This conference brings together the communities of white dwarf modelers and dense matter physicists to foster new collaborations and identify astrophysical problems that can be addressed with advanced physical theories, simulations, and experiments. White dwarf stars represent the end stage of the life of the vast majority of stars, including our Sun. These common stars are the sites of exotic physical conditions that are not encountered in other stars. Matter in such extreme conditions is beginning to be probed experimentally. Historically, theoretical work in dense plasma physics has found fertile applications in white dwarf models. The astrophysics of white dwarfs is a mature field, yet modern observations challenge many aspects of the models in regimes ranging from the relatively low-density gas at the observable surface through the deeper regions of partial ionization to the dense core. In many instances, modern physical theories, simulation methods and experimental techniques can be fruitfully applied to drive the field to a new level of understanding and resolve outstanding astrophysical problems.

Workshop Organizers

Didier Saumon (Los Alamos National Laboratory, USA, chair)
Leah Gonzalez (Los Alamos National Laboratory, USA, conference coordinator)
Simon Blouin (U. Victoria, Canada)
Jérôme Daligault (Los Alamos National Laboratory, USA)
Stephanie Hansen (Sandia National Laboratories, USA)
Amy Lazicki (Lawrence Livermore National Laboratory, USA)
Nicole Reindl (U. Heidelberg, Germany)

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Agenda

Sunday, March 24, 2024

5 - 7 pm -- Conference registration and reception

Monday, March 25, 2024

Overview Talks on White Dwarf Stars and Warm Dense Matter

Chair: Didier Saumon

8 - 8:45 a.m. — Breakfast
8:45-9 a.m. — Welcome address Didier Saumon

9 a.m. - 11:45 a.m. — Speaker Sessions

- 9:00-9:45 a.m. The Astrophysics of White Dwarfs — Ingrid Pelisoli
- 9:45-10:30 a.m. The physics of white dwarf interiors — Antoine Bédard
- 10:30-11:00 a.m. — **Break**
- 11:00-11:45 a.m. The Physics of White Dwarf Atmospheres — Mark Hollands

11:45 a.m. - 1:00 p.m. — Lunch

1 p.m. - 4:15 p.m. — Speaker Sessions

- 1:00-1:30 p.m. Unveiling White Dwarf Pulsations: A Window into Stellar Remnants — Leila Calcaferro (V)
- 1:30-2:15 p.m. White dwarfs as laboratories for fundamental physics — Marcelo Bertolami (V)
- 2:15-2:45 p.m. — **Break**
- 2:45-3:30 p.m. Theoretical approach for warm dense matter — Ronald Redmer
- 3:30-4:15 p.m. TBD (Experimental probes of warm dense matter) — Gilbert Collins

4:15 6:00 p.m. — Poster Session

Tuesday, March 26, 2024

Theme: Equations of State and Transport

Chair: Charles Starrett

8 - 9:00 a.m. — Breakfast

9 a.m.-Noon — Speaker Sessions

9:00-9:30 a.m. Equation of State — Frank Timmes

9:30-10:00 a.m. Describing the interior of white dwarfs with density functional theory – future or fiction? — Mandy Bethkenhagen

10:00-10:30 a.m. — **Break**

10:30-11:00 a.m. Material Properties from Average Atom Models — Stephanie Hansen

11:00-11:30 a.m. Models for Plasma Transport in the Challenging Conditions of White Dwarf Envelopes — Scott Baalrud

11:30-12:00 a.m. Recent Developments in the Theory of Electron Conduction Relevant to White Dwarf Envelopes — Nathaniel Shaffer

12:00 a.m. - 1:30 p.m. — Lunch

1-1:45 p.m. — Speaker Sessions

1:30-2:00 p.m. White dwarf photospheres on the benchtop — Stewart McWilliams

2:00-2:30 p.m. TBD (Warm dense matter experiments with lasers) — Tilo Doeppner

2:30-3:00 p.m. — **Break**

3 p.m. – 4:15 p.m. — Focused Discussion: EOS & transport — Moderator: Evan Bauer

4:15 - 6:00 p.m. — Poster Session

Wednesday, March 27, 2024

Theme: Crystallization

Chair: Jérôme Daligault

8 - 9:00 a.m. — Breakfast

9 a.m. – 11:45 a.m. — Speaker Sessions

9:00-9:30 a.m. The Impact of Phase Separation on White Dwarf Evolution and Cooling — Evan Bauer

9:30-10:00 a.m. 64 years of studies of plasma crystallization in white dwarfs — Denis Baiko (V)

10:00-10:15 a.m. — **Break**

10:15-10:45 a.m. Phase Diagrams for White Dwarf Core Crystallization — Simon Blouin

10:45-11:15 a.m. Separation and Diffusion in Crystallizing White Dwarfs — Matt Caplan

11:15-11:45 a.m. Crystallization Dynamos — Sivan Ginzburg

11:45 a.m. - 12:45 p.m. — Lunch

12-45 p.m. - 2:00 p.m. — Focused Discussion: Crystallization — Moderator: Simon Blouin

2 pm — Free time

Thursday, March 28, 2024

Theme: Opacities

Chair: Patrick Dufour

8 - 9:00 a.m. — Breakfast

9 a.m. - 11:30 a.m. — Speaker Sessions

9:00-9:30 a.m. Sources of opacity in white dwarfs stars	Michael Montgomery
9:30-10:00 a.m. Line profile models	Evgeny Stambulchik
10:00-10:30 a.m. — **Break**	
10:30-11:00 a.m. White Dwarf Spectra in the Lab	Bart Dunlap
11:00-11:30 a.m. Oxygen opacity experiments for stellar and white dwarf interiors	Daniel Mayes

11:30 a.m. - 1:00 p.m. — Lunch

1:00 - 2:00 p.m. — Speaker Sessions

1:00-1:30 p.m. Atomic data for White Dwarf spectroscopy	Matti Dorsch
1:30-2:00 p.m. Ultra High Excitation white dwarfs	Nicole Reindl
2:00-2:30 p.m. — **Break**	

2:30 4- :00 p.m. — Focused Discussion: Opacities — Moderator: Stephanie Hansen

4:00 - 6:00 p.m. — Poster Session

6:30 – 8:30 p.m. — Banquet

Friday, March 29, 2024

Theme: Magnetism

Chair: David Colas

8 - 9:00 a.m. — Breakfast

9 a.m. – 11:45 a.m. — Speaker Sessions

9:00-9:30 a.m. Observations of Magnetic White Dwarfs	Stephano Bagnulo
9:30-10:00 a.m. Origins of White Dwarf Magnetic fields	Matthias Schreiber
10:00-10:15 a.m. — **Break**	
10:15-10:45 a.m. Impact of magnetism on white dwarf atmospheres and interiors	Pier-Emmanuel Tremblay
10:45-11:15 a.m. Quantum chemistry simulations for the assignment of spectra from strongly magnetized white dwarf stars	Stella Stopkowicz (V)

11:15-11:45 a.m. Line profiles with combined Stark & Zeeman effects

Sandrine Ferri

11:45 a.m. - 12:45 p.m. — Lunch

12:45-2:00 p.m. — Focused Discussion: Magnetism Moderator: John Landstreet

2:00 p.m. — Wrap up

Invited talks Abstracts

(Alphabetical Order of Surname)

Models for Plasma Transport in the Challenging Conditions of White Dwarf Envelopes

S.D. Baalrud[1], J. Daligault[2], C. E. Starrett[2], D. Saumon[2], and R. A. Heinonen[3]

[1] Nuclear Engineering and Radiological Sciences, University of Michigan
[2] Los Alamos National Laboratory
[3] Department of Physics, University of Rome, Tor Vergata
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Abstract

The plasma in white dwarf envelopes reaches a warm dense matter regime that challenges theoretical models for transport properties. Its challenging because ions can range from weakly to strongly correlated, while electrons can range from classical to degenerate. This is a state that is too cold and dense for plasma models to apply, but too hot for condensed matter models to apply (or be computationally tractable). Here, we describe a method to extend plasma models into the warm dense matter regime. A new expansion parameter for the BBGKY hierarchy is proposed that provides an ordering related to the deviation of the system from equilibrium, rather than the strength of correlations [1,2]. This leads to an equation that is similar to a Boltzmann equation, but where particles interact through the potential of mean force, rather than the Coulomb potential. It also captures exact equation of state properties in the classical limit. The potential of mean force is computed using the average-atom two-component plasma model [3]. Considering ion transport properties, such as diffusion and viscosity, this has been shown to accurately extend plasma theories well into the warm dense matter regime, corresponding to coupling parameters less than approximately 10. Tests of these coefficients were performed with molecular dynamics simulations.

This talk will also discuss an application of this model to diffusion times of Si and Ca in the context of pollution of white dwarf photospheres by accretion of solid planetary material [4]. The model shows a factor of ~3 difference in comparison to previous leading models [5], and better agreement with molecular dynamics simulations. A main conclusion is that this provides a more accurate description of transport properties in dense plasmas, is relatively inexpensive to evaluate, and therefore may be of interest to models of transport properties in white dwarf astrophysics.

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[1] Baalrud and Daligault, Phy. Rev. Lett. 110, 235001 (2013).
[2] Baalrud and Daligault, Phys. Plasmas 26, 082106 (2019).
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[5] Paquette, Pelletier, Fontaine, and Michaud, Ap. J. Supp. 61, 177 (1986)

LA-UR-24-22175

Observations of Magnetic White Dwarfs

Stefano Bagnulo & John Landstreet

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Abstract

Until recently, our knowledge of the magnetic fields in white dwarfs came as a by-product of spectroscopic surveys, which are generally magnitude limited in nature and constrained by a low signal-to-noise ratio. Consequently, observations tended to favor strong magnetic fields in the youngest, brightest stars, leading to a biased representation. Recent spectro-polarimetric, volume-limited surveys have changed this perspective. These new surveys have detected magnetic fields even in featureless, or nearly featureless stars, and have probed samples representing the true population of white dwarfs in the solar neighborhood with significantly greater accuracy than before. As a result, they have allowed us to uncover clear patterns in the distribution of magnetic fields across the Cooling Age - Mass diagram. In this talk, we will present the results of these surveys and discuss their implications for the theories that attempt to explain the origin of magnetic fields in degenerate stars.

64 years of studies of plasma crystallization in white dwarfs

Denis Baiko

Abstract

After a brief summary of dense plasma properties with a focus on phase diagrams of crystallizing fully ionized mixtures, their types, representations, and astrophysical significance, a review is given of extensive theoretical efforts to understand the physics of the ion-plasma crystallization in compact stars undertaken over the past 64 years since the first suggestion of this possibility by David Kirzhnits in 1960. We describe the already classic sequence of one-component plasma studies; various first-principle and semi-analytical methods; the impressive progression in understanding the phase diagram of the C/O mixture, most relevant for the inner layers of white dwarf stars; the importance of ternary systems and theoretical approaches to their analysis; the effects of ion motion quantization; the research on multicomponent plasmas anticipated in accreted neutron star crusts; and more. While the main aspects of plasma crystallization physics seem to be understood, several remaining issues are outlined. These include detailed properties of random lattices (whether they are in fact random and whether they are necessarily of the body centered cubic type), self-consistent and eventually quantum thermodynamics of binary and ternary plasmas, liquid-like low-*Z* ions within the lattices, kinetics of the crystallization process and resulting macrostructures (eutectic systems, phase separation in the solid phase, possibility of the epitaxial crystal growth).

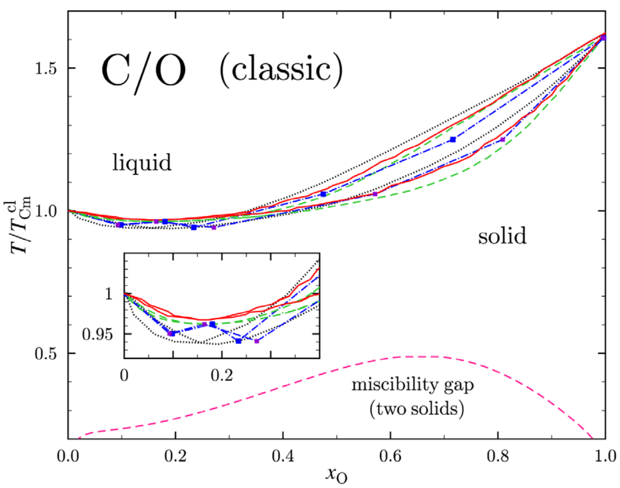

Figure: Phase diagram of fully ionized classic C/O plasma according to Ichimaru, Iyetomi & Ogata (1988) dotted black; Medin &Cumming (2010) dashed green; Horowitz, Schneider & Berry (2010) dot-dashed blue; Blouin et al (2020) solid red. Dashed pink: miscibility gap according to Baiko (2022).

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The Impact of Phase Separation on White Dwarf Evolution and Cooling

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Abstract

Phase separation of crystallizing carbon-oxygen plasma mixtures has long been understood to have an important impact on white dwarf cooling timescales. The last five years have seen reinvigorated interest in this subject for at least two reasons. First, new data from *Gaia* have suggested that at least some cooling white dwarfs experience processes related to phase separation leading to significantly more dramatic internal rearrangement than previously expected. Second, there is potential for the fluid mixing associated with phase separation to generate a dynamo that may explain some categories of white dwarf magnetism. This talk will review some aspects of phase separation that have become well-established in stellar evolution models such as MESA, and attempt to clarify where there is still room for improvement in the ways that our understanding of the physics of this process is translated into implementation for evolution codes, such as assumptions about the nature and timescales of fluid mixing excited by phase separation.

The physics of white dwarf interiors

Antoine Bédard

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Abstract

This talk will provide an overview of the physics of white dwarf interiors. I will first review the chemical composition and physical conditions encountered inside white dwarfs, from the dense carbon-oxygen core to the thin hydrogen-helium envelope. I will then discuss how these basic features shape their structure and evolution. In particular, I will describe the two main factors governing the slow cooling process of white dwarfs, namely, the storage and transport of thermal energy across the stellar interior. I will also highlight key events impacting the cooling rate at specific stages of the evolution, such as neutrino emission, core crystallization, and convective coupling. Finally, I will discuss the causes and effects of chemical element transport in the core and envelope of white dwarfs.

White dwarfs as laboratories for fundamental physics

Marcelo M. Miller Bertolami

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Abstract

To a first approximation, the evolution of white dwarfs can be understood as a gravothermal cooling process in which the basic ingredients are well identified. This peculiarity makes white dwarf stars, and collections of white dwarfs, very good candidates for testing physics beyond the Standard Model of Particle Physics. Any new physics that alters the cooling process through either heating or cooling of the white dwarf interior is expected to produce observable consequences that can help constrain or refute that new physics. Upcoming ground- and space-based observatories will offer an improved view of white dwarf stars both individually and as a population, improving our ability to use them as laboratories of fundamental physics. There are two main ways to test the cooling rate. One is the so-called luminosity function of a white dwarf population, and the other is the period drift of individual white dwarfs that experience non-radial pulsations. Each approach has its advantages and disadvantages. In this presentation, we will review how these techniques are applied and their shortcomings. And review the latest advances in applying these techniques to test physics beyond the Standard Model.

Describing the interior of white dwarf stars with density functional theory – future or fiction?

Mandy Bethkenhagen

LULI, CNRS UMR 7605, CEA, Sorbonne Université, École Polytechnique - Institut Polytechnique de Paris, France

Accurately modeling warm dense matter deep inside astrophysical objects is generally a great challenge. The associated thermodynamic states are characterized by solid-state densities, temperatures of thousands of Kelvin, and GPa pressures. The extreme of the conditions can vary gravely depending on the mass, radius, and composition of the studied object ranging from several GPa in planetary mantles to millions of GPa at the center of stellar interiors. A method that has proven highly successful in describing this peculiar state of matter is density functional theory molecular dynamics (DFT-MD). However, while the equations of states and transport properties for planets like Jupiter or even brown dwarfs became increasingly accessible with DFT-MD simulations in the last two decades, extreme conditions as predicted for the interiors of white dwarfs seem beyond the method's reach or at least at the limit of its capabilities.

In this talk, I will give an overview of recent theory advances in the field of density functional theory (e.g. spectral DFT [1], extended first-principles MD [2], orbital-free DFT [3]) that potentially allow us to describe the extreme density states in the interior of white dwarfs. In particular, I will show exemplary for carbon the capabilities of DFT to obtain the equation of state and transport properties including the ionization degree that is derived from the dynamic electrical conductivity [4].

References

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Phase Diagrams for White Dwarf Core Crystallization

Simon Blouin

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Abstract

The crystallization of the dense plasma found in white dwarf cores triggers various fractionation processes that separate elements between the coexisting liquid and solid phases. This chemical separation releases a sizable amount of gravitational energy, which can slow down the cooling of white dwarfs by up to multiple billions of years. Constraining this source of energy requires reliable phase diagrams to quantify the amplitude of the composition contrast between the liquid and solid phases. This is not only an interesting physics problem, but also a prerequisite for the use of old crystallized white dwarfs as accurate cosmic clocks.

Since the first edition of this conference in 2017, it has become possible to test our understanding of this chemical separation thanks to exquisite data from the Gaia mission, which has stimulated new theoretical efforts. In particular, the fractionation of trace species, until recently ignored in white dwarf evolution codes, has been under the spotlight.

In this talk, I will first give an overview of the different simulation techniques currently used to calculate phase diagrams of dense plasmas. After highlighting the strengths and weaknesses of each approach, I will present recent results produced by these techniques and their implications for white dwarf cooling. Finally, I will discuss outstanding questions that require further efforts on the theoretical front.

Unveiling White Dwarf Pulsations: A Window into Stellar Remnants

Leila M. Calcaferro

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Abstract

White dwarf (WD) stars represent the final evolutionary stage for more than 95% of all stars, including our Sun. Therefore, their study is fundamental in our understanding of the formation and evolution of stars, as well as the history of the Milky Way itself.

In recent years, the discovery that many stars, including WDs, exhibit pulsations has presented a significant opportunity to probe the interior of these stellar remnants. The field of stellar pulsations, also known as asteroseismology, has emerged as a powerful tool for studying WDs. By comparing the observed frequencies (periods) of pulsating stars with theoretical models, asteroseismology enables us to infer details about their origin, internal structure, and evolutionary history. Furthermore, this technique provides insights into properties such as stellar mass and rotation profile.

During this talk, we will delve into the properties of WDs and their pulsations, highlighting the various subtypes of pulsating WDs. We will discuss recent observational and theoretical progress in the field while exploring key areas for further research to enhance our models and comprehension of these fascinating objects.

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Separation and Diffusion in Crystallizing White Dwarfs

Matt Caplan

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Abstract

Much progress has been made in recent years on understanding the microphysics of crystallizing white dwarfs. Molecular dynamics simulations have proven especially valuable, being an irreplaceable tool for directly simulating crystallizing mixtures of astrophysical interest and in determining diffusion coefficients to high precision. I will summarize molecular dynamics simulations of several mixtures whose neutron rich nuclei may be important heat sources, including C-O-Ne, C-O-Fe, and O-Ne-Fe. A variety of phenomena are evident in these simulations, including direct confirmation of distillation in crystallizing mixtures. In addition, diffusion coefficients are important to this heat source as they determine the drift velocity of floating or sinking clusters. We report on new molecular dynamics simulations of diffusion in Coulomb plasmas near crystallization and describe our attempts at building a universal model for diffusion that accurately predicts diffusion coefficients across coupling regimes and screening lengths.

TBD (Experimental probes of warm dense matter)

G. Collins[1]
[1]*University of Rochester*

Observing the onset of pressure-driven K-shell delocalization*

T. Doeppner[1], M. Bethkenhagen[2], D. Gericke[3], D. Kraus[4], B. Bachmann[1], D. Chapman[5], M. Boehme[6], L. Divol[1], T. Dornheim[6], R. Falcone[7], L. Fletcher[8], M. Kruse[1], O. Landen[1], M. MacDonald[1], S. Glenzer[8], R. Redmer[4], M. Schoerner[4], P. Sterne[1], J. Vorberger[6]

[1]Lawrence Livermore National Laboratory, [2]University of Lyon, [3]University of Warwick, [4]University of Rostock, [5]First Light Fusion, [6]Helmholtz-Zentrum Dresden-Rossendorf, [7]University of Berkeley, [8]Stanford Linear Accelerator Laboratory

We have developed an experimental platform for x-ray Thomson scattering (XRTS) at NIF to characterize plasma conditions in indirectly-driven ICF capsule implosions near stagnation [1,2]. This enabled us to investigate up to 30 times compressed ablator materials reaching pressures above 3 Gigabars, at conditions where the distance between the nuclei becomes comparable to the extent of the core shell bound states, which will eventually lead to their pressure ionization. In this talk we will present results from experiments with beryllium shells. We observe reduced elastic scattering for the most extreme conditions [2]. We interpret this reduction as the precursor of pressure ionization of the remaining K-shell electrons, that is, a strongly modified bound state. The beryllium charge state inferred from the data is considerable higher than standard models predict but agrees well with results from DFT simulations [2,3]. Accurate modelling of the K-shell occupation of light elements is imperative for creating predictive capabilities for ICF implosions. Our experiments yield valuable benchmarks for this process and demonstrating a complex pathway of pressure ionization.

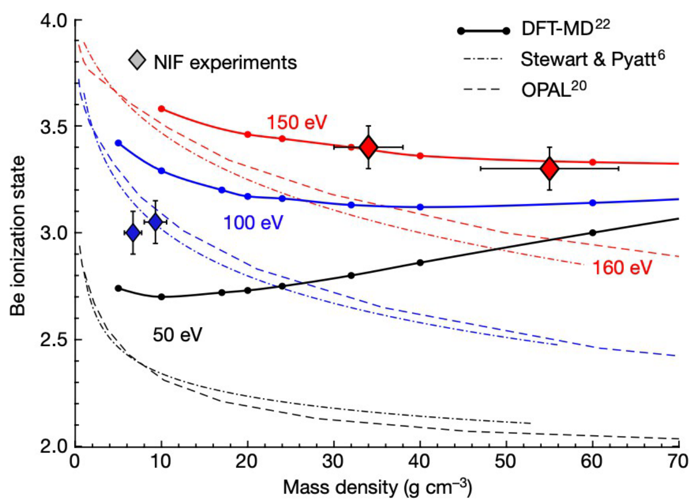

Fig. 1: For mass densities higher than 30 g/cc, NIF experiments [2] find significantly higher charge states than predicted by widely used ionization models but are in good agreement with quantum simulations (DFT-MD, [3]).

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[3] M. Bethkenhagen et al., Phys. Rev. Res. **2**, 023260 (2020).

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Atomic data for White Dwarf spectroscopy

Matti Dorsch

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Abstract

I will focus on atomic data for spectral line modelling in hot subdwarf and white dwarf stars. This includes wavelengths, oscillator strengths, and line broadening data, for commonly observed metals but also exotic elements, such as heavy s- and r-process elements. There is a large range of ionisation stages that need to be covered, given that hot subdwarfs and WDs can be amongst the hottest stars known, but then cool down to low temperatures. This data is not only relevant directly for line formation, but also for the opacity used in atmospheric structure calculations, diffusion calculations, and pulsation calculations. Collisional and photoionisation data will be discussed in the context of line formation. I will also summarise sources of atomic data: databases and individual calculations and experiments.

White Dwarf Spectra in the Lab

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Abstract

Much of what we know about white dwarf stars depends on fundamental properties inferred from model fits to their spectra. However, the values of surface gravity and temperature resulting from such fits systematically disagree with independent determinations using photometry and parallax. There is also evidence that the model spectra are internally inconsistent. This highlights the importance of examining the input physics of the model spectra. However, white dwarf atmospheres are sufficiently hot and dense that it is challenging to produce and study laboratory plasmas at the conditions necessary to test theoretical models. Nonetheless, using the 200 TW of x-ray power generated by the Z Machine at Sandia National Labs, it is possible to achieve the relevant temperatures and densities. We will describe our experimental measurements of these macroscopic plasmas, discuss recent platform developments aimed at making our measurements more reliable and robust, and place the results in their astrophysical context. We will also discuss possible directions for future experiments and briefly advertise the related theoretical work our group is pursuing.

Line profiles with combined Stark & Zeeman effects

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Abstract

Spectroscopic diagnostic techniques are based on comparing observed and modeled spectra. Their reliability requires accurate calculation of emission or absorption spectra, implying the use of analytic methods and computer codes of differing complexity and applicability limits. I present, here, a Stark-Zeeman spectral line-shape model and the associated numerical code, PPPB, designed to provide fast and accurate line shapes for arbitrary atomic systems for a large range of plasma conditions [1]. PPPB uses a B-field dependent atomic physics, including the quadratic Zeeman terms, that allows to go beyond the weak- and strong-field limits. The Stark effect is modeled by the standard line-broadening approach, i.e. quasi-static ion and impact electron approximations, augmented by the frequency fluctuation model [2,3] to account for the effect of ion dynamics. Application to hydrogen and helium line-shape calculations will be presented and the range of validity of the model and its limitations in the context of white dwarfs will be discussed.

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Crystallization Dynamos

Sivan Ginzburg[1*], Daniel Blatman[1], Jim Fuller[2]

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A convective dynamo operating during the crystallization of white dwarfs is one of the promising channels to produce their observed strong magnetic fields. However, the magnitude of the generated field is uncertain due to challenges in understanding the velocity of the convective flows and the scaling laws that govern magnetic dynamos. Timing the appearance of strong fields may serve as an orthogonal test of this channel's contribution. When white dwarfs begin to crystallize, the magnetic field is initially trapped inside the convection zone. Only once convection approaches the white dwarf's atmosphere, the field diffuses out to the surface, where it is observed. This magnetic breakout depends critically on the phase diagram of crystallizing white dwarfs, as well as on their initial chemical profile before crystallization. It is therefore sensitive to the nuclear reaction rates and to the convective boundary mixing processes in the white dwarfs' progenitor stars.

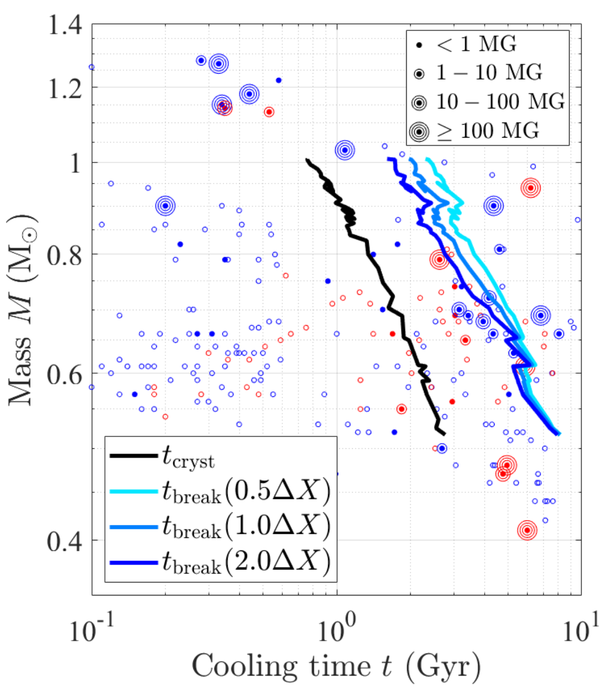

Figure 1: Magnetic fields break out to the white dwarf's surface several giga-years after the onset of crystallization. The figure demonstrates the dependence of the breakout time on the crystallizing Carbon – Oxygen phase diagram. Observed strongly magnetized white dwarfs are indicated by multiple surrounding circles.

References:

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2. Daniel Blatman & Sivan Ginzburg, 2024. MNRAS, 528, 3153 – 3162.

Material Properties from Average Atom Models

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Abstract

Understanding the properties of matter over a wide range of extreme conditions is a key part of reliably predicting the structure and evolution of white dwarf stars. With its combination of strong coupling, thermal, and degeneracy effects, the warm dense matter (WDM) regime offers particular challenges for material models. Multi-center models that use density functional theory (DFT) to simulate electronic structure and response offer reliable predictions for equation of state and transport properties of WDM, often at significant computational expense. Average-atom (AA) models, which collapse multi-center electronic structure onto a single atomic center, can capture similar physics in WDM liquids with much less computational expense, making these models well suited for producing tables of material properties. This talk will introduce the fundamentals of quantum AA models, compare their predictions with other modeling approaches, and describe extensions to standard AA models that enable accurate predictions of ionic transport coefficients and opacities.

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The Physics of White Dwarf Atmospheres

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Abstract

All light detected from distant stars is emitted from their atmospheric outer layers. Consequently, all investigations into their properties depend on a detailed understanding of the physics of stellar atmospheres, a fact which is equally true for white dwarfs. Where white dwarf atmospheres differ from their main sequence (Sun-like) counterparts is their much more extreme physical conditions owing to the compact nature of these stellar remnants. For example, the pressure, density, and magnetic field in a white dwarf atmosphere may be many orders of magnitude higher those in the Solar photosphere, and thus bespoke physics is required to accurately model their observational spectra.

In this talk, I will introduce the physics required to model white dwarf atmospheres, and how these are applied to observational spectra to infer stellar properties. I will cover recent advances in various aspects of white dwarf atmospheric physics such as convection, line profiles, and magnetism, while also discussing areas in need of further improvement.

Oxygen opacity experiments for stellar and white dwarf interiors

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Abstract

Opacities are one of the mechanisms within stars that control the flow of energy outward to the surface. To accurately model stellar interior structure and evolution, one must have accurate model calculations for the opacities of matter at the conditions within the star. For stars like the Sun, this can affect, for example, the predicted location of the base of the convection zone (CZB). In white dwarf stars (WDs), it can affect not only the predicted structure, but also the rate at which WDs are predicted to cool, affecting ages inferred when WDs are used as chronometers. To test opacity model predictions at stellar interior conditions, experiments at the Z Facility and the National Ignition Facility (NIF) are ongoing to measure the photon energy resolved opacity of iron and oxygen. The two platforms are considerably different from one another but are complementary because they allow cross-comparison of the experimental results. Previously, the experiments at Z revealed severe model-data discrepancies in iron opacity as conditions approach the solar CZB, suggesting that revisions may be needed for opacity theory as temperature and density are increased. Oxygen opacity is important in both WDs and the Sun, and it may be more affected by any inaccuracies in how density effects are handled when computing the opacity at stellar interior conditions. This talk will focus on the progress of the oxygen opacity experiments at each facility. It will discuss the experimental platforms, the methods used for diagnosing experiment conditions and measuring opacities, as well as some of the preliminary results from each platform.

This work was supported in part by the Wootton Center for Astrophysical Plasma Properties (WCAPP), the Z Fundamental Science Program, and NIF's Discovery Science Program. WCAPP is supported by the National Nuclear Security Administration, Stewardship Science Academic Alliances under Award Number DE-NA0004149.

White dwarf photospheres on the benchtop

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Abstract

The photospheres of white dwarf stars are central in our understanding of these objects, with the assumed properties of photospheres affecting models for structure, thermal evolution, composition, and age, and hence the interpretation of observational data. The conditions of white dwarf photospheres can occur at high density and low temperature conditions, difficult to accurately describe theoretically e.g. with conventional plasma physics models – but which are reachable in laboratory experiments. This enables direct evaluation of optical properties for relevant warm dense matter systems such as dense helium and hydrogen. I will discuss efforts to measure optical opacity and its spectral dependence at relevant conditions, establishing key physical properties for white dwarf stellar matter, with an emphasis on use of static pre-compression in diamond anvil cells combined with laser excitation to reach (and probe) relevant states [1,2]. I will explore how behavior of these warm dense materials often deviates from a conventional plasma viewpoint, with opacity and its spectral character more resembling the behavior of condensed matter, dominated by absorption from localized electronic states not included in typical stellar opacity models, having unusually high opacities at low density and temperature, and exhibiting opacity rising toward the blue near visible wavelengths possibly reddening photospheres dominated by such matter. I will also discuss emerging experimental techniques that expose a wider range of properties for relevant states of matter, including thermal conductivity [3], viscosity [4], and chemistry [5].

References:

[1] R. S. McWilliams, et al.. *Opacity and conductivity measurements in noble gases at conditions of planetary and stellar interiors*. Proceedings of the National Academy of Sciences **112**.
[2] R. S. McWilliams et al.. *Optical Properties of Fluid Hydrogen at the Transition to a Conducting State*. Physical Review Letters **116**, 255501 (2016).
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[4] H. B. Bartlett et al. *Viscosity measurement from microscale convection at high pressure and temperature*. Physical Review B **101**, 144202 (2020).
[5] M. Frost *et al. Diamond precipitation dynamics from hydrocarbons at icy planet interior conditions*. Nature Astronomy (2024).

Sources of Opacity in White Dwarf Stars

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Abstract

Opacity in stars controls the flow of radiation from the central regions to the surface. Since nuclear energy generation is negligible in white dwarfs (WDs), the opacity determines how quickly both the core and photosphere of the star evolve to cooler temperatures. Due to their higher gravities, the photospheres of WDs are relatively dense, complicating calculations of their spectral features and necessitating the use of concepts such as Occupation Probability. In this talk, we will concentrate on the current state of modeling of spectral features in WDs, focusing on atomic features involving hydrogen and helium, as well as the molecular opacities found in cool WDs, e.g., collisionally-induced absorption of the H_2 molecule.

The Astrophysics of White Dwarfs

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Abstract

Most stars are born with masses not exceeding ten times the mass of the Sun. After exhausting the hydrogen fuel in their cores, these stars might proceed to burn helium, but they will not reach conditions to fully fuse carbon before electron degeneracy sets in. Instead, after a phase of shell-burning that strips the outer layers of the star, they will leave behind a degenerate core with a light atmosphere – a white dwarf star. White dwarfs are thus the most common stellar remnants, offering not only insight into stellar evolution and galactic structure, but also presenting extreme conditions that allow for tests of fundamental physics. Obtaining large samples of observed white dwarfs is the first step required to exploit this stellar population. Photometric and spectroscopic surveys targeting blue objects were the main detection method until very recently, which often led to complicated observational biases due to colour selections. The *Gaia* mission has revolutionised this field by providing precise photometric and, importantly, astrometric data that allowed the identification of hundreds of thousands of white dwarf candidates. In particular, *Gaia* enabled the compilation of volume-limited samples which are less subject to selection biases, allowing more straightforward comparisons to models. The data provided by *Gaia* can also be used to derive white dwarf physical parameters – specifically temperature and surface gravity – but, given the lack of detailed spectroscopic information, assumptions are required about the atmospheric composition. Improved parameters can be obtained by combining *Gaia* data with spectroscopic follow-up. The advent of large spectroscopic surveys, combined with targeted efforts for nearby samples, is now providing extremely well-characterised benchmark samples that offer new challenges to white dwarf modelling. In this talk, I will provide an overview of the astrophysics of white dwarfs covering their formation channels and main characteristics, as well as how we find and characterise white dwarfs using observational data.

Theoretical approach for warm dense matter

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Abstract

The behavior of warm dense matter is of paramount importance for modeling the interior, evolution, and magnetic field of solar and extrasolar planets. While the lightest elements H and He are the main components of gas giants like Jupiter [1], H-C-N-O mixtures are relevant for Neptune-like planets [2], and minerals of the MgO-FeO-SiO_2 complex [3] are the building blocks of rocky planets (Earth, super-Earths). However, the high-pressure phase diagram of these elements and mixtures is not well known, in particular the slope of the melting line. Furthermore, insulator- to-metal transitions and phase separation may occur which have a strong impact on interior, evolution, and dynamo models and, simultaneously, constitute a major challenge to high-pressure, plasma, and computational physics.

Molecular dynamics simulations based on finite-temperature density functional theory (DFT-MD) are used to calculate the equation of state [4-6], the high-pressure phase diagram [7,8], and the transport properties [9] of warm dense matter for a wide range of densities and temperatures as typical for the interior of planets. The theoretical predictions can be verified by laser-heated diamond-anvil-cell and shock- wave experiments [10] and are applied to construct improved interior, evolution, and dynamo models for solar and extrasolar planets.

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[1] R. Helled, G. Mazzola, R. Redmer, Nature Rev. Phys. **2**, 562 (2020)
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[9] M. Preising et al., Astrophys. J. Suppl. **269**, 47 (2023)
[10] M. Millot et al., Nature **569**, 251 (2018)

UHE white dwarfs

Nicole Reindl

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Abstract

What happens when a star transforms into a white dwarf? Admittedly, for about 10% of all stars in the universe we fail to answer this question, because – suddenly – these freshly born white dwarfs display weird absorption lines, which were tentatively identified as Rydberg transitions of ultra highly excitation (UHE) metal lines. This UHE phenomenon is known for almost three decades, yet no satisfying answer has been found. In this talk I will present recent progress on UHE white dwarfs that was made thanks to Gaia, photometric surveys like TESS or ZTF, dedicated spectroscopic and spectropolarimetric follow-up, and discuss open questions.

Origins of White Dwarf Magnetic fields

Matthias R. Schreiber & Diogo Belloni

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Abstract

Roughly 20 per cent of all white dwarfs are strongly (>1MG) magnetic. These magnetic fields tend to appear late in the life of a white dwarf (at cooling ages of 2- 4 Gyr). While the first magnetic field of a white dwarf was detected more than 50 years ago, we still struggle to understand the origin of these magnetic fields. To give you a complete picture of our current understanding, I will briefly review observational constraints from single white dwarfs (Bagnulo & Landstreet 2021; Hernandez et al. 2024) and especially white dwarfs in different close binary star settings (e.g. Parsons et al. 2021). I will then confront these observational constraints with the predictions of currently discussed scenarios for the generation of white dwarf magnetic fields, such as the white dwarf merger theory, the fossil field scenario, and in particular, the rotation and crystallization driven dynamo idea (Isern et al. 2017, Schreiber et al. 2021; Ginzburg et al. 2022; Schreiber et al. 2022; Schreiber et al. 2023; Belloni et al. 2024). While we do not have a definitive answer as to where white dwarf magnetic fields come from, I will try to leave you with clear insight into the strengths and weaknesses of our current theories.

References:

Bagnulo & Landstreet, 2021, MNRAS 507, 5902 Belloni et al. 2024, A&A, submitted
Ginzburg et al. 2022, MNRAS 514, 4111 Hernandez et al. MNRAS, in press

Isern et al. 2017, ApJ Letters, 836, 28
Parsons et al. 2021, MNRAS 502, 4305 Schreiber et al 2021a, Nature Astronomy 5, 648 Schreiber et al. 2022, MNRAS 513, 3090 Schreiber et al. 2023, A&A Letters, 679, 8

Recent Developments in the Theory of Electron Conduction Relevant to White Dwarf Envelopes

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Abstract

The envelope of a white dwarf acts as an insulating layer between the radiating core and the convective atmosphere. Because of this, the cooling of white dwarfs is sensitive to the thermal conductivity of the envelope. The difficulty is that envelope conditions frequently correspond to those of a non-ideal, partially degenerate plasma, for which no simple models of the thermal conductivity exist. I will explain where and why standard conductivity models fail in white dwarf envelopes. Next, I will give an overview of some modern theoretical and computational approaches that try to fill in the gaps. I will present cooling sequences of DA and DB white dwarfs which illustrate the sensitivity of the cooling process to the particular choice of conductivity model. Finally, I will summarize the current state of theory for electron conduction relevant to white dwarfs, emphasizing the uncertainties that remain and some appealing directions for further progress.

Line profile models

Evgeny Stambulchik

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Abstract

Line-shape analysis is an important diagnostics tool used for laboratory and space plasmas alike. The talk will cover the theory of line-shape formation, focusing on the conditions found in white dwarf stars. Established models, their limitations, and recent advances in the field will be discussed.

Quantum chemistry simulations for the assignment of spectra from strongly magnetized White Dwarf Stars

Stella Stopkowicz[1,2]

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Abstract

Transition wave lengths and oscillator strengths are typically employed in the assignment of observational White Dwarf spectra via modelling within atmospheric codes. The corresponding input-data comes from high-level calculations as well as experiment. This approach works very well and has found its way into standard modelling of synthetic spectra. However, many White Dwarf stars are strongly magnetized and can exhibit magnetic-field strengths of up to about 100 MG. While for low magnetic fields, their effect can be taken into account in a perturbative manner, this is no longer the case for very strong magnetic fields. Well within the MG regime, the spectra change in complex and non-intuitive manners, hampering their assignment. It is then required to take the magnetic field into account within so-called finite-field calculations. In Fig. 1, an example of synthetic spectra from finite-field calculations together with B-λ curves is shown for transitions of Mg, Ca, and Na in different magnetic field strengths [1]. In this presentation, I will discuss the current challenges in the prediction of strong-field White Dwarf spectra using finite-field quantum-chemical methods.

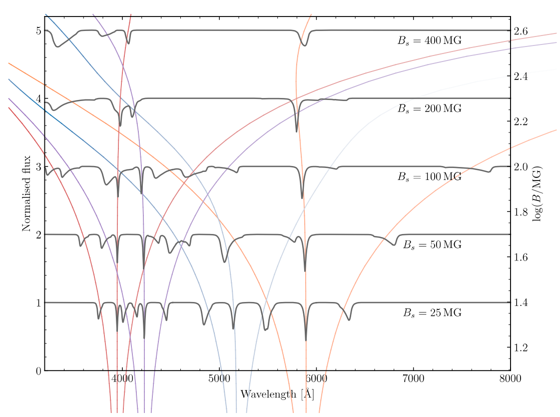

Fig. 1: Predicted spectra for selected transitions of Na, Mg, and Ca in varying magnetic field strengths, taken from Ref [1].

References:

[1] M. A. Hollands, S. Stopkowicz, M.-P. Kitsaras, F. Hampe, S. Blaschke, and J.J. Hermes, *Mon. Not. R. Astron. Soc.* **520**, 3, 3560–3575 (2023)

Equation of State

F.X. Timmes

Arizona State University fxtimmes@gmail.com

Abstract

I offer a broad overview of the thermodynamics relevant for white dwarf stars.

Impact of magnetism on white dwarf atmospheres and interiors

Pier-Emmanuel Tremblay

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Abstract

I will review the influence of magnetism on both the atmospheric and interior properties of white dwarfs. In contrast to reviews that predominantly focus on spectral lines under magnetic fields, I will discuss magnetic effects on convective and conductive energy transfer, and the implications for white dwarf model spectra, cooling sequences and spectral evolution. The presentation will include findings from magneto-hydrodynamics 3D simulations and evolution models incorporating magnetic effects. I will highlight the fundamental distinction between inhibition of convective energy transfer in the presence of magnetic fields, as opposed to the effects on chemical (metal or hydrogen) mixing.

Poster session

(In presentation order)

White dwarfs astrophysics

New Massive and Ultra-Massive White Dwarf Models
Ana SR Antonini and Alejandra D Romero

Investigating the Temperature Dependence of DA White Dwarf Structure using SDSS and Gaia Observations
Nicole R. Crumpler, Vedant Chandra, Nadia L. Zakamska, Gautham Adamane Pallathadka, and Stefan Arseneau

Hunting for Polluted White Dwarfs using Gaia XP Spectra and UMAP
Malia Kao, Keith Hawkins, Jason Sanders, Laura Rogers, and Amy Bonsor

Tidal heating and mass transfer stability in hot white dwarf binaries
Lucy O. McNeill, Ryosuke Hirai

Using observations of local 40 pc white dwarfs to inform modelling
Mairi O'Brien, Pier-Emmanuel Tremblay, et al.

Updated Spectroscopic Analysis of Hot DQ White Dwarfs
Olivier Vincent, Patrick Dufour, Pierre Bergeron

Asteroseismology

The Blue Edge of the DB Instability Strip
J. L. Provencal, M. H. Montgomery, J. J. Hermes, A. Nitta, S. J. Kleinman, Z. Vanderbosch

Constraints from parallaxes and average period spacings in the asteroseismic study of DAVs
Agnes Bischoff-Kim, Keaton Bell

Asteroseismic analysis for the most massive pulsating white dwarf: J0049-2525
Ozcan Caliskan, Mukremin Kilic, Adam G. Moss, Alejandro H. Córsico, Francisco C. De Genórimo, Ingrid Pelisoli, Vikram S. Dhilon, Steven G. Parsons

What's Happening in There? Using Photometry and Asteroseismology to Model GD 358
Kaylee E. Grace, Judith L. Provencal

Reclassifying the Instability Strip: An Asteroseismic Analysis of GD 358 and other White Dwarfs
Nova Moore, Paul Bradley, Aaron LaCluyzé

Asteroseismological Chronicle of the White Dwarf G29-38
Steven Z. Savery, Judith L. Provencal

Direct mass of a single white dwarf via astrometric microlensing
Peter McGill

On white dwarf internal stratification: Insights from asteroseismology
S. Charpinet, V. Van Grootel, W. Su, N. Giammichele and P. Brassard

Magnetism

Magnetic field breakout from white dwarf crystallization dynamos
Daniel Blatman, Sivan Ginzburg

Simulated outflows from accreting magnetized white dwarfs
M. Cemeljic, W. Kluzniak

First step to uncover the origin of high magnetic field in WDs: A convective, earth-like dynamo?
Mayusree Das, Piyali Chatterjee, Arpita Roy

Signs of Binary Evolution in 7 Magnetic DA White Dwarfs

Adam Moss, Mukremin Kilic, P. Bergeron, Megan Firgard and Warren Brown
Rotation in the magnetic white dwarf sample
Larissa Luciano Amorim and S. O. Kepler
White Dwarf Rotation
Gabriela Oliveira da Rosa, S. O. Kepler and Keaton J. Bell

Crystallization

Simulation of Freezing in Dense Yukawa Plasmas
B. Arnold, S. X. Hu, J. Daligault, D. Saumon
A Short Intense Dynamo Following Crystallization in White Dwarf Stars
Matias Castro-Tapia, J. R. Fuentes, Andrew Cumming, Shu Zhang
Fluid Mixing during Phase Separation in Crystallizing White Dwarfs
M. H. Montgomery and Bart H. Dunlap
Molecular Dynamics of O-Ne-Fe Coulomb Crystals
Nevin Smith, Matt Caplan

Opacities

A statistical approach to Stark broadening for complex ions
K. Adler [a], T. Gomez [b], N. Shaffer [c], C. Starrett [d], S. Hansen
Electronic structure analysis and radiative properties of FeH
Isuru R. Ariyarathna, Jeffery A. Leiding, Amanda J. Neukirch, and Mark C. Zammit
Development of Spectral Line Shapes for Magnetic White Dwarfs
Thomas Gomez, Mark Zammit, Christopher Fontes, Jackson White, Igor Bray, Zethran Berbel
Hydrogen line shape modeling with account of extreme magnetic fields
J. Rosato
Addressing the statistical properties of plasma electric microfield in the presence of a strong magnetic field using classical molecular dynamics
D. Guerroudj, J. Rosato, S. Ferri
Stark Broadened Atomic Line Shape Calculations Relevant to Hot DQ White Dwarfs
Bryce Hobbs, Thomas Gomez, Mike Montgomery, Zethran Berbel, Jackson White, Don Winget
Stark-Broadened Profiles for Neutral and Ionized Helium Lines Using Computer Simulation
Patrick Tremblay, Alain Beauchamp, Pierre Bergeron
Excited States in Dense Plasmas
C. E. Starrett, T. Q. Thelen, C. J. Fontes, and D. A. Rehn
Full-potential treatment for multiple-scattering calculation of hot dense plasma opacity
H. B. Tran Tan, C. E. Starrett, and C. J. Fontes
Continuum Lowering with Excited States Model
Trinity Thelen, Charles Starrett, Daniel Rehn, Chris Fontes
Exploring Anomalously Low Mass and Temperature White Dwarfs: Radiation Transport Simulations and Opacity Model Testing
Izaiha E. Martinez, Sarah R. Loebman, Howard A. Scott, Hai P. Le, and Paul E. Grabowski
Line broadening calculations for DA white dwarfs using accurate atmosphere models
David Colas, Sandrine Ferri and Joël Rosato
Towards a Direct Measurement of Opacity at Cool White Dwarf Atmospheric Conditions
Paul E. Grabowski, Jeffrey Nguyen, Rob Shelton, Hannah Shelton, and Minta Akin

Low-Temperature Opacity Modeling
Mark C. Zammit, Isuru R. Ariyarathna, James Colgan, Christopher J. Fontes, Aaron Forde, Jeffery A. Leiding, Amanda J. Neukirch, and Eddy Timmermans

EOS & Transport

Platinum in Liquid-Vapor Coexistence
Meghan K Lentz, Michael P Desjarlais, Joshua P Townsend
Reconstruction of 2D Radiographs for Enhanced Equation of State Measurements in the NIF WD Gbar Campaign
W. Martin, D. Swift, D. Saumon, A. Lazicki, T. Doeppner, N. Bhandarkar, S. Blouin, R. Falcone, S. Glenzer, A. Kritcher, R. London, M. Macdonald, B. Militzer, J. Nilsen, P. Sterne, H. D. Whitley
Pressure-ionized diamonds
D. Saumon, A. Lazicki, D. Swift, N. Bhandarkar, S. Blouin, T. Doeppner, R. Falcone, S. Glenzer, A. Kritcher, R. London, M. J. MacDonald, W. M. Martin, B. Militzer, J. Nilsen, P. Sterne, H. D. Whitley
Wide range equation of state for a chemically dissociative system: carbon dioxide
Christine J. Wu, David A. Young, Philip A. Sterne and Philip Myint
Towards a universal scaling law for diffusion in complex plasmas
Dany Yaacoub, Matt Caplan

Warm Dense Matter

Evidence of free-bound transitions in warm dense matter
Tobias Dornheim
Full Kohn-Sham DFT-MD in the Warm Dense Matter and Plasma Regime
Sebastien Hamel, Abhiraj Sharma, Babak Sadigh, John E. Pask
Signatures of Bound States Breaking in Warm Dense Hydrogen and the Relevance of Thermal Exchange- Correlation Effects
Zhandos A. Moldabekov, Sebastian Schwalbe, Maximilian P. Böhme, Jan Vorberger, Tobias Dornheim
Anomalous Sound Speed in Warm Dense Matter
J. Ryan Rygg
Quantum Electronic Response in Warm Dense Matter and Hot Dense Plasmas
Alexander J. White, Vidushi Sharma, Lee A. Collins
Mixed Stochastic-Deterministic Density Functional Theory for Electronic Transport in Matter in the Extremes
Vidushi Sharma, Lee A. Collins, Alexander J. White
Embedding Theory Contributions to DFT-based Average Atom Models for Warm Dense Matter
Sameen F. S. Yunus, David A. Strubbe