# RESEARCH PERFORMANCE PROGRESS REPORT

National Nuclear Security Administration

DE-NA0003843

(Wootton) Center for Astrophysical Plasma Properties

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

Reporting Period End Date: 02/14/2020, YR2

Report Term or Frequency: Annual

## 1. ACCOMPLISHMENTS: Mandatory

### What was done? What was learned?

WCAPP currently carries out ***four*** independent astrophysically-motivated experiments simultaneously on each shot 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

### 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.
- **Atomic kinetics, x-ray heating, and temperature of photoionized plasmas**
  The objective of this experiment is to make systematic measurements of heating and ionization 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 accretion disks and their associated winds.
- **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.
- **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 make 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 02/15/19 - 02/14/2020, the team carried out 5 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) make measurements of the gases hydrogen, helium, and carbon at white dwarf photosphere conditions. Given that the plasma in our experiment evolves dynamically, we can 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.

Our graduate student, 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 is also in the process of incorporating these new hydrogen line profile calculations into model white dwarf atmospheres, specifically the open source stellar atmosphere code *Tlusty*.

We have also made experiments involving helium and have attempted to measure the pressure shift of the line centers over a range of densities, as well as measurements that constrain the neutral broadening of these lines. After a recent improvement to our analysis techniques, we find that the measured line widths due to neutral broadening are consistent with those predicted by standard theory. These results are also being readied for publication.

In exploring other compositions, we recently achieved carbon plasma conditions relevant to white dwarfs with carbon-dominated atmospheres. These stars are likely the result of mergers of two white dwarfs, and are potentially useful in understanding type Ia supernovae. More carbon shots, as well as those with hydrogen and helium, are planned for the future.

- **Atomic kinetics, x-ray heating, and temperature of photoionized plasmas (Mancini, Mayes, Swanson)**

  We have finished data processing and analysis of gas cell transmission spectra, both time-integrated and gated. The time-integrated data (i.e., recorded on x-ray film) have produced 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. The gated data has confirmed the presence of transient effects on the neon atomic physics that had been predicted by modeling and simulation and has permitted us to assess its importance. Both results are now being written up for publication.

- **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 *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 in the last year, addressing a puzzle with emission from black hole accretion disks, and it is now led by NNSA LRGF graduate student Patricia Cho. Presently, the amount of iron required to model the spectral emission observed near several the black hole event horizons is five to twenty times the expected value from stellar evolution theory. No plausible solution has yet come forward. A leading hypothesis is that models used to predict photoionized iron emission might be deficient owing to the absence of constraining laboratory data. The first Fe emission spectra were obtained and pave the way to address this hypothesis.

- **Stellar interior opacity (Bailey, Nagayama, Loisel)**
  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%. In past work, we successfully measured iron opacity at conditions similar to the solar-convection-zone base. The measurements, published in the journal *Nature*, were higher than predictions. If correct, the data accounts for approximately one half the opacity increase needed to resolve the solar problem. Research must continue until the opacity theory and measurements are reconciled. Last year, the opacity of chromium and nickel at similar conditions as iron was also measured. By studying how the model-data opacity disagreement changes as a function of atomic number, this restricts the hypotheses for the discrepancy. We have also developed time-resolved measurement capability. The opacity sample condition time history was measured and will help provide further constraints on the opacity problem.

  Another major contributor to the total solar opacity is oxygen. While seemingly simpler to model than iron, it is actually believed to contribute 25% more than iron to the total opacity. 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 will provide a foundation for future data at near solar convection zone base conditions (“Anchor 2”, $T_e \sim 182$ eV, $n_e \sim 3.8 \times 10^{22}$ cm$^{-3}$).

c. **What opportunities for training and professional development has the project provided?**

Graduate student Zach Vanderbosch became a PhD candidate in Spring 2018. 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 is currently familiarizing herself with the Accretion Powered Matter and Radiation experiment currently run by Guillaume Loisel. She was also award a DOE NNSA LRGF fellowship for her continuing work at SNL. In addition, three undergraduate students have begun working with us (Malia Kao, Bryce Hobbs, and Isaac Huegel).

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)
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?**

We published 4 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, 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.

  Theoretical work: Include new 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 He.

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

  Continue studies of heating and ionization as a function of the ionization parameter. Write up results on both time-integrated and gated gas cell transmission spectra transient effects that had been predicted by modeling and simulation. 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.

- **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.

- **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: Mandatory**

**What has the project produced?**

a. **Publications**

- 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", Submitted to *Astrophysical Journal* (August 26, 2019), Accepted May 26, 2020.
- M. H. Montgomery, J. J. Hermes, D. E. Winget, B. H. Dunlap, and K. J. Bell, "Limits on Mode Coherence in Pulsating DA White Dwarfs Due to a Nonstatic Convection Zone", The Astrophysical Journal, vol. 890, 1, 2020
- M.-A. Schaeuble, T. Nagayama, J. E. Bailey, T. A. Gomez, M. H. Montgomery, and D. E. Winget, "Hß and Hγ Absorption-line Profile Inconsistencies in Laboratory Experiments Performed at White Dwarf Photosphere Conditions", *Astrophysical Journal*, vol. 885, 1, 2019.

- S. Coutu, P. Dufour, P. Bergeron, S. Blouin, E. Loranger, N. F. Allard, and B. H. Dunlap, "Analysis of Helium-rich White Dwarfs Polluted by Heavy Elements in the Gaia Era", *Astrophysical Journal*, vol. 885, 1, article id. 74, 2019.

b. **Books or other non-periodical, one-time publications.**
   Nothing to Report

c. **Other publications, conference papers and presentations**.
- "Measuring opacity effects on radiation cooling in plasmas at white dwarf and solar conditions", Don Winget, NIFUG, Livermore, CA, February 2020
- "The Wootton Center for Astrophysical Plasma Properties: Recent Highlights of Experiments on Z", Don Winget, ZNetUS Workshop, La Jolla, CA, January 2020
- "The UT Austin, UNR, Sandia Center of Excellence for Astrophysical Plasma Properties", Don Winget, University of Nevada Reno Physics Colloquium, Reno, NV, November 2019
- "Understanding spectra from white dwarf photospheres: benchmarking the atomic physics", Don Winget, IAU Symposium, Hilo, HI, October 2019
- "The White Dwarf Photosphere Experiment: Results for Neutral Helium Broadening", Mike Montgomery, APS DPP, Fort Lauderdale, FL, October 2019
- "Laboratory Measurements of Discrepancies between Hß and Hγ Absorption Line Profiles at the Conditions of White Dwarf Photospheres", Marc-Andre Schaeuble, APS DPP, Fort Lauderdale, FL, October 2019
- "Revised Laboratory Measurements of Iron Opacity for Stellar Interiors", Jim Bailey, APS DPP, Fort Lauderdale, FL, October 2019
- "Radiation Cooling of Laboratory Photoionized Plasmas", Roberto Mancini, APS DPP, Fort Lauderdale, FL, October 2019
- "First Experimental Assessment of the Z Opacity Sample Evolution using Time-resolved Spectroscopy with a Gated Hybrid CMOS Detector", Guillaume Loisel, APS DPP, Fort Lauderdale, FL, October 2019
- "Stellar Atmospheres in the Laboratory: A Testbed for Fundamental Atomic Processes", Mike Montgomery, NASA-NSF PI Review meeting on Laboratory Astrophysics, Washington, DC, October 2019
- "Understanding spectra from white dwarf photospheres in the context of WCAPP", Don Winget, IFSA, Osaka, Japan, September 2019
- "The Effect of a Variable Convection Zone on Coherence and Damping of Modes in Pulsating White Dwarfs", Mike Montgomery, TASC5/KASC12 Workshop, Cambridge, MA, July 2019
- "White Dwarfs and McDonald Observatory", Don Winget, Board of Visitors meeting, Fort Davis, TX, July 2019
- "Laboratory plasma experiments to test photoionized plasma models", Mayes, Daniel C.; Mancini, Roberto; Bailey, James E.; Loisel, Guillaume; Rochau, Gregory, American Astronomical Society Meeting #234, id. 209.03, June 2019.
- "Radiation cooling in laboratory photoionized plasmas", Mancini, Roberto; Mayes, Daniel C.; Ryan, Schoenfeld; Loisel, Guillaume; Bailey, James E.; Rochau,

Gregory; Liedahl, Duane A., American Astronomical Society Meeting #234, id. 209.03, June 2019.

- "The Wootton Center for Astrophysical Plasma Properties: First Results for Helium", Mike Montgomery, IAU Symposium on Laboratory Astrophysics, Cambridge, UK, April 2019
- "The Wootton Center for Astrophysical Plasma Properties: At-Parameter Experimental Astrophysics", Don Winget, Lakeway Men's Breakfast Club", Don Winget, Conopus, San Antonio, TX, April 2019
- "The Wootton Center for Astrophysical Plasma Properties: At-Parameter Experimental Astrophysics", Don Winget, OLUG, Rochester, NY, April 2019

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

http://www.as.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: 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

4. Name: Keith A. Hawkins
   - Total Number of Months: .8
   - 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

5. 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

6. Name: Zachary P. Vanderbosch
   - Total Number of Months: 7
   - Project Role: Graduate Student (research assistant)
   - Researcher Identifier: orcid.org/0000-0002-0853-3464
   - Contribution to Project: Zach fields experiments on the Z Machine at Sandia National Labs and reduces and analyzes the data from these shots. He also makes astronomical observations in support of these experiments.
   - State, U.S. territory, and/or country of residence: Texas, U.S.A.
   - Collaborated with individual in foreign country: No

7. Name: Patricia B. Cho

- Total Number of Months: 7
- Project Role: Graduate Student (research assistant)
- Researcher Identifier: orcid.org/0000-0002-9163-2905
- Contribution to Project: Patty 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

8. 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 large 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
     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

4. Support: Submitted
   Project/Proposal Title: Statistics and Morphology of Debris Disk Systems around White Dwarf Stars
   Source of Support: NSF
   Total Award Amount: $426,277
   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: .5 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

4. Support: Submitted
   Project/Proposal Title: Statistics and Morphology of Debris Disk Systems around White Dwarf Stars
   Source of Support: NSF
   Total Award Amount: $426,277
   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: .5 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, 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: 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

1. **CHANGES/PROBLEMS: Mandatory**
   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**
   Due to various circumstances, including the direct and indirect effects of the COVID-19 pandemic, we have had difficulty hiring postdocs. We have conducted several interviews and hope to be able to hire soon. We also are in the process of recruiting two new graduated students to our group.

   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

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

3. **BUDGETARY INFORMATION: Optional**

4. **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.