White Paper for Plasma Science Frontiers

Studies in Plasma Astrophysics

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(i) An oral presentation, if desired, could be presented by Alan Wootton; he will be present at the Town Hall Meeting.

(ii) Primary Workshop Panels most relevant to the research frontier or scientific challenge is **Panel 1: Plasma atomic physics and the interface with chemistry and biology.**

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The fundamental science described in the following white paper spreads across the first four topics for the Town Hall Meeting: (1) Fundamental Plasma Experiments, (2) Theory and Computation, (3) Astrophysical and Space Plasmas, (4) High Energy Density Plasmas (HEDP) and Warm Dense Matter (WDM). It has a greater concentration in areas (2) and (3).

The pursuit of fundamental science with national facilities is having a transformational impact on astrophysics that will accelerate in the coming decade. Historically, astrophysics has been considered an observational science—it is impossible to conduct experiments on astrophysical objects. This landscape has changed. Star-stuff has been created in the lab and its physical conditions diagnosed. With this work, astrophysics has joined its sister sciences as an experimental science.

The potential for this work with National Class Facilities like NIF and Z is nicely illustrated by several recent successes with the Z Facility at Sandia National Laboratories [Matzen et al., Phys. Plasmas, 12, 055503 (2005)]. The Z Facility is the most powerful pulsed-power X-ray source in the world; it produces power in excess of 0.3 PW. This is sufficient to create plasmas and materials under astrophysical conditions. Each firing, or shot, of the Z machine produces long-lived and stable macroscopic plasmas with volumes of 20cc, temperatures from 1–200 eV, and electron densities from 10^{17-23} cc^{-1}. In its present configuration with a tungsten wire array, the peak electrical power has been stable to 1.5% and the x-ray power has been reproducible and consistent from shot to shot at the level of 10%.

The efficiency of these fundamental science experiments is a model for future research. The key to this efficiency lies in the ability to conduct multiple experiments simultaneously with a single shot. This has resulted in a new effort called the Z Astrophysical Plasma Properties (ZAPP) collaboration [Rochau et al., Phys. Plasmas, 21, 056308 (2014)].

The ZAPP collaboration work is aimed at reproducing the characteristics of astrophysical plasmas as closely as possible in the laboratory and uses detailed spectral measurements to strengthen models for atoms in plasmas and properly diagnose the astrophysical plasma conditions. With a broad array of plasma diagnostics, including 59 spectra obtained for 4 fundamental astrophysics programs on one shot, ZAPP is a model of efficiency.

Astrophysical issues currently under investigation include the LTE opacity of iron at stellar-interior conditions [Bailey et al., Nature, 517, 56 (2015)], photoionization around active galactic nuclei, the efficiency of resonant Auger destruction in black-hole accretion disks, and H-Balmer line shapes in white dwarf photospheres [Falcon et al., ApJ, in press].

All four of these investigations are motivated by known inconsistencies in our understanding of the constitutive physics of astrophysical objects. For example, the iron opacity experiment addresses the serious inconsistency between the latest determinations of the solar abundances of carbon, nitrogen and oxygen, with the solar structure inferred from the observed solar oscillation frequencies through helioseismology. The problem is most severe near the base of the solar convection zone. The experiments show that theory has substantially underestimated the opacity of iron—only one of the several significant sources of opacity in this region of the Sun (T ~

1.9-2.3 million Kelvins and electron densities of $(0.7\text{-}4.0) \times 10^{22}\ cc^{-1}$); the iron opacity alone accounts for roughly half the reported discrepancy [Bailey, et al. Nature, 517, 56 (2015)]. This discrepancy applies not only to the Sun, but to our understanding of all sun-like stars—essentially all stars on or near the main sequence—hence affecting our understanding of most extrasolar planet hosting stars and their ages and structure.

A second example comes from work motivated by the ~15% disagreement between white dwarf masses based on gravitational redshift measurements and those inferred from comparison of the observed spectra with theoretical line-broadening calculations. This affects inferred ages and physical properties of white dwarf stars, one of the most fundamental chronometers for constraining the age of the universe and the age and evolution of our Milky Way galaxy. The white dwarf photospheric work is making benchmark measurements of line broadening in the hydrogen Balmer lines that are used to infer the plasma conditions in white dwarf stars—these provide the boundary conditions for all numerical modeling of white dwarf stars. The current benchmark experiments on hydrogen under white dwarf photospheric conditions are motivating new theoretical line-broadening calculations and point the way to improving our determination of the plasma conditions in white dwarf photospheres. This will improve cosmochronology and our understanding of the constitutive physics in white dwarf stars. This includes the process of crystallization in dense Coulomb plasmas and the EoS of hydrogen under the same density and temperature conditions required for ICF.

These things are possible because of our developing ability to reproduce cosmic conditions in the laboratory. Scientists are only beginning to scratch the surface of these kinds of on-parameter experiments relevant to astrophysical objects. The next decade will mark the maturation of NIF and Z, if time for fundamental science experiments is allowed. Possible investigations include exploring physics under conditions relevant for Black Hole accretion—the model for most active galactic nuclei, and things as previously exotic as neutron star atmospheres because these conditions are now attainable in the laboratory.

All astrophysical objects have magnetic fields, and often the magnetic field dominates the dynamics in the plasma. These effects can be reproduced in the laboratory as well and will affect the diagnoses of the plasma conditions. Future resources should be directed in simulating plasmas relevant to this significant part of the cosmos.

It is important that this type of fundamental scientific research be carried out at the national facilities in the coming decade. Carrying out such experiments on national facilities has the advantage that it allows partnering with academic institutions for individual investigations. This exposes undergraduate students, graduate students, and postdocs to the National Laboratory environment through their universities. By putting the national laboratories on the student's "career radar," it significantly expands the talent pool for the next generation of scientists at the national facilities and ensures a sustainable future for the important research being carried out there.