Exoplanets and Solar System Exploration

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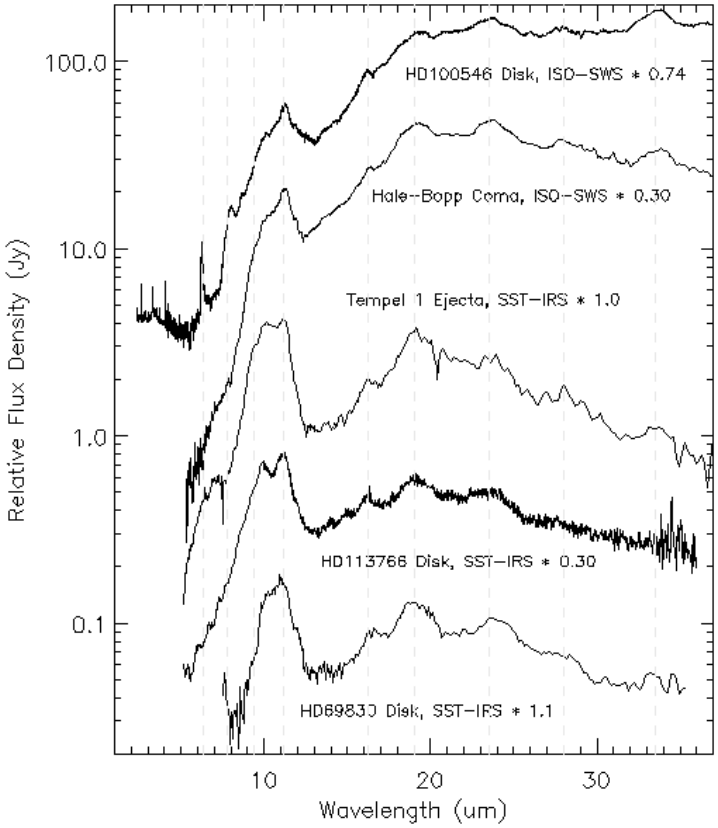


Similar spectra, near and far: Mid-IR spectra of Solar System comets and dust found around other stars, from observations with ISO and Spitzer. Objects shown are the YSO HD100546, the young terrestrial planet building system HD113766, the mature solar-system like HD69830 system, and the comets C/1995 O1 (Hale-Bopp) and 9P/Tempel 1.

Wesley A. Traub
Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Drive, Pasadena, CA. 818-393-5508, wtraub@jpl.nasa.gov
and
Charles Beichman (NExScI), Ruslan Belikov (NASA Ames), Geoff Bryden (JPL), Mark Clampin and William Danchi (NASA GSFC), Imke de Pater (UC Berkeley), Thomas Greene (NASA Ames), Olivier Guyon (NAOJ), Sara Heap (NASA GSFC), John Johnson (Caltech), Lisa Kaltenegger (CfA/Harvard), Jeremy Kasdin (Princeton), James Kasting (Penn State), Douglas Lin (Lick Observatory), Jack Lissauer (NASA Ames), Carey Lisse (APL), Jonathan Lunine (LPL), Bruce Macintosh (LLNL), Geoff Marcy (UC Berkeley), Mark Marley (NASA Ames), Michael Meyer (U. Arizona), Matt Mountain (STScI), Ben Oppenheimer (AMNH), Glenn Orton (JPL), Marc Postman (STScI), Aki Roberge (NASA GSFC), Sara Seager (MIT), Eugene Serabyn and Christophe Sotin (JPL), Remi Soummer (STScI), Karl Stapelfeldt, John Trauger, Stephen Unwin, and Michael Werner (JPL)

Abstract

The purpose of this White Paper is to highlight areas of knowledge of our Solar System that will be important in interpreting future observations of exoplanets, especially giant exoplanets, and also how the diversity of exoplanets can inform our understanding of the Solar System.

A major goal of planetary astronomy is to deduce how the present collection of objects found in our Solar System were formed from the original material present in the proto-solar nebula. As over three hundred exoplanetary systems are now known, and multitudes more are expected, the Solar System represents the closest and best system which we can study, and the only one in which we can clearly resolve individual bodies other than planets. Similarly, the study of exoplanetary systems, already known to be very diverse, is important in setting a context for a fuller understanding of the origin of our own Solar System, and to sharpen the questions that we should be asking about it. In this White Paper, we consider primarily giant planets and zodiacal dust but also mention the inner planets.

Introduction

Our understanding of exoplanet observations is informed by our knowledge of Solar System planets. This will be increasingly true in coming years as we learn more about exoplanets and their systems from combined-light observations and direct imaging in the visible and infrared. On the other hand, exoplanets have already yielded a number of surprises – most notably the discovery of ‘hot Jupiters’ for which, of course, there are no analogs in our Solar System.

Therefore it is particularly important that we achieve a mature understanding of the Solar System’s giant planets, which can tell us about their intrinsic properties, including those properties that provide clues to the origin and development of the Solar System. In parallel, and possibly on a similar timescale, we may anticipate having images of exoplanet systems, and spectra of individual giant and terrestrial exoplanets. The combination of these two great spheres of knowledge, specific close-up information about our own particular planets, plus a broad more distant view of many general types of exoplanet systems, will allow us to truly understand the origins, evolution, and future, of our own Solar System. We will then know with some confidence what today we can only speculate about, namely the origin of the Earth, and the astronomical conditions under which life on Earth began.

Extrasolar planets can help us properly understand the dimension of time in the formation and evolution of planetary systems: the history of the Solar System is written in its planets and moons and small relic bodies. Recent missions to elucidate this history have produced a wealth of new insights into the nature of Solar System bodies. We can, however, go back in time in another way – we can observe the dust and gas and planets around nearby young stellar objects and young main-sequence stars. The same processes that formed the bodies in the Solar System- the asteroids and comets and planets and debris clouds - are operating in these systems. By finding analogs in these systems for Solar System structures we can learn more about the physics causing these processes to occur, what they create, and how they evolve.

The purpose of this white paper is to outline the types of information on Solar System constituents that would be important for us to know in order to best interpret observations of exoplanet systems. There are two broad types of information that we will need.

First, we need specific properties of individual giant planets from which, and with the aid of theoretical models, we will be able to interpret data on giant exoplanets. Exoplanet data will be of low spectral resolution, zero spatial resolution on any exoplanet, limited time coverage, limited phase angle coverage, and relatively noisy, owing to the faintness of the targets. Spectral data on Solar System planets are of course already far superior. An example of how planetary exploration helps rather directly would be observations of night-side mid-IR emission from Jupiter. This kind of data on our own giant planets is of great benefit to interpreting exoplanet spectra.

Second, we need certain properties of the system as a whole, from which, and again with the aid of theoretical models, we will be able to understand the time evolution of our system as well as that of target exoplanet systems. The Nice model of our Solar System, in which the giant planets suddenly rearranged their orbits early in its life, is one such model. The physics of migration and planet-planet interactions, and interactions with protoplanets, are examples of 'tools' which help us view such disparate pieces of information as the observed orbits and abundances of elements of planets, moons, asteroids, and comets.

Together these two types of information will speak volumes to us about the origin and evolution of our Solar System as well as hundreds of nearby exoplanet systems, and will allow us to speculate knowledgeably where potential habitats form in outer planetary systems.

Interiors

A large number of giant exoplanets have been discovered in the last 15 years, including a class of 'hot Jupiters' for which there is no Solar System analog. And there are increasing numbers of exoplanets discovered with the mass and size of Uranus/Neptune and even several likely rocky worlds under 10 Earth masses. The masses and the radii (for transiting planets) of exoplanets can be measured and compared with Solar System planets. The relationship between mass and radius depends on the type of planets: iron-rich (Mercury type), silicate (Earth-like), icy (Uranus/Neptune like), gaseous (Jupiter/Neptune). The physical and chemical processes that drive the formation and evolution of these planets and determine the composition and evolution of their atmospheres depend on the materials, which compose their interior.

The internal dynamics and structures of these exoplanets are likely different from those operating on Jupiter and Saturn. For example, the magnetic field of Jupiter and Saturn is generated by circulation of metallic hydrogen, which cannot exist within Uranus and Neptune due to the much lower pressure and temperature. In fact, it is hard to find "modern" models for the evolution of Uranus and Neptune that can explain their current day properties. They highlight that our understanding of planet formation is in part a quest to explain the internal energy of planets that are young and/or far from their parent star such that insolation does not dominate their energy budget. These are the systems that preserve their "formation history" in their emissive luminosities. Solar System exploration provides the baseline that allows us to test our formation and evolution models.

A better knowledge of the interior structure of the giant planets is essential to the understanding of their formation and evolution. Such information is necessary to assess some key aspects of exoplanets such as the amount of tidal dissipation when a giant planet is orbiting close to its star, or the strength of the magnetic field and its interaction with the stellar electro-magnetic environment.

The internal mass distribution as a function of radius can be inferred from the determination of the moment of inertia. The location of the magnetic sources can be determined by analyzing the strength of the magnetic field at different harmonics. The interior structure can be constrained by recording the vibrational normal modes. Such information is important to obtain for both the gaseous planets (Jupiter and Saturn) and the icy giants (Uranus and Neptune). Ongoing observations by the Cassini spacecraft orbiting Saturn and future observations obtained by extending the Cassini mission (Cassini Solstice Mission) and by the Juno mission (Jupiter) will provide key information on the interior structure of the gaseous giants. On the other hand, little is known about the interior structure of the icy giants Uranus and Neptune. It would be important to understand their density profile and how the magnetic field is generated.

Atmospheres

The temperature structure of a planet controls the pressure level at which condensable gases can form clouds, and clouds in turn largely determine the depth in an atmosphere to which we can see in the visible and infrared. However by controlling the deposition of incoming energy from the Sun, the clouds themselves, and any other source of opacity, have an influence on the temperature structure of the troposphere, and on the degree to which there is a high-altitude temperature inversion, forming a stratosphere. In addition there is a possible high-temperature exosphere. All of these influence the visible spectrum, infrared spectrum, and possible loss rate of light elements. The more we know about these properties on our own giant planets, the better prepared we will be to anticipate or detect their existence on exoplanets.

Day and night-side atmospheres will differ, depending on the time constants for mixing and cooling. Observations of the spectra of the dark sides of the outer planets, for those with modest as well as large obliquities, will tell us about the changes in temperature structure, and of the changed presence of clouds, and will be of use in interpreting the infrared spectra of exoplanets, particularly when they are seen with their star off to one side or in the background.

Modeling clouds and convection patterns, as well as lab experiments to determine molecular opacities for giant planet atmospheres for our own Solar System and hot Jupiters are important tools to help connect observations of our own Solar System and other planetary systems.

Radiative Properties

Most of our knowledge of planets and stars comes from visible and infrared spectra, and the same will be true for exoplanets, particularly when we enter an age of direct imaging in the visible and infrared.

For the spectrum of reflected sunlight, or starlight, we need to know the spectral and angular properties of the albedo of clouds (condensable liquids and solids), the polarization properties, and the variation with respect to liquid or solid state. We need to know how the atmosphere varies with latitude (belts, zones, polar regions), longitude, obliquity, and phase angle. Measurements of these quantities on the giant planets will form a database of experience, from which we can extrapolate. Something a simple as the variation of exoplanet brightness with phase angle is not known, forcing us to model every exoplanet as a Lambert sphere. Likewise, we do not know if the reflected light is polarized, which could be used as a diagnostic probe, or whether it could be used to distinguish planet light from speckles (in a coronagraph).

For the spectrum of thermally radiated light, we need to know the relative fraction of re-radiated sunlight versus the fraction from an internal heat source. We need to understand why Uranus lacks an internal heat source. We need night-side thermal emission spectra, to help distinguish young versus mature giant exoplanets. We also want to know more about the radiative properties of high-obliquity planets, to help us interpret the unknown obliquities of exoplanets.

Exoplanets in short-period orbits prompt us to ask questions like how what the Solar System giants would look like if they were closer to the Sun. A better understanding of the physics, chemistry, and meteorology of gas giants would help us to explore what Jupiter would look like in the visible and infrared under different conditions. Detailed observations of the present giant planets would help us predict with confidence how their radiative properties would change as a function of insolation, for comparison with exoplanet spectra.

Abundances of Elements

Abundance variations in our own gas giants reflect a combination of origin and current state, including temperature/pressure and chemical structure, and condensation levels. The abundances of elements in exoplanets, relative to parent stars, could be a useful tool in learning about the formation and evolutionary history of a given planet. For example, deuterium in giant planets can be modeled in terms of fractionation between solid and gas phases in the disk. Isotopic studies of outer planets can be compared to models of disk chemistry and formation models. Exoplanet observations are not likely to be able to determine isotopic ratios in the first generation of instruments, but should be able to in a later generation.

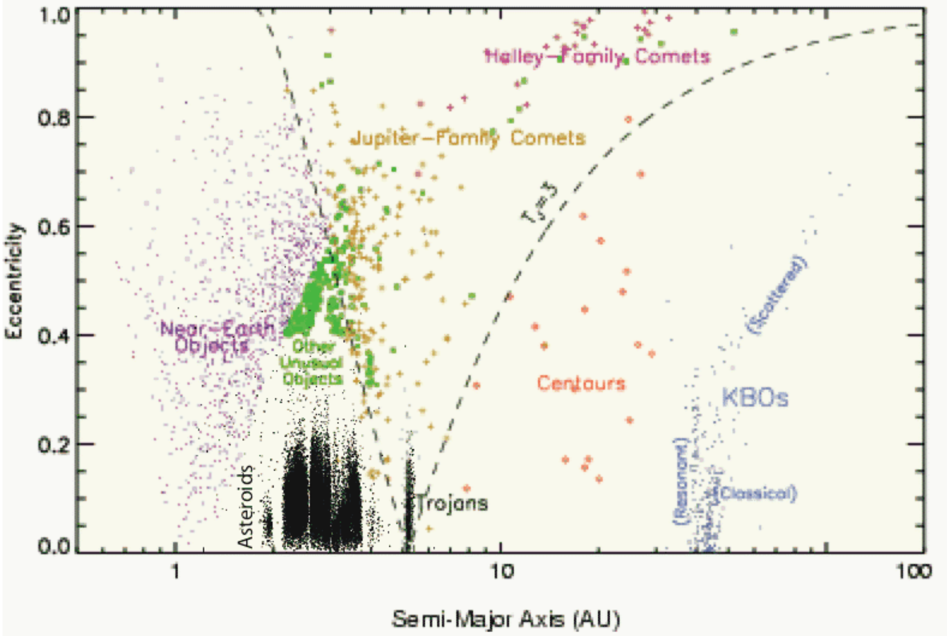
Determining the abundances of heavy elements in gas giants, as well as the ice giants (and in fact Solar System bodies) will be vital to testing our theories of planet. Measuring the bulk composition of major elements is still vital to compare with disk chemistry and formation scenarios as well as bulk densities of exoplanets.

Small Bodies

Small bodies in the Solar System are currently understood to be the source of a second generation of dust within the disk. Any fine-grained (first generation) dust that remains from the primordial cloud is blown out by the flux of stellar radiation. This initial phase, taking 1-6 million years, marks the end of the process of growth of planetisimals up to a kilometer or so in size.

The distribution of diameters, masses, densities, semi-major axes, and spectra of small bodies in the Solar System can be interpreted in terms of formation mechanisms, and are therefore valuable pieces of information. It is possible that the presence of such bodies in an exoplanet system could be directly measured by very sensitive imaging, showing for example an enhanced brightness at asteroid belt radii, or inferred by the absence of a dynamically-allowed planet at the same radius. Current models of these distributions in the Solar System could be improved with further observations. The secondary dust disks that small bodies generate are more readily observable in external systems than the objects themselves (see below).

We need to understand our Solar System debris belts if we are to understand those we see elsewhere. There is a close relationship between the belts of planetesimals and the dust that they produce, perhaps indicating where planets have failed to form (asteroid belt) or have not yet formed (the Kuiper Belt). Debris around other stars might represent similar zones where planets are not present (if all systems evolved from continuous T Tauri disks to dynamical "packed" systems).



The major families of Solar System objects, as revealed by their dynamical structure. *The Solar System's small bodies are shown plotted as a function of orbital semimajor axis (in AU) and orbital eccentricity. On the scale of this figure, the Sun and planets lie at approximately zero eccentricity. For clarity we reduced the eccentricity value of the asteroids by a factor of 2. The boundaries are not impermeable; for example there are inactivated asteroids in the nominal Jupiter-family comet region, and there are active comets in the near-Earth object region. This overlap hints at the evolutionary relationship among the groupings.*

Zodiacal Dust

Key question: What does our Solar System's interplanetary dust environment and our zodiacal cloud tell us about the nature of the dusty disks seen around other stars? Are the structures we see in mature exo-disks explainable by the erosional and collisional processes supporting the Solar System zodiacal cloud? Can the model timescales for these processes (cometary emission, asteroid fragmentation events, dust-dust collision, PR drag, and radiation pressure blowout) be reconciled with zodiacal clouds seen around nearby stars?

The zodiacal dust in an exoplanet system is a potential source for relatively bright reflected and thermally re-radiated starlight, and as such is a signal as well as a noise source. Structures in the exo-zodi cloud due to dust trapped in gravitational resonances could serve as a source of confusion in direct imaging searches while at the same time serving as signposts of the presence of planets. Strong similarities are seen between the spectra of dusty material emitted by comets, and of the dust in exo-systems – see figure on the title page. The clear implication is that small bodies must exist in other planetary systems.

Most of our knowledge of the structure and radiative properties of the zodiacal dust in the Solar System comes from observations deep within the cloud itself. We know little from direct observation about the ratio of asteroidal debris to cometary (Kuiper Belt) debris to interstellar material as a function of location in our own Solar System. Our ability to interpret infrared observations of Kuiper Belt or asteroidal debris disks toward other planetary systems in terms of the amount of material in the inner habitable zone is very limited.

Observations within our own Solar System would be very valuable in advancing our knowledge of our own and exozodiacal dust clouds. A simple experiment would use existing or planned visible or near-IR cameras on outer planet missions (>3 AU limit of the asteroid belt) during cruise phase to make occasional images of selected portions of our own zodiacal cloud. This would require only funding for cruise operations and hardware modifications to include a dark slide to facilitate absolute photometric measurements. More ambitious experiments might include a dedicated satellite making complete visible to far-IR tomographic images of the entire cloud from 1 AU out to >5 AU. In either case it would be valuable to combine the photometric measurements with physical dust collection experiments to assess the population (and possibly composition) of larger grains. Observations of dust from a point nearer the giant planets could help in determining observational parameters such as the visible albedo, infrared emissivity, phase function, and polarization properties, all as a function of wavelength and location. These will help us to model giant exoplanets taking into account these important functions.

From this information we would learn about the radial distribution of different populations of grains, including their sizes and composition. We could also learn about resonant structures in our own cloud as we observe (or directly traverse) regions affected by other planets in our Solar System. Support for theoretical investigations into these issues is an obvious and inexpensive way to expand our knowledge based on existing data.

Summary

Our ability to characterize exoplanets will depend greatly on our interpretation of planets in our Solar System. It will be necessary to observe our giant planets from the vantage point of orbiters and probes in order to understand what physical properties determine the observable properties. Planets are different from stars in the sense that knowing mass and angular momentum is not sufficient. In other words planets and exoplanets vary substantially in composition, are not in thermodynamic equilibrium, and their evolutionary histories depend more on the statistics of many-body interactions, and on the dynamical evolution of their birth disks, than on intrinsic mass alone. Therefore it is necessary to measure the properties of many exoplanets in order to characterize their diversity and estimate a typical evolutionary picture for the ensemble.

Some of the desired properties of the Solar System discussed in this White Paper are already in hand, from past decades of ground-based and space mission observations. However more detailed data are needed to allow us to interpret and characterize exoplanet spectra and set them in the context of our Solar System, given the larger range of conditions that we are already finding in them. Our future interpretation of the origin and development of exoplanet systems, and perhaps our understanding of the circumstances under which life can begin and evolve, will, for decades to come, depend on our ability to understand our own Solar System, by continued observation and analysis.

Priorities

What new observations in the outer Solar System would be most important in interpreting future exoplanet data? By posing this question in terms of the usefulness to the analysis of anticipated data on exoplanets, and not in terms of improved understanding of Solar System constituents, we are clearly focusing on a specific aspect of decision making for outer-planet missions.

Our highest priority for new measurements is to learn more about the ice giants, Uranus and Neptune. The reasons for this choice are that we anticipate that many new exoplanets will be discovered in the coming few years that have masses between an Earth and a Jupiter – planets that could be massive rocky super-Earths or small giant planets. To interpret the data from these exoplanets we will need a better understanding of the ice giants in our own Solar System. The lack of an internal heat source on Uranus is an outstanding example of such a question. Understanding compositions including core masses and internal structure of all giants (particularly Uranus and Neptune) is a related goal.

Our second priority is to have measurements of the zodiacal dust brightness, in the visible and infrared, in the outer Solar System. We need this information specifically to help model the exozodi dust disks that we expect to find. Understanding in detail the structure of our own zodiacal dust distribution will help in inferring the presence of planets from the dynamics of other zodis. An especially attractive experiment would be visible or near-IR observations during cruise phase of an outer planet mission.

We also recommend that exoplanet researchers should be involved in science planning and execution for missions. In addition there might be explicit proposal opportunities for guest observations that are relevant to exoplanet science; an example (mentioned above) might be cruise-phase measurements of zodiacal dust emission.

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