RESEARCH PERFORMANCE PROGRESS REPORT

National Nuclear Security Administration

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(Wootton) Center for Astrophysical Plasma Properties

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Project/Grant Period: 02/15/2018 to 02/14/2023

Reporting Period End Date: 02/14/2021, YR3

Report Term or Frequency: Annual

1. ACCOMPLISHMENTS: Mandatory

What was done? What was learned?

The primary focus for WCAPP is ***four*** independent astrophysically-motivated experiments carried out simultaneously on each shot at the Z facility in the following areas:

- White Dwarf stars
- Atomic kinetics, x-ray heating, and temperature of photoionized plasmas
- Accretion Powered Matter and Radiation
- Stellar interior opacity

WCAPP scientists execute theoretical research and astronomical observations in the same topical areas. Furthermore, during this reporting period we proposed and were awarded experiment time for stellar opacity experiments at the NIF. Planning for the iron opacity experiments has begun, and the first NIF shots measuring oxygen opacity at white dwarf and solar conditions have been carried out.

a. **What are the major goals and objectives of this project?**

- **White Dwarf Stars:**
  The objective of this experiment is to measure the spectral lines of hydrogen, helium, and carbon at the same conditions that are found in the photospheres of white dwarf stars. There is reason to believe that the atomic physics of these atoms is incomplete when immersed in dense plasmas, and theoretical calculations need to be benchmarked with laboratory data in this regime. The goal is improving mass determinations and evolutionary paths for white dwarf stars that depend on the spectral line profiles.
- **Atomic kinetics, x-ray heating, and temperature of photoionized plasmas:**
  The objective of this experiment is to make systematic measurements of x-ray heating, temperature and charged state distribution of photoionized plasmas relevant to astrophysics as a function of the ionization parameter. This will allow us make a quantitative check of the energy balance and ionization/recombination processes. These data challenge modeling codes that are relevant for interpreting x-ray astronomy observations of astrophysical photoionized plasmas.
- **Accretion Powered Matter and Radiation:**
  Understanding X-ray Binaries and AGN accretion disks requires complex models to interpret the observed spectra. These models are largely untested in the laboratory and need benchmark quality data. Present models do not reproduce either the relative or absolute emission that is observed, making their use for interpreting astronomical data problematic. The goal is testing and refining spectral synthesis models used for accretion powered objects, so that our understanding rests on a solid foundation verified by laboratory experimentation.
- **Stellar interior opacity:**
  Solar models presently disagree with helioseismology. This could be resolved if the true mean opacity is higher than calculated opacity used in the solar models by 10-30%. The goal of this experiment is to help resolve the solar problem using benchmark measurements of the opacity of various elements at conditions near those of the base of the solar convection zone.

b. **What was accomplished under these goals?**

During the reporting period covering 02/15/20 - 02/14/2021, the team carried out 11 shot experiments at the Z Pulsed Power Facility. Data were obtained for each of the 4 experiments described above. We detail the progress made on each of these experiments below:

- **White Dwarf Stars (Winget, Montgomery, Dunlap, Cho):**

  The white dwarf photosphere experiment (WDPE) makes measurements of hydrogen, helium, and carbon plasmas at white dwarf photosphere conditions. Our experiment evolves dynamically and we probe a broad range of densities on each shot. We exploit this to make a more comprehensive test of competing line broadening theories than previously possible.

  For the hydrogen experiments, we have reached significantly higher densities than the landmark studies of Wiese et al. (1972, PRA, 6, 1132), thereby putting competing line broadening theories to the test in a regime where their predictions strongly diverge. We deploy three lines of sight to simultaneously measure multiple lines in emission, absorption, and the backlighter continuum in macroscopic plasmas on Z. This represents a significant advance relative to hydrogen line-profile experiments of the past. Our recent results have highlighted a measured difference in the width of a line when measured in absorption versus emission (Schaeuble et al., 2019, ApJ, 885, 86). While our results are still preliminary, we find evidence of asymmetry in the Hβ and Hγ lines that the standard Vidal-Cooper-Smith theories, and its derivatives, are unable to fit; these asymmetries are also evident in WD spectra. From simultaneous fits to the strengths of multiple lines, we should also be able to constrain line quenching and the occupation probabilities (e.g., Hummer & Mihalas, ApJ, 331, 794) of higher-n states as they begin merging with the continuum/unbound states. We have also found evidence that the emission and absorption line shapes of Hγ do not agree, e.g., they have widths that differ by 20-30%. This is an extraordinary result and we are currently scrutinizing our experiment to make sure that this is not due to some artifact of our platform.

  To better understand our experimental platform and to further probe some of these recent results, we have modified our gas cell so that we can measure lines of sight orthogonal to our standard absorption and emission lines of sight. This past year, we have acquired the first data sets in this configuration, which we will use to place empirical constraints on the gradients in our plasma. Furthermore, we have taken advantage of a new diagnostic capability, a gated camera, that allows us to capture multiple lines of sight simultaneously on the same spectrograph/detector system. Using this, we have, for the first time, acquired spectra of absorption, emission, and backlighting continuum simultaneously. This advance reduces systematic uncertainties arising from the cross-calibration necessary to construct transmission spectra.

  As part of our platform development efforts, we have also fielded the first shots exploring the feasibility of using optical light from the Z pinch as a backlighter. In the current design, we place a collection optic 16 cm from the pinch and feed this light via fiber optic into the gas cell. This could allow us to achieve higher S/N absorption measurements that are not sensitive to the details of self-emission correction, and could also allow us to measure absorption at later times (when our current backlighting wedge is fading and the emission is increasing), and would allow us to remove our current backlighting wedge, which forms a hot (though presumably narrow) boundary layer plasma.

Also in the past year, we have fielded more shots with thin (~250 nm) entrance windows, showing that we can repeatably achieve the higher temperatures (~20,000 K) necessary to study the plasma conditions relevant to carbon atmosphere white dwarf (hot DQ) stars.

Our graduate student, Patricia "Patty" Cho, has improved both the physics and the numerics of the hydrogen line profile code *Xenomorph*, which was developed by Thomas Gomez (former UT-Austin graduate student and current Sandia postdoc). These results are currently being readied for publication. Patty and Bryce Hobbs (a postbac researcher) are in the process of incorporating these new hydrogen line profile calculations into model white dwarf atmospheres, specifically the open source stellar atmosphere code *Tlusty*.

Finally, we have initiated oxygen experiments at the NIF in an effort to measure the opacity of oxygen at conditions relevant to the base of the convection zones in white dwarfs and the Sun. The first shots have been made, and a preliminary analysis of the data is underway. These experiments complement the oxygen opacity experiments we have begun on Z as part of the stellar opacity project discussed below.

- **Atomic Kinetics, X-ray heating, and Temperature of Photoionized Plasmas (Mancini, Mayes, Swanson, Jaar)**
  In the warm absorber photoionized plasma experiment, we use the intense, energetic radiation from a z-pinch to drive a photoionized plasma contained within a gas cell. By changing the distance of the cell from the x-ray source and/or the gas filling pressure inside the cell, we are able produce photoionized plasmas over a wide range of ionization parameter values. The ionization parameter is the ratio of the photoionization to recombination rate in the plasma and is commonly used to characterize both astrophysical and laboratory photoionized plasmas. We use K-shell line absorption spectroscopy to measure the charge state distribution and the electron temperature as a function of the ionization parameter.

  In May 2020, work on understanding the x-ray heating and electron temperature in photoionized plasmas was published (Mancini et al., Physical Review E 101, 051201(R) (2020)). In this Rapid Communications publication, experimental measurements of the electron temperature of a laboratory photoionized plasmas provided a unique opportunity to study x-ray heating, photoelectron thermalization and electron temperature in laboratory photoionized plasmas for the first time. Two different modeling/simulation techniques, Boltzmann electron kinetics and radiation-hydrodynamics, were employed to interpret the measurements and gain insight into the physics of photoionized plasma x-ray heating. The findings demonstrated the interplay between atomic physics and heating characteristic of photoionized plasmas, and the key role of photoexcitation on excited state populations, line emissivity, and radiation cooling. Furthermore, the measurements were compared with predictions from astrophysical modeling codes, which significantly overestimated the temperature of the experiments.

We have carried out a comprehensive analysis of the large spectral dataset that we have been building from Z shots with the gas cell experiment. These data represent results from 25 Z shots over 11 different experimental campaigns, and consolidates information from 119 individual slit spectra. This has resulted in experimental measurements of fractional populations and charge state distribution covering an unprecedented order-of-magnitude range in the ionization parameter. This is the first set of measurements of its type, and it reveals trends in the charged state distribution of a laboratory photoionized plasma as a function of the ionization parameter. Detailed comparison of the experimental results with radiation-hydrodynamic simulations with inline non-equilibrium atomic physics and radiation transport showed good agreement in the mean charge predicted, however significant quantitative differences were found amongst the predictions of individual ion fractions. This work was included in the Ph.D. dissertation of Daniel Mayes, which he successfully defended in December 2020. It has also been accepted for publication in Physical Review E and will be published in October 2021.

We have successfully demonstrated the implementation of a new photon-Doppler-velocimetry (PDV) diagnostic into the photoionized plasma gas cell platform. This laser interferometry diagnostic allows us to measure the electron plasma column density along a line of sight perpendicular to the radial, i.e. x-ray transmission spectroscopy diagnostic line of sight, for the first time. This diagnostic system was successfully fielded for the first time on Z experiments in September 2020. From the recorded data we were able to extract electron column density and assess plasma uniformity in the gas cell. Also, this was the first fielding of the PDV diagnostic in Z at a very short distance from the z-pinch.

- **Accretion Powered Matter and Radiation (Loisel, Nagayama, Cho)**
  When matter accretes in a disk around a compact object such as a black hole or a neutron star, a copious amount of x-ray light is generated. These accretion-powered objects produce spectra that contain information about the accretion process and the nature of the accretor. For instance, the mass and spin of a black hole could be extracted, thus enabling a test of general relativity. The Z facility recreates the relevant state of x-ray photoionization of the radiation-dominated disk environment and its spectral emission. We collected data that show the full He-like sequence and the radiative recombination continuum (RRC), which is used as an important astrophysical diagnostic of disk temperature. This is the first time this feature has been observed in the laboratory.

  A novel topic has started recently, addressing a puzzle with emission from black hole accretion disks, and it is now led by NNSA LRGF graduate student Patty Cho. Fits to past observations reveal that the amount of iron required to model the spectral emission observed in several black hole systems can be as high as five to twenty times the expected value from stellar evolution theory. New high density effects have since been incorporated into the models used to fit these spectra and have produced revised iron abundances much closer to the expected value. However, there is an absence of constraining laboratory data to validate the new high density effects. The first Fe emission spectra ever recorded from a photoionized laboratory plasma were obtained and pave the way to testing the high density effects hypothesized as a solution to the super-solar iron abundance problem.

A second new topic related to accretion powered photoionized plasma experiment is the investigation of time-dependent kinetics. A subset of Active Galactic Nuclei are partially enshrouded by warm absorbers, which refer to a torus of gas ejected by the system. Comparisons of dynamical time-scales of matter in these systems relative to timescales of microscopic atomic processes suggest that there is not enough time for these accretion driven plasmas to reach a steady state. Yet, models of these systems assume steady state plasmas by default. A platform which provides the capability to measure time-resolved plasma emission has been developed and the first scoping shots have been taken with a surrogate material. We are actively working to continue to develop an additional platform to collect time-resolved data using an astrophysically relevant sample to validate new time-dependent astrophysical models of AGN.

- **Stellar Interior Opacity (Bailey, Nagayama, Loisel)**
  Solar models presently disagree with helioseismology. The disagreement is largest at the solar convection-zone base (CZB), which is the boundary between the Sun's convection zone and its radiative zone, located at 0.7 solar radius. This could be resolved if the true mean opacity at the CZB is 10-30% higher than the opacity used in the solar models. Iron and oxygen are the dominant sources of solar opacity at the CZB, and it is crucial to experimentally test their calculated opacities.

  In past work, we successfully measured iron opacity at conditions similar to the solar-convection-zone base. The measurements, published in the journal *Nature* (Bailey et al. 2015, *Nature*, 517, 56), were higher than predictions. If correct, the data account for approximately one-half the opacity increase needed to resolve the solar problem. Research must continue until the opacity theory and measurements are reconciled. Following the initial iron results, chromium and nickel opacities were measured at similar conditions (Nagayama et al. 2019, *PRL*, 122, 235001). Studying how the model-data opacity disagreement changes as a function of atomic number restricts the hypotheses for the discrepancy.

  In the last year, we have re-scrutinized the iron results by performing time-resolved iron opacity measurements. Iron absorption spectra were successfully measured at multiple times, with spectral features showing clear changes with time. Successful analysis of such data will minimize temporal-gradient concerns and test iron opacity at multiple conditions from a single experiment.

  Another major contributor to the total solar opacity is oxygen. Oxygen is simpler to model than iron, but it is extremely important since it contributes approximately 25% of the total opacity at the base of the solar convection zone. We have made preliminary oxygen opacity measurements at our "Anchor 1" conditions, which do not quite reach the conditions at the base of the solar convection zone: $T_e \sim 160$ eV, $n_e \sim 8 \times 10^{21}$ cm^{-3}. These experiments are already testing models for the density effects that challenge opacity models for conditions deep in the solar interior. Furthermore, they will provide a foundation for future data at near solar convection zone base conditions ("Anchor 2", T_e ~ 182 eV, n_e ~ 3.8 x 10^{22} cm^{-3}).

Opacity experiments at stellar interior conditions are highly challenging and warrant a commensurate degree of scrutiny. Consequently, we initiated oxygen opacity experiments at the NIF to complement our effort at the Z facility. The first such experiments were approved under the auspices of the NIF discovery science program and planning has begun.

c. **What opportunities for training and professional development has the project provided?**
UT graduate student Marc Schaeuble defended his PhD in November of 2018, and is now a senior member of the technical staff at Sandia National Laboratories. Graduate student Patty Cho has defended her second-year project on theoretical calculations of hydrogen line profiles and received her M.S. in May 2021. Patty is now working with Guillaume Loisel on the Accretion Powered Matter and Radiation experiment. She was also awarded a DOE NNSA LRGF fellowship for her continuing work at SNL. Graduate student Zach Vanderbosch became a PhD candidate in Spring 2018 and will graduate in Fall 2021. In addition, three undergraduate students have begun working with us (Malia Kao, Bryce Hobbs, and Isaac Huegel). Finally, Malia and Bryce, plus student Jackson White from Rice University will be joining our research group as first-year graduate students in Fall 2021.

In addition, numerous undergraduate students have participated in the research of our group, mainly through our two-semester Freshman Research Initiative (FRI) course at UT. They have learned the essentials of observing and data analysis as well as our experiments at SNL. Most have indicated an interest in graduate school in a scientific discipline. For instance, our former FRI student Hannah Hasson is currently in a laboratory astrophysics program at the University of Rochester. Since this program is in its 10th year, we have just begun to see our students graduate win awards. In addition to numerous smaller awards, our students have achieved the following:

1. Attending grad school at: 1) Harvard University (Astronomy), 2) University of Chicago (Astronomy), 3) University of Virginia (Astronomy), 4) University of Colorado (Physics), University of Texas (Physics), 5) Purdue University (Aerospace Engineering), 6) Southwestern Medical School at Dallas, 7) University of Rochester (Physics), 8) University of Wisconsin-Madison (Astronomy), 9) UC-Berkeley (Astronomy), 10) University of Minnesota (Astronomy), 11) Boston University (Astronomy)
2. Internships/REU programs at: 1) Sandia National Labs, 2) Greenbank Radio Observatory, 3) Microsoft Kinect Division, 4) Yahoo, 5) Yale (Astronomy REU), 6) Notre Dame (Physics REU), 7) SAO Astronomy Summer Intern (CFA), 8) Space Astronomy Summer Program at STScI, 9) Oakridge National Laboratory, 10) University of Michigan
3. Awards: 1) NSF 3-year Graduate Fellowship in Physics, 2) Grand Prize ($20,000) of George Mitchell Award for undergraduate research at UT-Austin, 3) First Place in Student Employee of the Year Award at UT-Austin, 4) Astronaut Scholarship
4. After graduating, one of our undergraduate students was recently hired as a telescope operator at the W. M. Keck Observatory.

d. **How have the results been disseminated to communities of interest?**

In the last year, we published 11 papers in scientific journals and attended approximately 12 conferences in our field to disseminate our results. We also continue to be responsive to media requests aimed at the general public. For instance, our work was featured in two online videos on Seeker.com:

- Inside the Most Powerful X-Ray Source in the World (> 175,000 views)
- The Z Machine Recreates a Dying Star on Earth (> 390,000 views)

In addition, the October 2019 Sky & Telescope issue has an article on our work at SNL ("Lab-made Stars", Liz Kruesi, Sky & Telescope, 2019 – subscription required: https://skyandtelescope.org/sky-and-telescope-magazine/inside-october-2019-issue/)

e. **What do you plan to do during the next reporting period to accomplish the goals and objectives?**

- **White Dwarf Stars**

  Experimental work: Continue H, He, and C experiments. Constrain inhomogeneities in H experiments with vertical measurements along the line-of-sight of the absorption and emission data. Further develop the WDPE platform for C. We will also make the second set of oxygen opacity shots on the NIF, with the goal of reaching higher temperatures and densities.

  Theoretical work: Include new H profiles in model atmosphere codes. Begin new state-of-the-art model atmosphere calculations incorporating H line profile calculations. Continue work on line broadened profiles for He, and develop ab initio calculations of continuum lowering and occupation probabilities for H.

- **Atomic kinetics, x-ray heating, and temperature of photoionized plasmas**

  Continue studies of x-ray heating and charged state distribution as a function of the ionization parameter for neon photoionized plasmas as well as in gas mixtures. Publish analysis results based on time-integrated gas cell transmission spectra. These are the first collection of experimental results that track charge-state distribution in the neon photoionized plasmas over an order of magnitude in the ionization parameter. Continue development of the new PDV diagnostic for the gas cell.

- **Accretion Powered Matter and Radiation**

  Continue work on photoionized emission spectra of Fe. The first Fe emission spectra have been obtained and pave the way to test atomic models. A leading hypothesis is that models used to predict photoionized iron emission might be deficient owing to the absence of benchmark laboratory data. Finalize work on spectral line identification in photoionized emission spectra of Si. Unprecedented high resolution Silicon emission spectra have been collected and provide an opportunity to validate and revise transition wavelengths in atomic databases used for both laboratory and astrophysical codes. Comparisons against the NIST database, the LANL based laboratory code ATOMIC, and astrophysical codes XSTAR and AtomDB are in progress. Valuable revisions have been identified and a complete account will be published within the next year.

- **Stellar Interior Opacity**
  Continue work to obtain data on oxygen opacity at solar conditions. We have made measurements at our "Anchor 1" conditions, which do not quite reach the conditions at the base of the solar convection zone: $T_e \sim 160$ eV, $n_e \sim 8 \times 10^{21}$ cm^{-3}. We will continue these experiments and attempt to reach the "Anchor 2" conditions more characteristic of the base of the solar convection zone ($T_e \sim 182$ eV, $n_e \sim 3.8 \times 10^{22}$ cm^{-3}).

2. PRODUCTS: Optional

What has the project produced?

a. **Publications**

- Joseph A. Guidry, Zachary P. Vanderbosch, J. J. Hermes, Brad N. Barlow, Isaac D. Lopez, Thomas M. Boudreaux, Kyle A. Corcoran, Keaton J. Bell, M. H. Montgomery, Tyler M. Heintz, Barbara G. Castanheira, Joshua S. Reding, Bart H. Dunlap, D. E. Winget, Karen I. Winget, and J. W. Kuehne, "I Spy Transits and Pulsations: Empirical Variability in White Dwarfs Using Gaia and the Zwicky Transient Facility," *The Astrophysical Journal*, vol. 912, 2, 2021.
- E. R. Newton, A. W. Mann, A. L. Kraus, J. H. Livingston, A. Vanderburg, J. L. Curtis, P. C. Thao, Keith Hawkins, et.al. "TESS Hunt for Young and Maturing Exoplanets (THYME). IV. Three Small Planets Orbiting a 120 Myr Old Star in the Pisces–Eridanus Stream*," *The Astrophysical Journal*, vol. 161, 2, 2021.
- S. O. Kepler, D. E. Winget, Zachary P. Vanderbosch, Barbara Garcia Castanheira, J. J. Hermes, Keaton J. Bell, Feral Mullally, Alejandra D. Romero, M. H. Montgomery, Steven DeGennaro, Karen I. Winget, Dean Chandler, Elizabeth J. Jeffery, Jamile K. Fritzen, Kurtis A. Williams, Paul Chote, and Staszek Zola, "The Pulsating White Dwarf G117-B15A: Still the Most Stable Optical Clock Known," *The Astrophysical Journal*, vol. 906, 1, 2021.
- S. L. Casewell, C. Belardi, S. G. Parsons, S. P. Littlefair, I. P. Braker, J. J. Hermes, J. Debes, Z. Vanderbosch, M. R. Burleigh, B. T. Gänsicke, V. S. Dhillon, T. R. Marsh, D. E. Winget, and K. I. Winget, "WD1032+011, an inflated brown dwarf in an old eclipsing binary with a white dwarf," *Monthly Notice of the Royal Astronomical Society*, vol. 497, 3, 2020.
- K. Hawkins, M. Lucey, and J. Curtis. "The chemical nature of the young 120-Myr-old nearby Pisces–Eridanus stellar stream flowing through the Galactic disc," *Monthly Notice of the Royal Astronomical Society*, vol. 496, 2, 2020.
- D. E. Winget, M. H. Montgomery, B. H. Dunlap, P. B. Cho, M.-A. Schaeuble, and T. A. Gomez, "Illuminating White Dwarf Spectra through Laboratory Experiments at Cosmic Conditions," *High Energy Density Physics*, vol. 37, id 100853, 2020.
- R. C. Mancini, T. E. Lockard, D. C. Mayes, I. M. Hall, G. P. Loisel, J. E. Bailey, G. A. Rochau, J. Abdallah, Jr., I. E. Golovkin, and D. Liedahl. "X-ray heating and electron temperature of laboratory photoionized plasmas" *Physical Review E*, vol. 101, 051201(R), 2020.
- D. C. Mayes, R. C. Mancini, T. E. Lockard, I. M. Hall, J. E. Bailey, G. P. Loisel, T. Nagayama, G. A. Rochau and D. A. Liedahl. "Observation of ionization trends in a

laboratory photoionized plasma experiment at *Z*" *Physical Review E* (accepted for publication 2021).

- M. H. Montgomery, D. E. Winget, M.-A. Schaeuble, B. H. Dunlap, J. T. Fuchs. "The Wootton center for astrophysical plasma properties: First results for helium" *Proceedings of the IAU*, vol. 15, Symposium S350, 2020.
- Z. Vanderbosch, J. J. Hermes, E. Dennihy, B. H. Dunlap, P. Izquierdo, P. -E. Tremblay, P. B. Cho, B. T. Gänsicke, O. Toloza, K. J. Bell, M. H. Montgomery, and D. E. Winget, "A White Dwarf with Transiting Circumstellar Material Far outside the Roche Limit," *The Astrophysical Journal*, vol. 897, 171, 2020.
- Morgan T. Chidester, F. X. Timmes, Josiah Schwab, Richard H. D. Townsend, Ebraheem Farag, Anne Thoul, C. E. Fields, Evan B. Bauer, and Michael H. Montgomery, "On the Impact of ^{22}Ne on the Pulsation Periods of Carbon-Oxygen White Dwarfs with Helium-dominated Atmospheres," *The Astrophysical Journal*, vol. 910, 24, 2021.

b. **Books or other non-periodical, one-time publications.**

Nothing to Report

c. **Other publications, conference papers and presentations**.

- "A Sampler of Opacity and Conductivity Needs in Stellar Astronomy," Don Winget, NNSA ICF Materials WG Workshop, Virtual, December 2020.
- "Solving Key Astrophysical Puzzles at Wootton Center for Astrophysical Plasma Properties," Don Winget, APS Division of Plasma Physics Meeting, Virtual, November 2020.
- "The Role of Occupation Probability in Hydrogen Line Profile Spectra," Mike Montgomery, APS Division of Plasma Physics Meeting, Virtual, November 2020.
- "Laboratory Spectra of Carbon-Atmosphere White Dwarfs with Implications for Type Ia Supernovae," Bart H. Dunlap, APS Division of Plasma Physics Meeting, Virtual, November 2020.
- "Spectral Line Identification in Photoionized Silicon Plasma Emission," Patricia Cho, APS Division of Plasma Physics Meeting, Virtual, November 2020.
- "Constraining Stellar Evolution through Helium Spectral Line Broadening Experiments at Sandia National Laboratories' Z-Machine," Marc Schaeuble, APS Division of Plasma Physics Meeting, Virtual, November 2020.
- "Ionization trends in a laboratory photoionized neon plasma experiment," Daniel Mayes, APS Division of Plasma Physics Meeting, Virtual, November 2020.
- "Increasing the accuracy of cold Fe opacity measurements to help resolve the Fe solar opacity puzzle," Malia Kao, APS Division of Plasma Physics Meeting, Virtual, November 2020.
- "Revisiting iron opacity discrepancies at stellar interior conditions," Taisuke Nagayama, APS Division of Plasma Physics Meeting, Virtual, November 2020.

- "Background measurement methods for opacity experiments conducted at the Z facility," Greg Dunham, APS Division of Plasma Physics Meeting, Virtual, November 2020.
- "Z opacity sample evolution using time-resolved spectroscopy with a gated hybrid CMOS detector," Guillaume Loisel, APS Division of Plasma Physics Meeting, Virtual, November 2020.
- "Oxygen opacity experiments for stellar interiors," James Bailey, APS Division of Plasma Physics Meeting, Virtual, November 2020.
- "White Dwarf Stars," Don Winget, Guest Speaker - *Intro to Modern Astronomy* (class), John Gianforte, Lecturer, University of New Hampshire, Virtual, November 2020.
- "The Dawn of the New Age of Experimental Astrophysics at Cosmic Conditions: Astronomy becomes an experimental science," Don Winget, National Opacity Workshop (NOW), Virtual, July 2020.
- "The Unique Value and Essential Nature of McDonald Observatory for Training Our Next Generation of Astronomers," Don Winget, McDonald Observatory Semi-Annual Meeting of the Board of Visitors, Virtual, July 2020.
- "The Dawn of the New Age of Experimental Astrophysics at Cosmic Conditions: Astronomy becomes an experimental science," Don Winget, DAMOP Annual Meeting, Virtual, June 2020.
- "Wootton Center for Astrophysical Plasma Properties; Experiments at Cosmic Conditions!" Mike Montgomery & Don Winget, SSAP Symposium, Washington, DC, February 2020.

d. **Website(s) or other Internet site(s)**

https://sites.cns.utexas.edu/wcapp

e. **Technologies or techniques**
Nothing to Report

f. **Inventions, patent applications, and/or licenses**
Nothing to Report

g. **Other products**
Nothing to Report

3. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS: Optional

Who has been involved?

a. **What individuals have worked on the project?**

1. Name: Donald E. Winget
   - Total Number of Months: 3
   - Project Role: PI
   - Researcher Identifier: orcid.org/0000-0003-0181-2521
   - Contribution to Project: PI Winget's role is to plan the overall scientific direction of the project, including the experiments, supplementary theoretical calculations, and to ready results for publication as appropriate.
   - State, U.S. territory, and/or country of residence: Texas, U.S.A.
   - Collaborated with individual in foreign country: Yes
   - Country(ies) of foreign collaborator: Porto Alegre, BRAZIL
   - Travelled to foreign country: No
   - If traveled to foreign country(ies), duration of stay: NA

2. Name: Michael H. Montgomery
   - Total Number of Months: 6
   - Project Role: Co-I
   - Researcher Identifier: orcid.org/0000-0002-6748-1748
   - Contribution to Project: Co-I Montgomery's role is to assist in planning the overall scientific direction of the project, including the experiments, supplementary theoretical calculations, and to ready results for publication as appropriate.
   - State, U.S. territory, and/or country of residence: Texas, U.S.A.
   - Collaborated with individual in foreign country: No

3. Name: Roberto Mancini (University of Nevada, Reno)
   - Total Number of Months: 1.1
   - Project Role: Co-I, Subaward
   - Researcher Identifier: orcid.org/0000-0002-8649-7251
   - Contribution to Project: Co-I Mancini an atomic physicist with extensive experience in both theoretical and experimental physics; he is leading the efforts from UNR. He has developed new platforms for radiation-dominated plasma experiments on Z, and directs graduate students in theoretical atomic physics as they develop into professional physicists.
   - State, U.S. territory, and/or country of residence: Nevada, U.S.A.
   - Collaborated with individual in foreign country: No

4. Name: John "Craig" Wheeler
   - Total Number of Months: 1
   - Project Role: Co-I
   - Researcher Identifier: orcid.org/0000-0003-1349-6538

- Contribution to Project: Co-I Wheeler's expertise in High Energy Astrophysics, specializing in cosmic explosions of Type Ia supernovae and stellar astrophysics is beneficial to the project.
- State, U.S. territory, and/or country of residence: Texas, U.S.A.
- Collaborated with individual in foreign country: No

5. Name: Keith A. Hawkins
    - Total Number of Months: 1
    - Project Role: Co-I
    - Researcher Identifier: orcid.org/0000-0002-1423-2174
    - Contribution to Project: Co-I Hawkins' work on stellar populations in large scale surveys is beneficial to the project.
    - State, U.S. territory, and/or country of residence: Texas, U.S.A.
    - Collaborated with individual in foreign country: No

6. Name: Bart H. Dunlap
    - Total Number of Months: 12
    - Project Role: Postdoctoral Fellow
    - Researcher Identifier: orcid.org/0000-0002-1086-8685
    - Contribution to Project: Bart designs and fields experiments on the Z Machine at Sandia National Labs and reduces and analyzes the data from these shots.
    - State, U.S. territory, and/or country of residence: New Mexico, U.S.A.
    - Collaborated with individual in foreign country: No

7. Name: Daniel Mayes
    - Total Number of Months as postdoc: 1.5
    - Project Role: Postdoctoral Fellow (hired 01/01/21)
    - Project Role: Graduate Student (02/16/20 – 12/31/20, UNR)
    - Researcher Identifier: orcid.org/0000-0002-7952-8101
    - Contribution to Project: Dan has extensive background with Z Machine and its diagnostics, and will field shots allocated for this upcoming year and the next.
    - State, U.S. territory, and/or country of residence: New Mexico, U.S.A.
    - Collaborated with individual in foreign country: No

8. Georges Jaar
    - Total Number of Months: 1.5
    - Project Role: Postdoctoral Fellow, UNR (hired 01/01/21)
    - Researcher Identifier: orcid.org/0000-0002-7952-8101
    - Contribution to Project: Georges is training to field the photoionized gas cell and white dwarf experiments on Z and will reduce and analyze data from the gas cell experiment.
    - State, U.S. territory, and/or country of residence: New Mexico, U.S.A.
    - Collaborated with individual in foreign country: No

9. Name: Patricia B. Cho
   - Total Number of Months: 6.5
   - Project Role: Graduate Student (research assistant)
   - Researcher Identifier: orcid.org/0000-0002-9163-2905
   - Contribution to Project: Patty has been trained on, and learned to field experiments on, the Z Machine at Sandia National Labs.
   - State, U.S. territory, and/or country of residence: New Mexico, U.S.A.
   - Collaborated with individual in foreign country: No

10. Name: Kyle Swanson
    - Total Number of Months: 6
    - Project Role: Graduate Student (research assistant, UNR)
    - Researcher Identifier: orcid.org/0000-0002-9731-596X
    - Contribution to Project: Kyle has extensive background with Z Machine and its diagnostics, particularly the new PDV diagnostic he is developing
    - State, U.S. territory, and/or country of residence: Nevada, U.S.A.
    - Collaborated with individual in foreign country: No

11. Name: Zachary P. Vanderbosch
    - Total Number of Months: 4.5
    - Project Role: Graduate Student (research assistant)
    - Researcher Identifier: orcid.org/0000-0002-0853-3464
    - Contribution to Project: Zach makes observations of white dwarf stars relevant to our WDPE experiments on the Z machine and our hydrogen line profile calculations.
    - State, U.S. territory, and/or country of residence: Texas, U.S.A.
    - Collaborated with individual in foreign country: No

12. Name: Benjamin Thomas
    - Total Number of Months: 1.5
    - Project Role: Postdoctoral fellow
    - Researcher Identifier: orcid.org/0000-0002-0977-1974
    - Contribution to Project: Ben has used Machine Learning techniques to find white dwarf stars in the HETDEX survey that is being conducted at McDonald Observatory.
    - State, U.S. territory, and/or country of residence: Texas, U.S.A.
    - Collaborated with individual in foreign country: No

13. Name: Bryce Hobbs
    - Total Number of Months: 8.5
    - Project Role: Graduate Student (GRA)
    - Researcher Identifier: orcid.org/0000-0002-2230-9362
    - Contribution to Project: Bryce has worked to include new theoretical line shapes for hydrogen lines in the model atmosphere code Tlusty, with the goal of calculating the emergent spectra of white dwarf stars, and will also help us with fitting the lab data with the "slab mode" of Tlusty.

- State, U.S. territory, and/or country of residence: Texas, U.S.A.
- Collaborated with individual in foreign country: No

14. Name: Andreia Carillo
    - Total Number of Months: 7.5
    - Project Role: Graduate Student (GRA)
    - Researcher Identifier: orcid.org/0000-0002-5786-0787
    - Contribution to Project: Student mentored freshman and sophomore students in our Freshman Research Initiative stream on scientific questions relevant to WCAPP.
    - State, U.S. territory, and/or country of residence: Texas, U.S.A.
    - Collaborated with individual in foreign country: No

15. Name: Madeline Lucey
    - Total Number of Months: 6.5
    - Project Role: Graduate Student (GRA)
    - Researcher Identifier: NA
    - Contribution to Project: Student mentored freshman and sophomore students in our Freshman Research Initiative stream on scientific questions relevant to WCAPP.
    - State, U.S. territory, and/or country of residence: Texas, U.S.A.
    - Collaborated with individual in foreign country: No

16. Name: Aryn Feldner
    - Total Number of Months: 3.5
    - Project Role: Undergraduate Student (URA)
    - Researcher Identifier: NA
    - Contribution to Project: Student mentored freshman and sophomore students in our Freshman Research Initiative stream on scientific questions relevant to WCAPP.
    - State, U.S. territory, and/or country of residence: Texas, U.S.A.
    - Collaborated with individual in foreign country: No

17. Name: Rylee Ross
    - Total Number of Months: 3.5
    - Project Role: Undergraduate Student (URA)
    - Researcher Identifier: orcid.org/0000-0003-1555-5693
    - Contribution to Project: Student mentored freshman and sophomore students in our Freshman Research Initiative stream on scientific questions relevant to WCAPP.
    - State, U.S. territory, and/or country of residence: Texas, U.S.A.
    - Collaborated with individual in foreign country: No

18. Name: Kendrick Mack-Simon
    - Total Number of Months: 2.5
    - Project Role: Undergraduate Student (URA)

- Researcher Identifier: NA
- Contribution to Project: Student mentored freshman and sophomore students in our Freshman Research Initiative stream on scientific questions relevant to WCAPP.
- State, U.S. territory, and/or country of residence: Texas, U.S.A.
- Collaborated with individual in foreign country: No

19. Name: Dolores E. Groves
    - Total Number of Months: 12
    - Project Role: Executive Assistant (Administration)
    - Researcher Identifier: NA
    - Contribution to Project: Provides administrative support to Director and Deputy Director with a large volume of complex administrative tasks while exercising a high degree of initiative and judgment. Coordinates center's activities with three major universities and three national laboratories.
    - State, U.S. territory, and/or country of residence: Texas, U.S.A.
    - Collaborated with individual in foreign country: No

b. **Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?**

- PI Don Winget
  1. Support: Current
     Project/Proposal Title: (Wootton) Center for Astrophysical Plasma Properties (WCAPP)
     Source of Support: DOE
     Total Award Amount: $7,000,000
     Total Award Period Covered: 02/15/2018 to 02/14/2023
     Location of Project: The University of Texas at Austin
     Person-Months Per Year Committed to the Project: 3 summer

  2. Support: Current
     Project/Proposal Title: Stellar Atmospheres in the Laboratory: A Testbed for Fundamental Atomic Processes
     Source of Support: NSF
     Total Award Amount: $450,000
     Total Award Period Covered: 09/01/2017 to 08/31/2021
     Location of Project: The University of Texas at Austin
     Person-Months Per Year Committed to the Project: 1 calendar

  3. Support: Current (*Subawardee*)
     Project/Proposal Title: Study of Spectroscopic Features of Plasma in a Strong Magnetic Field
     Source of Support: University of Nevada, Reno
     Total Award Amount: $105,177
     Total Award Period Covered: 09/01/2020 to 08/31/2023
     Location of Project: The University of Texas at Austin
     Person-Months Per Year Committed to the Project: .01 calendar

- Co-I Michael Montgomery
  1. Support: Current
     Project/Proposal Title: (Wootton) Center for Astrophysical Plasma Properties (WCAPP)
     Source of Support: DOE
     Total Award Amount: $7,000,000
     Total Award Period Covered: 02/15/2018 to 02/14/2023
     Location of Project: The University of Texas at Austin
     Person-Months Per Year Committed to the Project: 6 calendar

  2. Support: Current
     Project/Proposal Title: Stellar Atmospheres in the Laboratory: A Testbed for Fundamental Atomic Processes
     Source of Support: NSF
     Total Award Amount: $450,000
     Total Award Period Covered: 09/01/2017 to 08/31/2021
     Location of Project: The University of Texas at Austin
     Person-Months Per Year Committed to the Project: 2 calendar

  3. Support: Current
     Project/Proposal Title: Seismologically Mining White Dwarfs in the K2 Archive for their Rotation Rates, Convection Properties
     Source of Support: NASA
     Total Award Amount: $334,513
     Total Award Period Covered: 01/01/2020 to 12/31/2022
     Location of Project: The University of Texas at Austin
     Person-Months Per Year Committed to the Project: 3 calendar

- Co-I Roberto Mancini
  4. Support: Current
     Project/Proposal Title: (Wootton) Center for Astrophysical Plasma Properties (WCAPP)
     Source of Support: DOE
     Total Award Amount: $7,000,000
     Total Award Period Covered: 02/15/2018 to 02/14/2023
     Location of Project: The University of Texas at Austin
     Person-Months Per Year Committed to the Project: 6 calendar

- Co-I Craig Wheeler
  5. Support: Current
     Project/Proposal Title: (Wootton) Center for Astrophysical Plasma Properties (WCAPP)
     Source of Support: DOE
     Total Award Amount: $7,000,000
     Total Award Period Covered: 02/15/2018 to 02/14/2023
     Location of Project: The University of Texas at Austin
     Person-Months Per Year Committed to the Project: 6 calendar

- Co-I Keith Hawkins
  1. Support: Current
     Project/Proposal Title: Aging Gracefully: Stellar Ages Across the HR Diagram and Their Implications for Galactic Archaeology
     Source of Support: Heising-Simons Foundation
     Total Award Amount: $55,000
     Total Award Period Covered: 10/01/2019 to 09/30/2021
     Location of Project: The University of Texas at Austin
     Person-Months Per Year Committed to the Project: 1 calendar

  2. Support: Current
     Project/Proposal Title: The Origins and Application of Hypervelocity Stars: A Chemo-Kinematic Approach
     Source of Support: NSF
     Total Award Amount: $302,462
     Total Award Period Covered: 09/01/2019 to 08/31/2022
     Location of Project: The University of Texas at Austin
     Person-Months Per Year Committed to the Project: 1 calendar

  3. Support: Current
     Project/Proposal Title: (Wootton) Center for Astrophysical Plasma Properties (WCAPP)
     Source of Support: DOE
     Total Award Amount: $7,000,000
     Total Award Period Covered: 02/15/2018 to 02/14/2023
     Location of Project: The University of Texas at Austin
     Person-Months Per Year Committed to the Project: 1 calendar

  4. Support: Pending
     Project/Proposal Title: Collaborative research: Exploring the Galactic Halo and White Dwarfs with the HET Dark Energy Experiment (HETDEX)
     Source of Support: NSF
     Total Award Amount: $299,759
     Total Award Period Covered: 09/01/2021 to 08/31/2024
     Location of Project: The University of Texas at Austin
     Person-Months Per Year Committed to the Project: 1 calendar

c. **What other organizations have been involved as partners?**

1. Organization Name: Sandia National Laboratories
   Location of Organization: Albuquerque, NM
   Partner's contribution to the project: Facilities - Provide the Z machine, gas cells, and other support for our experiments there.
   Collaborative research: Collaborators James E. Bailey, Thomas A. Gomez, Marc-Andre Schaeuble, Stephanie B. Hansen, Guillaume P. Loisel, Taisuke Nagayama, and Gregory A. Rochau

d. **Have other collaborators or contacts been involved?**

1. Organization Name: University of Arizona
   Location of Organization: Tuscan, AZ
   Partner's contribution to the project: Collaborative research – Dr. Ivan Hubeny

2. Organization Name: Lawrence Livermore National Laboratory
   Location of Organization: Livermore, CA
   Partner's contribution to the project: Collaborative research – Drs. Carlos Iglesias and Duane Liedahl

3. Organization Name: National Ignition Facility
   Location of Organization: Livermore, CA
   Partner's contribution to the project: Collaborative research – Drs. Ted Perry, Robert Heeter, Kathy Opachich and Harry Robey

4. Organization Name: NASA's Goddard Space Flight Center
   Location of Organization: Greenbelt, MD
   Partner's contribution to the project: Collaborative research – Dr. Tim Kallman

4. IMPACT: Optional

What is the impact of the project? How has it contributed?

a. **What was the impact on the development of the principal discipline(s) of the project?**

b. **What was the impact on other disciplines?**

c. **What was the impact on the development of human resources?**
See section 1c

d. **What was the impact on teaching and educational experiences?**
Nothing to Report

e. **What was the impact on physical, institutional, and information resources that form infrastructure?**
Nothing to Report

f. **What was the impact on technology transfer?**
Nothing to Report

g. **What was the impact on society beyond science and technology?**
Nothing to Report

h. **What percentage of the award's budget was spent in foreign country(ies)?**
Nothing to Report

5. **CHANGES/PROBLEMS: Optional**
   a. **Changes in approach and reasons for change**
   Nothing to Report

   b. **Actual or anticipated problems or delays and actions or plans to resolve them**
   Nothing to Report

   c. **Changes that have a significant impact on expenditures**
   We have finally overcome the challenges of recruiting and hiring during the pandemic and have recently hired two new postdocs, and have three new graduate students joining us in Fall 2021. We have sufficient funds to cover these new expenditures.

   d. **Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents**
   Nothing to Report

   e. **Change of primary performance site location from that originally proposed**
   Nothing to Report

6. **SPECIAL REPORTING REQUIREMENTS: Mandatory**
   Nothing to Report

7. **BUDGETARY INFORMATION: Optional**

8. **PROJECT OUTCOMES: Optional**

What were the outcomes of the award?

This information is used at the completion of the award to ascertain the cumulative outcomes or findings of a project. Describe project outcomes specifically for the public to provide insight into the outcomes of Federally-funded research, education, and other activities. Agencies may make this information available to the public in an electronic format.

Project Outcomes

The recipient is to provide information regarding the cumulative outcomes or findings of the project. For the final RPPR for the project, provide a concise summary of the outcomes or findings of the award (no more than 8,000 characters) that:

a. is written for the general public (non-technical audiences) in clear, concise, and comprehensible language;
b. is suitable for dissemination to the general public, as the information may be available electronically;
c. does not include proprietary, confidential information or trade secrets; and

d. includes up to six images (images are optional).

Please note that this reporting of project outcomes does not constitute a formal dissemination of scientific and technical information (STI) but rather is used by agency program staff to publicize project results, outcomes or findings.

To ensure the public access to the results of federally funded research notify DOE Office of Scientific and Technical Information about the published results so the information will be made publicly accessible and discoverable through DOE web-based products. Access to and archival of DOE-funded STI are managed by the (OSTI). For information about OSTI see http://www.osti.gov.
For more information on STI submittals, see http://www.osti.gov/stip/submittal.