SAND2020-1957C

Understanding Spectra from White Dwarf Photospheres

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Abstract

We establish the work on white dwarf stars in the larger context of the "at-parameter" experiments of the Wootton Center for Astrophysical Plasma Properties (WCAPP). The current suite of experiments are all macroscopic plasmas under the density and temperature conditions we find in the cosmos. We will briefly summarize the results of these experiments to-date and their astrophysical and physical impact. Over 97% of stars either are, or will become, white dwarf stars, giving them broad relevance. We describe the astrophysical and physical problems associated with white dwarf photospheres, the plasma where the observed light arises. The astrophysical questions include the age of the universe, the age and history of star formation in our Galaxy's varied morphological components and the evolution of stars. The compact nature of these ubiquitous stars means that the atomic physics is not well constrained even in the outermost layers. Further, it suggests that many important processes, including crystallization in dense Coulomb plasma, occur and have a significant effect on the evolution and structure of these stars and thus all their many applications. We summarize the current problems being addressed and assess their astrophysical impact.

Keywords: `elsarticle.cls`, LaTeX, Elsevier, template

2010 MSC: 00-01, 99-00

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Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

1. Introduction to the Wootton Center for Astrophysical Plasma Properties

Goals of the WCAPP. Foremost among the many purposes of the Wootton Center for Astrophysical Plasma Properties (WCAPP) is to train the next generation of scientists to develop expertise in atomic physics and spectroscopy. This is important for the national interest. In parallel it involves lab scientists in fundamental science research that is publishable in the open literature. The graduate students and postdocs spend a significant fraction of their time in residence at Sandia National Laboratories (SNL). This not only makes them aware of the national labs, but introduces them to the scientific culture of the lab. This benefits the students by enlarging their scientific horizons and career options for their futures. It benefits the nation by developing and expanding a much-needed talent pool for the national laboratories. The emphasis of WCAPP on astrophysically relevant experiments increases the attraction of working and collaborating with the center as well as generating press and popular science coverage that advances the public image of the national laboratories (e.g. *Sky and Telescope*, Oct. 2019 [1]).

The Four Current WCAPP Experiments on Z. At present, we carry out experiments on the Z-machine at Sandia National Laboratories, the most powerful X-ray source in the world [2]. These experiments not only *involve* graduate students and postdocs, but also are often *led by* these junior colleagues.

One consequence of pulsed power experiments is that there are a limited number of shots available. This is particularly true of the Z-machine. The highest practical repetition rate is one shot per day. The allocation for fundamental science shots is about 10% of the total scheduled experiments per year, on average. Thus, each shot represents a very precious resource. For this reason, we typically field at least four independent astrophysical experiments simultaneously on each shot [3, and references therein]. This remains our optimum strategy for maximizing the scientific return of WCAPP shots.

The goal of the current suite of four experiments is to measure plasma properties in the laboratory under cosmic conditions, at-parameter. The purpose is to test the fundamental constitutive atomic physics that underlies the astrophysical models and provide benchmarks of the opacity, radiative transport and the response of the atoms to their plasma environs.

We have identified a variety of astrophysical objects where there is evidence that our understanding of the underlying plasma properties is incomplete or wrong. The current four experiments are designed around the constraint of improving our understanding and modeling of our Sun and Sun-like stars [see 4, 5], white dwarf photospheres [6] and the physics of accretion disks around supermassive black holes and other compact objects [7]. This includes experiments designed to study atomic kinetics in warm-absorber photoionized plasmas, studies of Resonant Auger Destruction(RAD) in Active Galactic Nuclei (AGNs) and Radiative Recombination Continuum in accretion powered objects. Already, Loisel et al. [7] have shown that the RAD model proposed by Ross and Fabian [8] to explain the line observations is contradicted by experiment: RAD is not 100% effective.

The four current experiments (see Figure 2) are the following:

- Stellar interior opacities
- Atomic kinetics in warm-absorber photoionized plasmas: code validation
- Resonant Auger Destruction and Radiative Recombination Continuum in accretion-powered objects
- White dwarf photospheres: line broadening

The X-rays from Z are used to produce macroscopic astrophysically relevant plasmas that persist for a long time relative to atomic processes. It is in this sense that the experiments on Z are at-parameter: We make “starstuff” in lab.

2. The White Dwarf Photosphere Experiment

This experiment was first conceived based on problems reconciling the mass and temperature distribution of white dwarf populations in the various morphological parts of our galaxy. Determinations of the mass are necessary for deriving an accurate relative age from their distributions' populations. This technique was developed by Winget et al. [9, see Figure 3] and used to show that the Hubble, or expansion age of the Universe was probably seriously overestimated based on prevalent estimates of the expansion age of the universe—the so-called Hubble age—as reported by many astronomers. This work demonstrated the importance of WD cosmochronometry, by reducing the age estimates of our own galaxy by about a factor of 2 (see, e.g., Peebles, in his book, Physical Cosmology [10], for a discussion). Following this, a the re-measurement of the Hubble constant, H_0, by Freedman et al. [11] using a large study of Cephieds with the Hubble Space Telescope (HST) demonstrated that the new value of H_0 is consistent with the White Dwarf Luminosity Function (WDLF) age of the disk of our galaxy. Many puzzles remained however, even after this factor of 2 was shaken out. This indicates the importance of chronometers that are independent of a particular cosmological model. This is as true now as it was then, especially with uncertainties in the history of dark energy.

Among these puzzles was the inconsistency of masses of white dwarf stars determined in multiple ways. Falcon et al. [12] developed a new technique that averaged out the random space motions of an ensemble of nearby white dwarf stars, so that the underlying systematic gravitational redshift [e.g., see 13, 14] of their spectroscopic lines could be determined, leading to a determination of the average mass of the sample. This work indicated that there may be a systematic underestimate of the mean mass of white dwarf stars. As the inset equation in Figure 3 shows, the age of the white dwarf stars is a function of the mass, so the uncertainties in mass limit WD cosmochronology.

Also illustrated in this figure, is the physical nature of white dwarf evolution: it is dominated by cooling, or release of the thermal energy stored in the core by prior nuclear burning and contraction. Due to electron degeneracy in the core, the WD eventually stops contracting. Energy is still radiated into space and lost by the star, so it cools. Thus the evolution, or cooling, demands that the space density of white dwarf stars increases as the luminosity drops from cooling. The basic slope of the luminosity function is easily understood in this way from the theory of Mestel [15]. We mention that for purposes of clarity in this discussion, we ignore the loss of energy in high temperature WDs from plasmon neutrinos, the added energy at low temperatures from the latent heat of crystallization, and the change due to Debye cooling of the resulting crystalline solid, although this information is included in the theoretical models shown. The boxed equation in Figure 3 shows that the cooling age of a white dwarf increases as the mass increases and the luminosity decreases. Eventually, at low luminosities, the finite age of the disk results in a precipitous drop in the space density of white dwarfs. Finding this in the stars, as the plot of the observational data shows, is the way to accurately read the age of a population of white dwarf stars.

In observations of stars, the WDs are easily distinguished from other less compact stars by their spectroscopically broad lines—caused by the high pressure at their photospheres where their light is emitted. A spectral type DA, or surface hydrogen, white dwarf star is shown in Figure 4. By far the leading way to determine the mass—or more concretely the plasma parameters at the surface of a white dwarf from which the mass is inferred— is fitting of the lines, in this case Balmer lines of hydrogen, in optically observed spectra. On the face of it, the line broadening models seem to give a very accurate way to fit the hydrogen Balmer lines in the optical spectra. Things are not quite as straightforward as they seem.

Figure 5 illustrates this point well. It shows fits to the Balmer lines in an observed white dwarf spectrum, used to determine surface gravity and effective temperature. In this figure, the same spectrum is fit, first with only Hβ then in each subsequent fit, the next higher order line is added to the fit and plotted as another point. The plot is from Tremblay and Bergeron [16] using the line profiles of [17]. As we would expect, the error ellipses get smaller as more lines are included. Note that the best fit point moves down to lower gravity as each successive line is added to the fit. This indicates that the individual line fits give different plasma conditions. Using the new line profiles of Tremblay and Bergeron reduces the size of this trend, but fitting different lines still gives different answers for the plasma conditions. This has been studied systematically in a large sample of DAs by Josh Fuchs in his Ph.D. thesis [18]. This is one of our motivations for the need for benchmark hydrogen plasma experiments. Is this because the calibrations for the theoretical models are based on emission line measurements? This result, along with the inconsistency of white dwarf masses from different methods, indicates that the absorption lines should be benchmarked in the laboratory, where the physical conditions are measured independently.

The Z Platform for the WDPE. The first work on white dwarfs at Z was led by R.E. Falcon, initially as a part of his PhD dissertation [19]. He continued to develop this platform as a postdoc at Sandia National Laboratories. The gas cell design and configurations evolved quickly in the beginning [20] and the last major platform change is the Absorption, Continuum, Emission (ACE) configuration gas cell described by Falcon et al. in 2015 [6] and shown in Figure 6. This last design allows the simultaneous measurement of the absorption, continuum and emission spectra.

The results of these experiments are shown for absorption lines in Figure 7. The independent fit for the emission lines of Hβ and Hγ give consistent measures of the plasma conditions, particularly with the latest generation of line profiles by Thomas Gomez [21]. The absorption lines, however, do not give consistent plasma conditions, no matter what line profile models are used. The plasma conditions from our experiments are shown as a function of shot time for a representative shot in Figure 8. The main takeaway from this is that the Hβ lines are consistently almost 40% higher in electron density than Hγ. What is very interesting is that this is consistent with the trend measured from absorption lines in observed white dwarf spectra.

This makes the laboratory result even more important. In his 2018 Ph.D. thesis [22] and subsequent publication [23], Schaeuble and collaborators examined the possible explanations for this result in our experiments. They used simulations to point out that this is not due to any reasonable possible inhomogeneities in the laboratory plasmas. Why this should be—if not due to some experimental error we haven't thought of yet—remains a mystery.

3. The Future

We are currently carrying out further hydrogen experiments to test the simulations which show the trend in electron density is not an experimental artifact of some kind. We will use measurements along the lines of sight in the gas cell to empirically determine the variation in derived electron density plasma parameters (See Figure 9).

Helium white dwarfs (called DBs) also suffer from mass determination issues. As shown in [24] and [25] as well as Fig. 10, DB WDs suffer from an unexpected surface gravity ($\log g$) increase at low surface temperatures ($T_{\rm eff}$). The origins of this behavior are currently unknown, but it seems unlikely that these trends are representative of the true DB mass-temperature relationship. If the trends depicted in Fig. 10 were real, they indicate that older (and therefore cooler) DBs are much more massive than younger (hotter) ones. A stellar evolutionary scenario that explains this behavior would be difficult to reconcile with the currently accepted WD evolutionary models [24, 25].

An incomplete helium neutral broadening model is a much more likely explanation for the $\log g$ trends observed in Fig. 10. At precisely the temperature at which the upturn in DB $\log g$ becomes evident, neutrals are the dominant source of line broadening in DB atmospheres. The WD community currently uses the [26] and [27] models to account for this effect [28]. However, these calculations were developed for the sun, whose atmospheric density is about 5 orders of magnitude lower than that of a DB. Our initial neutral broadening experiments seem to confirm the suspicion that neutral helium broadening is not correctly accounted for in WD atmospheric models and suggest the theoretical broadening is underestimated. If these experimental results are confirmed, this would imply that electron broadening is overestimated in DB atmospheres, leading to the overestimated $\log g$ values at lower $T_{\rm eff}$, just as observed in Fig. 10.

In addition to our work on white dwarfs with H and He atmospheres, we have recently modified our standard gas cell to achieve the higher temperatures ($\sim 20,000$ K) necessary for benchmarking the spectra of the carbon atmosphere hot DQ white dwarfs [29]. These stars likely result from the merger of two white dwarf stars, making them "failed Type Ia supernovae" [30]. As such, they have relevance to cosmology, but our understanding of them has been hindered by our inability to determine accurate spectroscopic $\log g$ values, which is a result of uncertainties in the theoretical broadening of C II. Our measurements will enable us to test the input physics to the model atmospheres, resulting in believable surface gravity determinations of these stars, allowing us to better understand their evolutionary origins.

4. Acknowledgements

We acknowledge support from the Wootton Center for Astrophysical Plasma Properties under the United States Department of Energy collaborative agreement DE-NA0003843, from the United States Department of Energy grant under DE-SC0010623, and from the National Science Foundation grant under AST 1707419.

This work was performed at Sandia National Laboratories. We thank the Z-facility teams and in particular G. Loisel, D. Scogiletti, S. Patel, D. Begay, D. Bliss, K. Shelton, A. York, and K. MacRunnels for their support. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA 0003525. This

paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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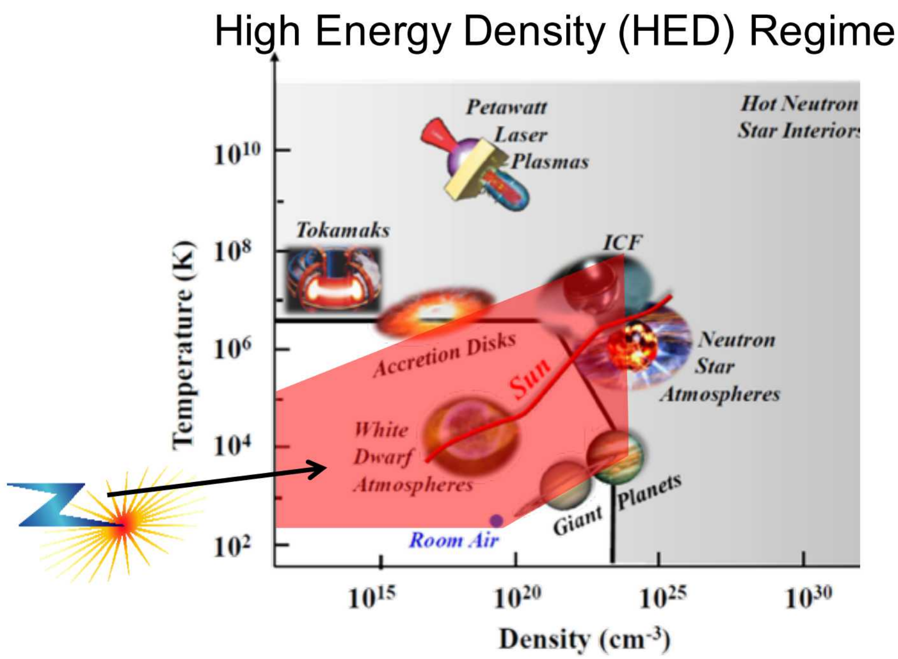

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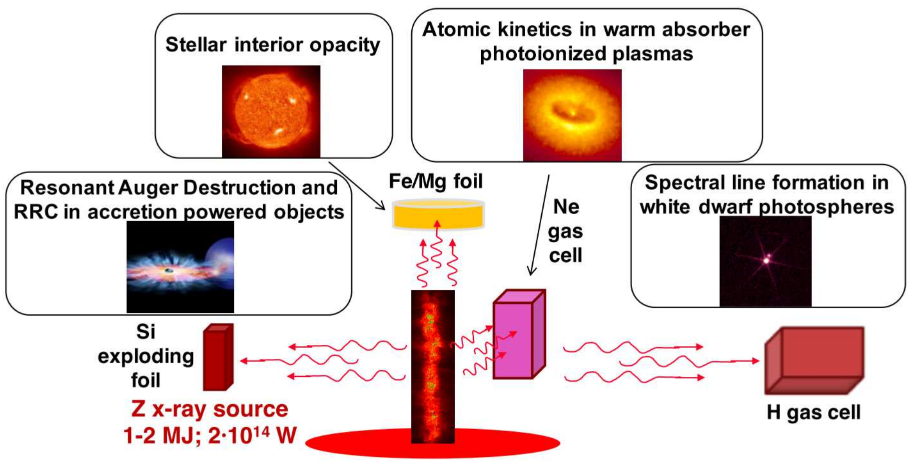

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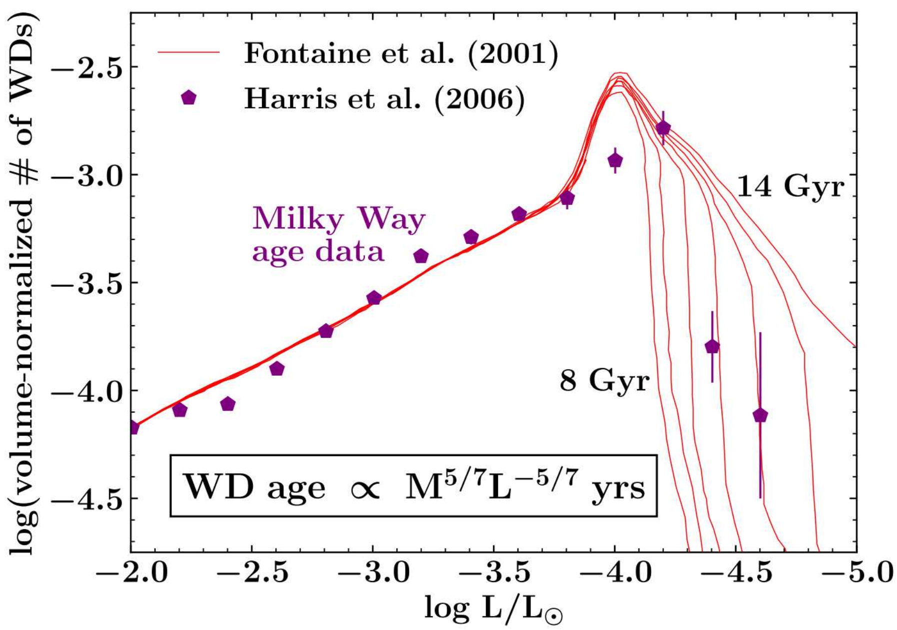

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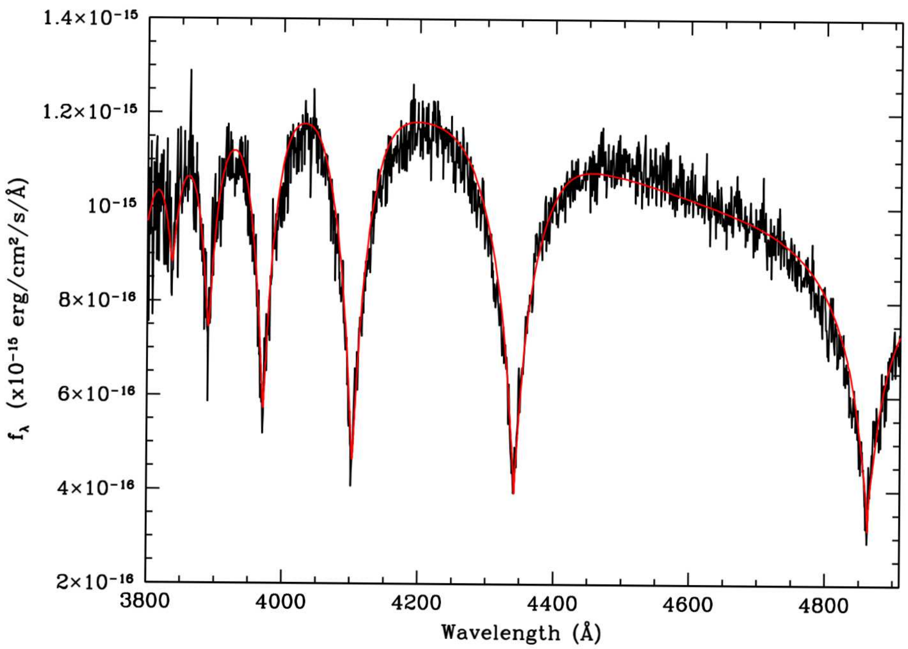

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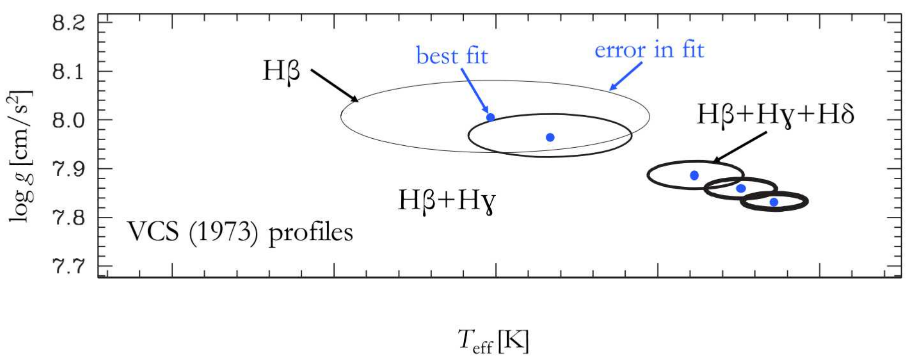

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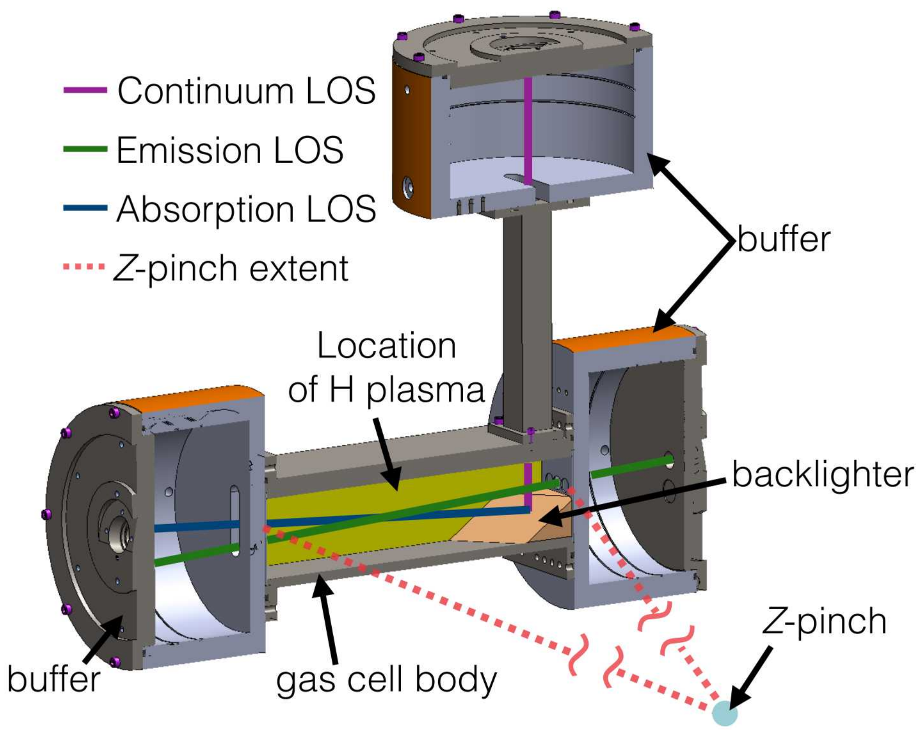

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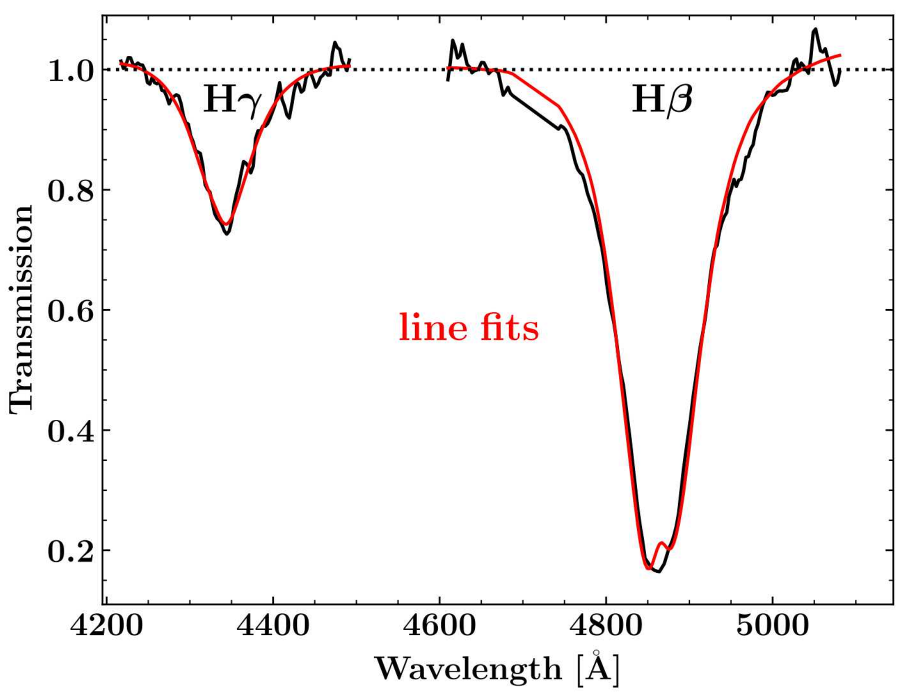

Figure 7: The Hβ and Hγ lines in absorption measured in one of our gas cells, plotted with fits at one of the electron densities during a shot. Figure from Schauble et al. (2019) [23].

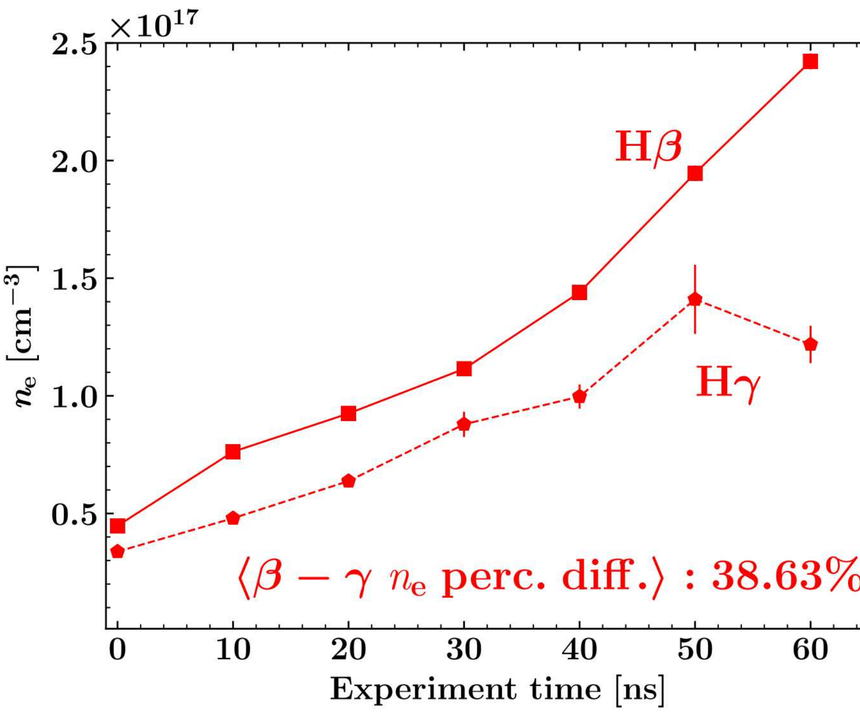

Figure 8: The electron density determined from fits using line broadening models of Gomez et al. (2016 and 2019) over the changing electron density of 60 ns in experiment time; this relative difference is model independent and corresponds to roughly a 40% decrease in electron density from Beta over Gamma. Figure from Schauble et al. (2019) [23].

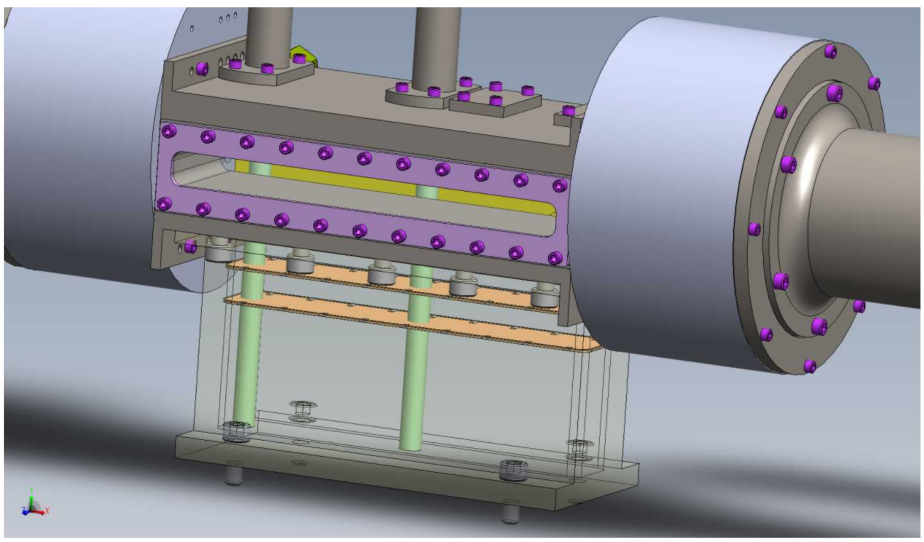

Figure 9: The modified cell design to measure any spatial inhomogeneities in the plasma along the absorption or emission line of sight.

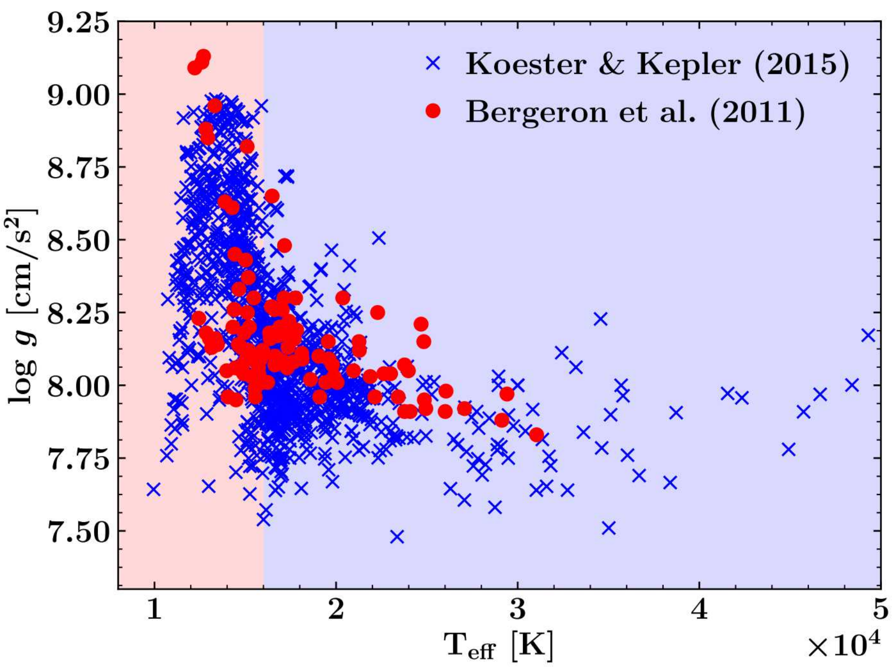

Figure 10: Unphysical increase in surface gravity, log g, vs effective temperature ($T_{\rm eff}$). Our hypothesis is that neutral He-broadening is underestimated.