

New Discoveries in Planetary Systems and Star Formation through Advances in Laboratory Astrophysics

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1. Introduction

As the panel on Planetary Systems and Star Formation (PSF) is fully aware, the next decade will see major advances in our understanding of these areas of research. To quote from their charge, these advances will occur in studies of “solar system bodies (other than the Sun) and extrasolar planets, debris disks, exobiology, the formation of individual stars, protostellar and protoplanetary disks, molecular clouds and the cold ISM, dust, and astrochemistry.”

Central to the progress in these areas are the corresponding advances in laboratory astrophysics which are required for fully realizing the PSF scientific opportunities in the decade 2010-2020. Laboratory astrophysics comprises both theoretical and experimental studies of the underlying physics and chemistry which produce the observed spectra and describe the astrophysical processes. We discuss four areas of laboratory astrophysics relevant to the PSF panel: atomic, molecular, solid matter, and plasma physics.

Section 2 describes some of the new opportunities and compelling themes which will be enabled by advances in laboratory astrophysics. Section 3 provides the scientific context for these opportunities. Section 4 discusses some experimental and theoretical advances in laboratory astrophysics required to realize the PSF scientific opportunities of the next decade. As requested in the Call for White Papers, we present in Section 5 four central questions and one area with unusual discovery potential. We give a short postlude in Section 6.

2. New scientific opportunities and compelling scientific themes

In the upcoming decade, we will make progress in understanding the evolution from clouds of gas and dust to systems of stars and planets. Studies of protostellar and protoplanetary disks and debris disks will inspire new ideas to explain how planets form and migrate within young systems. We will not only continue to discover new and interesting planets but we will also begin to characterize and classify the properties of these planets and their atmospheres and cores. The discoveries of earth-like planets and other planets in habitable zones will challenge us to address the origin of life. We expect to solve long-standing mysteries, such as the nature of the diffuse interstellar bands (DIBs), believed to be the manifestation of an unidentified reservoir of organic material. Discovery of the carriers of these bands promises to revolutionize our understanding of organic chemistry in the interstellar medium (ISM).

Perhaps the most exciting new opportunities will come in the area of the origins of life. The cosmic pathway to life begins in interstellar gas clouds where atomic carbon is fixed into molecules, thereby initiating the synthesis of the complex organic species that are eventually sequestered on planets. These reactions initiate not only the formation of organic molecules in the cosmos, but also provide some of the first threads knitting atoms and molecules into solid material. Such processes are critical for the eventual formation of planets and may determine a major component of the organic chemistry that is present on their young surfaces. To place the new worlds we discover in proper context requires that we understand the chain of events that dictates their potential chemical inventories.

3. Scientific context

With a multitude of current and planned space-based and ground-based telescopes, including *Spitzer*, *Hubble*, *Chandra*, *XMM-Newton*, *Suzaku*, *Herschel*, *SOFIA*, *Kepler*, *Keck*, *Magellan*, the MMT, *Hobby-Eberly*, *SALT*, *LBT*, the Gemini telescopes, and eventually *ALMA* and *JWST*, the upcoming decade promises numerous opportunities for progress in

the areas of planet and star formation. Studies from the radio to X-rays contribute to our overall understanding of the physical and chemical processes.

Understanding the process of accretion is key to astrophysics from the formation of the lowest mass stars to the growth of super-massive black holes. Star formation studies over the past decade have begun to recognize the importance of the interaction between a young star and its environment. X-ray and ultraviolet (UV) radiation produced by a low mass star can have profound effects on the ionization and heating of gas and dust in the disk (Glassgold et al. 2004; Jonkheid et al. 2004). The star's magnetic fields can extend to the disk and help to channel the accreting material. Flares are ubiquitous in young low-mass stars (Feigelson et al. 2007) and thus the inner disk experiences highly time-variable phenomena. In addition to disk-driven winds, magnetic accretion can generate jets and winds.

The explosion of exoplanet discoveries over the past decade suggests that the next decade will revolutionize our understanding of the formation of planets, their atmospheres and cores, and the rich diversity of planetary systems. The transit method of exoplanet searching, at the core of *Kepler's* goal to discover other Earths, requires accurate and finely-tuned atmosphere models. The first direct studies of light emitted by an exoplanet itself (Deming et al. 2005; Charbonneau et al. 2005) estimate temperatures from simple models fit to broad-band infrared (IR) observations; water has now been observed spectroscopically on an exoplanet (Grillmair et al. 2008). In the next decade observations will continue to drive the sophistication of planet atmosphere models (e.g. winds from close-in Jupiters; Murray-Clay et al. 2008). Gas giants dominate our planetary system by mass and may be ubiquitous in stellar systems. A favored model for their formation requires a metallic core; however, it is not clear whether the heavy core survives, an issue which can be addressed by experimental studies of high density plasmas.

The evolution of gas and mineral dust in protoplanetary disks traces the formation process of planets and other objects. Comparisons of exoplanet observations with studies of objects in our own solar system will help to determine the common evolutionary histories (e.g. Bergin et al. 2007). Discoveries of smaller planets and multi-planet systems will shed light on the timescales for formation, migration, destruction, and the relative roles of dust and gas. The growth of dust grains in the presence of stellar radiation depends on the gas-to-dust ratio and the dust temperature which, in turn, control the chemistry. Gas and dust are coupled at the high densities found in the mid-plane of the disk, suggesting that some molecules are frozen onto grains. Disk dynamics can alter the properties of gas and dust through mixing.

The discovery of over 140 different chemical molecules in interstellar gas, with the vast majority organic molecules, and the realization that obscuring dust pervades vast regions of the ISM have revealed the complexity of interstellar chemistry. The first stars are thought to have formed from primordial clouds where H_2 and HD controlled their cooling and collapse (Bromm et al. 2002). Subsequent stars and planetary systems have formed out of the most complex molecular environments deep inside cold gas and dust clouds, often obscured by hundreds of visual magnitudes of extinction. All the main functional groups known to organic chemists have now been observed in interstellar molecules, suggesting that interstellar chemistry contains the organic complexity seen on Earth. The next decade may establish the gas phase and grain chemistries of interstellar clouds that can lead to the origin of life.

4. Required advances in Laboratory Astrophysics

Spectroscopic studies are key to identifying the constituents of various environments, diagnosing the physical and chemical conditions, and testing models of the physical processes and chemical reactions. A strong program in laboratory astrophysics allows us to make steady progress in compiling databases of the spectral properties of neutral atoms and ions, molecules, and minerals, and to react quickly to address surprises from new observations. While laboratory astrophysics has contributed to many successes in astrophysics,¹ in many areas of ongoing research in PSF fields, we know that the linelists are not complete enough and that the rate coefficients are not accurate enough to take full advantage of the wealth of new data expected over the next decade. Moreover, models of astrophysical plasma processes should be tested experimentally to ensure that the assumptions are valid.

4.1. Atomic Physics

Understanding the star-disk interaction in protostellar and young stellar systems requires accurate knowledge of the atomic physics and fundamental spectroscopy across many wavebands. X-ray emission from an accretion shock has been identified by X-ray spectral line ratios indicative of high electron density (Kastner et al. 2002). Unprecedented accuracy has now been demonstrated for atomic theory and experiment (Chen et al. 2006), but much more work is needed to generate a comprehensive set of reliable diagnostics for temperature and density. Stellar X-ray and UV radiation can excite specific lines in the disk, such Fe K α (Imanishi et al. 2001) and [Ne II] 12.8 μ (Pascucci et al. 2007). The processes involved in understanding such emission include photoionization, radiative and dielectronic recombination, collisional excitation, X-ray fluorescence, Auger ionization, and charge exchange. Accurate line lists, oscillator strengths, atomic transition probabilities, and collisional rate coefficients are needed to develop new diagnostics from the IR to the X-ray.

Planet searches require accurate stellar atmosphere models for cross correlation with the observed spectra (e.g. Konacki et al. 2004). Characterization of planetary atmospheres places new demands on atmosphere models for accurate and complete atomic line opacities. Ultimately the accuracy of the derived parameters depends on the accuracy of the template spectra; where lines are missing in the template, the observed spectrum cannot be used.

4.2. Molecular Physics

High-resolution laboratory spectroscopy is absolutely essential in establishing the identity and abundances of molecules observed in astronomical data. For molecules already identified in astronomical sources, transitions including higher energy levels and new isotopic species are needed as we move into new spectral regions and higher resolving powers. Furthermore, the spectra of as yet undiscovered species that promise to serve as important new probes of astronomical sources need to be identified. For example, the recent astronomical discovery of the negative ion C₆H⁻ (McCarthy et al. 2006) was driven by laboratory work. We anticipate that additional discoveries of anions in the coming decade will challenge the existing view of interstellar chemistry.

New line diagnostics of disk heating, cooling, and ionization are expected from continuing laboratory work on abundant molecules. For example, submillimeter (sub-mm) lines of CO

¹<http://www.physics.unlv.edu/labastro/>

from high rotational levels have recently been observed in the outer disk of a young star, requiring additional heating such as by X-rays (Qi et al. 2006); numerous UV lines of H₂ were observed in the same system, pumped by X-ray or UV radiation (Herczeg et al. 2002).

The “unidentified line” problem needs to be addressed by systematic measurements of a variety of molecules. The DIBs were first observed in 1919, but despite many decades of intense efforts by laboratory spectroscopists and astronomers, the molecular carriers of these bands remain a mystery. Mid-IR spectra of individual objects such as H II regions, reflection nebulae, and planetary nebulae as well as the general ISM are dominated by a set of emission features due to large aromatic molecules (PAH bands). Studies of the IR spectroscopy of such molecules and their characteristic features which depend on molecular structure and charge state are of key importance for our understanding of this ubiquitous molecular component of the ISM. Millimeter and sub-mm spectra contain hundreds of unidentified gas-phase lines. Intense laboratory work continues to be a vital component in unlocking the mystery of the DIBs, the PAH emission bands, and other observed, but unidentified, spectral features (Salama 1999). Missing molecular lines in the coolest stellar atmosphere models and in the atmosphere models being developed for planets create an acute problem for interpreting and exploiting astronomical spectra. Discovery of biological molecules from planetary atmospheres may occur in the next decade (see Robinson et al. 2008).

A vast number of molecules which are difficult to detect by standard means may exist in the ISM and stellar systems. The identification of most interstellar/circumstellar species is done through observations of emission spectra in the radio and millimeter, with an observational bias in favor of molecules with large dipole moments. A big challenge for observation is to find ways to detect molecules with small or zero dipole moments. Laboratory spectroscopy in other wavebands would be useful.

Understanding line profiles will also provide new tools for PSF studies. For example, pressure broadening of the strong resonance absorption lines of Na and K, observed in brown dwarfs (Burrows et al. 2001) and predicted in extra-solar gas giants, occurs through collisions with neutrals, including molecular hydrogen (Seager & Sasselov 2000). Quantum collision calculations, benchmarked by laboratory measurements, can provide accurate line profiles which can serve as diagnostics of the temperature and pressure (e.g. Zhu et al. 2005).

Interpreting spectral observations requires the use of sophisticated astrochemical models, which include the ionization and dissociation mechanisms (by radiation and cosmic rays) and the time-dependent history of the clouds. To understand the chemical composition of these environments and to direct future molecular searches in the framework of new astronomical observatories, it is important to untangle the detailed chemical reactions and processes leading to the formation of new molecules in extraterrestrial environments. Breakthroughs in our understanding of the molecular universe are limited by uncertainties in the underlying chemical data in these models (e.g. Glover et al. 2006). Laboratory spectroscopy is crucial for understanding interstellar molecule formation in the gas phase and on grains.

Of particular importance are data for reactions of neutral atomic carbon atoms with molecular ions which are critical in initiating interstellar organic chemistry. Theory is limited to classical methods, as fully quantum mechanical reactions for systems with four or more atoms are beyond computational capabilities now and for the foreseeable future. Existing laboratory experiments have produced ambiguous results owing to the extraordinary

challenge of generating and characterizing atomic carbon beams with no internal energy. The spectroscopic study of such molecules, many of which are complex structures that cannot be produced in large abundance in the laboratory, requires the development and application of state-of-the-art ultra-sensitive spectroscopic instruments. Tracking the cosmo-chemical pathway towards life requires cross-disciplinary work at the intersection of astronomy, chemistry, biology, and physics.

4.3. Solid Material

Spectroscopy provides unique information on stellar outflows and protoplanetary disks, accreting envelopes, the surrounding medium, the radiation fields, and planetary atmospheres. To be useful, however, this tool requires an ability first to identify the lines of gas phase molecules and solid state band features of grains, and then to explain their appearance using reliable physical excitation constants. Laboratory measurements supplemented by theoretical modeling provide this essential information.

An example of the problem of identification is the emission feature near $21\ \mu\text{m}$, originally discovered in four objects with large far IR excesses due to a circumstellar dust envelope surrounding a carbon-rich central star (Kwok et al. 1989). A similar feature, but with varying wavelength centroid, has been observed with Spitzer in the Carina nebula, the supernova remnant Cas A, and some H II regions and is likely associated with dust grains composed of FeO and a mix of silicates (e.g. Rho et al. 2008).

Laboratory measurements of molecules and grains at different temperatures and under various radiation environments are needed to inform the search for specific elements. For example, oxygen is the third most abundant element in the universe, and early models of gas clouds predicted that O I, O₂, and H₂O should be relatively abundant. But observations over the past decade by SWAS, Odin, ISO, and other instruments found that H₂O is about 100 times less abundant than expected in star forming regions; O₂ is similarly scarce. Oxygen plays a crucial role in the chemistry of star forming regions: pairing with carbon to make the crucial species CO for cooling the clouds (and thus facilitating cloud collapse), acting as a key ingredient in the chemical pathways that make most complex organic species, and by joining with silicon or hydrogen on the dust grains to form complex molecules. Recent calculations suggest that the missing oxygen may be in the form of water ice.

Studies of silicate and carbonaceous dust precursor molecules and grains are required as are studies of the interaction between dust and its environment, including radiation and gas (Tielens 2005). Studies of dust and ice provide a clear connection between astronomy within and beyond the solar system. Astronomical observations and supporting laboratory experiments over a wavelength range that extends from the X-ray domain to the UV, IR, and sub-mm are of paramount importance for studies of the molecular and dusty universe. Observations at IR and sub-mm wavelengths penetrate the dusty regions and probe the processes occurring deep within them. These wavelengths provide detailed profiles of molecular transitions associated with dust.

At longer wavelengths, the continuum dust opacity is uncertain by an order of magnitude. IR spectral features of interstellar dust grains are used to determine their specific mineral composition, hence their opacities, which determine inferred grain temperatures and the masses of dusty objects, including the ISM of entire galaxies. Emission bands from warm

astronomical environments such as circumstellar regions, planetary nebulae, and star-forming clouds lead to the determination of the composition and physical conditions in regions where stars and planets form. The laboratory data essential for investigations of dust include measurements of the optical properties of candidate grain materials (including carbonaceous and silicate materials, as well as metallic carbides, sulfides, and oxides) as a function of temperature.

For abundant materials (e.g., forms of carbon such as PAHs), the measurements should range from gas-phase molecules to nanoparticles to bulk materials. The IR spectral region is critical for the identification of grain composition, but results are also required for the UV. Previous studies in the UV have focused on the only identified spectral feature (at 2200 Å), but COS on *Hubble* is expected to find UV spectral signatures for many materials, including specific individual aromatics.

4.4. Plasma Physics

Accretion from a disk orbiting a protostar requires efficient transport of angular momentum through the disk, but how this happens, and the extent to which it is dominated by nonlinear hydrodynamic turbulence or magnetohydrodynamic (MHD) turbulence via magnetorotational instability (MRI) (Balbus & Hawley 1998), has been much debated. Recent laboratory experiments show that pure hydrodynamic turbulence probably cannot explain the observed fast accretion (Ji et al. 2006). Laboratory jets are also providing tests of models, including studies on radiative cooling and collimation (Lebedev et al. 2002), instabilities (Ciardi et al. 2009), and dynamics and mixing (Foster et al. 2005).

How magnetic field changes its topology and releases its energy is an outstanding problem in plasma astrophysics (Biskamp 2000). Reconnection has been proposed as a mechanism for releasing the energy built up as a result of differential rotation between the star and the disk (van Ballegooijen 1994). Only recently have reconnection models been tested experimentally. For example, the well-known Sweet-Parker model was tested quantitatively in the laboratory (Ji et al. 1998) 40 years after its birth, and the conjectured Hall effect has also now been successfully verified in the laboratory (Ren et al. 2005).

Knowledge of planetary interiors depends on models that incorporate the properties of the interior matter. As the interior pressure approaches and exceeds 1 Mbar (0.1 TPa, 10^{12} dynes/cm²), the interior matter ionizes and becomes a high-energy-density plasma. There are important transitions involving molecular dissociation, ionization, Fermi degeneracy, and other effects under conditions where standard theoretical treatments for cold, condensed matter, or hot, ionized plasma are invalid. This is precisely the region of interest for planetary formation, structure and interior dynamics. Understanding the compressibility of the material is essential to develop structural models consistent with data. Understanding conductivity is essential to understand planetary magnetospheres. The existence of a metallic state of hydrogen has been confirmed in the laboratory (Weir et al. 1996), but the full insulator-to-conductor transition has yet to be explored. Understanding phase transitions and material mixing is essential to know how gravitational potential energy contributes to the energy balance. The anomalous radiation from nearby gas giant planets may be due to the separation, condensation, and raining downward of helium that is initially mixed with hydrogen (Guillot 1999). Alternatively, perhaps so-called pycnonuclear reactions (Ichimaru & Kitamura 1999) may release energy in dense, metallic hydrogen and deuterium.

In the next decade, further results are expected from the laboratory in the areas of MHD, jets and magnetic reconnection. Experimental facilities that can create and study the states of matter present in planetary interiors exist or are under construction both in the US and worldwide. What is required is to exploit and to extend the diagnostic capabilities that can quantify the detailed properties of matter in planetary interiors, including not only density and pressure but also conductivity, viscosity, and other characteristics.

5. Four central questions and one area with unusual discovery potential

- How does a young star interact with its environment?
- What are the characteristics of planetary systems and their atmospheres and interiors?
- How do the gas and dust in disks around stars evolve and how are they affected by disk dynamics, stellar radiation, and grain growth?
- What are the abundances, distribution and formation mechanisms of the chemical compounds found in the ISM?
- ★ What is the cosmo-chemical pathway from atoms in interstellar space to life?

6. Postlude

Laboratory astrophysics and complementary theoretical calculations are part of the foundation for our understanding of PSF and will remain so for many decades to come. From the level of scientific conception to that of scientific return, our understanding of the underlying processes allows us to address fundamental questions in these areas. Laboratory astrophysics is constantly necessary to maximize the scientific return from astronomical observations.

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