Probing the Giant Planets

More than a hundred extrasolar giant planets have been discovered in the past few years. To understand how they were formed, we must study in detail the giants closest to us: Jupiter and Saturn.

Tristan Guillot

Before 1995, most astronomers expected giant extrasolar planets to orbit their stars in quasicircular orbits at a distance of more than a few astronomical units. (1 AU is the mean distance between Earth and the Sun.) In our Solar System, the orbits of the four giant planets—Jupiter, Saturn, Uranus, and Neptune—have semimajor axes ranging from 5.2 to 30 AU and eccentricities no larger than 5.6%.

Since then, more than 100 extrasolar planets have been discovered, all of them giants with at least 10% the mass of Jupiter (0.1 M_J, about twice the mass of Uranus or Neptune). Much smaller Earthlike ("terrestrial") extrasolar planets would not be massive enough to be detected by current methods.

The newly found planets are strange—not at all what we expected. A significant fraction of the extrasolar giants detected thus far orbit extremely close to their star, that is, at less than 0.1 AU. Some semimajor axes are as small as 0.04 AU, implying a period of revolution around the star of only about three Earth days. The archetype of these so-called Pegasi planets (also called "hot Jupiters") is the first one to have been discovered: 51 Pegasi b, a roughly Jupiter-mass giant orbiting at only 0.05 AU from a sunlike star in the constellation Pegasus.[1]

The other fraction of extrasolar planets discovered since 1995 may be even stranger. As shown in figure 1, many of them exhibit very eccentric orbits,[2] quite unlike our own giant planets. It may be, however, that Solar System analogs are common but hard to discover. After all, Jupiter and Saturn are so far from the Sun that they take 12 and 29 years, respectively, to complete an orbit. A few planets in figure 1 have large orbits with low eccentricity. Discovering more objects like these will require patience and improved observational techniques.

It has been very difficult to construct a coherent scenario that would explain the formation of giant planets as we see them both within and beyond our solar system. The presence of close-in planets is generally thought to be due to early migration of planets forming in a disk of gas and dust surrounding the young central star.[3] But that's not the only possibility, and it doesn't explain why Jupiter and its sisters didn't share such a fate.

Similarly, it is not clear why extrasolar planets often have very eccentric orbits while our own giant planets orbit the Sun in sedate circles. Could it be that "ordinary" circular orbits are in fact quite extraordinary by Galactic standards? Is our solar system an unlikely outcome of the general mechanism of planet formation? Or perhaps, might extrasolar planets be formed by a different mechanism?

These are but a few of the questions that confront us. There's no shortage of suggested answers, but none thus far has given satisfaction. A large part of the problem is that the so-called radiovelocimetry method used until now to discover extrasolar planets provides only a lower limit on the planetary mass M. Relying on the tiny Doppler modulation as the star is tugged to and fro by its orbiting planet, the method determines the orbit's diameter and eccentricity. But the inclination angle i between the normal to the orbital plane and the line of sight is unknown, and radiovelocimetry only determines the product $M \sin i$.

Of course, we do have interesting additional measurements. For example, it is becoming clear that stars with planets tend to be enriched in heavy elements—meaning, in astronomers' jargon, anything other than hydrogen and helium. That tells us something about planetary formation, namely that planets probably grew more rapidly in environments rich in dust. (Most heavy elements form chemical species that condense at low temperatures.) But we do not know two crucial properties of the extrasolar giants: their exact masses and their sizes. Except for one serendipitous case[4]—the planet HD209458b.

A planet in transit

HD209458 is a faint star in Pegasus, barely visible to the naked eye. Like 51 Pegasi, its planet has a mass close to that of Jupiter, and a tiny semimajor axis, a mere 0.045 AU. The particularity of the HD209458 system is that, as seen from Earth, the planet passes in front of the star every 3.5 days. Therefore, we can measure the time it takes for the planet to transit the stellar surface and the consequent dimming of the star (about 2%). Thus we can also calculate the planet's size, the inclination of its orbit, and therefore its mass.[5]

The radius measured for the giant planet HD209458b is about 35% larger than that of Jupiter, although its mass is 30% *less* than Jupiter's. This apparent contradiction is understood by realizing that gaseous giant planets tend to cool slowly by infrared emission and thus contract, and that planets heavily irradiated by their stars contract more slowly. Jupiter itself is estimated to be contracting at a rate of about 3 mm per year.

The observations of HD209458b, a hundred times closer to its star than is Jupiter, confirmed the general theoretical picture and showed that the planet, discovered in 2000, is made mostly of hydrogen and helium.[6] The study of this transiting Jovian giant was the first confirmation

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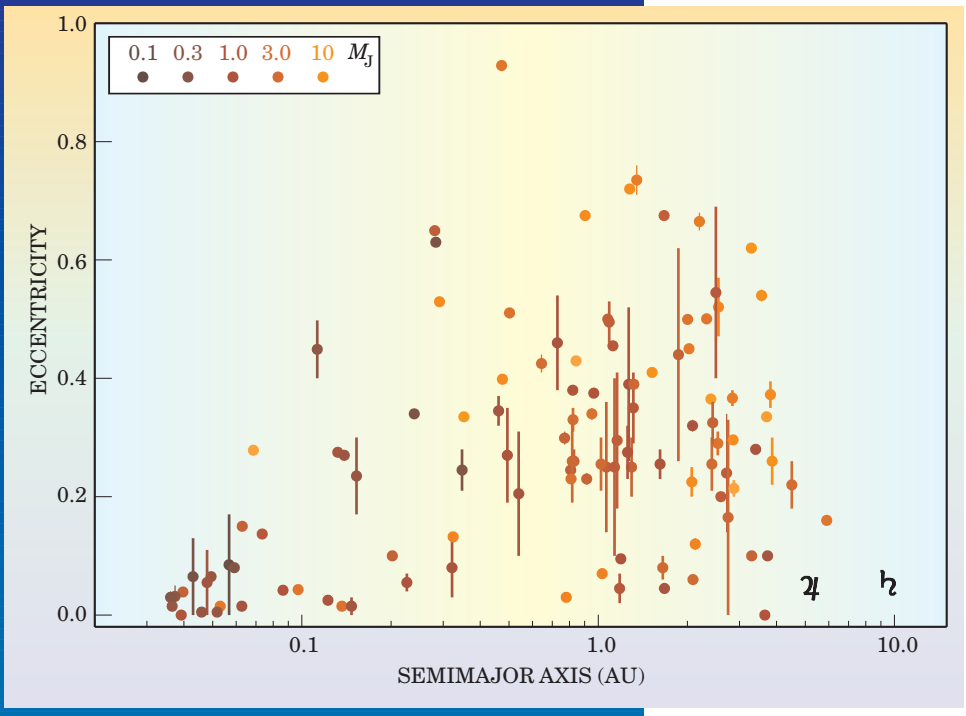


Figure 1. A planetary zoo is represented in this scatter plot of orbital eccentricity versus semimajor axis for every extrasolar planet detected thus far. Colors indicate the lower mass limit deduced for each planet. They range from 0.11 to 17.5 times the mass of Jupiter. The planets closest to their stars appear to have had their orbits circularized by tidal interactions. Among the planets farther out are many with much larger eccentricities than those of Jupiter and Saturn (marked by the traditional symbols at 5.2 and 9.5 AU, respectively). Those surprisingly high eccentricities are still unexplained. (Adapted from ref. 2.)

that our models of planet formation were not completely off-track. Had HD209458b been found to have a smaller diameter than Jupiter, it would have meant that the new planet consists mostly of heavy material, which would patently contradict our formation models.

However, the hope that we would be able to learn more precisely the composition of HD209458b has dwindled rapidly. The planet's radius turned out to be slightly larger than expected. So we're probably missing some energy source that prevents the planet from cooling faster.[7] It appears that tides may be dissipating heat into the planet's interior and thus slowing its contraction. The energy source might be the orbital energy of an unseen eccentric giant companion planet, or it might be winds generated in the planet's atmosphere by the strong stellar irradiation.

Alternatively, the atmosphere may be hotter than most models predict (see figure 2). We know little about meteorology and tides on gaseous planets. Tens of Earth masses of heavy elements could be mixed in with the hydrogen and helium without our being able to tell. Better understanding the giant planets will require more examples of transiting extrasolar planets, with different masses and orbital distances. That's an important goal of space missions such as *COROT*, *Kepler* and, we hope, *Eddington* (see box 1).

In the meantime, the power of transit observations has been demonstrated. Because we know exactly when the planet is due to transit in front of its star, we can make very accurate measurements and compare the on-transit to off-transit results. In just that way, David Charbonneau and coworkers,[8] in 2001, detected the presence of sodium in the atmosphere of HD209458b. The sodium, it turned out, was less abundant than expected. But because we know so little about the atmospheres of these exotic planets, it's not yet clear what that means. The sodium shortfall could, for example, be due to colder atmospheric temperatures than expected. Or it might result from atmospheric dynamics or nonequilibrium effects. In any case, the observation was a milestone in the study of extrasolar planets, because it showed that we can detect constituents in the atmospheres of planets millions of times further from us than Jupiter.

Another crucial recent discovery is that HD209458b is slowly losing mass. Last year, Alfred Vidal-Madjar and coworkers found that when one observes the transiting planet at the UV wavelength of the Lyman-α absorption line of hydrogen, it appears three times larger than at other wavelengths.[9] This suggests the presence of an extended, tenuous, envelope of hydrogen escaping from the planet as a result of heating of the upper atmosphere and bombardment by ionized stellar wind. The magnitude of this mass loss appears to be consistent with estimates based on Jupiter, but scaled up by a factor 10 000 because the star is 100 times closer to the planet than the Sun is to Jupiter.[6] The Lyman-α measurements give us the first possibility of quantifying such processes more precisely and examining how gaseous planets manage to survive so close to their stars.

Impressive as they are, the HD209458b measurements tell us only about the upper atmospheres of giant gas planets. How can we better constrain their interior compositions? To do so, we have to learn how surface measurements relate to interior compositions. And to that end, we must look more carefully to the gas giants closest to us.

Our own giant planets

We can, of course, measure very accurately the masses, sizes, and hence the mean densities of Jupiter, Saturn, Uranus, and Neptune. The densities turn out to be quite low—ranging from 0.7 g/cm^3 for Saturn to 1.6 g/cm^3 for Neptune. For comparison, the four inner terrestrial planets have mean densities near 5 g/cm^3. One might have attributed the difference to the conjecture that the giant planets have the same composition as Earth but very much hotter. Alternatively, one could suppose that they are very much colder but made of light material. Of course, we've known for a hundred years that only the second explanation is valid.

Indeed, a look at the atmospheres of the giant planets shows that they are made mostly of hydrogen and helium, with only traces of heavier elements. Exactly how much of these trace elements is present is a big question. Remote sensing cannot probe very deep, because the atmospheres become too opaque and because cloud formation sequesters a number of important elements in the deep regions. The

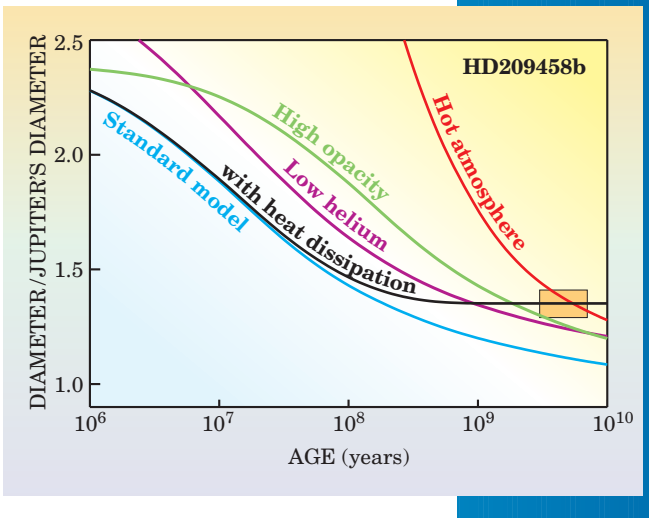


Figure 2. Contraction of the transiting extrasolar planet HD209458b with time, as predicted by various models, is compared to its measured radius and inferred age (indicated by the box). Standard models (blue curve) for the evolution of a planet with 70% of Jupiter's mass generally yield a present radius only about half the observed radius, even for no central core and a composition very low in heavy elements. (A large core and more heavy elements imply an even smaller size for a given age.) Models with unrealistically low helium abundance (purple) or unusually high opacities (green) lead to evolutionary tracks that just skirt the observational box. A possibility that fits the observations is the dissipation of heat into the planet's interior by stellar tides (black curve). Alternatively, the atmosphere may be hotter than expected because of heating by strong zonal winds and shear instabilities (red curve).

sequestered elements include water, the main carrier of oxygen. Being the third most abundant element in the universe, oxygen is a critical but hidden component of the giant gas planets.

The *Galileo* probe, which was sent down into the Jovian atmosphere in September 1995, was designed to detect some of the hidden atmospheric ingredients. It successfully probed Jupiter's atmosphere down to a pressure of 22 bar. (1 bar = 10^5 pascals, roughly the mean sea-level atmospheric pressure on Earth.) Thus the probe was able to measure accurately the abundance of constituents such as helium, methane, hydrogen sulfur, neon, argon, krypton, and xenon. Except for helium and neon, all these species appear to be enriched by about a factor of three relative to their abundances in the Sun.

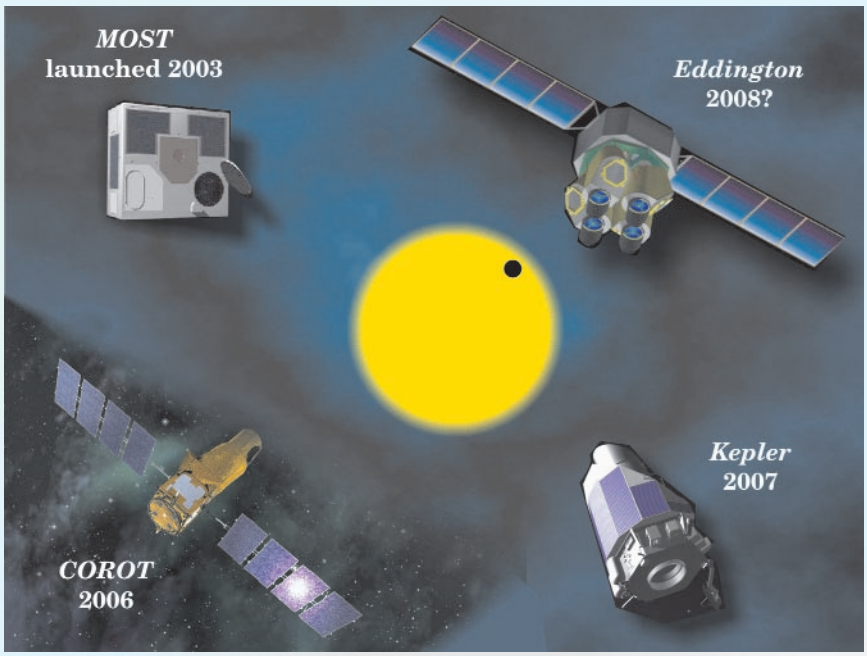
Ammonia was also detected, but measuring its abundance posed problems because of its tendency to stick to the walls of the probe's mass spectrometer. The most elusive species, however, proved to be the one that was most sought after—water. The probe did detect some water, but much less than expected, and its abundance was still rising in the last measurements before the probe finally fell silent.[10]

What does that deficit mean? In the frigid outermost precincts of the Jovian atmosphere, the water is condensed. To properly measure its bulk abundance, the probe had to reach levels deep and hot enough for the water to be entirely vaporized. It had been thought that probing down to 5 bar would suffice. Obviously, that was too optimistic.

Box 1. Attracted by the Dark Side

The formidable promise of the transit method of studying extrasolar planets has led to the development of several space missions dedicated to the discovery and measurement of more extrasolar planets transiting in front of their stars. Canada's 15-cm *MOST* telescope, launched in August 2003, can follow giant extrasolar planets closely orbiting their stars, even if they don't transit the stellar disk. Two other missions, the French Space Agency's *COROT* and NASA's *Kepler*, are due to be launched in 2006–07. The future of the European Space Agency's Eddington mission, originally scheduled for a 2008 launch, is unclear.

These missions are designed to search hundreds of thousands of stars for planets ranging from Pegasi giants down to Earth-sized planets. To do all that, the instruments will have to achieve very stable and accurate photometric measurements. The dimming of a sunlike star by a transiting giant planet is only of order 1%; for a transiting Earth-sized planet, the dimming is 100 times weaker still.



By combining the space-based observations with ground-based radiovelocimetry, we will be able to determine the radii and masses of gas giants and ice giants. For the largest extrasolar planets that are also very close to their stars, we should also be able to measure the modulation of the planet's brightness as its phase changes from our vantage point. Such measurements might tell us how the planetary atmospheres absorb stellar light. In addition to teaching us much about the structure and formation of giant planets, these missions will also reveal whether or not planets resembling Earth abound in the Galactic neighborhood.

After the fact, the consensus of the community is that the probe fell into a rare dry hot spot. It's as if an alien race designed a probe for Earth's atmosphere and it just happened to fall onto the Sahara desert. Very likely, there is more water elsewhere on Jupiter, or at greater depths.

The only secure conclusion is that we don't understand the meteorology of giant planets. That's because the meteorology is inherently complex. We don't know how it's tied to the planet's internal structure, and data are painfully scarce. Visible and IR observations, and even the deepest probe we could design, only provide skin-deep incursions into the interior. To really understand the giant gas planets, we have to avail ourselves of another technique.

Gravimetry

One possible method is seismology. Solar astronomers have learned much from observing helioseismic modes. Unfortunately, it is not clear that the giant planets can oscillate like the Sun. Attempts to measure seismic oscillations on the giant planets of the Solar System have thus far been inconclusive.[11]

Our last resort is gravimetry. The giant planets rotate quite rapidly. The fastest is Jupiter, with a diurnal period of 9 hours, 55 minutes; the slowest is Uranus, with a period of 17 hours, 14 minutes.

Therefore, all the Solar System giants are significantly flattened by centrifugal acceleration. The consequent departure of the gravitational field from spherical symmetry can be measured by careful monitoring of the trajectory of a spacecraft coming close to the planet, preferably on a polar orbit. Roughly speaking, when the spacecraft is near the equator, its trajectory is less influenced by the planet's core, and more by the outer regions, than when it flies close to either pole.

For a fluid planet in the absence of tidal forces, the gravitational potential V just outside the planet is given by

$$V(r,\cos\theta) = \frac{GM}{r}\left[1 - \sum_{i=1}^{\infty}\left(\frac{R_0}{r}\right)^{2i} J_{2i} P_{2i}(\cos\theta)\right],$$

where r and θ are the radial and polar coordinates and M and R_0 are the planet's mass and equatorial radius. The functions $P_{2i}(\cos\theta)$ are Legendre polynomials and J_{2i} the corresponding gravitational moments that parameterize the cylindrically symmetric mass distribution.

The mass and gravitational moments determined by satellite measurements of the gravitational potential translate into a constraint on the interior density profile $\rho(r, \theta)$. These constraints can be written

$$M = \int \rho(r,\theta)\,\mathrm{d}\tau$$

$$J_{2i} = -\frac{1}{MR_0^{2i}} \int \rho(r,\theta) r^{2i} P_{2i}(\cos\theta)\,\mathrm{d}\tau,$$

where $d\tau$ is a volume element and the integrations are performed over the entire volume of the planet.

Because of the form of the Legendre polynomials, gravitational moments of progressively higher order constrain the density profile of regions closer to the planet's atmosphere. Unfortunately, only J_2 and J_4 are presently known well enough to provide useful constraints on the interiors of Jupiter, Saturn, Uranus, and Neptune.

The density ρ is itself a function of several thermodynamic variables: pressure, temperature, and composition. The pressure can be calculated quite accurately because giant planets are always very close to hydrostatic equilibrium; internal pressure equilibrates gravity and inertial forces at all points. Determination of the internal temperature is more problematic. Fortunately, the giant planets radiate more energy than they receive from the Sun. We can measure the rate of energy loss and estimate how they cool. Jupiter, for example, cools by about 1 K per million years. We can then infer how heat is transported within the planetary interiors.

Convection appears to be the dominant form of transport in Jupiter, Saturn, and Neptune, and probably also in Uranus. Because convection is very efficient in these fluid planets, temperature structure should be close to an adiabat—that is, a system that exchanges no heat with its environment. The temperature distribution can then be calculated as a function of pressure, composition and the known atmospheric boundary conditions.

Composition is the knotty problem. It affects the temperature structure and can also affect convection. That leaves an infinite number of

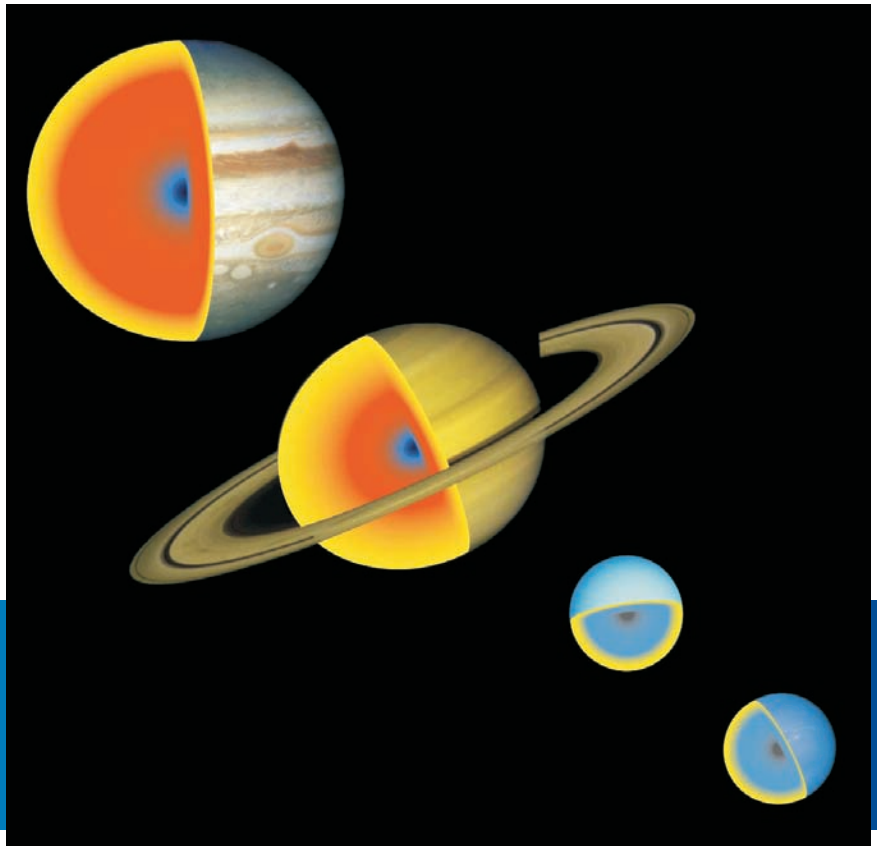


Figure 3. The interiors of the giant planets (left to right) Jupiter, Saturn, Uranus, and Neptune. Sizes are shown approximately to scale. The colors indicate regions dominated by molecular hydrogen (yellow), metallic hydrogen (red), ices (blue), and rock (gray).

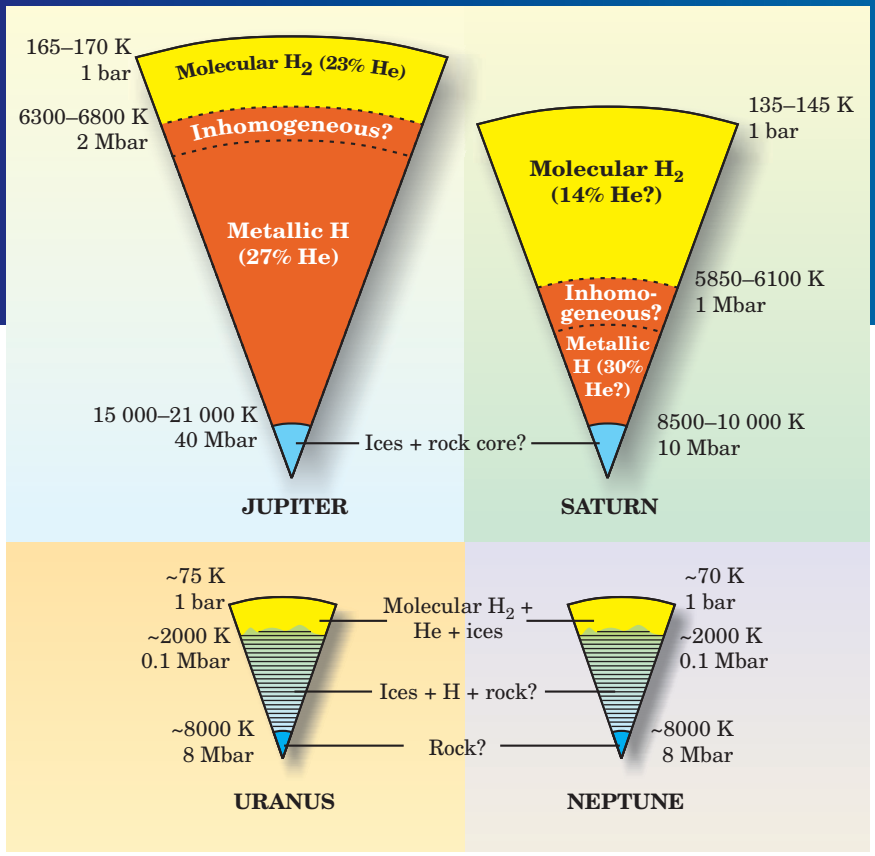


Figure 4. Putative composition of successive shells inside the giant planets. Temperature and pressure estimates are given for the boundaries. The helium percentages are mass fractions. The sizes of the rock and ice cores of Jupiter and Saturn are very uncertain. For Neptune and Uranus, whose interiors are even more uncertain, a representative model is shown. (Adapted from ref. 13.)

solutions describing how pressure, temperature, density, and composition might depend on r. The true solution may depend on the initial conditions.

The Gedanken Café

To illustrate the conundrum, let's assume you're sitting comfortably in the sun at a café and you're served an espresso. I like it sweet and, in any case, our gedanken experiment requires sugar. If you drop a sugar cube into the cup and let it dissolve, most of the sugar will stay at the bottom. If you stir the liquid gently (let's say for fear of spilling it on your laptop), only part of the sugar will mix with the coffee. You get a homogeneous system only if you stir vigorously enough.

An alternative method would be to drop finely granulated sugar instead of cubes into the coffee. If the sugar is fine enough, it will dissolve before reaching the bottom, and very little stirring is needed. But that's only if the espresso is hot enough. If it's only lukewarm, the sugar has a hard time dissolving; it tends to sink to the bottom. Finally, after all this preparation, let a friend arrive at the table and try to guess, from his first sip, how much sugar there is in the cup.

For giant planets, the problem is similar, only more complex. If the coffee itself is a good analog for the hydrogen, the sugar is replaced by a mixture of helium, water, methane, ammonia, neon, and many more chemical species, all of which behave differently. They could, for example, either be mixed with the hydrogen or sequestered in the deepest regions.

Part of the helium is believed to have fallen into the interiors of Jupiter and Saturn. Less of it is observed in their atmospheres than must have been present when the Solar System was formed. This sequestration is thought to be due to a phase separation between helium and hydrogen in which helium-rich droplets form and fall to deeper regions. Such phase separation should occur at high pressures and low temperatures. But neither laboratory experiments nor calculations have yet confirmed that it really does happen under conditions relevant to Jupiter and Saturn. Interestingly, the *Galileo* probe found a lower concentration of neon in the outer reaches of Jupiter than the Sun has. That's consistent with the prediction that neon should efficiently dissolve into the falling helium droplets.[12]

Other constituents, such as ices and silicates, may have been delivered to the forming planet very early on, as ingredients of a central solid core. They may have arrived in small pieces and mixed with the mostly hydrogen–helium envelope, or they may have come as large—say, Earth-sized—protoplanets. In the latter case, the materials would have penetrated deep into Jupiter.

To make matters even more complicated, any primordial central core might either have remained largely intact until now or, like the sugar cube in our espresso cup, it might have been eroded by convection. The spoon in the cup plays the role of convection in the giant planets. Depending on the vigor and depth of the convection, it either will or will not scoop core material up into higher precincts.

But independently of how you stirred the espresso, so long as it's been stirred even a little bit, you expect it to be fairly homogeneous. Only the last sip might be significantly sweeter, and there might be a residue of sugar left in the bottom of the cup. In the same way, we expect our giant planets, which are mostly convective, to be reasonably well-mixed. That simplifies the problem enormously. We have to consider only three principal layers. For Jupiter and Saturn, they are a central core and an envelope that is split into a helium-rich interior and a helium-poor outer shell (see figures 3 and 4.) For Uranus and Neptune, the two much smaller giants, it is less clear that this approach is valid. Nonetheless, astronomers often divide their interiors into a central rock core, a surrounding ice mantle, and an outermost hydrogen–helium envelope.

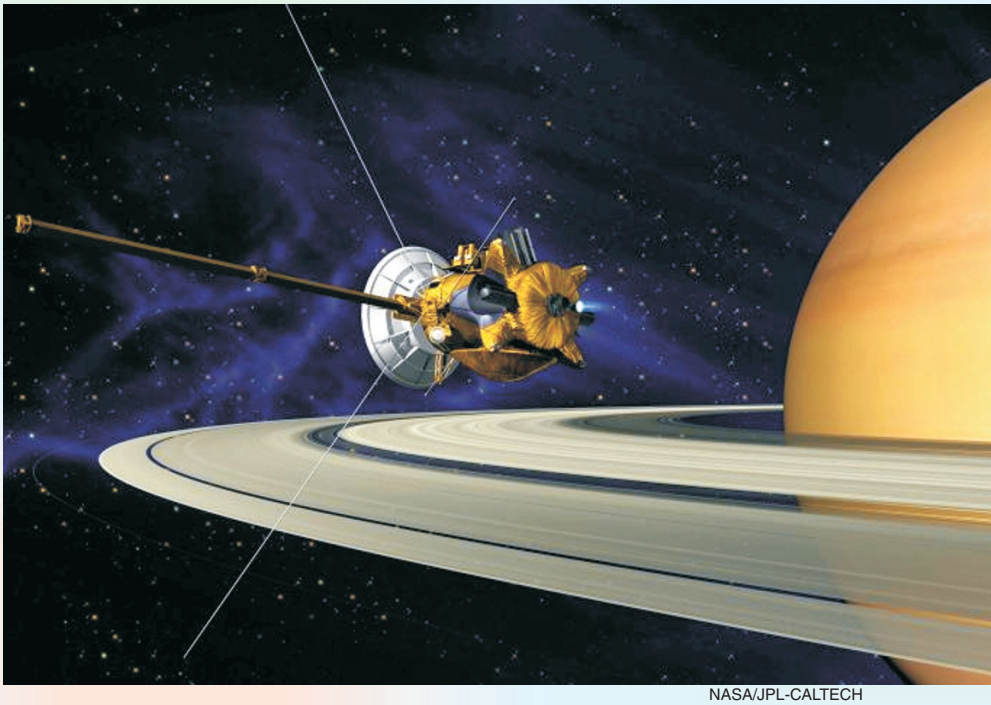
Models of the planetary interiors that match all the observational constraints conclude that Jupiter and Saturn consist mostly of hydrogen and helium. Saturn appears to require a dense central core of 10–25 Earth masses, while Jupiter's core has no more than 12 Earth masses.[13] Uranus and Neptune are quite different in structure from their larger cousins. While Jupiter and Saturn are called gas giants, the other two are really ice giants. Indeed, for more than 70% of their interiors, the density profile appears to be consistent with that of compressed water ice. Their outer precincts appear to be gas envelopes

Box 2. *Cassini* at Saturn

On 1 July 2004, Saturn will acquire a new satellite. The *Cassini* spacecraft will fire its engines for orbit insertion into the Saturnian system. For the next four years, it will study Saturn's moons, rings, and magnetosphere, and also the planet's intriguing meteorology. The spacecraft will remotely measure the composition of Saturn's atmosphere.

Cassini will also determine the gravity field much more accurately than has been done before. Gravitational moments at least up to J_8 should be determined with high precision, which would allow a much better determination of Saturn's internal structure. We should then begin to understand the planet's interior rotation. At present, we don't know whether Saturn's atmospheric winds are superficial or deep-rooted.

Early next year, *Cassini* will drop a probe, called *Huygens*, into the atmosphere of Titan, Saturn's largest moon. The *Cassini–Huygens* mission is an impressive example of a successful cooperation between NASA, the European Space Agency, and the Italian Space Agency.



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consisting mostly of a few Earth masses of hydrogen and helium.[14] The few measurements we have don't allow a more accurate estimate of the structures of Uranus and Neptune.

For Jupiter and Saturn, it is important also to consider their total content of heavy elements. Present models estimate the heavy-element component at 20–30 Earth masses for Saturn and 10–40 Earth masses for Jupiter. The uncertainty is significant. Most of it is due to our limited understanding of the behavior of hydrogen at ultrahigh pressures on the order of a megabar.

Shock compression experiments can now reach these high pressures in the laboratory. However, two sets of such experiments have yielded conflicting results.[15] The 1998 laser-induced shock experiments at Lawrence Livermore National Laboratory measured a maximum density compression of about a factor of 6 for hydrogen at 1 Mbar. The more recent experiment by Marcus Knudson and coworkers with magnetically accelerated plates at Sandia National Laboratories found a maximum compression of only about 4 at the same high pressure.

For Jupiter, the greater hydrogen compressibility implies a significantly smaller component of heavy elements. Hence the wide uncertainty range of 10–40 Earth masses. For Saturn, on the other hand, the total amounts of heavy elements appear to be more or less independent of hydrogen's equation of state at ultrahigh pressure. That's mostly because the pressures in Saturn's interior are smaller. Our hopes rest on the *Cassini* mission, which should allow a much better determination of Saturn's gravity field (see box 2).

Lessons and prospects

Our knowledge of the interior structure of the giant planets remains vague, which severely limits our progress in understanding how they formed. For example, one of the unexpected results from the *Galileo* probe is the presence of argon at three times the solar abundance inside Jupiter's atmosphere.[10] Argon is a noble gas that is expected to condense in the protosolar nebula only at very low temperature—no higher than 30 K. One therefore expects that the ratio of argon to hydrogen should be about the same in Jupiter and in the Sun. The unexpectedly large Jovian argon abundance indicates that some physical process led to the separation of argon and hydrogen during the planet's formation. That points to relatively low temperatures at the time of Jupiter's formation.

One possibility is that small ice grains grabbed some of the argon in the protosolar nebula (in a process called clathration) and that the grains were somehow efficiently brought into Jupiter.[16] This process would imply that water is abundant inside the planet. Unfortunately, present models of the Jovian interior are too uncertain to tell us whether clathration is the correct answer.

Future high-pressure laboratory experiments on deuterium compression and numerical calculations of the behavior of the hydrogen–helium mixture at the relevant pressures and temperatures will give us a clearer picture of the interiors of the giant planets. So will the *Cassini* satellite's precise determination of Saturn's gravitational moments. But we'll still be missing crucial pieces of the puzzle: the abundance of water in Jupiter and Saturn, and a precise knowledge of Jupiter's gravitational and magnetic fields. Uranus and Neptune will remain mysterious.

Jupiter is the next giant planet on the agenda. It is easier to reach than the other Solar System giants, and it's the one from which we can learn the most. How, specifically, should we proceed? One possibility, inspired by the *Galileo* mission, is to send several more probes into the atmosphere. They should be able to penetrate deeper than the *Galileo* probe—down to at least 100 bar. The *Galileo* probe taught us that Jupiter's atmosphere is complex. Although the new probes would provide unique local data, the measurements could be difficult to interpret without

prior knowledge of deep winds, meteorological structures, and so forth.

Therefore we must, first of all, learn more about the global structure of Jupiter's deep atmosphere. Using an orbiter that comes within 4000 km of the planet's cloud tops on a polar orbit, one can get very accurate measurements of the planet's gravitational and magnetic fields. The measurement of higher-order gravitational moments would reveal whether or not the zonal winds are rooted deep in the interior.[17] That issue is critical for understanding the meteorology and internal structure of rapidly rotating gaseous planets.

With a radiometer added to the spacecraft, one can measure variations in the deep atmosphere's temperature and its ammonia and water abundances as a function of latitude and longitude, down to pressures of a few hundred bar. Using meteorological and radiative-transfer models together with the most up-to-date laboratory measurements of molecular opacities at high temperature, one can then disentangle the different satellite data to determine constraints on the abundance of water. Thus equipped, the next generation of missions to the giant planets, probably including a few well-designed probes to be dropped into specific locations, should do much to unlock their secrets.

Giant planets, extrasolar as well as our solar system neighbors, retain most of the keys to understanding how planets form and evolve. Their exploration began with the *Pioneer*, *Voyager*, and *Galileo* missions. The scheduled *Cassini–Huygens* mission to Saturn promises great scientific returns. But the most significant void in the inventory of Solar System data is probably Jupiter's unknown composition. To understand how the Solar System formed and to acquire fundamental data that will be crucial for the following generation of astronomers, let the exploration continue!

References

1. M. Mayor, D. Queloz, *Nature* **378**, 355 (1996).
2. G. W. Marcy, R. P. Butler, *Annu. Rev. Astron. Astrophys.* **36**, 57 (1998); D. A. Fischer et al., *Astrophys. J.* **586**, 1394 (2003); C. Perrier et al., *Astron. Astrophys.*, **410**, 1039 (2003).
3. D. N. C. Lin, P. Bodenheimer, D. C. Richardson, *Nature* **380**, 606 (1996).
4. There are other transiting candidates, but they have yet to be confirmed. See M. Konacki et al., *Nature* **421**, 507 (2003).
5. D. Charbonneau, T. M. Brown, D. W. Latham, M. Mayor, *Astrophys. J. Lett.* **529**, L45 (2000); G. W. Henry, G. W. Marcy, R. P. Butler, S. S. Vogt, *Astrophys. J. Lett.* **529**, L41 (2000); T. Brown et al., *Astrophys. J.* **552**, 699 (2001).
6. T. Guillot et al., *Astrophys. J. Lett.* **460**, L993 (1996).
7. P. Bodenheimer, D. N. C. Lin, R. Mardling, *Astrophys. J.* **548**, 466 (2001); T. Guillot, A. P. Showman, *Astron. Astrophys.* **385**, 156 (2002); I. Baraffe et al., *Astron. Astrophys.* **402**, 701 (2003); A. Burrows, D. Sudarsky, W. B. Hubbard, *Astrophys. J.* **594**, 545 (2003).
8. D. Charbonneau et al., *Astrophys. J.* **568**, 377 (2002).
9. A. Vidal-Madjar et al., *Nature* **422**, 143 (2003).
10. T. Owen et al, *Nature* **402**, 269 (1999); S. K. Atreya et al., *Planet. Space Sci.* **51**, 105 (2003).
11. B. Mosser, J. P. Maillard, D. Mékarnia, *Icarus* **144**, 104 (2000).
12. See abstract, M. S. Roustlon, D. J. Stevenson *EOS Trans. Am. Geophys. Union* **76**, 343 (1995).
13. T. Guillot, *Science* **286**, 72 (1999); D. Saumon, T. Guillot, *Astrophys. J.* (in press).
14. M. Podolak, J. I. Podolak, M. S. Marley, *Planet. Space Sci.* **48**, 143 (2000).
15. G. W. Collins et al., *Science* **281**, 1178 (1998); M. D. Knudson et al., *Phys. Rev. Lett.* **90**, 035505 (2003).
16. D. Gautier, F. Hersant, O. Mousis, J. I. Lunine, *Astrophys. J.* **550**, 227 (2001).
17. W. B. Hubbard, *Icarus* **137**, 196 (1999). ■