Astro2020: Decadal Survey on Astronomy and Astrophysics : State of the Profession Considerations for Laboratory Astrophysics

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State of the Profession Considerations for Laboratory Astrophysics

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Key Issues and Overview of the Impact on the Field

Astrophysics advances, in part, through continual improvements in observational capabilities, such as collecting area and spatial resolution of telescopes, and corresponding advances in the associated spectroscopic instrumentation. However, our understanding of the underlying processes that control the observed properties of the Cosmos is lacking relative to these improvements. The relevant processes include atomic, molecular, dust, ice, surface, condensed matter, plasma, nuclear, and particle physics as well as planetary science. Observations by new facilities invariably find that the scientific return of our astronomical explorations is hindered by shortcomings in our understanding of these processes that drive the cosmos. The study of these processes is known as laboratory astrophysics, a term encompassing both theoretical and experimental research.

Many of the recent and upcoming astronomical flagship facilities are $1B class investments by NSF, NASA, and other international science organizations, such as the European Southern Observatory (ESO). Maximizing the scientific return of these facilities hinges, to a large extent, on significant advances in laboratory astrophysics that go beyond our current capabilities. Achieving these advancements will require robust laboratory astrophysics support by NSF, NASA, national laboratories (such as the Department of Energy [DOE] and Department of Defense [DOD]), universities, and beyond. Here, we highlight a few of the many astrophysical advances that will become possible with robust laboratory astrophysics support. We provide examples for all 8 thematic areas identified in the Call to the Astronomy & Astrophysics Community for Science White Papers (Astro2020 Decadal Survey), using the numbering system given there for the thematic areas. The focus here mostly on atomic, molecular, and optical (AMO) laboratory astrophysics only reflects the research expertise for many of the authors of this white paper. The other areas in laboratory astrophysics are equally important.

1. Planetary Systems

Exoplanets: Over 4,000 exoplanets have been discovered to date. Observational constraints have limited these primarily to planets more massive than Earth or with smaller separations from their host stars. Most planets are unlikely to transit across their host stars from our perspective, precluding the use of eclipse or transit methods. Hence, future searches for Earth-like planets will be dominated by detecting Doppler shifts in the stellar spectrum induced by the orbital motion of the planet. These studies will require visible and IR spectrometers calibrated to an accuracy of a few parts in 10^9 or better and with a stability on the order of decades. Commercially available Th/Ar calibration lamps are contaminated by ThO, iodine lamps affect the measured stellar spectra, and thus new alternatives are needed, with U/Ne being one such proposed lamp. Laser frequency combs can achieve stability to ~ 1 part in 10^{18} but they are not yet turnkey devices for observatory use. It is anticipated that lamps will be in use for some time as references for radial velocity measurements in exoplanet studies. *In order to enable our ability to detect exoplanets with masses and orbits similar to Earth's, significant advances are needed in AMO laboratory astrophysics.*

Exoplanetary atmospheres: Clues to the habitability of exoplanets are provided by their atmospheres (Seager & Deming 2010, Wakeford et al. 2018). As a planet passes in front of its host star, the star light is filtered by the planet's atmosphere, yielding spectroscopic data. The planned 2021 launch of the *James Web Space Telescope* (*JWST*) will open up the near- and mid-infrared (IR) range to spectroscopy of planetary atmospheres. But our ability to interpret exoplanetary atmospheres is limited by shortcomings in our understanding of the underlying molecular and condensed matter physics that generates the observed spectra (Fortney et al.

2019). The spectra of many small molecules are incomplete, inaccurate, or completely unknown. Some of the important molecules include: H_2, H_2O, OH, HF, NH_3, CH_4, HCN, KOH, HCl, H_2S, PH_3, CO, SiO, CO_2, C_2S_2, KCl, O_3, SO_2, TiO, and VO. Data are needed for pressure-induced line broadening parameters, continuum opacity due to collision-induced absorption, molecular opacities at high spectral resolution, photoabsorption cross sections for small molecules at high temperatures, and expanded public databases for atmospherically relevant chemical reactions. In addition, complex-refractive indices of condensed matter particles that contribute to the observed continuum in exoplanet atmospheres are needed. The laboratory spectra of analogs to exoplanetary aerosols can provide a first step in this direction. *Meeting these astrophysical needs requires new advances in theoretical and experimental molecular physics methods.*

Exoplanetary interiors: The discovery of accretion onto white dwarf stars of tidally disrupted rocky planets and asteroids has given us a unique and direct way to explore exoplanet interiors (Jura & Young 2014). In the strong gravities of white dwarfs, heavy elements quickly sink below the observable photosphere. So the heavy elements observed in these stars are from the continual accretion of tidally disrupted objects. The relative abundances of the heavy elements indicate the geological composition of the rocky planetary interiors. New time domain surveys like the Zwicky Transit Facility (ZTF) at Caltech are turning up more of these objects. This survey, started in 2017, will increase the sample from a handful of objects to thousands, giving us a window into the internal compositions of rocky planets and asteroids throughout the galaxy. Spectroscopy will be possible for this larger (and therefore fainter) sample through improved infrared sensitivity available with *JWST* and the next generation large telescopes. *Our only window into the interior composition of rocky worlds for the next decade and beyond is likely to be spectroscopy of white dwarf atmospheres, which will require accurate spectroscopic data for those heavy elements forming the planetary interiors.*

Solar wind interactions with planetary bodies: Charge exchange (CX) recombination of solar wind ions with neutrals atoms and molecules around comets, in planetary exospheres, and within the heliosphere can be a sensitive probe of both the solar wind and the neutral gas it interacts with (Dennerl et al. 2012). However, laboratory benchmarks have shown that many of the most common CX models are flawed (Betancourt-Martinez 2018). *Using CX to probe solar system objects require further experiments and more advanced theoretical methods to better understand the CX process.*

Atmosphereless Solar System Bodies (ASSBs) as exoplanet analogs: Reflected light is the primary means used to understand the chemical and physical properties of regolith on the surface of an ASSB. This light is the product of the interaction between the solar spectrum and the spectrally active species on the surface of the body and may be polarized. The spectral properties of the airless surface can also be altered by micrometeorite impacts, solar wind ion irradiation, photon stimulated desorption, and other processes that are collectively known as space weathering. Spectrophotometric measurements of ASSBs are interpreted by comparison to laboratory reflectance measurements of simulated regolith (Nelson et al. 2018) and simulated space weathering of regoliths (Domingue et al. 2014). *Deepening our experimental and theoretical understanding into the physical and chemical nature of ASSB surfaces and the effects of space weathering in our own solar system will aid in the interpretation of exoplanet data.*

2. Star and Planet Formation

Understanding the evolutionary pathway of baryonic matter from atoms in space to the formation of a planetary system around a host star lies at the forefront of current day astrophysical research. This pathway encompasses diffuse atomic and molecular clouds, dense molecular clouds, interstellar dust, prestellar cores, protostars, protoplanetary disks, interplanetary dust particles, comets, and meteorites. *Unambiguously tracing out this evolutionary history will need new theoretical and experimental advances in various areas of laboratory astrophysics.*

The molecular Universe: We have entered a new era of discovery, due to facilities such as the Atacama Large Millimeter/submillimeter Array (ALMA), the Stratospheric Observatory for Infrared Astronomy (SOFIA), and the upcoming *JWST*. Over 200 different molecules have been identified to date in the interstellar medium and in circumstellar media (McGuire 2018). However, the species responsible for the vast majority of the astronomically observed molecular spectral features remain unidentified (Cernicharo et al. 2013, McGuire et al. 2017). Many of these are thought to be associated with larger and more complex molecules such as polycyclic aromatic hydrocarbons (PAHs), which are abundant and ubiquitous in space (Tielens 2013). Theoretical methods have proven to be insufficiently accurate to correctly predict molecular spectra, notably when it concerns effects due to anharmonicity. Overall, lab spectra are the only reliable way at present to identify molecules in space, but many of the experiments are difficult and time consuming. As a result, new molecules are being identified in space at the rate of about 3.7 per year and it will take decades to catch up with existing observations. *Unlocking the full mystery of the molecular Universe requires new AMO theoretical and experimental advances in molecular spectroscopy.*

Molecular observations also reveal important gas-phase chemical processes driving the evolution of baryonic gas, such as inorganic chemistry forming dust (raw material for planets) and organic chemistry leading to the formation of aromatic molecules and other molecules necessary for life as we know it. The complexity of the multi-atom reaction systems challenges current quantum mechanical and experimental capabilities; most of the relevant gas-phase reaction rate coefficients can only be roughly estimated (O'Connor et al. 2015). *Reliably modeling and interpreting the molecular properties of the Cosmos requires new AMO theoretical and experimental advances in inelastic and reactive scattering techniques.*

The presence of complex organic molecules (COMs) is only easily explained by physicochemical processing in condensed matter environments driven by light and particle radiation (Linnartz et al. 2015, Oberg 2016). *JWST* promises a new era for observations of icy solids (for which high resolution COM spectra are needed), while ALMA will reveal the extent of gas-phase chemical complexity. Understanding the link between the gas and solid phases is essential. *Addressing this issue necessitates advances in theoretical and experimental surface physics and chemistry.*

Using chemistry to study star forming clouds: The transition from diffuse atomic to diffuse molecular clouds is studied using observations of molecules such as OH^+, CF^+, HCl^+, and ArH^+, while observations of the exoergically formed CH^+ and SH^+ are used to study the input of mechanical energy into the gas (Gerin et al. 2016). Interpreting the astrophysical properties of the observed clouds requires quantitatively understanding the scattering processes that control the observed molecular abundances, in particular dissociative recombination (DR), which destroys these molecules. Accurate DR calculations are challenging, as it is a many-body problem with multiple electrons and nuclei. Common theoretical approximations are usually inadequate, making a rigorous theoretical description of the problem quite challenging, thus requiring new theoretical advances. In the lab, the challenge is to measure DR on heavy cations with internal excitation levels of only about 10 to 100 K. *Generating the required DR data will* *require state-of-the-art facilities such as the heavy ion Cryogenic Storage Ring (CSR) at the Max Planck Institute for Nuclear Physics (von Hahn et al. 2016).*

Studies of star forming clouds use observations of ortho (o-) and para (p-) H_2D^+ and D_2H^+ to determine the age of the prestellar cores, follow their evolution, and infer the role that magnetic fields may play in the collapse of the cloud (Harju et al. 2017). Utilizing the observed ratios of o-H_2D^+/p-H_2D^+ and o-D_2H^+/p-D_2H^+, combined with chemical models for the nuclear spin evolution of the gas, estimates can be made for the age of the cloud and compared to the gravitational free-fall time. The inferred ages can exceed that of the free-fall timescale, implying that magnetic fields may be slowing the collapse of the cloud (Kong et al. 2015). *The reliability of these prestellar core studies is limited by existing uncertainties in the reaction o/p-H_2 + o/p-H_3^+ $\rightarrow$ o/p-H_2 + o/p-H_3^+, and the deuterated isotopic variations, which challenge current quantum theoretical capabilities.*

Protoplanetary disk chemistry: Protoplanetary disks are studied using deuterated molecules. These are powerful probes of cold astrophysical environments, yielding information about the temperature, density, chemistry, abundances, ionization level, evolutionary stage, and thermal history of the disk (Ceccarelli et al. 2014, Millar 2015). The diagnostic power of D-bearing molecules arises because the zero-point energy of deuterated molecules is lower than the normal isotope, typically by several hundred kelvin. Important species driving deuteration are H_2D^+, N_2D^+, CH_2D^+, C_2HD^+, and CH_4D^+ (Millar 2015, Aikawa et al. 2018). *The complexity of these reactive scattering systems requires advances in current quantum mechanical theory and challenges current experimental methods.*

COMs in protoplanetary disks are the foundation from which biology may be built. Frost lines reveal the presence of the simple molecular precursors and their distribution within disks. Condense matter processing, solid-gas interactions and gas-phase processing contribute to the evolution of chemical complexity in these environments. For example (Chutjian et al. 2012), the presence of ferromagnesosilica (MgFeSiO) grains; coated with the relatively abundant CO_2, NH_3 and CH_4 species; and bombarded by energetic $H(^2S)$ and $O(^3P)$ atoms; can be a scenario for synthesis of amino acids such as NH_2CH_2COOH (glycine) and NH_2CHCH_3COOH (alanine). *Advances in theoretical and experimental surface science and AMO physics are necessary to fully understand these complex processes and their interplay*.

Accretion processes: The fast accretion required to form stars and planets is necessarily accompanied by turbulence in the corresponding disks. Numerous turbulence generation mechanisms have been proposed, including magnetorotational instability (MRI) or nonlinear hydrodynamic turbulence. Few of them, if any, can be confirmed from observation. Numerical simulations have been the main research approach, but unrealistic assumptions have been necessary. Laboratory experiments, when well controlled and well diagnosed, serve a much-needed complementary approach for the problems (Ji & Balbus, 2013). *Advances in experimental and numerical research in the laboratory settings, using liquids, gases, and plasmas, to test and challenge the proposed concepts to generate and sustain turbulence and its consequences are necessary to confirm their existence and effectiveness for accretion in disks.*

Dust in the interstellar medium (ISM): Dust is ubiquitous throughout the cold ISM and plays an important role in the local chemistry, where grain surfaces serve as a catalyst for molecular formation (Tielens 2013). Dust grains are the building blocks out of which larger solid bodies form. The inferred grain sizes and shapes provide diagnostics for their local physical environment (pressure, temperature, etc.). The properties of the dust grains can be studied through the ISM absorption spectra from a variety of stellar objects (Gao et al. 2009), absorption that is impacted by the size, shape, and composition of the dust grains. *Using ISM dust studies to advance our understanding of the presence, generation, and role of solid matter in the Universe will require laboratory experiments to quantify light absorption and scattering by dust.*

Solid body formation in protoplanetary disks: Solid body formation in protoplanetary disks occurs as µm-sized grains grow into larger aggregates. Our understanding of these early stages of planetesimal formation is based on studies of our own Solar System. Hierarchical aggregate growth is expected to proceed through binary sticking collisions from µm to mm sizes. But this growth stalls as the aggregates start bouncing and fragmenting upon collision rather than sticking and growing, a phenomenon called the "bouncing barrier" (Zsom, et al. 2010). To overcome this barrier, aggregate growth is believed to proceed further through local concentrations in the gas, for example in streaming instabilities (Krapp et al. 2019), that collapse under their own weight. Laboratory experimental data on the coagulation of dust simulants have helped to advance our understanding of these early stages of planet formation by uncovering growth barriers (Schräpler et al., 2018). *Understanding of dust growth and planet formation will require further experiments on the formation of aggregates at all growth stages using a variety of realistic analog materials.*

3. Stars and Stellar Evolution

Stellar spectroscopy: Measurement of stellar properties such as chemical compositions, masses, and ages is a fundamental problem in astrophysics (Heiter et al. 2015). The problem has become even more relevant in the era of current and future large astrometric surveys such as the Sloan Digital Sky Survey (SDSS), Global Astrometric Interferometer for Astrophysics (GAIA), Large Synoptic Survey Telescope (LSST) and Skymapper, complimented by large, high-resolution and high-signal-to-noise ratio spectroscopic surveys such as Sloan Extension for Galactic Understanding and Exploration (SEGUE), Apache Point Observatory Galactic Evolution Experiment (APOGEE), 4-meter Multi-Object Spectroscopic Telescope (4MOST), William Herschel Telescope Enhanced Area Velocity Explorer (WEAVE), GALactic Archaeology with HERMES (GALAH), and GAIA-ESO. While stellar spectral line strengths are now routinely measured at accuracies of 1% or better, AMO uncertainties dominate the interpretation, and the actual errors in derived properties, such as the abundance of a chemical element, are at least an order of magnitude larger. Advances in the accuracy of the interpretation of stellar spectra, and thus the accuracy of stellar chemical compositions and other properties, are needed to gain insight into many current problems in modern astrophysics, such as the formation of planets, stars, and galaxies (especially the Milky Way, so-called Galactic archeology) as well as studies into fundamental stellar physics, the origin and evolution of the chemical elements, and cosmology. Analysis of stellar spectra at the 1% accuracy level is a significant challenge, and requires atomic and molecular data, including wavelengths, transition probabilities (*gf*-values), photoionization cross sections, line broadening parameters, and collisional cross sections, with a high level of accuracy and completeness (see Barklem 2016 for a recent overview). *Advances in AMO theory and experiment, with interplay between theoretical atomic physics, laboratory spectroscopy, and astrophysical observations, are needed to generate the data with the required accuracy and completeness.*

Solar physics: The recent launch of the *Parker Solar Probe*, the 2019 commissioning of the Daniel K. Inoyue Solar Telescope (DKIST), and the upcoming launch of the *Interstellar Mapping and Acceleration Probe* all herald a new era in solar physics. These facilities and missions will study the magnetohydrodynamics and dynamo processes of the Sun, flares and eruptive events that can affect life on Earth, the flow of mass and energy through the solar atmosphere, and the long-term behavior of the Sun. Analyzing DKIST spectra will require extensive new AMO data needs for maximum scientific return (Judge 2017). The DKIST spectral range will extend from the visible into the near-IR, the latter of which is largely unexplored spectroscopically. Line identifications, oscillator strengths, transition rates, and branching ratios will be needed for multi-electron systems. New magnetic field diagnostics in the IR will also become available using the Hanle and Zeeman effects, all of which will require the relevant atomic data. Lastly, the solar plasma is dynamic and not in equilibrium. The ionization states of abundant elements encode the thermal history of the plasma, but they can only be interpreted in terms of plasma heating processes if accurate ionization and recombination data are known. *Advances in AMO theory and experiment are needed to generate all of the above required data.*

Solar eruptions and flares: The underlying physics of solar eruptions and flares involves ideal MHD instabilities and magnetic reconnection. Despite the long history of observational efforts to study these processes, direct confirmation is still out of reach due to inaccessibility of the microscopic plasma processes. New progress is being made on these processes from laboratory experiments that are designed to study these phenomena in isolated environments much simpler than the complicated situations on the solar surface (Yamada et al. 2010, Ji & Daughton 2011, Myers et al. 2015). *Further advances in plasma laboratory experiments, supported by numerical modeling, are needed to directly test the proposed concepts and in addition to predict solar eruptions.*

Solar interior physics: Helioseismology has shown that our best models of the Sun are unable to reproduce the measured depth of its convection zone, although a 15% revision to the opacities at the base of the solar convection zone could resolve this difficulty. Recent measurements of iron at these conditions show that larger-than-expected opacities of iron could produce a 7% increase in the mean total opacity of solar material (Bailey et al. 2015). Measurements of other elements under solar convection zone conditions may revise this number further. *Reliable astrophysical modeling of the Sun and other stars will require advances in modeling the opacities of heavy elements around the iron peak.*

4. Formation and Evolution of Compact Objects

White dwarf stars: White dwarfs are the endpoint of the stellar life-cycle for more than 97% of all stars. White dwarfs are also the most accurate chronometers for determining the age and star-formation history of the galaxy and provide an independent constraint on the age of the universe. Their interiors ca provide information about crystallization in dense Coulomb plasmas. White Dwarfs are also thought to be the site of Type Ia supernovae, which are crucial for determining cosmological distances and understanding the increasing expansion rate of the Universe due to “dark energy”. Such studies build on understanding the plasma conditions at their photospheres, which is critical to providing the boundary conditions for determining their global parameters. *Developing new theoretical calculations appropriate to the surface conditions of white dwarfs will require a concerting theoretical and experimental effort to study laboratory plasmas under these conditions.*

Accreting neutron stars, X-ray bursts, and the rp-process: X-ray bursts are some of the most energetic stellar events, believed to occur when a neutron star accretes matter from a companion main-sequence star. The bursts of X-rays emitted regularly, every few hours to days, have been observed by various X-ray missions, and the characteristic light curve has been well studied. Modeling the events, and interpreting the astronomical observations requires an accurate description of the nuclear reaction rates that drive the explosive hydrogen and helium burning.

In addition, understanding the nucleosynthesis during this rapid-proton capture process (rp-process) is essential for predicting the element composition of the ashes that are deposited on the neutron star at the end of each burst. Much of the necessary nuclear input data is not accessible with current facilities using either direct or indirect techniques. Many of these data will become accessible with the Facility for Rare Isotope Beams (FRIB), currently under construction in the U.S., combined with state-of-the-art equipment such as the Separator for Capture Reactions (SECAR). *Deeper understanding of X-ray burst events will require direct measurements of some of the most critical nuclear reaction rates using these next generation facilities.*

5. Resolved stellar populations and their environment

Nucleosynthesis in our Galaxy: Direct measurement of γ-rays from long-lived radionuclides have been observed by various γ-ray missions. Detecting isotopes such as ^{44}Ti, ^{26}Al, and ^{60}Fe provide unique signatures of active nucleosynthesis in our Galaxy. Combining the observations of the various isotopes provides insights into their production mechanisms and the astrophysical events themselves. However, to interpret the observations it is crucial to have a good understanding of the nuclear reaction chains that produce or destroy the relevant isotopes. Current radioactive beam facilities can measure only some of the needed nuclear data. Next generation facilities such as FRIB combined with SECAR are needed to measure currently inaccessible systems. *Reliable nuclear reaction data are critically important for understanding the chemical evolution of our Galaxy.*

6. Galaxy Evolution

X-ray astrophysics: X-ray observations probe some of the most energetic events in the Cosmos. Observations of supernova remnants provide information on the physics of the explosion and the corresponding nucleosynthesis. Active galactic nuclei host supermassive black holes with masses of 10^6 to 10^9 M_{Sun}. Accretion onto the central black hole and the subsequent feedback sends energy into the galaxy and regulates star formation. Clusters of galaxies are the most massive gravitationally bound objects in the Universe and can be used to constrain various cosmological parameters. These are all extended objects and require studies with non-dispersive instruments with high spatial and spectral resolution, such as was provided by the X-ray microcalorimeter on the recently lost *Hitomi* mission, which observed the Perseus cluster of galaxies (Hitomi Collaboration 2016), and will be provided by the *X-ray Imaging and Spectroscopy Mission* (*XRISM)* planned for launch in 2021. Other important upcoming X-ray astrophysics missions include *Lynx* and the *Advanced Telescope for High Energy Astrophysics* (*ATHENA*). Interpreting the collected spectra requires an accurate understanding of the underlying atomic physics for elements with atomic number $Z \leq 30$. Important data and processes include: transition wavelengths, rates, and branching ratios; electron impact excitation; innershell excitation and the corresponding Auger and fluorescence yields; electron impact ionization; the electron-ion recombination process known as dielectronic recombination and the corresponding emission line wavelengths and fluxes; and charge balance calculations. *Though these processes have been studied for decades, shortcomings in our AMO understanding still limit our ability to reliably interpret astrophysical observations, often related to the underlying highly-correlated, multi-electron interactions inherent in heavy, highly-ionized species.*

7. Cosmology and Fundamental Physics

Fundamental constants: Astronomical spectra can be used to test for variations in fundamental constants as a function of redshift such as the fine structure constant α and the ratio of the electron-to-proton mass μ (Ubachs et al. 2016). *These studies require highly accurate* *atomic and molecular structure data that will require new intellectual advances in AMO scientific capabilities.*

8. Multi-Messenger Astronomy and Astrophysics

Nucleosynthesis by kilonovae: Merging neutron stars were found using gravitational waves. Nucleosynthesis during the neutron-star merger takes place via the rapid-neutron capture process (r-process). The nuclear physics properties that drive this process are still highly uncertain. Specifically, the properties needed are nuclear masses, decay properties, neutron-capture rates and fission properties. In addition, the kilonova itself is fueled by the radioactive decay of r-process nuclei and their decay products. The next generation FRIB will give access to the majority of r-process nuclei. *Advancing our knowledge into the physics of kilonovae and the accompanying nucleosynthesis will require improving our understanding r-process nucleosynthesis for numerous heavy nuclei that are currently experimentally inaccessible.*

Kilonovae seem to match predictions that they are the formation site for most of the elements with atomic numbers $Z \geq 44$. Optical and infrared spectra from the expanding remnants enable us to study the rapid neutron-capture nucleosynthesis processes that occur during the merger (Kasen et al. 2017). To this end, opacities are needed for low ionization stages of heavy elements, especially for the lanthanides and actinides. High-level atomic structure methods can provide reasonable atomic data for low resolutions spectral analysis, but it is only in combination with laboratory work and critical evaluations of the data that the needed high resolution spectral information can be generated. *Significant advances are required in both AMO theoretical and experimental methods in order to maximize our scientific understanding of these newly discovered objects.*

Gravitational waves: Squeezed light methods, combined with enhanced power in the interferometer detectors, are predicted to enhance gravitational wave detections at high frequencies (50 – 5,000 Hz). These advances will double the spatial detection volume, provide better sky localization, enable better estimates for the tidal deformability parameters of the merging compact objects, open up the ability to study the post-merger phase, and constrain the neutron star equation of state. *Continued advances in AMO techniques hold the promise of expanding our ability to use gravitational waves to open a new window into some of the most extreme conditions in the Cosmos.*

Strategic Plan – Workforce, Funding, and Facilities

Workforce: Compared to other areas in astronomy and astrophysics, there are very few laboratory astrophysics faculty working to address the needs of the astrophysics community. This is a major concern for the U.S., Europe, and Asia. The small number of laboratories is remarkable, as laboratory astrophysics studies provide the needed understanding that enables us to fully benefit from astronomical research. But these interdisciplinary studies typically fall outside of traditional academic departments and funding agency divisions. As a result, laboratory astrophysics does not get the robust level of support needed to advance our astrophysical understanding of the cosmos. For example, physics departments are currently interested in quantum, ultracold, and ultrafast AMO studies and point AMO laboratory astrophysicists to astronomy departments. On the other hand, astronomy departments are primarily interested in observational and astrophysical theoretical/modeling studies. So if one is studying molecules, astronomy departments will direct that person to chemistry departments. But chemistry departments are primarily focused on large molecules and biochemistry and are uninterested in astrophysically important molecules such as PAHs or C- and Si-based structures. Such “small” molecules, they say, are the realm of a physics department. But traditional AMO laboratories are designed primarily for the study of two- or three-atom molecules and are poorly equipped to study more complex systems. So AMO laboratory astrophysics lies at the interface of three academic departments, none of whom want to take ownership. In addition, the workforce issue begins early in the academic pipeline with junior scientists finding it difficult to get professional and financial support for their laboratory astrophysics work. Similar situations exist for plasma laboratory astrophysics, as they often fall in between physics, astronomy, and engineering departments. These issues raise the serious question: how will we train the next generation of laboratory astrophysicists? Mirroring this issue, it should be noted that laboratory astrophysics is not a research area that is currently represented in the National Academy of Sciences and hence lacks the robust leadership in this critical interdisciplinary area that is needed to advance the field.

Funding: It is extremely hard to get funding for laboratory astrophysics. One of the main reasons for this is that in the current era of restricted funding means, the review panels for the NSF Division of Physics, the NSF Division of Chemistry, and the DOE tend to move the responsibility for funding laboratory astrophysics proposals to other disciplines. The multidisciplinary aspect of laboratory astrophysics then turns out to become a real disadvantage. For example, one proposal submitted to the NSF Division of Physics Experimental AMO program was declined, in part, because "This work is more appropriately funded through the Foundation's Division of Astronomy [sic] or by NASA." Another NSF proposal submitted to the same program was declined, in part, because "There does not seem to be a pre-existing demand from theory for the measurements." These reviews are despite the fact that the complex AMO physics that describes the Cosmos is a largely unexplored frontier in physics and chemistry. But the NSF Divisions of Physics and Chemistry have moved in directions different from the AMO complexity studies needed for astrophysics. DOE support for AMO laboratory astrophysics research has dried up over the last few decades and does not appear likely to be resurrected. For plasmas experiments, the NSF Directorate for Engineering supports primarily specific applications to societal needs rather than astrophysics. Hence, it is clear that NASA and the NSF Division of Astronomical Sciences are going to have to increase their funding for the frontier laboratory astrophysics research needed by the astrophysics community.

Facilities: Laboratory astrophysics facilities range in scale from table top to national laboratory. Table-top devices, excellent for training students, are disappearing as laboratory astrophysics faculty retire and close their labs. These faculty are not being replaced. For the soft-money scientists who remain in the field, it is extremely hard to build a new lab without start-up funds. National laboratories can sometimes carry out critically needed studies. For example, the Linac Coherent Light Source – II (LCLS II) will have the wavelength stability to study the opacity of multiply ionized heavy elements needed for kilonova spectra. However, it is extremely hard to get beamtime os such a facility for a project unlikely to result in a Science, Nature, or Phys. Rev. Lett. publication. Supercomputer support and funding for modern code development are also critical for the advanced theoretical computations that are now needed.

Changes since 2010: Many of the above workforce, funding, and facilities issues were raised in the white paper entitled "Laboratory Astrophysics and the State of Astronomy and Astrophysics" (AAS WGLA et al. 2009) submitted to the 2010 Astronomy & Astrophysics Decadal Survey. We refer the reader to that white paper for additional discussion on the state of laboratory astrophysics as the situation has only deteriorated since then. It is true that a number of the white paper recommendations were incorporated into the report of the 2010 Decadal Survey (National Research Council 2010). Unfortunately the recommendations had little impact on the funding priorities of the major funding agencies. The issues have become even more urgent in the intervening decade and action is needed even more desperately to grow the laboratory astrophysics program in the U.S. back to the level needed to fully meet the needs of the astronomy & astrophysics community. These concerns are reinforced in the report from the 2018 NASA Laboratory Astrophysics Workshop (2019), which both prioritized laboratory astrophysics work for the next decade and addressed the needs of the community.

Recommendations

Laboratory astrophysics is the Rosetta stone that helps us to unlock the mysteries of the Cosmos. The next decade of astronomical exploration will require significant laboratory astrophysics advances into our understanding of the underlying complexity that drives much of the Universe. Major astrophysical advances will come from these studies, but no academic department has taken intellectual ownership for this field. Maximizing the scientific return from the next decade of astronomical exploration will require a rejuvenation of laboratory astrophysics faculty and a corresponding restoration of funding from NASA, NSF, and DOE for such studies.

We close by reiterating many of the recommendations made in AAS WGLA et al. (2009) that are even more urgently needed now:

- **Increased and steady support for laboratory astrophysics among the various agencies is critical for future advances in astronomy and astrophysics.**
- **Explicit support for laboratory astrophysics by missions, facilities, and projects is essential to maximize their astronomical and astrophysical scientific return.**
- **Faculty development in laboratory astrophysics, possibly through federal agency programs, is necessary to ensure the health and vitality of laboratory astrophysics on university teaching faculties.**
- **Strong instrumentation, technology, and facilities development programs in laboratory astrophysics are needed to support the development, construction, and maintenance of state-of-the-art instrumentation and facilities.**
- **Adequate funding for critically evaluated databases needed by those analyzing astronomical measurements and modeling the associated environments.**

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