Wootton Center for Astrophysical Plasma Properties
Department of Astronomy and McDonald Observatory

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Center Scientific Advisory Committee meeting for the Wootton Center for Astrophysical Plasma Properties

Meeting date: 27 January 2021

Location: Via Zoom

Members of Center Scientific Advisory Committee meeting (CSAC) for the Wootton Center for Astrophysical Plasma Properties (WCAPP) present:

Nancy Brickhouse, Harvard-Smithsonian Center for Astrophysics,
Chris Fontes, Los Alamos National Laboratory
David Kilcrease, Los Alamos National Laboratory
Don Lamb, Department of Astronomy and Astrophysics, University of Chicago
Keith Matzen, Sandia National Laboratories, Albuquerque
Marilyn Schneider, Lawrence Livermore National Laboratory
Hugh Van Horn, Department of Physics and Astronomy, University of Rochester (retired)
Alan Wootton (retired)

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1. Summary

The Wootton Center for Astrophysical Plasma Properties (WCAPP) is engaged in an exciting research program. It is built on the PI's and Co PIs' successful ~5 year Fundamental Science Program at the Z facility at Sandia National Laboratories (SNL), which included the precursor ZAPP (Z Astrophysical Plasma Properties) program. The research focus remains unique: "At-parameter" experiments, with high-fidelity data, resulting in publications with high impact for both astrophysical and DOE/NNSA interests. Efficient use of the Z facility is assured by fielding multiple experiments (typically 4) on every shot. In addition, the Center provides an education leading to a future source of young scientists in the important area of atomic and radiation physics of warm dense matter.

The committee meeting demonstrated that the team, a combination of experimental, theoretical and computational scientists, has made great progress in the past year. An outstanding accomplishment is that they have overcome the well-understood challenge of personnel needs and have recruited the high-quality post-doctoral fellows (postdocs) needed. The three postdocs will be located at SNL and involved in the studies of white-dwarf, solar-opacity, photoionized, and accretion-powered plasma projects. In addition, the graduate-student recruitment problem has been solved, and the pipeline has been restarted.

Findings and Recommendations are given in individual sections, and also in the Final Summary.

2. Introduction

The Wootton Center for Astrophysical Plasma Properties (WCAPP) received funding in February 2018. It is focused on the atomic and radiation physics of matter over a wide range of temperatures and densities. Academics currently funded by the grant are from the University of Texas at Austin (UT) and the University of Reno, Nevada (UNR). The experiments undertaken to date have been performed at the Sandia National Laboratories (SNL) Z Facility. Experiments also are now scheduled for the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL). In addition to the heavily involved SNL staff, there is significant participation from Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL), as well as from the University of Arizona. While motivated by astrophysics, the Center also addresses problems of interest for stockpile stewardship, inertial confinement fusion (ICF) and high-energy-density (HED) physics. This document is a summary of the third meeting of the Center Scientific Advisory Committee (CSAC).

The panel met from 10:00 am CST to 5:00 pm on Wednesday January 27, 2021, using Zoom: The meeting agenda is listed in the Appendix. The discussions were structured around the areas where advice was requested:

a) Is the science planned for years 4 and 5 unique, world-class, and likely to succeed?

b) Are the personnel (including postdocs, students, additional institutions) needed to achieve these science goals adequate for success?
c) In preparation for the period beyond year 5, are there any science ideas that need exploratory studies in the next two years?
d) What renewal strategies are suggested?

3. Discussions, Findings and Recommendations

After presentations and a general discussion with WCAPP researchers (including students) around focused questions, the committee met alone for discussions in the areas noted above. We summarize those discussions below, including any Findings and Recommendations.

3.1 Science in years 4 and 5 (2021 and 2022)

Despite the emergence of the worldwide COVID-19 pandemic in calendar year 2020, WCAPP has succeeded in making substantial progress in each of the four categories of experiments it is conducting at the Z facility at SNL. These experiments have the goals of improving the understanding of (1) spectral-line formation in white dwarfs, (2) the opacity of matter inside stars, (3) atomic kinetics in photoionized plasmas, and (4) radiation from accretion disks around compact objects. This work is first rate: Approximately 15 Fundamental Science shots are available on Z each year and WCAPP scientists have been successful in securing about 40% of them, despite the extremely strong competition. Data for all four areas of investigation are collected in each shot. The Center's unique approach combines observational astronomy, laboratory experiments, theory, and modeling. In addition to performing forefront research, WCAPP scientists also train advanced undergraduates, graduate students, and postdocs in these areas of investigation and expose them to the exceptional capabilities of the NNSA national security laboratories.

3.1.1 White-dwarf photospheres

Measurements of the line profiles in a white-dwarf photosphere can be used to determine the surface gravity g (and therefore the mass M), the composition, and the effective temperature T_{eff} of the white dwarf. The increasing precision of such measurements has made white dwarfs a valuable tool for addressing important astrophysical problems ranging from the age and history of the Galaxy, to the interior compositions of exoplanets, to the nature of Type Ia (thermonuclear powered) supernovae.

The atmospheres of white dwarfs are dominated by either H, He, or C. WCAPP has therefore concentrated on making precision laboratory measurements and improving theoretical modeling of the line profiles of these elements at the temperatures and densities characteristic of white-dwarf photospheres. Center Director Don Winget and Deputy Director Mike Montgomery are recognized world leaders in white-dwarf research, and they are leading the WCAPP effort at UT to measure the absorption-line profiles for H, He, and C at the Z facility.

During 2020, experimental work conducted by Bart Dunlap (UT postdoc), Mike Montgomery and colleagues continued on all three elements, with a significant expansion of the work on C. The first simultaneous absorption/continuum/emission data were collected for DA (H-atmosphere) white dwarfs. For DB (He-atmosphere) white dwarfs, further analysis of the experimental line-profile data has established that well-understood Stark broadening can account for the measured line widths. This means that spectroscopic masses for DB white dwarfs above $T_{eff} > 16,000$ K should be reliable. However, at lower temperatures the spectroscopic fits to the He lines indicate significantly larger masses, which increase as the temperature drops. This result suggests that the atomic physics of atoms immersed in dense plasmas warrants further investigation.

Experiments this year also successfully achieved temperatures and densities characteristic of the photospheres of DQ white dwarfs (i.e., with C-dominated atmospheres). These experiments collected simultaneous absorption/continuum/emission data, allowing transmission measurements, and measured the time evolution of the emission. Initial experimental data were also collected on downward lines of sight that can provide empirical constraints on gradients of the electron density n_e and temperature T_e in the gas cell.

Significant theoretical and modeling work on line profiles was also done. Work by Patty Cho (UT graduate student) included the development of an ability to model experimental plasmas using TLUSTY; significant improvements in Thomas Gomez' Xenomorph code, including cleaner profiles suitable for use in atmospheric models and the ability to treat occupation-probability effects; and development of the ability to generate white-dwarf spectra using the new Xenomorph profiles in TLUSTY. Patty finds that the H-line fits yield measurably higher values for M and T_{eff} than do photometric fits. This result, like the result for He lines at low temperatures discussed above, suggests that the atomic physics of atoms immersed in dense plasmas needs to be investigated thoroughly.

These are significant accomplishments that strengthen the case for renewal of WCAPP.

3.1.2 Stellar-interior opacity measurements

WCAPP scientists have long wanted more involvement in this high-visibility and important project, but the lack of suitable postdocs and graduate students prevented it. This has changed for 2021 and beyond with the recent hiring of postdoc Dan Mayes and the prospective graduate student Malia Kao; both will have the solar-opacity experiments as their focus.

The opacity of matter inside the stars is an essential component of all calculations of stellar structure and evolution. To date, the opacity has mainly been obtained from theoretical models for conditions relevant to the deep interiors of stars. The Sun provides an important testbed for these calculations, but a significant disagreement exists between the internal temperature distribution in the Standard Solar Model and the results obtained from helioseismology. Specifically, solar physicists find that solar models need 10%–30% higher opacities at the base of the convection zone to match the results from helioseismology. Oxygen and iron dominate the opacity in this region. This has led to experiments on Z to measure the Fe and O opacities at the temperatures and densities characteristic of the base of the solar convection zone.

The experimental measurements, which were conducted at SNL by Jim Bailey, Taisuke Nagayama, Guillaume Loisel and colleagues, are significantly higher than theoretical calculations of the Fe opacity at these physical conditions–by an amount that would account for about half of the difference between the opacity used in current solar models and the opacity implied by helioseismology measurements. The experimental Fe results are therefore being revisited, with increased attention to the uncertainties in the experiments, the initiation of time-resolved Fe experiments–because evidence suggests that the physical conditions in the experiments vary with time–and to the first steps to tackle measurements of the oxygen opacity. A systematic study of the experimental results has also revealed that a discrepancy appears at open L-shell configurations (i.e., in Cr and Fe but not in Ni), suggesting possible problems with calculations of the equation of state and spectral-line shapes. New experiments–and improved estimates of the uncertainties–have reduced the model discrepancy to ~ 3 sigma for the Fe quasi-continuum at shorter wavelengths, although about a 10 sigma difference remains in the windows between the strong lines at longer wavelengths. This is important progress.

We look forward to WCAPP participation in this research, including the possibility of performing high-fidelity exploratory two-dimensional (2D) simulations followed by high-fidelity, three-dimensional (3D) simulations. Such simulations could be done with a well-established simulation package (e.g., FLASH, which works seamlessly with Prism Scientific's Spec3D package), which would enable a WCAPP graduate student or postdoc to do them. We commend WCAPP for its efforts to recruit a graduate student who could carry out these simulations.

3.1.3 Photoionized plasmas

Photoionization in astrophysical plasmas depends upon the atomic kinetics driven by both photons and electrons. The UNR team led by Roberto Mancini and his colleagues is developing a gas cell for use at the SNL Z facility to study these phenomena. Current investigations indicate that the astrophysical codes Xstar and CLOUDY significantly overestimate the electron temperature in photoionized plasmas, demonstrating the need for data to benchmark these codes. To date, work has focused on the development of the gas cell and on producing appropriate Photon Doppler Velocimetry (PDV) diagnostics. Three experiments at Z–using both the UNR gas cell and the University of Michigan gas cell–have been performed with empty cells. They have demonstrated the importance of shielding the gas cell and have identified radiation-induced darkening of the optical fibers used to transmit the data from the gas cell to the instruments as an important experimental problem to be addressed. They are also planning the first experiments with an argon-filled gas cell. However, while interesting physics is being probed, the overall strategic goal of these experimental campaigns was not clear to the CSAC. Development of the PDV diagnostic will provide velocity data for the first time, but the purpose and value of these data were not made adequately clear.

New time-gated results have also provided data on the time evolution of the plasma near the X-ray drive peak. This represents a distinct advance, and it shows that the time-integrated data agree with the time-gated data.

3.1.4 Black-hole accretion-disk radiation

The analysis of radiation from accretion disks around compact objects currently relies on theoretical models that have not been adequately tested, making the results obtained for the compact objects (neutron stars, black holes, and active galactic nuclei) uncertain. The goal of this project is therefore to build a laboratory analog of the X-ray emission from an astronomical accretion disk. The experimental work at Z, conducted by Guillaume Loisel and colleagues, is designed to obtain all the necessary input data to benchmark the astrophysical models for accretion-disk emission from a single Z shot. During 2020, this group obtained the first laboratory measurements of the radiative recombination continuum in photoionized plasma.

A particularly important current problem is that the inferred Fe abundance exceeds the abundance expected from normal stellar evolution by large factors in some accretion-powered black-hole X-ray sources. During 2020 the team attacked this problem by obtaining the first photoionization laboratory observations of L-shell emission from Fe. UT graduate student Patty Cho has joined the team and is working to identify Fe lines in these spectra that have never been reported before. Investigations in this focus area will be very important not only for providing benchmark data to improve current astrophysical codes but also for interpreting the results from future space missions. These accomplishments represent important progress.

Finding 1:
WCAPP is continuing to conduct important experiments on the Z facility at SNL. WCAPP scientists are continuing to identify opportunities for new experiments relevant to each of the Center's four main areas of investigation.

Recommendation 1:

a) *WCAPP should continue to conduct experiments to measure the line profiles of H, He, and C under conditions found in the atmospheres of white dwarfs, especially at lower temperatures and higher densities. These line profiles are important for addressing important astrophysical problems ranging from the age and history of the Galaxy, to the interior composition of exoplanets, to the nature of thermonuclear-powered supernovae.*
b) *WCAPP should continue to use the experimental data for H and He from Z to update the astrophysical line-profile and model-atmosphere codes and to extend this work to C when sufficient experimental data become available. This will enable astrophysicists to benefit fully from this experimental work.*
c) *The opacity of matter inside stars is essential for obtaining accurate stellar models, which underpin our understanding of much of astrophysics. The critical investigations of the Fe opacity should be continued, and WCAPP's newly begun investigations of O, which is the dominant opacity source at the base of the solar convection zone, should be pursued.*

d) *Photoionization is ubiquitous in astrophysical plasmas, and it is important to be able to determine the ionization equilibrium in such plasmas in order to determine the properties of many astrophysical sources. Attention should be given to solving the radiation-darkening problem, which is key to obtaining useful data.*
e) *Experiments relevant to X-ray emission from accretion disks are of fundamental importance for astrophysics and should be continued; in particular, experiments probing the cause of the apparent overabundance of Fe in some accretion-powered X-ray sources should be pursued.*
f) *Some results obtained from measurements of the H and He line profiles in white-dwarf photospheres suggest that the atomic physics of atoms immersed in dense plasmas merits further investigation. This may point toward a promising new research focus (see section 3.3).*

3.1.5 The role of simulations

Simulations can play an important role for WCAPP, both in guiding experimental direction and design, and in validating and improving the physics models incorporated in codes. This is true for the atomic physics studies and also for the platforms used to generate the plasmas whose atomic physics is interrogated. For example, the experimental measurements of H-, He-, and C-line profiles at conditions typical of white-dwarf photospheres have already benefitted from preliminary 3D simulations of the experimental platform carried out by Mark Hess of SNL using the HYDRA code. The results confirm previous simulations: Heating of the Au back wall of the experimental cell and of the H gas are uniform. Future simulations will be used to help optimize the design of the platform, possibly leading to a reduction in the energy of the backlighter. WCAPP participation in such platform simulations has not been possible until now (early 2021) because of the postdoc and graduate-student recruiting challenges. These challenges have now been overcome, and a prospective graduate student (Jackson White) has been identified who wants to be involved.

As noted in section 3.1.2 above, performing high-fidelity exploratory two-dimensional (2D) simulations followed by high-fidelity three-dimensional (3D) simulations of the time-resolved opacity experiments would again be useful both to guide future experimental design and improve the physics incorporated in codes. Although the opacity experiments to date have been SNL investigations, such simulations could be undertaken with a well-established simulation package (e.g., FLASH, which works seamlessly with Prism Scientific's Spec3D package), which would enable a WCAPP graduate student or postdoc to do them.

One-dimensional Helios radiation-hydrodynamics simulations have been used to gain qualitative insights into the physics of the photoionized-plasma experiments. The results compare well with experimental results, but there are quantitative differences. For example, the time-gated data exhibit large differences from the results of the 1D Helios simulations, and these simulations show widely different behaviors for the ionization fraction of, e.g., H-like and Li-like neon at the front and rear of the gas cell. One suggested explanation is that there may be large gradients in ionization in the cell, whose effects will be explored. Gaining a deeper understanding of what is actually going on in these experiments is clearly important: Conducting high-fidelity exploratory 2D simulations followed by high-fidelity 3D simulations of the experiment is a route forward, and with the right code could be undertaken by a WCAPP member.

We commend WCAPP for its efforts to recruit a graduate student who could carry out these simulations.

Finding 2:
Preliminary simulations of the experimental white-dwarf platform using HYDRA have confirmed that the Au *back wall and H gas heating are uniform. Further higher-fidelity simulations–of all four experimental platforms–would be expected to provide an important tool for improving the experimental platforms, guiding future experiments, and validating (or otherwise) the physics models in the codes. Prior to 2021, any WCAPP participation in this work has not been possible because of the recruiting challenges, but these have now been overcome, and a prospective graduate student has been identified for this role.*

Recommendation 2:

a. *Simulations of the H, He, and C line-profile experiments should be continued and expanded, utilizing a new WCAPP graduate student or–depending on funding–possibly a future postdoc.*
b. *High-fidelity modeling of all four experimental platforms should be considered by WCAPP, depending on the future availability of sufficient personnel.*
c. *Such simulations should involve a well-established simulation package that permits the involvement of a WCAPP graduate student (or postdoc).*
d. *WCAPP should continue to recruit aggressively a graduate student to carry out these simulations.*

3.2 Personnel

A very-high-priority item for WCAPP over the past two years has been to hire a sufficient number of postdocs and graduate students to support the various research projects. This goal has been largely met due to significant recruitment efforts. Don Winget and Mike Montgomery are to be highly commended for investing the effort and resources necessary to implement previous recommendations of this committee. They noted that a change in admission procedures played a crucial role in the recruitment of prospective graduate students. At least two of the graduate students noted that the upgraded WCAPP website attracted them to the Center, and some of the members of this committee were also instrumental in directing prospective graduate students to the Center.

Three postdocs (Bart Dunlap, George Jaar and Dan Mayes) and two graduate students (Patricia Cho and Kyle Swanson) are currently on board, and four additional graduate students (Joseph Guidry, Bryce Hobbs, Malia Kao, Jackson White) have declared their intent to arrive in the fall. Currently one postdoc, Bart Dunlap, and one graduate student, Patty Cho, are in Albuquerque to support experimental efforts at SNL. They will be joined at SNL by the two new postdocs–Georges Jaar and Dan Mayes–as soon as is feasible. Their roles are:

a) *Bart Dunlap* (UT postdoc) fields the white-dwarf photosphere experiments.
b) *Dan Mayes* (UT postdoc), Roberto Mancini's former UNR graduate student, who defended his thesis in December 2020, will be mentored by Jim Bailey while working on the solar-opacity project. Active participation in this project has been a goal of the Center since its inception, and again Don and Mike are congratulated for achieving this objective.
c) *Georges Jaar* (UNR postdoc) will split his time working on experiments to benchmark astrophysical codes and on white-dwarf photospheres.
d) *Patty Cho* (UT Graduate student) has been appointed a Laboratory Resident Graduate Fellow at SNL to participate in experimental work at the Z facility that is relevant to the emission of radiation from accretion disks around compact objects. She has now completed her SNL training, and is fully qualified to field Z experiments independently. She is also continuing to update fits to the H-line data from Z into the widely used stellar-atmosphere code TLUSTY.
e) *Kyle Swanson* (UNR graduate student) has taken over the UNR experiment under the supervision of Roberto Mancini, and is preparing for PDV experiments using the argon-filled UNR gas cell at SNL.

Each of the four experimental areas (radiation from accretion disks around compact objects, the opacity of matter inside the stars, atomic kinetics in photoionized plasmas, and spectral-line formation in white dwarfs) now has active Center involvement. In addition, a prospective graduate student (Jackson White) is anticipated to become involved in modeling, e.g., using the FLASH code.

Finding 3:
The WCAPP recruiting efforts have alleviated the staffing issues identified in the previous report: The Center is now staffed at an appropriate level, with on-site (at SNL) participation in all four experimental areas. The distribution of young scientists among the sites has considerably improved the cohesiveness and communication channels of this multi-site Center.

Recommendation 3:
a) The committee recommends the continuation of the very effective methods of staffing and recruitment that have produced such positive results.
b) WCAPP should ensure that its website remains up to date and attractive.

3.3. Exploratory studies (planning for the future)

The current research is clearly exciting and successful, as discussed in Section 3.1 above. CSAC was asked to consider if any additional exploratory research could or should be undertaken in the next two years (2021 and 2022) in anticipation of renewed funding for additional years, beginning early in calendar-year 2023. In this regard, in 2020 CSAC noted (Finding number 9) the opportunity to investigate scaled atomic physics: the concept of micro-equivalence. For WCAPP, the interest would be to see if a lower-Z element at existing conditions could test iron-opacity models deep in the sun. However, the current ongoing projects require full-time commitment for the next two years, so this should probably be delayed.

Finding 4:
WCAPP recognizes that the four ongoing projects require full-time commitment from their staff for the next two years, so that any additional exploratory studies would most likely involve analysis and interpretation of data already in hand or anticipated shortly. In order to help prioritize any near-term exploratory studies aimed at initiating or guiding the Center's future research directions, the committee makes the following Recommendations.

Recommendation 4:
- a) *The team should be mindful of new spectroscopic data that will be available from future satellites. XRISM (https://heasarc.gsfc.nasa.gov/docs/xrism/) has a planned launch date by March 2023. The X-ray micro-calorimeter on XRISM will provide broadband spectra with high spectral resolution for the Fe K-shell spectral region.*
- b) *The team should strengthen collaborations with the X-ray spectral modeling groups that provide publicly available modeling tools and databases (e.g., in the U.S. XSTAR and CLOUDY for photoionized plasmas and AtomDB for collisionally ionized plasmas). These groups set priorities for improvements based on "critical evaluation," which include assessment of atomic-data uncertainties, as well as atomic-data needs established by existing and future missions.*
- c) *The Center has white-dwarf experiments planned and scheduled on the NIF platform, which is designed to replicate conditions at Z for measuring the oxygen opacity. However, NIF may offer more options and new opportunities, because it provides a more controllable environment, so experimenters can systematically vary parameters such as temperature, density, and even line shape, and measure emission and absorption.*
- d) *Heavier elements are observed in white-dwarf spectra and are believed to be debris from objects ripped apart. Benchmark experiments are needed to interpret spectra for heavy-element abundances, and the Center is discussing these as a future direction. We endorse this direction, while agreeing that they are not near-term projects; they will require significant modifications of the white-dwarf-photospheres platform in order to be able to handle and study these elements.*
- e) *The best current astrophysical model for the structures of atoms immersed in dense plasmas is the "occupational-probability" model. Because the analysis of white-dwarf spectra using this model leads to unexpected results in some cases, WCAPP investigators are encouraged to explore experiments that could be deployed to test this model.*

3.4. Renewal strategy

The 2020 CSAC report noted: "A successful renewal proposal requires an exciting plan (research and personnel). Some limited and targeted evaluation of new opportunities is necessary, and limited exploratory studies are warranted. However, this must be done without jeopardizing the Center's unique focus and reputation (world-class, high-fidelity atomic and radiation physics of warm- and high-energy-density plasmas, in particular "at parameter"). Data analysis (both of existing Z data and presumed NIF data), and perhaps the NIF experiments themselves, will be a part of the renewal."

The above statements still stand, as do Finding and Recommendation number 10 from 2020:

***"Finding 10 (from 2020)**:*
A successful renewal proposal requires a successful history, proven by metrics. These include not only research metrics (e.g., peer-reviewed papers), but also metrics that address the important objective of training graduate students and postdocs in the specialties of the Center, and exposing them to the capabilities of the NNSA national security laboratories.

***Recommendation 10 (from 2020)**:*

a. *WCAPP is strongly encouraged to highlight the people it is sending to SNL and other U.S. National Laboratories.*
b. *WCAPP is encouraged to highlight areas in which the Center's work has influenced other institutions and/or investigations.*

The CSAC continues to endorse this finding and these recommendations strongly. The timeline for renewal proposals is not currently known, but an estimate is that a proposal might be required somewhere between January 2022 and summer 2022. We applaud both the plans to increase the number of peer-reviewed publications greatly during the next year, and the success both in recruiting new graduate students and postdocs to the Center and in placing them at the National Laboratories. These successes must be emphasized. Given this proposal timescale, obtaining preliminary data in support of proposed new directions (e.g., micro equivalence) may not be possible with the limited number of shots and time available. Therefore, one option is to propose additional and complementary exciting goals that have <u>new and distinct scientific headlines</u>, and at the same time are outgrowths of the current science rather than distinctly new directions. The Center already introduced the committee to one: Understanding planetary debris as observed in white dwarf spectra. Another is that the NIF experiment will access solar conditions in addition to white dwarf conditions; is there an associated solar-science headline? The oxygen line profile may be another example. Are experiments to address the occupation-probability formalism a potential headline? Another possible headline experiment discussed briefly by the committee is addressing the long-standing Fe-line problem. Strong lines from the Fe L-complex are observed in both photoionized and collisionally ionized astrophysical plasmas, and in principle, they can provide diagnostics for electron temperature, density, chemical abundances, gas motions, and photon-scattering opacity for the sources. The Fe XVII resonance line is the strongest X-ray line in the quiescent solar corona. Despite decades of theoretical, observational, and experimental progress, however, the theoretical line ratios do not agree with experimental benchmarks with sufficient accuracy for astrophysical diagnostic use.

The future direction of the Stockpile Stewardship Academic Alliance Program is not entirely clear. Historically, value has been placed on collaborations between university partners. The WCAPP has a unique atomic-physics niche. Looking to the future, the Center might consider including an additional early-career academic scientist with atomic physics and / or astrophysical expertise from a complementary institution to enhance the proposal. Perhaps WCAPP might consider one or two who are already known to center members (e.g., in the academic departments at Princeton or the University of Michigan).

One of the main goals of the research is to validate atomic-physics codes. The strength of a renewal proposal would be increased if a proposed route can be identified to obtain recognition of the Center's relevant data and its inclusion into these atomic-physics codes. In the X-ray astrophysics community, spectral-code developers tend to be the liaisons between astronomy users and atomic-physics providers. Historically, experimental benchmarks have been rare, so theoretical atomic-rate coefficients have been used in the public databases without even uncertainty estimates. The Center is working to some extent with the spectral-code developers already, but strengthening these ties would not only improve the spectral modeling efforts, but also bring more recognition to the Center.

Finding 5:
The Center should plan on a call for a renewal proposal being issued in the timeframe between January 2022 to Summer 2022.

Recommendation 5:
- a) *The renewal proposal should emphasize scientific success through peer-reviewed publications and influence on other institutions or investigations. Personnel education, development and training success should emphasize student and postdoc hires and their placements at US National Laboratories.*
- b) *The proposed research should continue to emphasize exciting "at-parameter" experiments, with high-fidelity data that produce publications that have high impact for both astrophysical and DOE/NNSA interests, as well as education leading to a future source of young scientists in the important area of atomic and radiation physics of warm dense matter.*
- c) *Including new scientific headline experiments would strengthen a renewal proposal. Some were presented and discussed; there appear to be many! For example, identifying debris in white dwarf spectra, the long-standing Fe XVII resonance-line problem, the O-line profile, and the occupation- probability formalism.*
- d) *A strength of a renewal proposal would be to include collaborations with X-ray spectral-modeling group(s) that provide publicly available modeling tools and databases. This would help in obtaining recognition of the Center's relevant data and its inclusion into atomic-physics codes.*
- e) *See also the Recommendations in Section 3.3.*

3.5 Other

3.5.1 Collaborations

Finding 6:
WCAPP has explored collaborations with Carolyn Kuranz (University of Michigan), who seeks to conduct experiments on Z, and with Didier Saumon (LANL), who has approved experiments on NIF to measure the equations of state of C, H_2O, and $C_2O_2H_4$ at gigabar pressures. Collaborations like these are likely to produce valuable synergies both in science and in the recruitment of graduate students and postdocs (an instance of the

latter has already occurred), and by so doing, to increase the chances for WCAPP to be renewed.

***<u>Recommendation 6</u>*:**
Continue the effort to establish collaborations with Carolyn Kuranz and Didier Saumon.

3.5.2 Metrics

***<u>Finding 7</u>*:**
WCAPP reported that there were many results that are ready to be written up and subsequently submitted for publication.

***<u>Recommendation 7</u>*:**
Writing peer-reviewed publications is recognized as important. Priority should be given to those that have a realistic chance of being published before any renewal proposal is required, i.e., in the next 12 to 18 months.

4. Final Summary

Here we list the Findings and Recommendations.

Finding 1:
WCAPP is continuing to conduct important experiments on the Z facility at SNL. WCAPP scientists are continuing to identify opportunities for new experiments relevant to each of the Center's four main areas of investigation.

Recommendation 1:

a) *WCAPP should continue to conduct experiments to measure the line profiles of H, He, and C under conditions found in the atmospheres of white dwarfs, especially at lower temperatures and higher densities. These line profiles are important for addressing important astrophysical problems ranging from the age and history of the Galaxy, to the interior composition of exoplanets, to the nature of thermonuclear-powered supernovae.*
b) *WCAPP should continue to use the experimental data for H and He from Z to update the astrophysical line-profile and model-atmosphere codes and to extend this work to C when sufficient experimental data become available. This will enable astrophysicists to benefit fully from this experimental work.*
c) *The opacity of matter inside stars is essential for obtaining accurate stellar models, which underpin our understanding of much of astrophysics. The critical investigations of the Fe opacity should be continued, and WCAPP's newly begun investigations of O, which is the dominant opacity source at the base of the solar convection zone, should be pursued.*
d) *Photoionization is ubiquitous in astrophysical plasmas, and it is important to be able to determine the ionization equilibrium in such plasmas in order to determine the properties of many astrophysical sources. Attention should be given to solving the radiation-darkening problem, which is key to obtaining useful data.*
e) *Experiments relevant to X-ray emission from accretion disks are of fundamental importance for astrophysics and should be continued; in particular, experiments probing the cause of the apparent overabundance of Fe in some accretion-powered X-ray sources should be pursued.*
f) *Some results obtained from measurements of the H and He line profiles in white-dwarf photospheres suggest that the atomic physics of atoms immersed in dense plasmas merits further investigation. This may point toward a promising new research focus (see section 3.3).*

Finding 2:
Preliminary simulations of the experimental white-dwarf platform using HYDRA have confirmed that the Au *back wall and H gas heating are uniform. Further higher-fidelity simulations–of all four experimental platforms–would be expected to provide an important tool for improving the experimental platforms, guiding future experiments, and validating (or otherwise) the physics models in the codes. Prior to 2021, any WCAPP participation in this work has not been possible because of the recruiting challenges, but these have now been overcome, and a prospective graduate student has been identified for this role.*

Recommendation 2:

a. *Simulations of the H, He, and C line-profile experiments should be continued and expanded, utilizing a new WCAPP graduate student or–depending on funding–possibly a future postdoc.*
b. *High-fidelity modeling of all four experimental platforms should be considered by WCAPP, depending on the future availability of sufficient personnel.*
c. *Such simulations should involve a well-established simulation package that permits the involvement of a WCAPP graduate student (or postdoc).*
d. *WCAPP should continue to recruit aggressively a graduate student to carry out these simulations.*

Finding 3:

The WCAPP recruiting efforts have alleviated the staffing issues identified in the previous report: The Center is now staffed at an appropriate level, with on-site (at SNL) participation in all four experimental areas. The distribution of young scientists among the sites has considerably improved the cohesiveness and communication channels of this multi-site Center.

Recommendation 3:

a) *The committee recommends the continuation of the very effective methods of staffing and recruitment that have produced such positive results.*
b) *WCAPP should ensure that its website remains up to date and attractive.*

Finding 4:

WCAPP recognizes that the four ongoing projects require full-time commitment from their staff for the next two years, so that any additional exploratory studies would most likely involve analysis and interpretation of data already in hand or anticipated shortly. In order to help prioritize any near-term exploratory studies aimed at initiating or guiding the Center's future research directions, the committee makes the following Recommendations.

Recommendation 4:

a) *The team should be mindful of new spectroscopic data that will be available from future satellites. XRISM (https://heasarc.gsfc.nasa.gov/docs/xrism/) has a planned launch date by March 2023. The X-ray micro-calorimeter on XRISM will provide broadband spectra with high spectral resolution for the Fe K-shell spectral region.*
b) *The team should strengthen collaborations with the X-ray spectral-modeling groups that provide publicly available modeling tools and databases (e.g., in the U.S., XSTAR and CLOUDY for photoionized plasmas and AtomDB for collisionally ionized plasmas). These groups set priorities for improvements based on "critical evaluation," which include assessments of atomic-data uncertainties, as well as atomic-data needs established by existing and future missions.*
c) *The Center has white-dwarf experiments planned and scheduled on the NIF platform, which is designed to replicate conditions at Z for measuring the oxygen opacity. However, NIF may offer more options and new opportunities, because it provides a more controllable environment, so experimenters can systematically vary parameters*

such as temperature, density, and even line shape, and measure emission and absorption.

d) *Heavier elements are observed in white-dwarf spectra and are believed to be debris from objects ripped apart. Benchmark experiments are needed to interpret spectra for heavy element abundances, and the Center is discussing these as a future direction. We endorse this direction, while agreeing that they are not near-term projects; they will require significant modifications of the white-dwarf-photospheres platform in order to be able to handle and study these elements.*

e) *The best current astrophysical model for the structures of atoms immersed in dense plasmas is the "occupational-probability" model. Because the analysis of white-dwarf spectra using this model leads to unexpected results in some cases, WCAPP investigators are encouraged to explore experiments that could be deployed to test this model.*

Finding 5:

The Center should plan on a call for a renewal proposal being issued in the timeframe between January 2022 to Summer 2022.

Recommendation 5:

a) *The renewal proposal should emphasize scientific success through peer-reviewed publications and influence on other institutions or investigations. Personnel education, development and training success should emphasize student and postdoc hires and their placements at US National Laboratories.*

b) *The proposed research should continue to emphasize exciting "at-parameter" experiments, with high-fidelity data that produce publications that have high impact for both astrophysical and DOE/NNSA interests, as well as education leading to a future source of young scientists in the important area of atomic and radiation physics of warm dense matter.*

c) *Including new scientific headline experiments would strengthen a renewal proposal. Some were presented and discussed; there appear to be many! For example, identifying debris in white dwarf spectra, the long-standing Fe XVII resonance-line problem, the O-line profile, and the occupation-probability formalism.*

d) *A strength of a renewal proposal would be to include collaborations with X-ray spectral-modeling group(s) that provide publicly available modeling tools and databases. This would help in obtaining recognition of the Center's relevant data and its inclusion into atomic-physics codes.*

e) *See also the Recommendations in Section 3.3.*

Finding 6:

WCAPP has explored collaborations with Carolyn Kuranz (University of Michigan), who seeks to conduct experiments on Z, and with Didier Saumon (LANL), who has approved experiments on NIF to measure the equations of state of C, H_2O*, and* $C_2O_2H_4$ *at gigabar pressures. Collaborations like these are likely to produce valuable synergies both in science and in the recruitment of graduate students and postdocs (an instance of the latter has already occurred), and by so doing, to increase the chances for WCAPP to be renewed.*

Recommendation 6:
Continue the efforts to establish collaborations with Carolyn Kuranz and Didier Saumon.

Finding 7:
WCAPP reported that there were many results that are ready to be written up and subsequently submitted for publication.

Recommendation 7:
Writing peer-reviewed publications is recognized as important. Priority should be given to those that have a realistic chance of being published before any renewal proposal is required, i.e., in the next 12 to 18 months.

Appendix. Meeting Agenda

DOE/NNSA

Stockpile Stewardship Academic Alliance Program

Center Scientific Advisory Committee (CSAC)

27 January 2021

Zoom link: https://utexas.zoom.us/j/99355641917

AGENDA (all times are CST)

I. Welcome and introduction to Meeting (10:00 – 10:10 am)
by Chair of CSAC, Alan Wootton

II. Introduction to WCAPP (Don Winget) (10:10–10:40)

a. Finishing year 3. What has changed in the last year, particularly in response to the CSAC 2020 report?
b. Four general areas where advice is requested from the committee: science in the years 4-5, personnel needed to achieve these science goals, and longer-term science ideas that need exploratory studies in the 1- to 2-year time frame, and renewal strategies.

III. Evolving Relation of WCAPP to Sandia (Jim Bailey) (10:40 –11:00)

IV. Highlights of current experiments and modeling finishing 3 years and leading to years 4–5 (11:00 am – 2:05 pm, lunch ~ 12:30 pm)

a. Opacities in the Sun and related stars – Tai Nagayama (25 min.)
b. Atomic physics and x-ray heating of photoionized plasmas – Roberto Mancini (25 min.)
c. White dwarf photospheres and theoretical developments – Bart Dunlap and Mike Montgomery (25 min.)
d. *Lunch break (15 minutes to gather lunch and return)*
e. Black hole accretion disc radiation – Guillaume Loisel (25 min.)
f. Shot schedule for NIF (motivations and time-frames) – Don (10 min.)
g. Student input – Patty, Dan, Kyle (30 minutes)

V. Discussions with CSAC (CSAC, PIs, and Co PIs) (2:20 – 3:15)
Focus Questions for the discussion:

a. Years 4-5: Is the proposed research that is focused around the Z facility at SNL (physics and astrophysics, experiment and theory, and tools) unique, world class, likely to be approved for time on Z, and likely to succeed?

b. Is the research planning, especially human effort (including postdocs, students, additional institutions) adequate for success?
c. Looking to year 5 and beyond, are there any exploratory studies we should be undertaking in the 1- to 2-year time frame? Is it the right time to be evaluating what could be done not only "at parameter on Z" but also on lasers, and including scaled experiments?
d. Strategies for renewal.

VI. CSAC meets alone (CSAC Breakout room) (3:15 – 4:30)

VII. OUTBRIEF to PI and Co PIs (4:30 – 5:00)

5:00 pm adjourn

Link to the Wootton Center for Astrophysical Plasma Properties:
https://sites.cns.utexas.edu/wcapp

Signature Page

Wootton Center for Astrophysical Plasma Properties
Center Scientific Advisory Committee

Nancy Brickhouse	Date
Chris Fontes	Date
David Kilcrease	Date
Don Lamb	Date
Keith Matzen	Date
Marilyn Schneider	Date
Hugh Van Horn	Date
Alan Wootton, Chair	Date