White Paper for *Frontiers of Plasma Science Panel*

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Title:	Theory of Plasmas in White Dwarf Stars
Corresponding Author:	Didier Saumon
• Institution:	Los Alamos National Laboratory (LANL)
• email:	dsaumon@lanl.gov
Co-Authors:	Jerome Daligault (LANL) Charles Starrett (LANL)

Theory of Plasmas in White Dwarf Stars

Didier Saumon, Jérôme Daligault, Charles Starrett
Los Alamos National Laboratory

- **Research Frontier and importance of the scientific challenge.**

The vast majority of stars end their lives as white dwarf stars, the slowly cooling embers produced by the earlier phases of nuclear fusion. This will be the fate of the Sun about 5 billion years from now. White dwarfs are very common stars -- thousands are known --, are well-characterized observationally, and form a class of rather exotic stars: they pack about the Sun's mass of material in a volume the size of the Earth (Fontaine et al. 2001, Hansen & Liebert 2003). Proceeding from the surface to the center of a white dwarf, the constitutive plasma goes from a nearly ideal, partially ionized plasma of hydrogen at a temperature of ~ 1eV, to a fully ionized, solid density helium plasma and up to a strongly coupled plasma of carbon/oxygen with fully degenerate electrons at a density of ~ 10^6 g/cm^3 and a temperature of several 100 eV.

A detailed knowledge of the underlying plasma properties across this wide range of conditions is essential for the realistic modeling of these stars. While the properties of matter near the surface are well described by mature theories, such as the Saha equation for ionization equilibrium of a low-density plasma, the strongly-coupled Coulomb mixtures in the interior and, to a greater extent, the intermediate regime of warm dense matter are much less well understood.

Thus, models of the structure, evolution, spectra and of stellar pulsations of white dwarfs are sensitive to the properties of warm dense matter. A survey of current state-of-the-art white dwarf models reveal that much of the constitutive physics is out of date (often by decades) if not boldly interpolated across the warm dense matter regime where no results are available. Important physical quantities that are poorly known include the equation of state, the optical properties, and the ionic (e.g., mutual diffusion and thermal diffusion coefficients) and electronic transport properties (e.g., thermal conduction). These are needed for both single-component plasmas and for (at least) binary mixtures.

Similarly, a much better description of the plasma interior is desirable that accounts for the quantum, wave-mechanical character of the ions. Indeed, under the extremely high densities of white dwarfs cores, the thermal de Broglie wavelength of the ions is a significant fraction of their average inter-particle distance. The effect becomes more pronounced in higher mass stars since they have a smaller radius and therefore denser cores. The prime physics questions are the impact of the ionic quantum effects on the phase diagram and transport properties of fluid carbon/oxygen mixtures, and on the diffusion of impurities like ^{22}Ne that are believed to play a non-negligible role on the cooling evolution of white dwarf stars (Deloye & Bildsten 2002)

In the next 4-5 years, the European Space Agency mission Gaia (launched in 2013) will produce a catalog of positions and motions of astonishing precision for 1 billion stars, including 10^5 white dwarfs (Gaensicke et al. 2015).This profusion of accurate data will severely test current models of white dwarfs stars, and efforts towards a better understanding of the exotic underlying plasma conditions are timely.

- **Approach to advancing the frontier.**

Critical needs to help improve the plasma physics relevant to white dwarfs modeling include:

- Development of ab initio simulation algorithm that can handle large warm dense matter systems (>10^5 ions, mixtures) over long ionic time scales (>10^5 inverse plasma frequency). The prevalent simulation tools in use today, such as quantum molecular dynamics with or without orbitals or path-integral Monte-Carlo methods, are unable to efficiently describe the range of chemical compositions, concentrations and physical conditions typical of white dwarfs. Large scale simulation tools are particularly useful to validate practical models (see below), and to give insights into the microphysics. The development of new algorithms and simulation codes is typically poorly supported, which forces the community to rely on codes designed for other purposes.
- Development of simple, more efficient models that can produce large tabulations of results that can be directly used in astrophysics codes. Of particular interest are models of warm dense matter that are self-consistent, i.e. that can produce both the thermodynamic and transport properties within the same framework. Stellar astrophysics codes typically demand that calls to routines providing the microphysics be fast, such as a table lookup or evaluation of a closed-form equation.
- Development of new theoretical approaches to account for the quantum character of ions on the properties of white dwarf interiors. Here, unlike the electrons in dense plasmas and metals, ions are not degenerate, and the main effect to describe is quantum diffraction during collisions.

- **Impact on plasma science and related disciplines, and potential for societal benefit**.

White dwarfs are a fertile ground to apply models of warm dense matter in regimes that are not achievable in the laboratory. Moreover, they offer a unique opportunity for physicists studying dense plasmas to contribute significantly to an important field of astrophysics. Aspects of white dwarf research that will be directly affected by such work include refined studies of their internal structure from white dwarf pulsations, the inference of the nature and composition of solid planetary material infalling onto the surface (the fact that such material survived the earlier phases of the star's evolution is quite exotic in itself) (Jura et al. 2015), as well as the inference of the age of our Galaxy and of clusters of stars from their cooling white dwarf population (Fontaine et al. 2002). The astrophysical impact will be substantial as it overlaps with stellar evolution prior to the white dwarf stage, cosmochronology of stellar systems, and the survival of planetary systems, which we now know are ubiquitous around stars that will become white dwarfs (Petigura et al. 2013). The modeling tools that will result from the efforts proposed herein will benefit the experimental and theoretical efforts that are underway to understand the warm dense matter regime.

References (Maximum 1 page)

Deloye, C.J. & Bildsten, L. 2002, Astrophys. J. 580, 1077

Fontaine, G., Brassard, P. & Bergeron, P. 2001, Publ. Astron. Soc. Pacific,113, 409

Gaensicke, B. et al. 2015, Asp conf. Ser., in press. http://arxiv.org/abs/1506.02653

Hansen, B.M.S. & Liebert, J. 2003, Ann. Rev. Astron. Astrophys., 41,465

Jura et al. 2015, Astrophys. J. 799, 109

Petigura, E.A., Howard, A.W. & Marcy, G.W. 2013, PNAS 110, 19273

Figures (maximum 1 page)