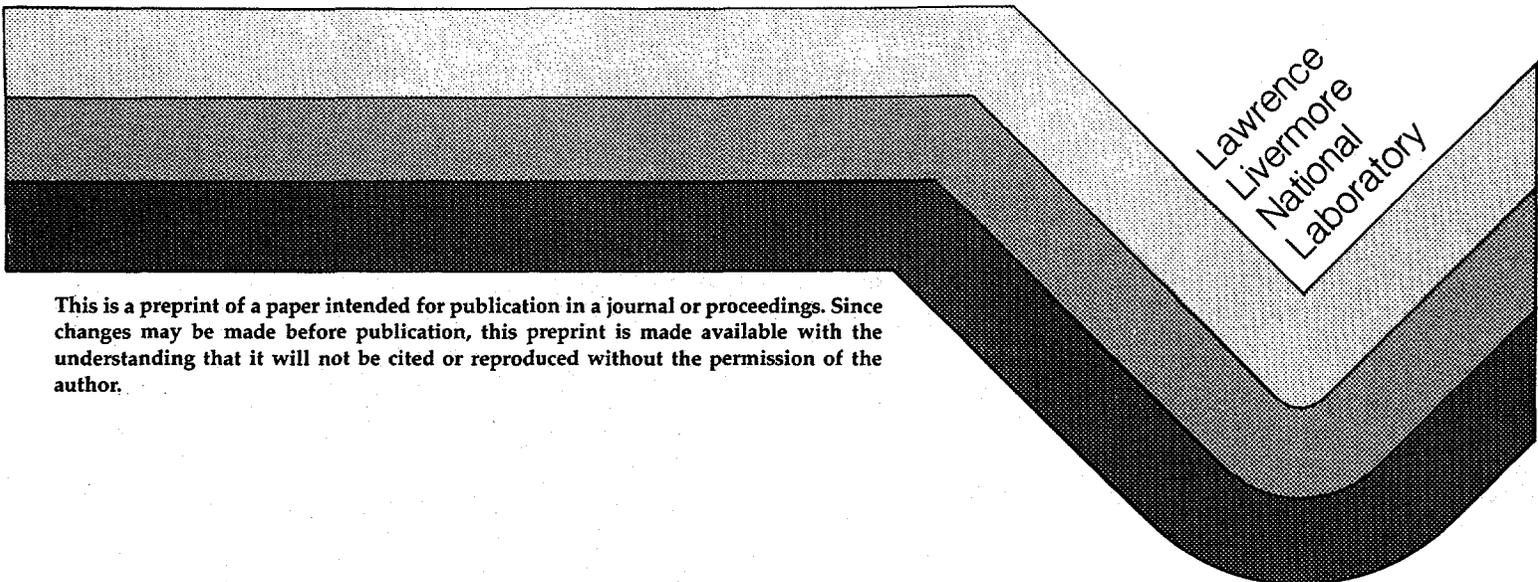


COSMIC BOMBARDMENT IV:
Averting Catastrophe In The Here-And-Now*

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Prepared for Presentation as an Invited Paper to the
Problems of Earth Protection Against The Impact
With Near-Earth Objects (SPE-94)
International Conference
Chelyabinsk Region, Russia
September 26-30, 1994

September 23, 1994



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COSMIC BOMBARDMENT IV: Averting Catastrophe In The Here-And-Now*

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"Those who have eyes with which to see, let them see!"

"Where there is no vision, the people perish."

Introduction. It is widely accepted that the Earth, along with the other major planets, was formed by gravitationally mediated accretion of far smaller objects populating the proto-solar nebula. Moreover, it is believed that this process occurred on such short time-scales, with perhaps 90% of the total mass of the inner planets accreting on a time-scale of 10^8 years and planetary accretion of >100 km-scale objects essentially ceasing well within 10^9 years of Sol's settling down onto the Main Sequence.

While details – and even basic confirmation – of these processes must await fine-grained inspection of other planetary surfaces (particularly those having little or no atmospheres), bombardment of at least the inner planets by cosmic objects of ≥ 1 km diameter is now believed to occur at a frequency of $\leq 10^{-5}$ /year, and this condition is believed to have been characteristic of at least the most recent $1-2 \times 10^9$ years (i.e., 1-2 Aeons). Significant alteration of the mass, rotational angular momentum, orbital elements or even gross atmospheric composition of any of the inner planets by cosmic bombardment processes thus ceased at least 1 Aeon before the present. This is presently understood to be a consequence of the long-term instability of orbits of less-than-planetary mass and non-negligible eccentricity in the planetary system: the collective motions of the major planets long ago gravitationally 'swept clean' the space which they currently occupy, and small objects in the inner solar system having orbital ages greater than ~ 0.1 Aeon are believed to be exponentially rare.

However, evidence presented only during the past decade strongly suggests that profound modifications of at least the terrestrial biosphere by cosmic bombardment have continued until geologically very recent times, and the current general belief is that it may still be underway. It is well-known that

* Prepared for invited presentation at the International Conference Problems of Earth Protection Against The Impact With Near-Earth Objects (SPE-94), September 26-30, 1994, Russian Federal Nuclear Center, Chelyabinsk-70, Chelyabinsk Region, Russia. Work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48. The views and opinions of the author expressed herein do not necessarily state or reflect those of the U.S. Government or the University of California.

the Cretaceous-Tertiary (K-T) discontinuity in the geologic and paleontological records is now very strongly associated with an impact crater of eminently consistent age in Yucatan, one whose size is congruent with impact debris and other impact phenomena of world-wide distribution, moreover whose North American features all seem to point back to the crater's location on the southern rim of the Caribbean Basin. At least the K-T discontinuity now appears to have been impact-generated.

Moreover, it has been widely recognized during the past several years that fundamental discontinuities in the progression of terrestrial life – 'Great Extinctions' involving the abrupt disappearance from the fossil record of at least half of all then-extant species – are a quasi-periodic phenomenon extending back from the present at least several tenths of an Aeon, with a fundamental frequency of ~30-40 per Aeon. Some, e.g. Professor Edward Teller, have speculated that cosmic bombardment of the Earth by multi-km diameter objects has driven all of these Great Extinctions, either by direct effects by the impacts on the Earth's atmosphere (e.g., transient particulate loading or chemistry changes) or by triggering extremely large-scale volcanic eruptions, geomagnetic field anomalies and associated cosmic-ray flux variations, gross changes in planetary circulation, etc.

However, the requirement to point to a plausible source of such bombarding objects from the cosmos – "cosmic bomblets" – would seem to pose basic difficulties for such speculations, since just-noted basic astrodynamical arguments regarding long-term orbit stability indicate that the inner solar system harbors essentially no primordial objects on the interesting size-scales. The postulated – and apparently observed – finite density, flux and collision-rates of such objects thus require a continuing source, one which can sustain over Aeon time-scales a population of cosmic bomblets which, if in orbit in the inner solar system, tends to die away with a ~0.1-Aeon time-constant.

At least two plausible sources have been widely identified. The first of these involves the unceasing 'grinding up' of larger asteroids into smaller ones by mostly glancing collisions in the Asteroid Belt between Mars and Jupiter, with the resulting debris either being ejected from Belt-like orbits into the innermost solar system by the collision itself or by subsequent quasi-resonant interactions with the Jovian gravitational field, e.g., being collision-inserted into the Kirkwood Gap, then to be slung out into the innermost solar system. This mechanism can hardly be doubted, though estimates of its effective rates for bomblets of various size-scales are still of a rough-order-of-magnitude character. Only more detailed observations seem likely to much improve the quantitative outlook for such estimates, and it isn't at all clear from the present vantage-point why this source mechanism would have a dominant periodicity of a few hundredths of an Aeon.

The second widely discussed source mechanism for cosmic bomblets is occasional catastrophic loss of angular momentum from the orbit of a proto-comet in the still rather hypothetical Oort Cloud surrounding the solar system-as-we-observe-it. Such a loss, which must remove >90% of the orbital angular momentum of an initially quasi-circular orbit in order to even depress the

perihelion of a comet-like object inside the orbit of Pluto, would seem to be a relatively very rare event. However, the Oort Cloud could easily have a population of $\sim 10^{12}$ icy proto-comets of ~ 10 km diameter while still having a total mass less than Jupiter's, so that the population-available-for-gravitational-self-collisions is potentially very large. Also, denizens of this Cloud are presumably only very weakly bound gravitationally to the Sun, e.g., typical escape speeds from the solar system are only ~ 1 km/second for orbits with 1000 AU semi-major axes. A velocity change of the order of 10 meters/second – corresponding to a perihelion shift of a dozen AU – could be induced by two 12 km diameter ice-rich proto-comets passing within a few diameters of each other.

Now a population of 10^{12} proto-cometary objects with a full spectrum of eccentricities and semi-major axes confined in a sphere of 1000 AU radius and having a mean relative speed of ~ 1 km/second (the Virial Theorem's mean speed for 1000 AU orbits about Sol) and a gravitational scattering collisional cross-section of $\sim \pi(10 \text{ km})^2$ has a self-collision rate of $\geq 10^{-1}$ /year, which is order-of-magnitude consistent with the 'observed' injection rate of proto-comets into the portion of the solar system inside the Saturnian orbit, where they then become reasonably apparent as comets – and subject to very vigorous evolution of their orbital elements though gravitational interaction with the major planets. Again, it isn't clear why this bomblet source mechanism would have a dominant periodicity of the order of a few hundredths of an Aeon; searches for *Zeitgebers* such as a very small, dim binary companion of Sol in a highly eccentric orbit having a few dozen megayear orbital period, e.g., by Professor Richard Muller's group, have thus far been unavailing. Yet again, illumination of this possibility via improved and more extended observations is required.

In any case, we have a very recent example of cosmic bombardment of a solar planet to lend verisimilitude to these otherwise somewhat scholastic considerations: the collision of the debris of Comet Shoemaker-Levy IX with Jupiter during the week of 20 July 1994, when the 25th anniversary of the first human landing on the Moon was being commemorated. In the course of this multi-day event, somewhere between 10 and 100 km³ of cometary debris compacted into a half-dozen large objects and more than a dozen smaller ones plunged into the Jovian atmosphere at speeds in excess of 60 km/second, depositing tens of *teratons* of TNT-equivalent energy while doing so.

It seems reasonable to expect that, if this cometary debris string had struck the Earth instead of Jupiter, even when correcting for the $\sim 2X$ lower impact speed, the terrestrial biosphere would have been profoundly impacted by the crustal debris lofted into the high atmosphere and most, if not all, land-based higher lifeforms would have perished in this aftermath. More poetically, *this* Great Extinction would have included that of our own species. Two months ago, then, we may have seen the eventual fate of all species of life presently on Earth played out for our edification on the face of a neighbor planet.

In this context, we make the standard assumption regarding interpretation of observations of the large-scale aspects of the universe that there is nothing special or particular about our own space and time, that even unusual events

are occurring with likelihoods representative of their mean density in space-time. If this is true, then either ruinously large-scale cosmic bombardment of the Earth is indeed a very real prospect (even noting the much smaller gravitational cross-section of the Earth relative to Jupiter) within the predictable lifespan of the human species, or else we somehow just happened to see something exceedingly unlikely happen on Jupiter two months ago. But the linear sequences of impact craters on the faces of other planetary bodies in the inner solar system reiterate the non-uniqueness of even the exotic serial cosmic bombardment of Jupiter two months ago.

*It is an utterly remarkable – and presumably unique – feature of our times that we stand precisely at the transition between being subject to cosmic bombardment at Nature's whim and being able to avert such damage at will. A mere half-century ago – when our species was perhaps 99.99% of its current age – had the human race seen Comet Shoemaker-Levy IX coming toward the Earth, we would have only been able to do one thing: prepare to die. A half-century hence, when we shall be perhaps 0.01% older as a species, upon seeing such a comet come toward the Earth, humanity shall easily be able to laugh, and prepare to enjoy watching the fireworks of its destruction far from our planetary home. **In one short century – barely the lifespan of a single human individual – we shall have advanced from nearly perfect ignorance and utter helplessness in the face of large-scale cosmic bombardment to not only thoroughly understand what such bombardment would mean to life on Earth but to brush aside the possibility of its happening, megaseconds in advance and gigameters from Earth.** Truly, "What a piece of work is a man! How noble in reason! How infinite in faculty!...In action how like an angel! In apprehension how like a god!" And, "What times these are that we live in!"*

Pertinent Physical Scales Of Bomblets. The physical scales of cosmic bomblets which poses threats to humanity as a whole – to the ability of the terrestrial biosphere to sustain human life on scales comparable to the current one – are rather clearly those of objects having diameters ≥ 1 km, masses ≥ 1 gigatonne and total kinetic energies at impact $\geq 10^2$ gigatons of TNT-equivalent. Cosmic bomblets which would credibly threaten the ability of the biosphere to sustain any human life likely have parameters 10^2 - 10^3 greater than this 'threshold' one, and can be aptly called "Great Extinctors;" 5-10 km in diameter, 0.1-1 teratonne in mass and 10-100 teratons-HE in energy delivery.

Present estimates indicate that comets of ≥ 100 km diameter are exceedingly rare objects – $\geq 10^3$ times less prevalent than the "Great Extinctors" responsible for the K-T boundary – and thus the *a priori* likelihood that one such would impact the Earth before Sol evolves off the Main Sequence is well under 10%. (This 'Fermi Miracle' is a happy result, as none of the relatively near-term collision-averting approaches which we will discuss below would be of reliable utility against a ≥ 100 km diameter bomblet.) Again, more reliable estimates seemingly must await results of the first significant census of at least the inner edge of the Oort Cloud.

On the other hand, bomblets of 0.1 km scale are expected to strike the Earth far more frequently – impact event rates of the order of 10^{-3} /year are currently

estimated. While these may be expected to induce Tunguska-scale local devastation, their implications for the biosphere as a whole appear to be remarkably limited, e.g., mean biospheric cooling of <1 K for intervals of at most a few years, due to impact-lofted atmospheric particulates.

It is appropriate to recall that the Earth-impact speeds of Apollo-Amor asteroids (which have heliocentric orbital parameters not greatly different from those of the Earth) and those of long-period comets may easily differ by at least a half-order-of-magnitude (particularly when differing collision geometries are considered: long-period comets in their near-unit-eccentricity orbits are significantly more likely to have head-on collisions with the Earth than are co-revolving near-Earth asteroids). Thus, kinetic energy densities of various types of cosmic bomblets upon Earth-impact may differ by at least an order-of-magnitude. For km-scale bomblets, it is likely the total kinetic energy, rather than the mass or even composition, which most accurately indexes the biospheric damage-expectancy, as bomblets of these size-scales are all "earth-penetrating explosives," whether they are composed of dirty snow or nickel-iron alloy.

Bomblet Detection. A necessary-though-insufficient condition for being able to avert cosmic bombardment is to see the attack coming sufficiently far in advance as to be able to react.

The signatures of collision-bent bomblets are characteristically small by standards of contemporary human technology. They are those of dielectric objects with permittivity functions whose magnitudes at near-optical frequencies are less than twice that of vacuum, with corresponding permeability function ratios of essentially unit magnitudes; electrical conductivities are typically $<10^{-9}$ of good metals (with the notable exception, of course, of iron-group-intensive asteroids, which are relatively rare). The emissivities and reflectivities of all classes of bomblets in all sizes studied at close hand are typically a few percent of ideal black-bodies and reflectors, respectively.

Comets in the inner solar system are often strongly signature-enhanced by relatively high-rate effusion of gas and particulates, apparently arising from solar heating of embedded volatiles lying within ~ 1 thermal skin-depth of the Sol-presented comet's surface at the fundamental apparition frequency (which is orbit-determined): comet-tails may simply originate as cometary geysers operating in near-zero gee, the major components of whose jets are hydrides of the CNO elemental group. Such signature-enhancement has both transient and quasi-steady-state features; the former is quite unpredictable on any but the shortest time-scales at present, while the latter is not reliably predictable from apparition to apparition of the same object. Sunlight scattering-based signatures are also subject to secular variations arising from cometary disruption by planetary tidal and solar thermal effects, typified by the time-evolution of Shoemaker-Levy IX's signature during the past few years during which it passed within its Roche Limit distance of Jupiter.

However, prudence in designing planetary defenses against cosmic bombardment requires that, while signature enhancement is to be exploited if present, its

possible presence will be disregarded in baselining the performance of the threat detection and tracking system. Thus, we must consider only the unenhanced signature of a comet or asteroid when seeking to detect its approach to the Earth.

It is splendidly convenient that the object whose gravitational mass binds our planetary system also happens to be strongly self-luminous, and thus illuminates its contents quite vigorously (at least in our neighborhood). The luminous source strength of any object in the solar system is lower-bounded by $\sim 4 \times 10^{17} \epsilon / R_{AU}^2$ photons/cm²-sec, for photons with wavelength λ , $0.2 \mu\text{m} < \lambda < 1 \mu\text{m}$, just from scattering of sunlight, where ϵ is the spectrum-weighted, wavelength-averaged reflectivity and R_{AU} is the object's distance from the sun. The signal strength S of such a diffusely scattering object then is $S \sim 4 \times 10^{17} \epsilon A_O A_D \cos \phi / R_{AU}^2 2\pi R_{OD}^2$, where A_O and A_D are the areas of the object and of the (presumably, near-Earth) signal-detector, ϕ is the sun-object-detector aspect angle, and R_{OD} is the object-detector separation distance. For basic scaling purposes, take $\epsilon \sim 0.04$, A_O and A_D as 1 km^2 and 1 m^2 , respectively, and convert R_{OD} into AU unit, denoted by \mathcal{R}_{OD} . Then it is clear that $S \sim 10^3 \cos \phi / R_{AU}^2 \mathcal{R}_{OD}^2$.

It is notable for present purposes that a comet with a 1 km^2 presented area diffusely scatters ~ 0.1 near-optical photon/sec into a 1 m^2 near-Earth aperture, even when it is 10 AU out from the sun, just crossing the orbit of Saturn (noting that $\cos \phi \sim 1$ under all circumstances pertinent for initial detection of long-period comets). It is likewise notable that a 0.1 km diameter asteroid of comparable diffuse reflectivity presents a comparable signal to such a near-Earth detector when ~ 3 AU out from the Sun, still in the inner edge of the Belt.

In determining whether a presented signal of 0.1 optical photon/sec is large or small in a practical sense, it is necessary to consider both the equivalent signal intrinsic to operation of the detector and the equivalent signal presented by the scene in the vicinity of the object; following the usual convention, we refer to the former as the detector's (signal-equivalent) noise and the latter as the (signal-equivalent) clutter. Both noise and clutter may be reduced very significantly from their 'raw' levels by use of appropriate techniques.

Detection of near-optical photons with the best contemporary technology involves the use of silicon-based photodetector elements, which have essentially quantum-limited detectivity, when operated under optimal conditions. For present purposes, the silicon-based detectors are most aptly segmented into 2-D (square) arrays of micro-photodetectors, interconnected in rows as charge-coupled devices (CCDs) to facilitate read-out at the edges of the lattices of micro-photodetectors. Lattices which contain as many as 25 million such detectors are now commercially available, with row-to-row and column-to-column pitches $\sim 10^{-3} \text{ cm}$.

When the accumulated photoelectron signals from the best modern CCD arrays are read out carefully, and the arrays are operated at suitably low temperatures – in the neighborhood of 250 K – the total [read-out+dark current] noise signal may

be made to be less than 1 photon-equivalent per photodetector element. Suitable overcoating of these arrays' active surfaces can make available overall quantum efficiencies across the photon wavelength range 0.2-1.0 μm which are in excess of 0.30, with mid-optical values consistently exceeding 0.50.

In most every respect, then, these 'megapixel CCDs' are essentially ideal detectors for sunlight scattered by small, distant objects viewed against dark space. Their electronic noise figures are essentially negligible, against the quantum shot noise of the photodetection event itself. When placed in the focal plane of optical systems whose Airy disc diameters are not more than half of the pixel-to-pixel pitch, they provide nearly single photon detectivity at exquisite angular resolution – and excellent time-resolution (though this is usually not exploitable in the present context).

The clutter signal-equivalent noise situation can be made to be comparably ideal. While starlight constitutes a significant source of 'veiling glare', it has very substantial spatial variability, or "patchiness", all the way down to the resolution limit of the optical instrument: stars are truly point-sources, and thoroughly dominant signal-levels of diffuse sources such as scattering by interstellar and interplanetary dust. Of course, this spatial variability can be effectively subtracted out, and the signal-to-clutter ratio of the target object drastically improved, by slewing the optical system precisely to compensate for the apparent proper motion of the target object, so that the object's image stays centered on one single spot in the focal plane, while the background slowly moves across it. Trivial signal processing of the time-dependent signals from the CCD focal plane array then effectively time-averages out the clutter signal, with corresponding enhancement of the all-important signal-to-clutter ratio of the target object. Application of such techniques can be tedious when time is pressing, but that isn't the case when searching for distant objects in the solar system, for which the pertinent time-frames are weeks to months.

More importantly, the only objects of real planetary defensive interest are the classic ones of "constant bearing/closing range" – the ones on apparent interception trajectories. Proper motion-compensating clutter-rejection for such target objects can be performed very precisely, so that clutter-rejection is both quantitatively improved and its implementation facilitated. While, under rare circumstances, gravitational perturbation of a comet or asteroid orbit can generate a valid threat object with relatively little time-to-go until collision occurs, the available time will still be adequate for defensive purposes – after all, the major sources of gravitational perturbation are never less than several AU distant from Earth, and even a long-period comet never moves through the inner solar system at heliocentric speeds in excess of 30 km/sec, or 0.02 AU/day.

To assess the relative performance of ground- and space-based telescopes for threat-object detection purposes, we can compare the signal-to-noise-ratio (SNR) for the two sensor systems. The general form is $\text{SNR} = \text{Sqt}/[(\text{S}+\text{B})\text{Qt} + \text{Ct} + \text{R}^2]$, where S is the signal, Q is the quantum efficiency of photon conversion to photoelectrons (typically ≥ 0.3), t is the integration time, B is the background signal, C is the dark-current count-rate and R is the RMS readout noise. For the best contemporary CCDs, the RMS readout noise can be nominally 1 electron.

The dark current for appropriately cooled CCDs can be less than 0.01 counts/sec per pixel. As sketched above, we take the signal S collected from light scattered from the threat object into a 1 m^2 area aperture to be 0.1 photon/sec.

The background signal (B) collected is proportional to the product of the telescope area (A_0), solid angle of the pixel (pixel subtense squared, ϕ^2) and the background sky brightness per unit solid angle, I_{sky} , which is measured in units of the equivalent stellar magnitude per unit solid-angle. Typical background sky brightness values for ground based telescopes in the best locations are 22 stellar-magnitude/(arc-sec) 2 , while that for space-based 'sky' backgrounds, such as seen by the Hubble Space Telescope, are 23 mag/(arc-sec) 2 . Ground-based telescopes thus see approximately 2.5X higher levels of background sky brightness levels than do space-based systems. More importantly, atmospheric 'seeing' limits the effective ground-based pixel subtense to $\sim 10^{-5}$ radians, whereas there is no comparable limitation on space-based systems.

Choosing an angular subtense of 10^{-6} radian (readily compatible with the reference 1 m^2 aperture and optical wavelengths) for the space-based system, we find that a 1 m^2 aperture collects 0.25 photon/sec per pixel of background sky signal. (This corresponds to the reference sky brightness value and includes typical obscuration effects on the Airy disk, as found in systems with a central obscuration such as Cassegrain telescopes. These effects reduce the fraction of the inscribed energy found in the first Airy ring of the diffraction disk by a factor of 0.7.) An identical ground-based telescope of 1 m^2 collection area will collect essentially the same signal level per pixel as does the space-based system. However, it will see a 2.5X larger background sky brightness and, with its 100X larger per-pixel solid angle, will collect 250 times more background photons per pixel than does the space-based system.

In the space-based system, the signal and sky background levels are comparable but the other noise terms can be neglected. This reduces the expression for the SNR to $S/(Qt/[S+B])^{1/2}$. In the ground-based system, the sky background signal dominates the threat object's signal and the detector noise terms, so the SNR can be further reduced to the expression of the form $\text{SNR}=S/(Qt/B)^{1/2}$. For the space-based system, we can have approximately 2400 seconds of integration time (40 minutes in the 'night' portion of the orbit) and, since $Q \geq 0.3$, the SNR becomes 4.5:1. For its ground-based twin, the corresponding SNR is only 0.3:1, assuming that the integration time could be comparably long. Then, in order to match the SNR of a space-based system, a ground-based system would need a $\geq 100 \text{ m}^2$ aperture.

We therefore conclude that ground-based cameras will have utility in imaging cosmic bomblets only when they have relatively large angular subtenses from the Earth, i.e. are relatively proximate – and, of course, when the sun and moon are not in the camera's local sky and the "seeing" is good and clouds are absent. On the other hand, space-based cameras, free from airglow veiling glare and all other atmospheric and from kHz-rate 'image-steering' due to atmospheric density fluctuations, can detect the same objects when they are at least an order-of-magnitude more distant from Earth – and correspondingly an order-of-magnitude

longer time from possible Earth-strike – and they can be used for sky patrol 24 hours per day, every day, without exceptions.

It seems quite likely that the greater per-aperture cost of intelligently implemented (e.g., non-HST Program-like) sky-patrolling cameras in Earth orbit will be more than offset by the very large gains in availability which they offer and, even more importantly, in the order-of-magnitude gain in threat response time which their qualitatively superior signal-to-clutter ratios and thus target detectivities will buy for active planetary defenses. The fundamental importance of time-to-go until Earth collision occurs will be elaborated below.

The Time-Varying Nature Of Active Planetary Defenses. Already noted was the fundamental fact that the Earth has only exceedingly recently gain a single species which has just in the present instant of geologic time acquired some non-trivial potential capability to defend the Earth's biosphere from cosmic bombardment. What this potential capability may be a half-century hence, we can only dimly estimate; what it will be a century from now, we have no idea. What would our predecessors in the 1890s have estimated, if even presented with this problem, moreover when they were looking into prospective future in which human technology was advancing at a far more measured pace than that of our discernible near-term future? *"We know in part, and we prophesy in part."*

In the following, we discuss the potential defensive capabilities which could be deployed on a time-scale a decade hence, employing means which can be readily drawn from the existing human technology base. We make no pretense that these capabilities are ultimate ones, in any sense; they are merely the ones which the human race can exercise to ensure the safety of the terrestrial biosphere in the face of the cosmic bombardment threat – in the here-and-now.

Cosmic Bomblet Interception. We have already noted that the most threatening class of cosmic bomblet has two characteristic features: it features large-sized objects – diameters of ≥ 0.1 km – and these objects are "first-pass-deadly": they are first observed when they are on a collision course with the Earth, within a single period of their orbit. An outstanding example known to us at present is the long-period comet, perhaps on its first pass through the inner solar system. Shoemaker-Levy IX typifies such "first-pass-deadly" threats.

As noted above, such objects will approach the Earth with speeds of the order of 30 km/sec, or ~ 0.02 AU/day, and will first be readily detectable from Earth-orbiting cameras of reasonable size at ~ 10 AU distances if they are of ~ 1 km diameter, or ~ 3 AU ranges, if of ~ 0.1 km diameter. There is then ~ 200 days available in which to deal with the smaller threat-objects, or ~ 1000 days grace before the "Great Extinctors" can arrive. Somewhere between 27 and 140 weeks thus appear to be available between 'first warning' and biospheric impact, for the objects which pose the really severe threats.

We know of no feasible means for preventing cosmic bombardment by this class of threat objects which doesn't involve the introduction of some type of human

machinery into the immediate vicinity of the threat object, sometime between its initial detection and its Earth-impact. Obviously, if a threat object with a sufficiently large surface-to-volume ratio – e.g., a sufficiently small mass – is somehow determined to be on a collision course with the Earth sufficiently far in advance, then, given the time-quadratic character of Newton's Second Law of Motion, arbitrarily gentle means can be employed to persuade such an object to fly by the Earth, rather than impacting it: in principle, the radiation pressure from a laser-pointer briefly aimed through a child's telescope would do the job. The concatenated likelihood of such trains of low-probability circumstances removes them from our consideration. Instead, we examine threats which are grave ones, of the Comet Shoemaker-Levy IX category, and we consider means for reliably, even robustly, dealing with them.

There is a strong imperative to intercept the incoming objects as far away from the Earth as possible. A long-range intercept gives more time for our defensive effort to act; this benefits us either linearly, for abrupt measures, or quadratically, for gradually acting ones.

Two coins are available with which to buy increased intercept range: time, and interceptor speed. As discussed above, the key to increasing time-to-act is an early detection of the threat, followed by prompt commencement of the intercept mission. The cost of these measures is a space-based surveillance system and a thoroughly prepared and pre-authorized operational capability.

Unfortunately, buying a longer intercept range by simply increasing the speed with which the interdiction machinery is sent toward the threat object is a much more costly proposition. We note that presently available means for emplacing any human machinery into interplanetary space are still exclusively dependent upon chemical rocket propulsion. The nature of existing upper-stage propulsion modules is such that every ~3 km/sec of speed in excess of Earth-orbital speed is purchased with roughly 3X greater mass of the rocket-stack, when mass residuals are considered; i.e., the purchase cost of greater speed in interplanetary space is *exponentially* greater Earth lift-off mass. For a fixed travel-time, the amount of interdiction machinery mass which must be delivered into the vicinity of the threat object shrinks polynomially with speed K , as K^{-1} or K^{-2} , but the Earth lift-off mass required to emplace it grows as e^K . Clearly, the mission is best performed with moderate K s, e.g., speeds ~5/km/sec; higher speeds are simply too expensive to attain.

We note that the maximum masses of machinery which can be emplaced on interplanetary trajectories in the present era are perhaps a few dozen tonnes in a single launch, using an augmented *Energiya*. This suggests that the total machinery inventory which can feasibly be emplaced at/near an incoming cosmic bomblet in a 1-2 decade time-frame is ~100 tonnes, launch rates and system-level reliabilities taken into consideration. Whatever we propose to do to actively defend the terrestrial biosphere from any given cosmic bomblet must be done accomplished within such an overall mass budget.

Now the geocentric approach speed of a bomblet-threat object, ~30 km/sec, is an order-of magnitude greater than that of the interdiction machinery dispatched to

prevent the bomblet from arriving at Earth. Thus, even if it is launched at the time of 'first warning' from the sky-surveying system, well before a reasonably exact trajectory can be derived and the likelihood of collision assessed, the interdiction machinery will arrive at the bomblet when it has covered ~90% of the distance to the Earth. Big, km-scale objects will therefore be at ~1 AU distances and smaller, ~0.1 km ones will be at ~0.3 AU range; they will be ~17 and ~50 days pre-impact at such ranges, respectively.

The effective transverse velocity change which must be imparted to the object must be sufficient for it to reliably miss the Earth, a target of ~ 10^4 km radius (when 50% margin is allowed). If 17 days, or $\sim 1.5 \times 10^6$ seconds, is the time-to-go, then obviously a velocity change of ≥ 7 meters/second is required to be applied to the object by the interdiction machinery. If 50 days are available, an imparted transverse velocity change of ≥ 2 meters/second will suffice – though the total required impulse is ~2.5 orders-of-magnitude larger.

Bomblet Deflection, Disruption/Dispersal and Vaporization. We know of only two basic approaches for dealing with cosmic bomblets on collision trajectories with the Earth within the overall few-decade time-frame of present interest: push them onto non-impacting trajectories, or disassemble and/or disperse them. We consider each of these possibilities, relative to the various classes of bomblets and the interdiction system's mass budget.

Deflection. Pushing 0.1 - 1 km diameter incoming bomblets of unit density so as to change their speeds by 7 - 2 meters/second, respectively, requires $3 \times 10^9 - 10^{12}$ N-sec of impulse, which could be generated by $\sim 6 \times 10^2 - 2 \times 10^5$ tonnes of LH₂/LO₂ optimally exhausted at ≤ 5 km/sec speeds through a rocket engine. Furthermore, the soft-landing of a Centaur-type rocket propulsion package on the incoming bomblet's surface involves velocity-matching to an object whose relative speed is N km/sec. This imposes an additional penalty of at least $e^{N/5}$, which is >100 for typical closing speeds (which are >25 km/sec); this raises the mass requirement to $6 \times 10^4 - 2 \times 10^7$ tonnes. We therefore conclude on quite fundamental grounds that chemical rocket propulsion-based means cannot be employed to deflect incoming bomblets in the ≥ 100 meter diameter class.

Now it is remarkable that an object with a speed of 28 km/sec has a kinetic energy density $\sim 10^2$ times that of chemical high-explosive. The question naturally arises as to whether the interdiction machinery could possibly convert some non-trivial fraction of this energy density into a mass-jet whose reaction would generate the required impulse to deflect the main body of the object. After all, jetting mass at 28 km/second, even if done with modest efficiency, is clearly superior to exhausting LH₂/LO₂ at ≤ 5 km/sec. This superiority may be magnified exponentially (via the Rocket Equation) if the corresponding machinery doesn't have to be velocity-matched to the object before it does its work. Similarly, this exceptional kinetic energy density might be converted, even with low efficiency, to operate a mass-jet of much lower speed.

A particularly simple – and thus particularly robust – example of such machinery is what might be called a ‘hypervelocity sand-blaster’. If a stream of cm-scale projectiles is directed onto the face of the object from the approaching interdiction machinery, they will form blast craters at each of their impact sites, and the material which formerly filled these craters will leave the surface at a speed characteristic of the temperature of the impact event. Since this expansion-defining temperature may be made to be not much at all in excess of the critical temperature of the material composing the bomblet’s surface by appropriate choice of geometry and composition of the set of identical projectiles thrown by the approaching interdiction machinery, the speed of the resulting jet may be expected to be ≤ 2 times the adiabatic sound-speed in the bomblet’s surface layer – which is 1-3 km/sec, depending on whether it’s ice or rock.

Mass incoming at ~ 25 -30 km/second thus generates a mass-jet with a characteristic speed ~ 10 times smaller. Since the optimized energy efficiency of such jet-generation may be several tens of percent, this ‘hypervelocity sand-blaster’ makes feasible the multiplication of the incident impulse of the projectiles by ~ 3 - 5-fold, though multiple mass-jet formation on the object’s surface. (This may be further multiplied, though probably by less than 2-fold, by late-time, low-speed loss from the object’s surface of the material forming the walls of the blast-crater jet-formers.)

This particular interdiction system essentially allows the incoming bomblet to deflect itself, by reactively blowing away the face which it presents in the direction opposite to which it’s desired to have the object accelerate. The energy to execute the blowing-away is taken from the object’s kinetic energy reserves; the mass to provoke this conversion is provided by the incoming projectiles; the conversion operation is specified by the manner in which the appropriately formed projectiles are made to be incident on the chosen face of the object.

Consider what a single non-augmented *Energiya*’s payload might be able to accomplish along these lines. The available projectile mass in such an interdiction system would be ~ 10 tonnes, with the projectile-aiming and -firing system requiring another 5-10 tonnes. It would be able to blow-off at least 300 tonnes of threat object surface at a characteristic speed of ≥ 3 km/second, so that $\sim 10^9$ N-sec of total impulse would be generated. (More readily vaporized surfaces, e.g., ice vs. rock, would jet off relatively more mass at comparatively lower speeds, so that total impulse generation should be relatively insensitive to threat object composition.)

Impulses of this magnitude, we have estimated above, may be sufficient to adequately deflect 0.1 km diameter objects, if they may be interdicted with sufficient time-to-go – and should be readily sufficient to deflect adequately threat objects of significantly smaller classes, even with significantly less time-to-go. Perhaps quite importantly, the impulse could be applied over quite longer total intervals, so that large-scale, high-intensity shock-wave generation within the body of the threat object could be avoided. This may be of critical importance when deflecting very fragile threat objects whose yield modulus is effectively the square of their meter/second-scale escape-speed, e.g., the ‘flying rubble-piles’ believed to be the end-stage of some classes of comets. (If deflection of an intact fragile object,

rather than its disruption – possibly into fragments which cannot then be gracefully managed – is desired, then very low peak rates of impulse application are probably required.)

It appears unlikely that these impulse-multiplication gambits may be successfully employed for objects of km diameter, simply because of likely-enduring limitations on the interdiction system's mass budget, the accessible impulse-amplification coefficients, and the cubically-growing mass of the threat objects with increasing diameter. Schemes and mechanisms of great interest for dealing with 0.1 km asteroids become comically inadequate when confronting an Alvarez-level "Great Extincter" of a 10^6 -fold greater mass: a 'flying hillock' is not to be confused with a 'flying mountain'!

From the admittedly parochial viewpoint of a physicist contemplating this general issue, Nature is endowed with a somewhat slender collection of forces of differing coupling strengths. We have just discussed the employment for cosmic bombardment avoidance purposes of energy densities two orders of magnitude in excess of those found in chemical bonds, simply because these are conveniently available as kinetic energy densities in the incoming bomblets. Now, when we need perhaps an additional 2 - 3 orders of magnitude greater energy density to be able to deal with the "Great Extincters" within our (admittedly modest!) system mass budget, we find that we have no force with a really appropriate coupling strength to invoke. There is simply no natural force intermediate in strength between the electromagnetic and the strong forces!

We are therefore obliged to consider the use of nuclear energies and energy densities, in order to have any means at all adequate this side of the indefinite future for coping with the "Great Extincter" class of cosmic bombardment threat objects. We note that the shortfall in impulse-generating capability is ~2.5 orders-of-magnitude; a 10 km-diameter threat object can presumably be first detected at ~3-fold greater range than a 1 km one with the reference sky-surveillance system, and interdiction operations commenced with 3-fold greater time-to-go, so that $10^{-0.5}$ of the impulse per unit mass must be applied to 10^3 -fold greater mass. It is clear that a few-fold relaxation in basic parameters, e.g., in system mass budget via invocation of enhanced rocket technology, would be quite unavailing.

Now a 20 tonne nuclear energy-generating system – the class which might be emplaced at a threat object by a single unaugmented *Energiya* – has an energy output which is upper-bounded by fundamental nucleonic binding energy considerations of ~ 1.5 GT of chemical HE-equivalent; practical considerations reduce this to perhaps ~ 0.5 GT. (It is worth recalling in this context that Sakharov et al demonstrated a ~ 0.1 GT system in 1962, albeit with lower mass efficiency.)

If 0.5 GT of energy could be converted to sound-speed-levels of impulse by blowing off the surface of a threat object with, say, 10% efficiency, then $\sim 2 \times 10^{14}$ N-sec of impulse could be realized. This is essentially the $\sim 3 \times 10^{14}$ N-sec of impulse needed to deflect a 10 km-diameter "Great Extincter" with ~ 170 days of time-to-go.

However, there is a definite requirement to remove superficial material at blow-off speeds not much in excess of the adiabatic sound-speed, both for reasons of overall

energy efficiency and in order to avoid excessively shocking the deflected threat object. It is immediately apparent that $\sim 1 \times 10^{14}$ grams of material must be rather gently evaporated from one side of the object which, for a 10 km diameter object, implies removal of material to a depth of ~ 30 cm. Considerations of the opacities of condensed-phase matter of cometary or asteroidal compositions to the various radiations available from the entire class of nuclear explosives then clearly require the use of explosives rich in relatively penetrating radiations, e.g., high-energy photons or neutrons, as one of us first pointed out a decade ago. Fortunately, this requirement is quite compatible with high mass-efficiency explosives.

It may be preferable from a deflection reliability standpoint to deploy a small set of explosives of comparable aggregate total energy release but having order-of-magnitude smaller individual energy outputs, and to thereby expose the threat object's surface to a rapidly applied sequence of heating pulses over a total time interval of ~ 1 second, in order to absolutely minimize the shock-loading of the underlying material. The resulting 'slow shove' then well-approximates that discussed above for the shower-of-small-projectiles mode of impulse generation. Loss of applied impulse, e.g., due to relatively large masses being carried off the far side of the object by a too-strong release wave, is thereby reliably precluded.

Disruption/Dispersion. It is remarkable that remarkably little energy (in relative terms) is required in principle to completely disperse even an object of "Great Extincter" size-scale: a 'dirty snowball' comet of 10 km diameter has a gravitational binding energy of barely 1 MT HE-equivalent – and this binding energy scales with the fifth power of the object's diameter. It is therefore natural to inquire as to how various threat objects might be most readily disrupted and then dispersed adequately in less than their characteristic times-to-go, so that each ceases to be a biospheric hazard.

Applying the standard of 'practical within the next 1 - 2 decades' which we have adopted for the present discussion, a particularly attractive scheme involves an interdiction machine which throws a shower of projectiles directly at the threat object, as it closes upon it. However, in contrast to ones discussed above which penetrate relatively shallowly, forming mass-jetting channels in the penetration process, the ones of present interest would penetrate substantially more deeply, and then would stop relatively abruptly with great local energy release, much like a Tunguska-type meteorite penetrates the Earth's atmosphere. An obvious physics design for such a projectile would feature a high aspect ratio, a comparatively thin refractory/ablative shell and a Rayleigh-Taylor-unstable core exposed to the surrounding flow when the overlying shell had ablated away.

The aspect ratio and scale of these projectiles would be chosen so as to penetrate the target object to a depth of ~ 10 meters before the 'hydrodynamic explosion' of the core mass, expending perhaps 10% of its mass in boring the 'entry shaft'. The remaining 90% of the mass would effectively deposit its kinetic energy in an explosive manner in a mass of material $\sim 10^2$ times its own mass, creating local peak pressures readily adequate to shatter the overlying material and then lift it off the incoming bomblet with greater-than-escape-speed. Successive waves of such projectiles would successively reduce the entire incoming bomblet to meter-scale rubble – and disperse it at multi-meter/second speeds.

In the case of 'dirty snowballs', it is reasonable to expect this process to proceed with ~30% energy efficiency relative to the gravitational binding energy, since the compacted snow could be disrupted with little more energy than its gravitational self-energy; recall that naturally formed ice has very low strength in tension. Thus, ~ 3 MT of delivered energy would be required for this "jackhammer" mode of disruption of a 10 km-diameter threat object, and ~30 kilotons of projectile mass arriving at 10^2 times chemical HE energy density, would be required. This is $\sim 3 \times 10^3$ more mass than the ~10 tonnes of projectiles potentially available from a *Energiya*-lofted interdiction machine. However, since an object's gravitational self-energy increases with the fifth power of its diameter, such a scheme would be quite interesting for dispersing incoming 'dirty snowballs' with diameters ≤ 2 km.

The use of the "jackhammer" mode in disrupting smaller threat objects composed, or containing large inclusions, of reasonably compacted rock is more problematic. The explosively-applied energy typically used to shatter hard rock into even meter-sized chunks of rubble is $\sim 10^4$ times greater than the ~0.1 J/kg gravitational binding energy of a 1 km-diameter threat object, and varies by more than an order-of-magnitude, depending on the compaction history and composition of the rock in question. Since 10 tonnes of projectiles can carry only 1 KT of energy into an threat object closing at ~30 km/sec, a 1 J/gm "rubblization energy density" suggests that hard-rock threat objects with diameters much in excess of 0.1 km cannot be successfully rubblized with a "jackhammer" approach, which is the most mass-efficient one of which we are aware. Indeed, an attempt to disperse a "dirty snowball" via the "jackhammer" mode might result in a quite unpleasant surprise, if such an interdiction attempt merely stripped the snow and ice off of a number of large rocky inclusions left largely intact and still heading Earth-ward – now, with little time-to-go.

Vaporization. If a credible threat to the fundamental integrity of entire biosphere of any nature presents itself, the human race's response may be remarkably non-linear in the damage-weighted risk, simply because relatively few voting citizens are deeply committed statisticians. The technical community preparing responses to cosmic bombardment threats therefore may be tasked with developing and preparing extremely definitive measures for eliminating at least the larger classes of threat objects. Such measures may be reasonably anticipated to involve a layered defense, with very different technologies employed in each layer, so as to preclude common-mode failures. It may also be plausibly required that each defensive layer be demonstrably independent of both the functioning and the possible failures-to-function of all previously operated layers.

It therefore seems likely that at least one such defensive layer will involve the effectively complete vaporization of the incoming threat object, and that the object will be assumed for purposes of this layer to be composed of largely or exclusively of strong, refractory material, e.g., hard rock or metal.

Now 1 GT of energy – of the order of that available from a nuclear explosive launched on an *Energiya* – can vaporize roughly 1 GT of rock, which is about that which would constitute a 1 km-diameter asteroid. Applying this energy to

accomplish the vaporization with reasonable efficiency may require a mildly sophisticated interdiction machine, however.

It presently seems to us most straightforward – and thus most reliable – to employ a series of small explosives (each with an energy output of ≤ 0.1 MT) to rapidly drill a channel of $\sim 10^2$ meters diameter toward the center of the threat object, with only modest perturbation to the threat object as a whole. When this channel has been extended to the approximate center of the object, the string of modest explosives culminates with a single high-energy explosive. The operation of this final explosive drives a radially-outgoing shock wave to the surface of the object of sufficient strength (when it reaches the surface) to raise the post-shock superficial layers to their critical temperature. (The high aspect-ratio channel into the object's center clearly does not significantly diminish either the strength or the radial symmetry of the outgoing shock.) The energy efficiency of this approach is comparatively high; while material closer to the object's center is significantly overheated, its fractional mass is cubically small – and much of the excess energy density is hydrodynamically recovered during the expansion of the vaporized object and is more uniformly distributed.

While a mass-optimized nuclear explosive payload of a single *Energiya* is sufficient to completely vaporize only a 1 km-diameter threat object, we note that it also sufficient to rubblize into meter-scale fragments the entire mass of a 10 km-diameter, when centrally deployed as just discussed. Even well-compacted rock is quite weak in tension, and $\leq 10^2$ bar shock strengths when the radially diverging wave breaks through the object's surface will very reliably rubblize even the superficial layers (especially so, when the release wave reflection is considered). Moreover, such rubblization will necessarily be associated with few meter/second dispersion speeds at the object's surface, easily sufficient to adequately disperse the rubble-sphere over the 5-15 megasecond times-to-go characteristic of 1-10 km-diameter threat objects.

Basic Uncertainties And The Requirement For Practice. The human race presently knows virtually nothing of the structure and composition of any of the classes of threat objects of present interest; the very modest knowledge that we do have is inference-based.

Clearly, we need passive and active fly-bys and landings on asteroids and comets in the inner solar system, so as to gain first-level understandings of the structure and composition of even the superficial layers of these objects. Complementary observational studies from Earth orbit can generate much-needed knowledge of their populations and the dynamics thereof, out to at least the orbit of Saturn.

Richard Feynman memorably remarked that high-energy physicists study elementary particles in a manner akin to inferring the structure and functioning of Swiss watches by throwing them at each other at speeds of hundreds of kilometers per hour and then carefully studying the debris patterns from the resulting collisions. With this eminently respectable precedent in front of us, we believe that asteroids and comets may be best probed in their possibly quite complex depths by exercising scaled-down versions of the active defense schemes which we have just

reviewed, in association with appropriate diagnostics packages deployed modest distances away from the deep-probing operations.

Such probing exercises on targets-of-opportunity flying-by the Earth at ≤ 0.1 AU ranges will naturally also constitute very valuable 'practice sessions' with respect to detection, tracking and interception of actual threat objects, as well as providing performance-evaluation opportunities for interdiction machinery in sub-scale. We believe that they should commence, on as modest terms as may be necessary, in the immediate future.

Because such applied research activities address fundamental concerns of the entire human race – e.g., survival of mankind – it seems eminently appropriate for participation in such work to be as universal as ever possible, and it appears imperative that all such activities be completely transparent and the subject of as much consensus as is feasible without completely excessive time-delays.

At the same time, it must be recognized yet another time that various peoples and nations have widely varying levels of economic and technological capabilities, and that the most capable people and nations must necessarily shoulder the bulk of the responsibility for initiating and carrying forward this survival-directed work. Doing so is neither arrogance nor charity; it's simply the way the human race has advanced to the stage it is at today: through cooperation, with those stronger at any given moment assisting those weaker.

We therefore respectfully suggest to this Conference that it call upon the Governments of the most economically and technologically advanced nations to immediately take definite steps to actualize plans of the general type which we and others present here have sketched. In a similar spirit, we urge the setting-aside of all philosophical preconceptions and political prejudices, and the consideration of all systems for planetary defense and all components thereof purely on their technical merits. The task before us – ensuring the survival of the entire terrestrial biosphere, including the human species – is surely far too important to clutter and impede with prejudice!

Recommendations and Conclusions. At the present time, it is at least arguable that large-scale cosmic bombardment has been a major driver of the evolution of the terrestrial biosphere. *The fundamental motivation of the present paper is the (high) likelihood that the advent and rise of the human species hasn't coincided with the cessation of soft and hard collisions in the Asteroid Belt or in the Oort Cloud, and that we will either stop the cosmic bombardment or it will eventually stop us.*

In the foregoing, we have briefly reviewed the prospects for active planetary defenses against cosmic bombardment in the very near-term, employing only technologies which exist now and could be brought-to-bear in a defensive system on a one-decade time-scale. We have sketched various means and mechanisms from a physicist's viewpoint by which such defensive systems might detect threat objects, launch interdiction machinery toward them and operate such machinery in their vicinity to alternately deflect, disperse or vaporize objects in

the 0.1-10 km-diameter range, the ones whose size and population constitute the greatest threats to our biosphere.

We conclude that active defenses of all types are readily feasible against 0.1 km-diameter incoming cosmic bomblets and that even complete vaporization-class defenses are feasible against 1 km-diameter class objects of all compositions. When facing Great Extinctors of up to 10 km diameter, the feasible defensive methods depend upon the object's size and composition. Dispersion defenses are feasible against all threat-classes, as are deflection approaches for bomblets up to ~10 km diameter; vaporization-level protection is, however, available only against 'dirty snowballs' of the ~1 - 2 km diameter class. Great Extinctors of sizes significantly greater than 10 km diameter challenge contemporary human technology ever more severely; fortunately, they appear to be rare on the several Aeon time-scales over which Sol will shift its spectral class.

These defensive feasibility assessments are critically dependent on realization of adequate time-to-go in the positioning of interdiction machinery in the neighborhood of the threat objects. Assuring adequately large time-to-go, in turn, is crucially dependent on meter-aperture sky-surveilling camera systems of a performance level which can be attained only above the Earth's atmosphere. Ground-based optical systems of virtually any scale appear to be qualitatively inadequate as "distant early warning systems" due to atmospheric effects.

We urge very near-term observational studies with genuinely state-of-the-art camera equipment – particularly systems deployed above the atmosphere in Earth orbit – of

- the inner solar system for asteroids already in the orbital element parameter space of the Earth, with which eventual collisions are highly likely;
- the Asteroid Belt, to generate improved understanding of the sub-populations and dynamics one of the principal sources of terrestrial threat objects;
- the Oort Cloud, for fundamental orbital element parameter space population-density assessment and corresponding threat-object generation-rate prediction purposes.

While such studies cannot provide definitive threat assessments with near-term technology, they can usefully degrade humanity's present-day nearly perfect ignorance on many scientific and technical issues central to a first-level quantitative assessment of the cosmic bombardment threat.

We also urge immediate creation by cognizant Governments of international study groups

- to quantitatively assess and authoritatively document the technical prospects for active defenses of all technically feasible types against cosmic bombardment, and

- to propose detailed plans and associated programs for developing and testing active defenses employing various technologies on objects-of-convenience passing in reasonable proximity to the Earth – and on smaller objects actually impacting the Earth – during the next two decades, for urgent consideration by political leaders of the advanced nations.

We suggest that, if Comet Shoemaker-Levy IX could impact Jupiter with several tens of teratons of chemical-HE-equivalent energy in our own time with an advance notification interval measured in months, its twin could also do this to the Earth – in our own time, likewise with mere months of advance notice. If it were to do so, many extant species, including our own, would likely be annihilated.

Actuarial reassurance is never much valued by the guy whose 'number comes up' anyway, and the human race will likely never be more firmly 'put on notice' than it was this past July. To paraphrase Benjamin Franklin into the current context, "Those who would trade safety for a little temporary convenience deserve neither safety nor convenience."