Exploring Strange New Worlds:
From Giant Planets to Super Earths

# PLANETARY SCIENCE AND EXOPLANETS: PERSPECTIVES AND PROSPECTS

Torrence V. Johnson
Jet Propulsion Laboratory, California Institute of Technology
2 May 2011

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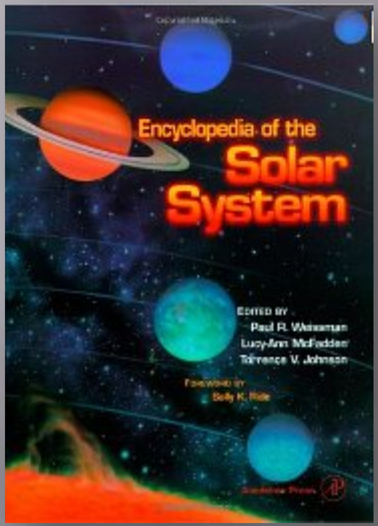
# 1999




# EXTRA-SOLAR PLANETS: SEARCHING FOR OTHER PLANETARY SYSTEMS

I. Introduction
II. Some Key Concepts
III. Results to Date
IV. Future Directions and Opportunities

David C. Black
*Lunar and Planetary Institute*

## GLOSSARY

**Astrometry:** Observations of the position of celestial objects and how they vary over time. Measurements of the position of a "target" star relative to the positions of several other stars can be used to determine if the target star has companions. The presence of companions is inferred from "wobbles" in the apparent motion of the target star.

**Brown dwarf:** Object formed by the same process(es) that form stars but of insufficient mass to burn hydrogen into helium (roughly 80 times the mass of Jupiter). The lower limit to the mass of a brown dwarf is unknown.

**Planet:** Object formed by accretion of dust and gas. This process is different from the process that forms stars and brown dwarfs.

**Planetary system:** System consisting of at least two planets in Keplerian orbit around a star.

**Pulsar:** Magnetic neutron star that remains after a star has undergone a supernova. Pulsars rotate, in some cases as fast as a thousand revolutions per second. This gives rise to pulsed radio emission from charged particles present in the pulsar's magnetic field.

**Spectroscopy:** Observational technique that breaks the light from an object into discrete wavelength bins. Comparison of the wavelength of known emission or absorption lines in the light from a star with the wavelength of those lines from a source that is at rest with respect to an observer provides a measure of the velocity of the star along the line of sight to the observer. The velocity is determined by the extent of the Doppler shift in the observed wavelength.

Ever since Copernicus proposed that Earth was part of a planetary system that revolved around the Sun, philosophers and scientists have long sought evidence of the existence of other planetary systems. It has only recently been realized fully that we will never understand the origin of our planetary system if we do not have information concerning others. For example, what fraction of stars have planetary companions, and what are the detailed characteristics of other planetary systems? We have developed a paradigm that describes

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## 19 "Substellar Companions"



**TABLE II**
**Properties of Newly Discovered Substellar Companions**

| Star | Mass[a] | Period (days) | Eccentricity |
|---|---|---|---|
| 51 Peg[1] | 0.45 | 4.23 | 0.00 |
| υ And[2] | 0.65 | 4.61 | 0.11 |
| 55 Cnc[2] | 0.84 | 14.65 | 0.05 |
| Rho Cr[3] | 1.1 | 39.64 | 0.03 |
| 16 Cyg[4] | 1.6 | 804 | 0.65 |
| 47 UMa[2] | 2.3 | 1090 | 0.03 |
| τ Boo[2] | 3.9 | 3.31 | 0.00 |
| 70 Vir[2] | 7.4 | 116.7 | 0.37 |
| HD 114762[5] | 9.0 | 84.02 | 0.33 |
| HD 110833[6] | 17 | 270 | 0.69 |
| BD −04:782[6] | 21 | 240.92 | 0.28 |
| HD 112758[6] | 35 | 103.22 | 0.16 |
| HD 98230[7] | 37 | 3.98 | 0.00 |
| HD 18445[6] | 39 | 554.67 | 0.54 |
| HD 29587[6] | 40 | 1471.70 | 0.37 |
| HD 140913[6] | 46 | 147.94 | 0.61 |
| BD +26:730[6] | 50 | 1.79 | 0.02 |
| HD 89707[6] | 54 | 298.25 | 0.95 |
| HD 217580[6] | 60 | 454.66 | 0.52 |

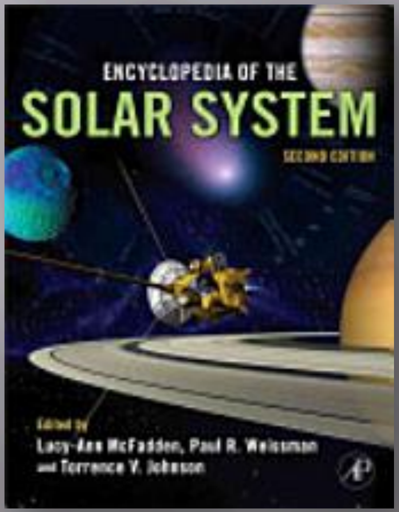
[a] Mass is expressed in Jupiter masses.

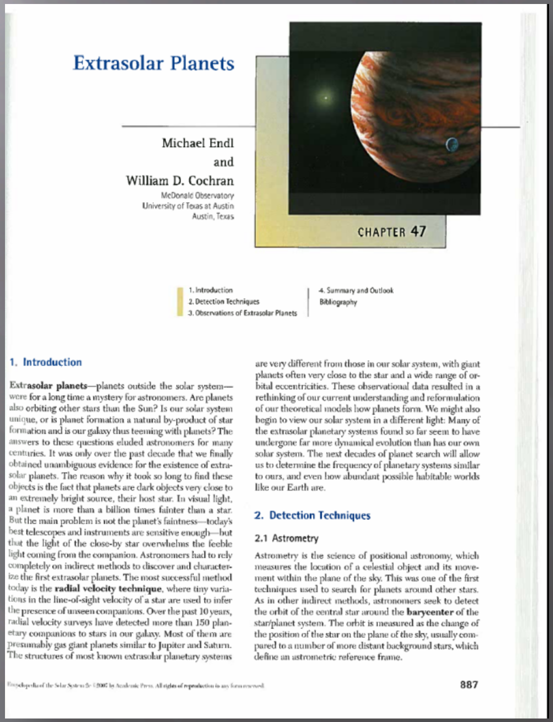
## What's a Planet?

Weissman, P. R., et al. (Eds.) (1999), *Encyclopedia of the Solar System, 1 ed., 992 pp., Academic Press.*

# 2007

## ~150 Exoplanets (200 by press time)



## Extrasolar Planets


Michael Endl
and
William D. Cochran
McDonald Observatory
University of Texas at Austin
Austin, Texas


CHAPTER 47


1. Introduction
2. Detection Techniques
3. Observations of Extrasolar Planets
4. Summary and Outlook
Bibliography


### 1. Introduction

**Extrasolar planets**—planets outside the solar system—were for a long time a mystery for astronomers. Are planets also orbiting other stars than the Sun? Is our solar system unique, or is planet formation a natural by-product of star formation and is our galaxy thus teeming with planets? The answers to these questions eluded astronomers for many centuries. It was only over the past decade that we finally obtained unambiguous evidence for the existence of extrasolar planets. The reason why it took so long to find these objects is the fact that planets are dark objects very close to an extremely bright source, their host star. In visual light, a planet is more than a billion times fainter than a star. But the main problem is not the planet's faintness—today's best telescopes and instruments are sensitive enough—but that the light of the close-by star overwhelms the feeble light coming from the companion. Astronomers had to rely completely on indirect methods to discover and characterize the first extrasolar planets. The most successful method today is the **radial velocity technique**, where tiny variations in the line-of-sight velocity of a star are used to infer the presence of unseen companions. Over the past 10 years, radial velocity surveys have detected more than 150 planetary companions to stars in our galaxy. Most of them are presumably gas giant planets similar to Jupiter and Saturn. The structures of most known extrasolar planetary systems are very different from those in our solar system, with giant planets often very close to the star and a wide range of orbital eccentricities. These observational data resulted in a rethinking of our current understanding and reformulation of our theoretical models how planets form. We might also begin to view our solar system in a different light: Many of the extrasolar planetary systems found so far seem to have undergone far more dynamical evolution than has our own solar system. The next decades of planet search will allow us to determine the frequency of planetary systems similar to ours, and even how abundant possible habitable worlds like our Earth are.

### 2. Detection Techniques

#### 2.1 Astrometry

Astrometry is the science of positional astronomy, which measures the location of a celestial object and its movement within the plane of the sky. This was one of the first techniques used to search for planets around other stars. As in other indirect methods, astronomers seek to detect the orbit of the central star around the **barycenter** of the star/planet system. The orbit is measured as the change of the position of the star on the plane of the sky, usually compared to a number of more distant background stars, which define an astrometric reference frame.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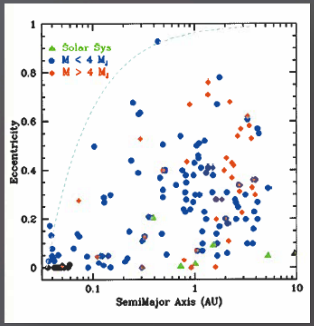
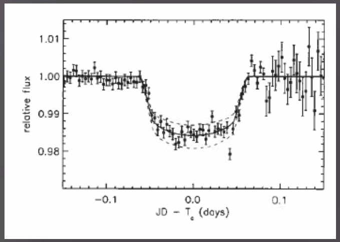
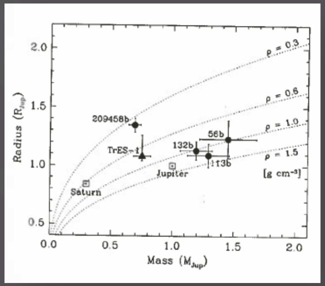
## Orbits




## Transits!

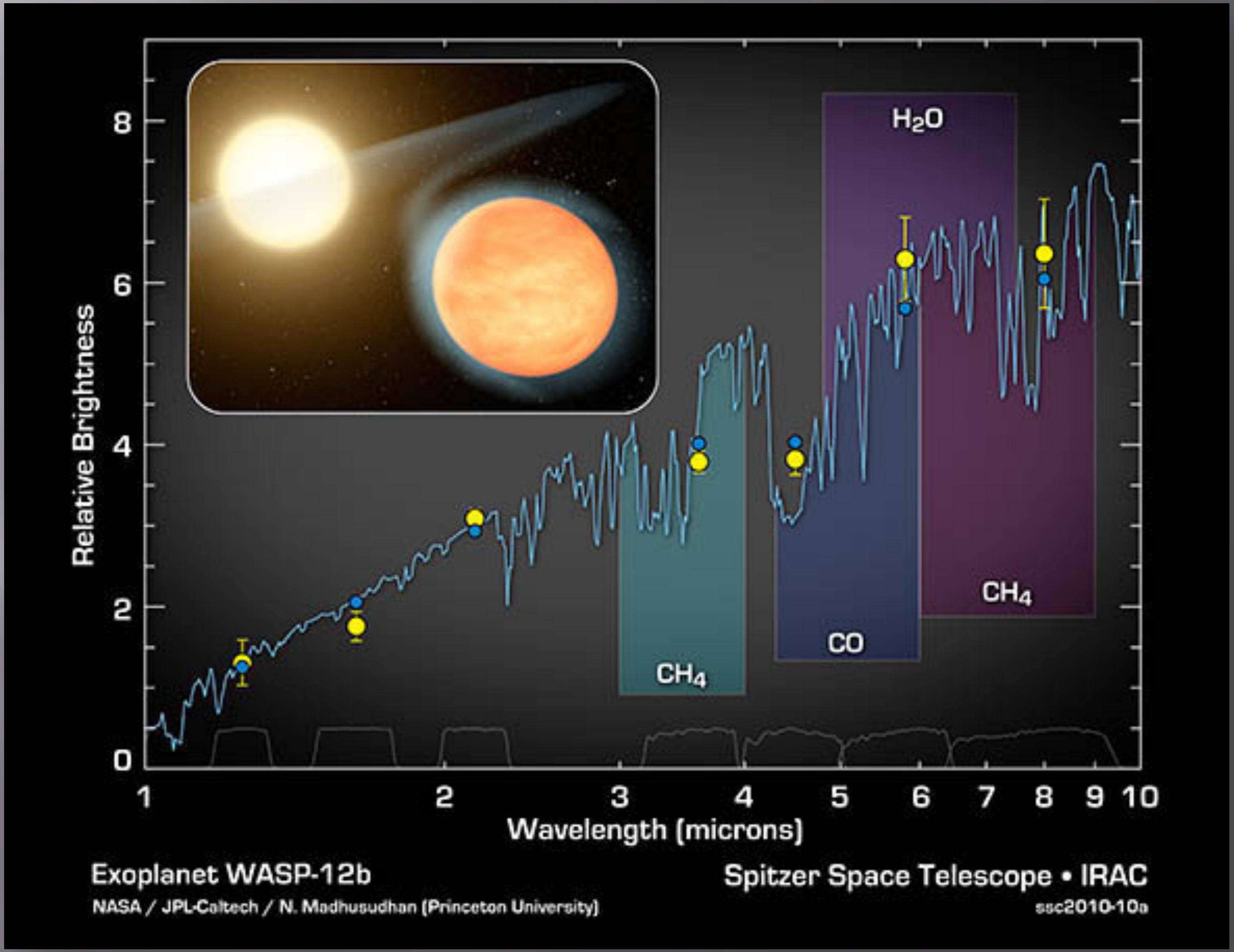



## Densities!!




McFadden, L.-A., et al. (Eds.) (2007), *Encyclopedia of the Solar System, 2 ed., 966 pp., Academic Press.*

# And Spectra !!!



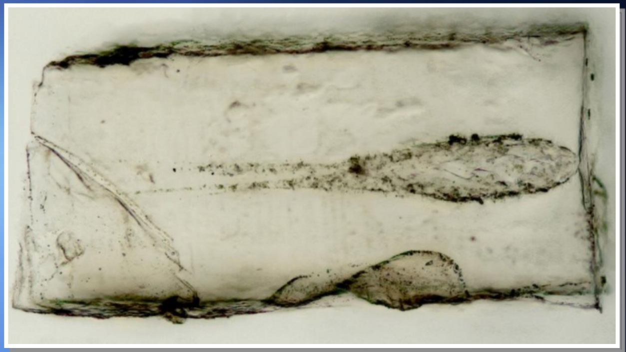
Relative Brightness
0
2
4
6
8
1
2
3
4
5
6
7
8
9
10
Wavelength (microns)
$H_2O$
$CH_4$
CO
$CH_4$
Exoplanet WASP-12b
NASA / JPL-Caltech / N. Madhusudhan (Princeton University)
Spitzer Space Telescope • IRAC
ssc2010-10a

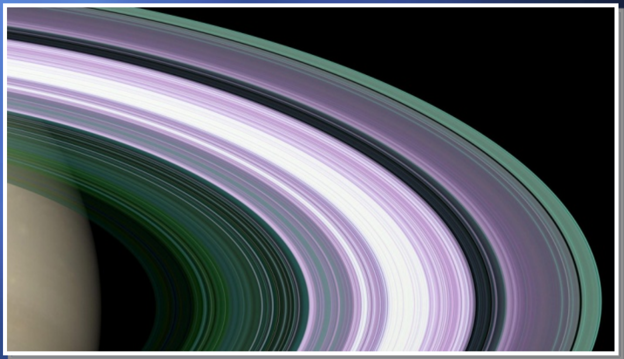
# Vision and Voyages for Planetary Science in the Decade 2013-2022

- Decadal Survey for solar system science highlights connections between exoplanet systems and planetary science goals throughout the document
  - Origins of planetary systems
  - Architecture  - orbits, planet migration, planetary size/mass
  - Giant planets in the solar system as laboratories for understanding exoplanets
  - Habitable zones
  - Need for understanding the solar system ice giants, Uranus and Neptune – New Flagship mission

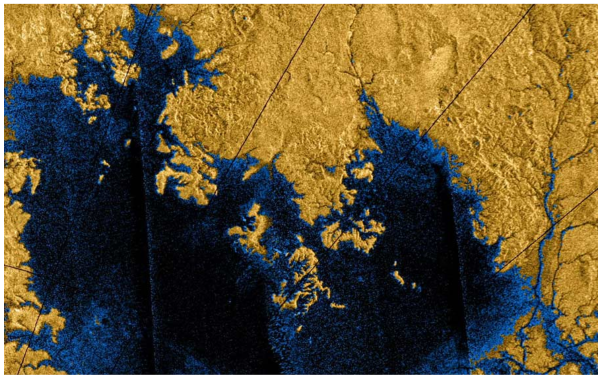
# Building New Worlds

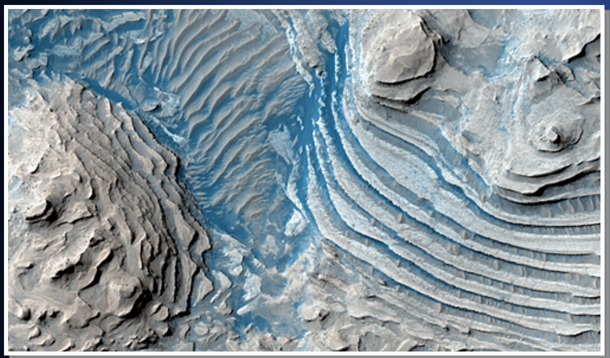
- What were the initial stages, conditions and processes of solar system formation and the nature of the interstellar matter that was incorporated?
- How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions?
- What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?

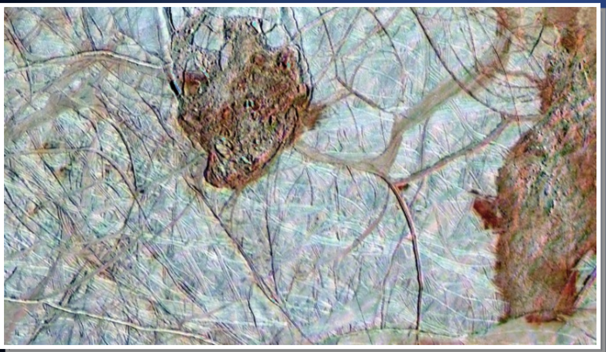




# Planetary Habitats



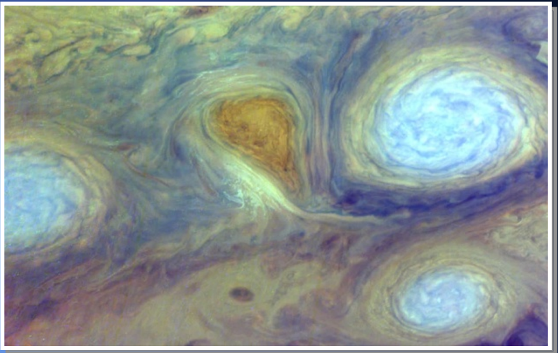




- What were the primordial sources of organic matter, and where does organic synthesis continue today?
- Did Mars or Venus host ancient aqueous environments conducive to early life, and is there evidence that life emerged?
- Beyond Earth, are there modern habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?

# Workings of Solar Systems

- How do the giant planets serve as laboratories to understand the Earth, the solar system and extrasolar planetary systems?
- What solar system bodies endanger and what mechanisms shield the Earth's biosphere?
- Can understanding the roles of physics, chemistry, geology, and dynamics in driving planetary atmospheres and climates lead to a better understanding of climate change on Earth?
- How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?



# Origins

**THE MOTIVATIONS FOR PLANETARY SCIENCE**

In the past, scientists only had one planet to study in detail. Our Earth, however, the only place where life demonstrably exists and thrives, is a complex interwoven system of atmosphere, hydrosphere, lithosphere, and biosphere. Today, planetary scientists can apply their knowledge to the whole solar system, and to hundreds of worlds around other stars. By investigating planetary properties and processes in different settings, some of them far simpler than Earth, we gain substantial advances in understanding exactly how planets form, how the complex interplay of diverse physical and chemical processes create the diversity of planetary environments seen in the solar system today, and how interactions between the physical and chemical processes on at least one of those planets led to creation of conditions favoring the origin and evolution of multifarious forms of life. These basic motivational threads will be built upon and developed into the three principal scientific themes of this report—building new worlds, workings of solar systems, and planetary habitats—in Chapter 3.

**NASA's Astrophysics Division**

The major science goals of the Astrophysics Division are to discover how the universe works, explore how the universe began and evolved, and to search planetary environments that may hold keys to life's origins or even might themselves sustain life.[2] Strong scientific synergy exists between the studies of extrasolar planets and Earth's planetary neighborhood. The former provides an immense variety of planetary systems in their structures and stages of evolution: known exoplanets now range from super-Jupiters to super-Earths. The latter affords the opportunity for detailed—often in situ—examination of the

From "Vision and Voyagers for Planetary Science in the Decade 2013-2022, NRC, 2011

# Planetary System Architecture

**How Did the Giant Planets and Their Satellite Systems Accrete and Is There Evidence that They Migrated to New Orbital Positions?**

- Planetary Migration investigated in the solar system for many years
- Discovery of 'hot Jupiters' shows that migration is a common process
- "Nice Model" for the solar system now the current working hypothesis – in latest version Jupiter may have come in to <2 au.

From "Vision and Voyagers for Planetary Science in the Decade 2013-2022, NRC, 2011

# Giant planets in the solar system as laboratories for understanding exoplanets

**How do the Giant Planets Serve as Laboratories to Understand Earth, the Solar System, and Extrasolar Planetary Systems?**

Among the mind-stretching advances in space science of the last ten years is the recognition of the immense diversity of planets orbiting other stars; those confirmed number nearly 500 as of the writing of this report.[53] These worlds exhibit an incredible array of planetary characteristics, orbits, and stellar environments. Moreover, some of these planetary systems are found to contain multiple planets. Some exoplanets orbit close to their stellar companions; some have orbits that are highly eccentric or even retrograde. In size and composition known exoplanets range from massive super-Jupiters, mostly hydrogen and helium, to Uranus- and Neptune-sized ice giants, dubbed water worlds, down to super-Earths seeming to have ice-rock compositions.[54] Discovery and characterization of watery Earth-sized planets are likely within the decadal horizon. New areas of research seek to extrapolate the understanding of the solar system to exoplanets—therefore more complete knowledge of the origin, evolution, and operative processes in our solar system, in particular of the giant planets, becomes ever more urgent.[55]

Exoplanets exist in broad range of stellar conditions and illustrate extremes in planetary properties. Many exoplanets "inflated" by close proximity to their star have radii much larger than can be explained by our best thermal history models. Hot Jupiters orbit close in where the internal heat flow is dwarfed by enormous stellar fluxes; others exhibit the reverse, orbiting far from their central stars.[56] Analogously, Uranus's heat flow is a small fraction of the solar flux but at Jupiter the two are similar.

From "Vision and Voyagers for Planetary Science in the Decade 2013-2022, NRC, 2011

# Giant planets in the solar system as laboratories for understanding exoplanets - Example

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ON THE VOLATILE ENRICHMENTS AND HEAVY ELEMENT CONTENT IN HD189733b

O. Mousis[1], J. I. Lunine[2], J.-M. Petit[1], K. Zahnle[3], L. Biennier[4,5], S. Picaud[1], T. V. Johnson[6], J. B. A. Mitchell[4,5], V. Boudon[7], D. Cordier[4,5,8], M. Devel[9], R. Georges[4,5], C. Griffith[10], N. Iro[11], M. S. Marley[3], and U. Marboeuf[12]
[1] Institut UTINAM, CNRS-UMR 6213, Observatoire de Besançon, Université de Franche-Comté, BP 1615, 25010 Besançon Cedex, France; olivier.mousis@obs-besancon.fr
[2] Dipartimento di Fisica, Università degli Studi di Roma "Tor Vergata," Roma, Italy
[3] NASA Ames Research Center, Moffett Field, CA 94035, USA
[4] Université européenne de Bretagne, Rennes, France
[5] Institut de Physique de Rennes, CNRS, UMR 6251, Université de Rennes 1, Campus de Beaulieu, 35042 Rennes, France
[6] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[7] Laboratoire Interdisciplinaire Carnot de Bourgogne, UMR 5209 CNRS-Université de Bourgogne, 9 Avenue Alain Savary, BP 47870, F-21078 Dijon Cedex France
[8] Ecole Nationale Supérieure de Chimie de Rennes, CNRS, UMR 6226, Avenue du Général Leclerc, CS 50837, 35708 Rennes Cedex 7, France
[9] FEMTO-ST, CNRS, UFC, UTBM, ENSMM, Besançon, France
[10] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA
[11] NASA/Goddard Space Flight Center, Greenbelt, MD, USA
[12] Laboratoire de Planétologie de Grenoble, Université Joseph Fourier, CNRS INSU, France
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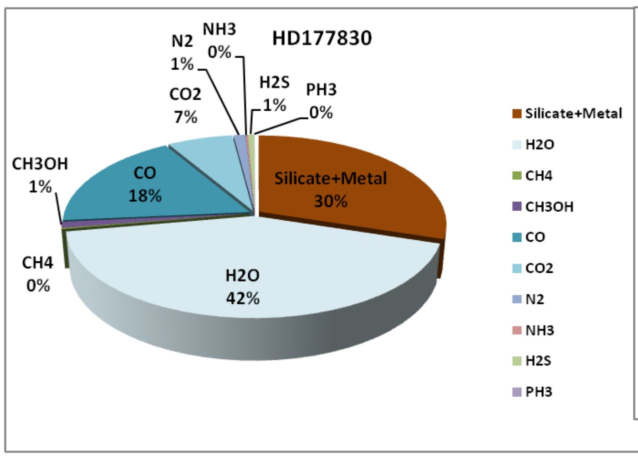
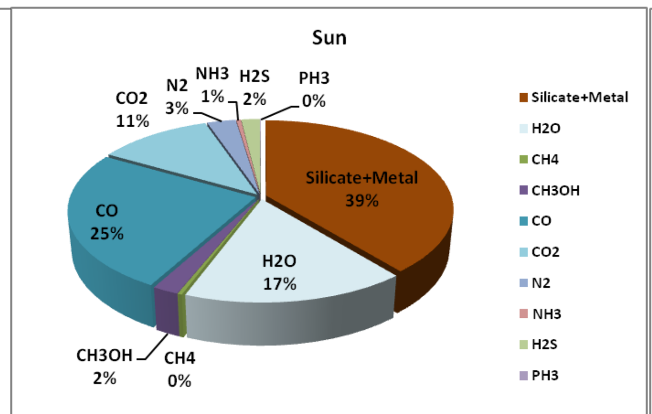
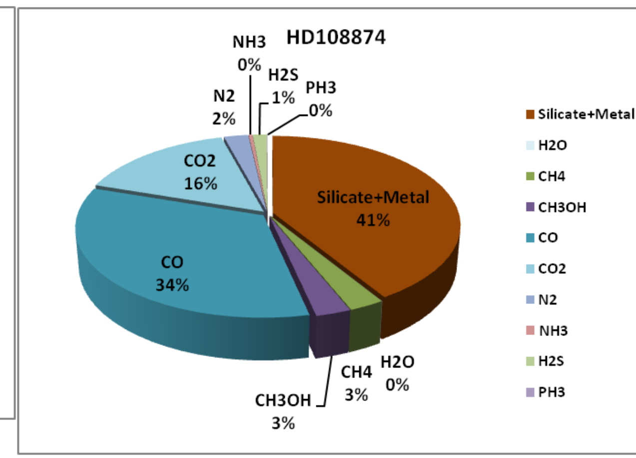
Uses methodology developed to explain volatile and noble gas enrichment in Jupiter to address constraints on structure and composition of transiting hot Jupiter HD189733b

# Planetesimal Compostion in Exoplanet Systems
## (ad for Poster ID Formation.04, p 111)

Uses methodology developed to explain proportions of silicate and metal versus condensed volatile ices in the solar system as a function of the C/O ratio of nebular gas. Uses measured host star composition to calculate composition of condensates.



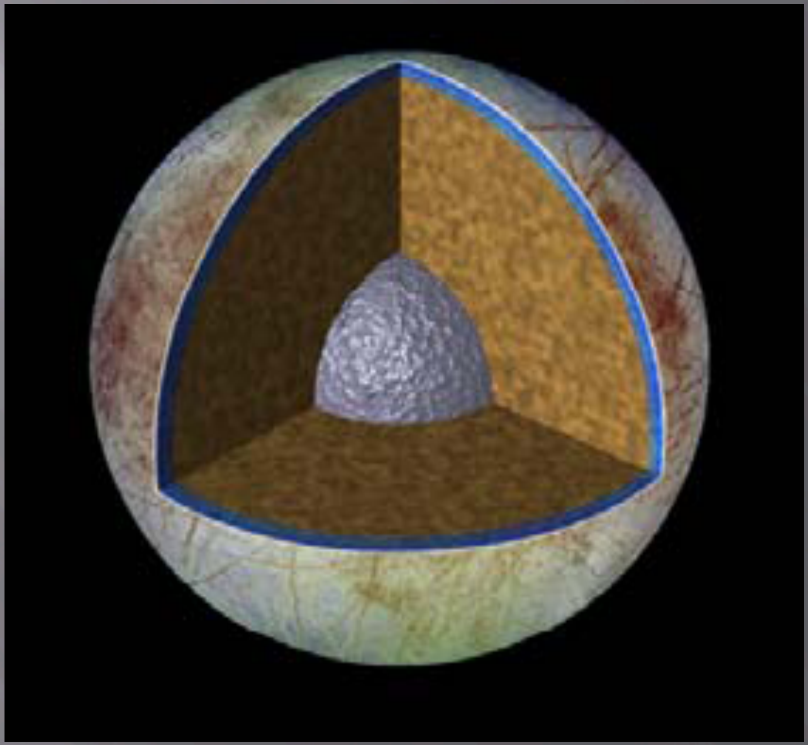




Stellar C/O = 0.35
Silicate+Metal poor
$H_2O$ ice rich
CO ice if cold nebula

Stellar C/O = 0.55
Silicate+Metal rich
$H_2O$ ice
CO ice if cold nebula

Stellar C/O = 0.71
Silicate+Metal rich
No $H_2O$ ice
CO ice if cold nebula

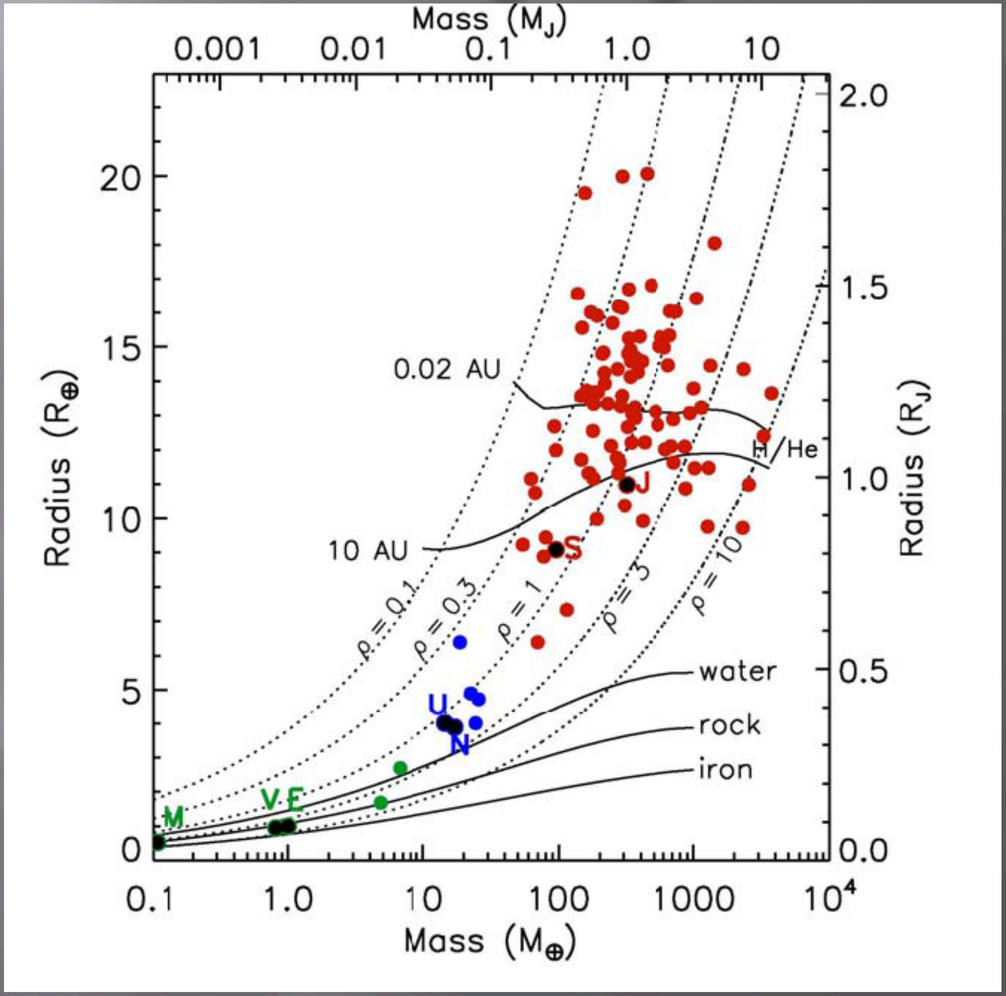
# Habitable Zones



Evidence for subsurface liquid water oceans on icy satellites has extended the concept of the HZ beyond 'orbital distance required for liquid water at the surface'.

# Ice Giant Exoplanets Common

## We have less information about U and N than the gas giants

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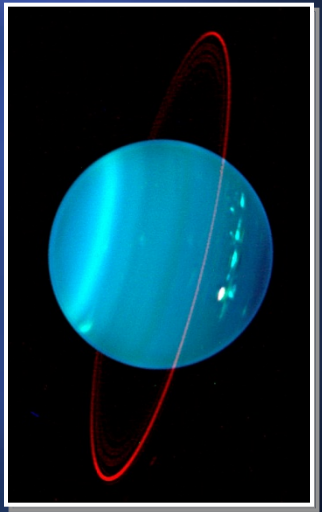
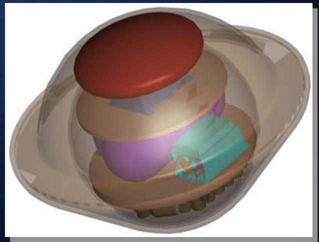
# Flagship Priority 3: Uranus Orbiter and Probe





- Uranus and Neptune belong to a distinct class of planet: the Ice Giants
  - Small hydrogen envelopes
  - Dominated by heavier elements
  - The only class of planet that has never been explored in detail
- Orbiter to perform remote sensing of planet's atmosphere, magnetic field, rings, and satellites.
- Atmospheric entry probe.
- Potential for new discoveries comparable to Galileo at Jupiter and Cassini at Saturn.
- *Uranus is preferred over Neptune for 2013-2022 for practical reasons involving available trajectories, flight times, and cost.*



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# Exoplanets – Prospects

or

Why does this seem so familiar?

# At the Frontier

**1970**

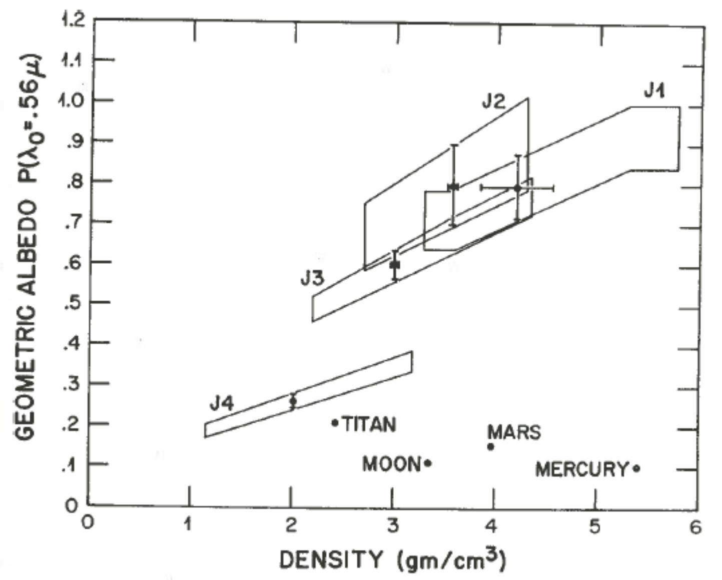
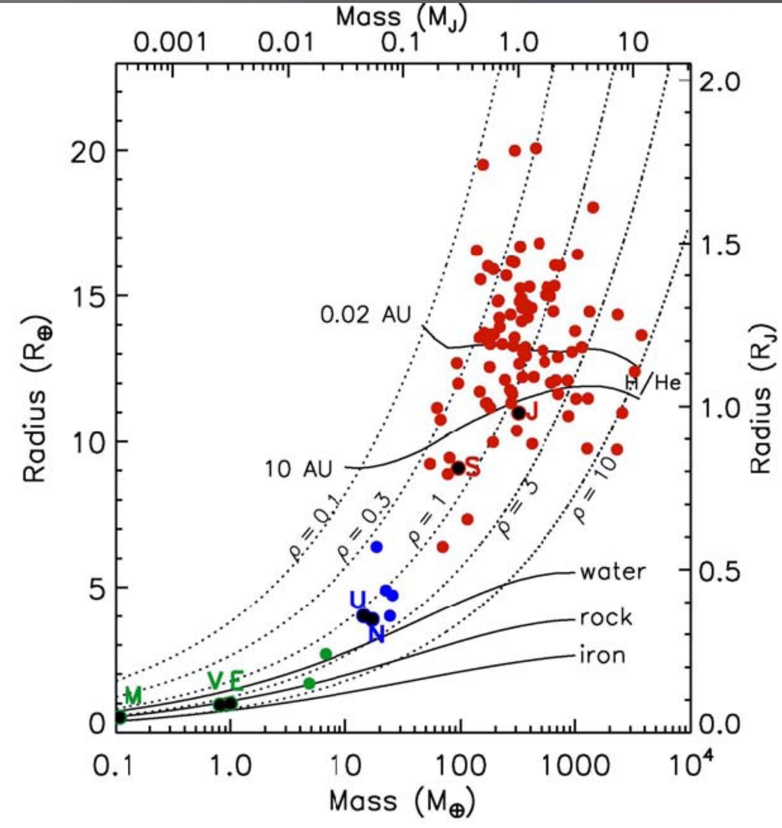



Figure 19. Geometric albedo vs density of the satellites. The point for each satellite represents the values of p and ρ for the mean of the measured diameters. The density error bar gives the limits of two mass determinations (Porter, 1960) and the geometric albedo range is determined from the rotation variation shown by the satellite. The regions indicated for each satellite indicate the limits of the given error bars for the range of diameter measurements compiled by Sharonov (1958).

**2011**




T. V. Johnson, PhD Dissertation, 1970