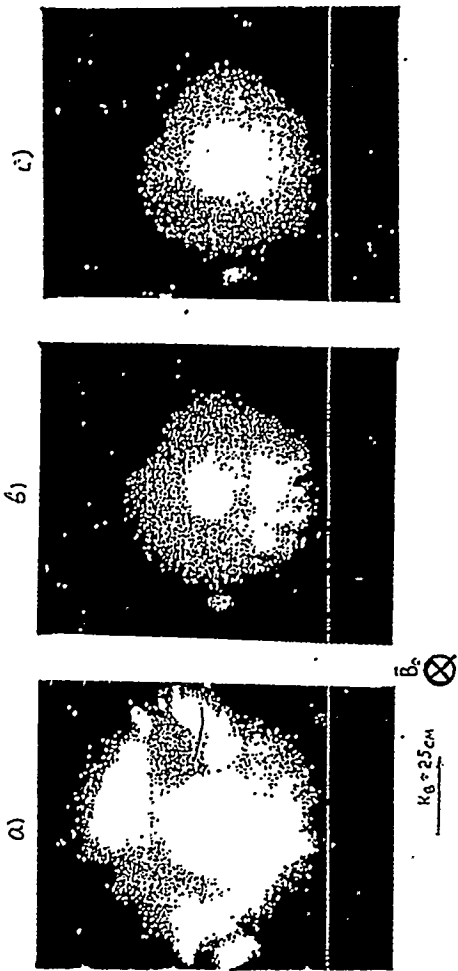


Fig. 3 The control frame photo data ($C_{inf} \sim 100$ ns), when demonstrating the effect of the relative growth depression by a uniform background with the density $n_{rel} = 1.5 \cdot 10^{18} \text{ cm}^{-3}$; $R_0 = 25 \text{ cm}$; $B_0 = 260 \text{ G}$; $R_p/R_s = 0.5$.

Summary and Conclusion:

1. The first confirmation of real efficiency of the Magnetic Laminar Mechanism of the interaction between interpenetrating plasma flows at $M_p > 5$ and magnetization of ions was obtained. There are deceleration of the super-Alfvénic plasma flow and generation of the waves, travelling in the background at various angles with respect to $\vec{B}_0$.
2. At the plasma cloud interaction with B_0 ($M_p < 1$) there takes place microturbulent diffusion of magnetic field into the cloud (diamagnetic cavity). If the ions cloud magnetization is the strong enough ($R_p/R_s < 1$), the cloud decelerates on the scale R_s , where plasma and field pressures becomes equal, and then continues to propagate with low velocity in perpendicular to $\vec{B}_0$ direction in the form of separate filaments.
3. Obtained data may be used for analysis of natural explosive-type phenomena in space plasma like Supernova bursts, Barium releases of Amplitude type or very greater plasma releases of "Starfish" type.

Laser plasma cloud simulation for investigation of a collisionless interaction processes between exploding plasmas and media in space.

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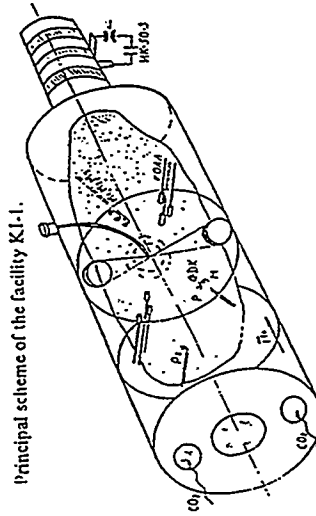
THE PROGRAM OF THE FACILITY KI-1 WORK.

MODELLED PHENOMENA.

1. Deceleration of Nova's and Supernova's shells in interstellar space.
2. Movement of plasmoids and artificial clouds in magnetosphere of the Earth.
3. Generation of interplanetary shock waves by solar flashes.
4. Evolution of planetary nebulae in galaxy field.

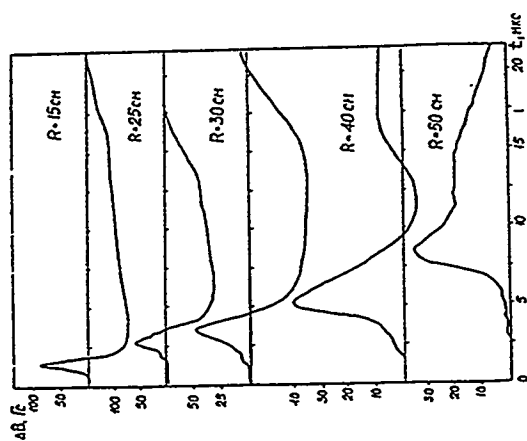
PROCESSES UNDER INVESTIGATION.

1. Collisionless interaction of super-Alfvenic plasma flows.
2. Transformation of flows energy into collisionless disturbances of background.
3. Interaction of plasma flows with magnetic field, role of turbulence.
4. Plasma dynamics at non-stationary energy isolation, generation of compact plasma shells.
5. Ionization waves.

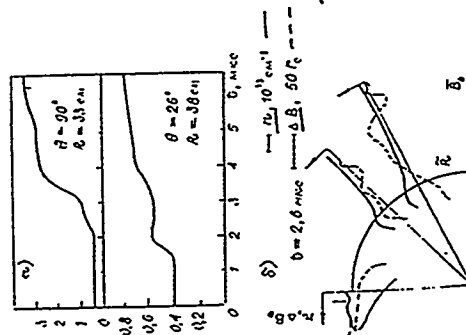


Principal scheme of the facility KI-1.

1. A large-scale (5 m long and 1.2 m in diameter) high-vacuum (10^{-10} torr) interactive chamber.
2. A system of CO_2 -laser and CO_2 -amplifier with output energy ~ 1 kJ.
3. A quasi-stationary source of a background plasma to fill the volume ~ 1 m³ of the vacuum chamber by a highly-ionized density up to $n \sim 10^{18} \text{ cm}^{-3}$. $T_e = 5 \cdot 10^4 \text{ eV}$ (H^+ , Ar^+).
4. One or several carbon-hydrogen targets (Nylon). Plasma clouds of an axially-symmetrical or near spherical form with energy E_p up to 500 J and total mass M_p up to $100 \mu\text{g}$ has been obtained by two-sided irradiation of cylindrical and spherical targets.
5. Magnetic field $B_0 \approx 0.1$ kG.
6. Diagnostic of the plasma density n , the ions flow J_{ion} , the perturbation of magnetic field ΔB , the electron temperature T_e .



Dynamics of the magnetic field at the interaction of laser plasma cloud with H^+ - background at $R_0, R_0^* \leq R^{01}, M_0 \geq 6$ ($n_0 = 2 \times 10^{11} \text{ cm}^{-3}$, $B_0 = 100 \text{ G}$).



a) Disturbance of plasma concentration at various angles.
b) Regenerated space distribution of n_e and B_z in the experiment $M_0 = 1.5$ and $R^* = 40 \text{ cm}$.

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Detailed Opacities relevant to Stellar Interiors
Radiation and Thermal Transport
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