The occurrence of Jovian planets and the habitability of planetary systems

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Planets of mass comparable to or larger than Jupiter's have been detected around over 50 stars, and for one such object a definitive test of its nature as a gas giant has been accomplished with data from an observed planetary transit. By virtue of their strong gravitational pull, giant planets define the dynamical and collisional environment within which terrestrial planets form. In our solar system, the position and timing of the formation of Jupiter determined the amount and source of the volatiles from which Earth's oceans and the source elements for life were derived. This paper reviews and brings together diverse observational and modeling results to infer the frequency and distribution of giant planets around solar-type stars and to assess implications for the habitability of terrestrial planets.

The past 5 years have seen the field of extrasolar giant planets mature from one in which the principal question to be addressed was, "Do planets exist around other stars?" to one in which comparative planetology and cosmogony could be conducted on multiple systems. More than 2 years passed after the discovery of the first extrasolar planet, 51 Peg B (1), before the debate was settled over whether a planet or stellar pulsations were responsible for the oscillating Doppler shift that is the telltale signature of the radial velocity technique (2). Today the situation is vastly different. Over 50 nearby stars, all roughly similar in spectral type to the Sun, have companions detected by radial velocity (3), at least one system has multiple planets (4), and one planet (HD209458b) can be directly detected as it transits its parent star (5). These data have enabled meaningful statistics to be accumulated on the frequency of planets around solar-type stars[†] (4), as well as allowed modeling to reveal the bulk density and early history of one planet (6).

The most striking, and oft-quoted, characteristic of the extrasolar planet menagerie is the preponderance of Jovian-mass[‡] planets at small orbital distances from their parent stars. Although the apparent statistical overrepresentation of such tight orbits in the observed cohort of planets is biased by the fact that Doppler spectroscopy is most sensitive to smaller orbital semimajor axes (9), the mere existence of such objects forces a paradigm shift in our expectations regarding planetary system architectures. Leaving aside just for the moment the issue of whether giant planets could form in place at small orbital distances or must migrate inward, the presence of giant planets scattered uniformly from 0.04 astronomical units (AU) through 3 AU has enormous implications for the frequency of habitable Earth-like planets in the galaxy. What fraction of solar-type stars might be precluded from having Earth-like planets through occupation of the habitable zone by giant planets? Do the processes of giant planet formation and dynamical evolution generally suppress or encourage the production of habitable planets, in terms of planetary growth, supply of volatiles and organic material to the habitable zone, and long-term collision rates of planetesimal debris with habitable planets?

In this paper, I review and extend existing models and their foundational observations that constrain the frequency of formation of giant planets around solar-type stars, as well as the rough distribution of their orbits and their effect on the incidence of terrestrial planets. I also show how modeling of the origin of Earth's oceans through dynamical scattering of planetesimals allows some constraints on equivalent scenarios of delivery of water and other volatiles to extrasolar terrestrial planets.

My intention here is to focus on giant planets themselves and to provide a guide to and extension of the literature on their nature, abundance, and quantitative effects on other components of planetary systems. Other recent work of related interest concerns planetary system habitability in terms of a key indicator such as the carbon-to-oxygen ratio (10), the specific orbital positions of terrestrial planets around stars (11), or moons around giant planets (12). General discussions about the formation and habitability of terrestrial planets have appeared recently in the scientific (13) and popular literature (14).

HD209458 b and the Reality of Extrasolar Giant Planets

The detection of planetary mass bodies through Doppler spectroscopy yields no information about these objects except for the orbital semimajor axis and eccentricity and a lower limit to the planetary mass. In fact, because all that is measured is the radial component of the reflex motion of the star, the planet itself is not directly detected (9). We have no information about the size of the planet, hence no way to gauge its bulk density and thus composition. Without other types of data, we must assume that a Jovian-mass object is like Jupiter in size and composition. Because hydrogen and helium are the most abundant elements in the cosmos, this is not an unreasonable assumption, but it is nonetheless an assumption.

A breakthrough that revealed the nature of one Jovian-mass extrasolar planet came in the successful observation of a planetary transit across the disk of a star. The system, HD209458, consists of a star roughly the age of the Sun and just slightly more massive, along with a planetary companion at least 0.7 times the mass of Jupiter, orbiting just 0.047 AU from the parent (15). The transit observation consists of observing the dimming of the light

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Abbreviations: AU, astronomical unit; D/H, deuterium-to-hydrogen ratio; SMOW, Standard Mean Ocean Water.

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[†] "Solar-type" stars are considered here to be F-, G-, and K-type stars, on which the Doppler spectroscopic search for planetary companions is focused. The Sun itself is a G-type star, so designated in a well-characterized sequence based on spectral classification, so my use of the term "solar-type" is a loose one.

[‡] There is no standardized nomenclature in this field. In this paper, the term "Jovian mass" does not denote an object of exactly one Jupiter mass, but rather one that ranges from 0.1–13 Jupiter masses. The upper mass is the minimum mass for deuterium fusion in solar-composition objects (7), a convenient and perhaps not entirely arbitrary (8) cutoff for planets. The term "giant planets" used earlier in the text is defined here to refer specifically to bodies in the mass range given above that are primarily hydrogen–helium, with a greater or lesser admixture of heavier elements. Such objects implicitly are like our own giant planets in rough composition. There is only one extrasolar planet that we can assign with confidence to be a "giant planet," because we know its radius, hence bulk density and composition. In our own system, Uranus and Neptune barely qualify, because they are so rich in heavy elements; some planetologists call them "ice giants" to distinguish them from Jupiter and Saturn.

from the star by about 1% as the nonluminous planet crosses the disk. Because the orbital radius of the planetary companion is known, and the star's radius is determined fairly reliably from stellar evolution theory, the dimming can be geometrically related to the physical size of the planet. The decrease in light as the planet blocks part of the stellar disk is best fitted by a planet with radius between 1.25 and 1.55 that of Jupiter, on the basis of data from two ground-based telescopes and a set of Hubble Space Telescope observations of the transit (5, 15).

That transits occur in this system immediately sets a tight constraint on the orbital inclination of the planet–star system as seen from Earth: the orbit plane of the planet must be roughly along the line of sight to Earth. Because very slight departures from coplanarity of the planet's orbit with the Earth line of sight affect which part of the stellar disk is transited, the timing of the transit allows a numerical value to be put on the orbit inclination. For HD209458, it is within 3° of being coplanar with the line to Earth. Thus the minimum mass derived from the radial velocity studies for HD209458 b, 0.7 Jupiter masses, is in fact the physical mass; then combining the mass with the radius, one finds the planet's bulk density to be between 0.3–0.5 g/cm^3, half that of Jupiter or Saturn. The derived radius of HD209458 b immediately rules out a rocky planet, which would have a far smaller radius for the determined mass of 0.7 Jupiter masses (16). The planet must be primarily hydrogen, with presumably an admixture of helium and heavier elements. But why is the planet so large compared with Jupiter?

The facile answer, which seems intuitive, is that the proximity to the parent star caused HD209458 b to expand. There is, however, an important subtlety here that is key to understanding the early history of the body. The expansion cannot be a superficial effect of the outer atmosphere. Why? The scale height of the atmosphere—kT/mg, where k is Boltzmann's constant, T is atmospheric temperature, m is atmospheric molecular mass, and g is gravity—is about 400 km (for an effective temperature of about 1,200 K and molecular hydrogen–helium composition). This scale height is less than 1% of the radius of the planet. Hence, even though the scale height is about 20 times that in Jupiter's much colder atmosphere, it is not large enough to be implicated in a swelling of the planet by a factor of 1.4 relative to Jupiter.

What is in fact happening is that the prodigious stellar flux retards the cooling of the planetary interior. Formation of a massive self-gravitating object from the collapse of spatially dispersed gas and dust must, by simple application of the virial theorem, lead to an initially hot distended object, which then cools and contracts as thermal energy is removed from the interior (17). Detailed theoretical models of the cooling and shrinking of giant planets over time provide a satisfactory fit to the details of the giant planets of our own solar system (18). These models show that isolated giant planets (not affected by irradiation from the parent star) cool quickly. It takes less than 1 million years for such an object to drop below 2 Jupiter radii (6).

Strong stellar irradiation, which giant planets on close orbits such as HD209458 b receive, flattens the atmospheric temperature profile. In consequence, the rate at which heat can be transported outward from the deep interior is reduced, and contraction of the planet with time is retarded. Assuming that HD209458 b was born in place at 0.046 AU from the star, detailed models of these effects (6) yield excellent agreement with the planet's radius at its current age of 4–7 billion years (the age being derived from the properties of the star and stellar evolution theory). But more importantly, one cannot arrive at such an expanded radius for the companion if it moved inward to its present orbit later than a few tens of millions of years after formation. It can be shown that it would then take longer than the age of the universe for external heat to diffuse in to the interior and expand the planet to its observed size (6).

It is remarkable that, from basic information about an extrasolar planet derived from transit and radial velocity data, we can constrain aspects of its history. We now know that HD209458 b is a hydrogen-rich gas giant like Jupiter. We know that it either formed in place at 0.046 AU or it moved in to its present orbit within the first tens of millions of years after formation. This migration, in turn, does not preclude terrestrial planets on Earth-like orbits in that system, because HD209458 b could have been in place early enough not to disrupt terrestrial planet formation on reasonable timescales (19).

The Frequency of Giant Planets Around Solar-Type Stars

Searches for extrasolar planetary companions to mature F-, G-, and K-type stars to date have yielded an occurrence of Jovian-mass companions of approximately 4% (4). Because other search techniques have either failed to definitively detect planetary-mass candidates (astrometry) or have not covered enough objects in a constrained volume of space to enable statistics to be accumulated (photometric transits, microlensing), this figure is the only statistically significant determination of planetary frequency.

There are two reasons, however, why the 4% number is probably not the actual frequency of extrasolar giant planets. First, the planetary mass determined by Doppler spectroscopy is a minimum mass, because only the velocity component of planet's orbit along the line of sight to Earth produces a Doppler shift. However, this is likely a small effect, because for a random distribution of planetary orbital inclinations to our line of site, the vast majority of detected objects should have masses within a factor of two of the Doppler spectroscopic mass (4). Second, the occurrence of planets beyond several AU around surveyed stars is effectively unknown, because the Doppler spectroscopic technique declines in sensitivity as planetary orbital semimajor axis increases. Therefore, in principle there could be a large number of giant planets around nearby stars in orbits equivalent to those of Jupiter or Saturn around our Sun still awaiting detection. Indeed, the process of giant planet formation hints at the possibility that the detected cohort of close-in giant planets may be derived from an initial population of more distant bodies. The remainder of the present section is devoted to a brief examination of this hypothesis.

It is generally agreed that the formation of giant planets occurs in disks of gas and dust spun out around newly forming stars. Disks are a product of the conservation of angular momentum during the collapse of a portion of the star-forming molecular cloud. They may range in mass during the planet-forming stage around a solar-type star from 0.001–0.3 solar masses, the lower limit driven by the mass required to form giant planets, the upper by fragmentation in more massive disks leading to multiple star formation (20, 21). Instabilities can be triggered in the gas either locally or by global processes in the disk, leading to direct collapse of the gas to form a giant planet (22). Alternatively, the collapse of the gas can be seeded by first forming a core accreted from solid materials. The core then attracts mostly gas but additional solids as well (23).

No compelling models have been offered by which giant planets form in place some 0.05 AU from their parent stars, either by nucleated accretion or by direct collapse. Various proposed mechanisms for formation of giant planets in close proximity to the parent star require a very large mass density of solids (difficult to sustain very close to a growing star) and some *ad hoc* assumptions regarding how a core might grow in such an environment (23). On the other hand, the extended radius of the transit planet HD209458 b requires that it be in place in its 0.05 AU orbit within tens of millions of years after formation (6). If the problems with *in situ* formation of close-in giant planets are

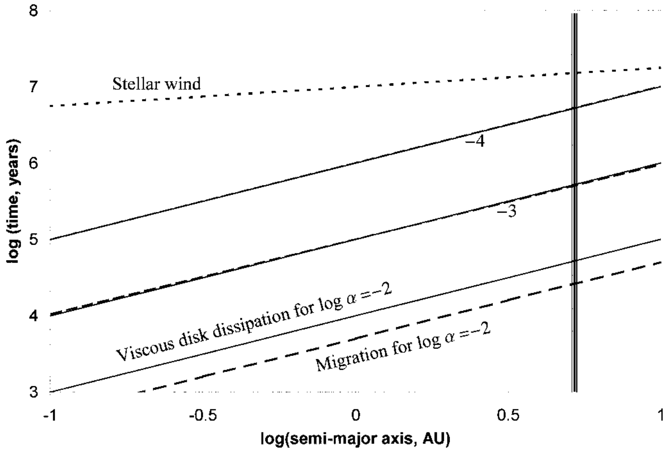

Fig. 1. Logarithm of the timescale versus logarithm of the semimajor axis for viscous dissipation of a gaseous disk, stellar wind dissipation of the disk, and migration of a one-Jupiter mass object. The migration model used is that of Ward *et al.* (28), and the viscous dissipation that of Hollenbach *et al.* (30). The turbulence parameter α is the dynamic viscosity divided by the product of the disk sound speed and vertical scale height. For small-to-moderate values of α, the timescales for both migration and disk dissipation are formally identical and depend only on the location of the orbit, the sound speed, and the turbulence parameter for the disk surrounding this solar mass star. For a highly turbulent disk ($\alpha = 10^{-2}$), other effects come into the migration to decrease its timescale relative to overall disk dissipation. Note that the dynamic timescales plotted here imply that the time available to make a Jupiter at 5 AU (heavy vertical line) is no more than a few million years for a quiescent disk and less than 10^4 years for a very turbulent disk.

physically real, then the case of HD209458 b argues for prompt inward evolution of giant planets—rapid migration—from more distant orbits where formation occurred to the orbits in which we observe them today.

There are three distinct environments within which giant planets might migrate. During formation, giant planets can interact gravitationally with and transfer angular momentum to the gaseous disk such that rapid inward evolution of their orbits takes place (24). After formation, giant planets gravitationally scatter icy and rocky debris; if this material is abundant, the angular momentum exchange produces significant inward orbital migration (25). Finally, giant planets can undergo mutual gravitational interactions, resulting in modification of orbits, ejection (26), and even merging to make larger planets (27). Migration through the gaseous disk arguably occurs before the other mechanisms because the gaseous disk is the earliest and most massive structure to form during planet growth. Giant planets can migrate rapidly enough to be consumed by the central star as the orbit reaches the point of Roche lobe overflow within a few stellar radii on timescales of 10^6 years or less (28, 29).

The existence of giant planets in extreme proximity to solar-type stars suggests ways of slowing or stopping the migration of some planets before they are consumed by the central star. Various mechanisms have been offered, and particularly intriguing is that the gaseous disk might be truncated late in its evolution on its inner edge by a magnetic cavity around the central star (24), which could act to slow or halt migration. Alternatively, the dissipation, or clearing out, of the disk toward the end of its lifetime might strand migrating planets at a range of semimajor axes (Fig. 1). In either case, the cohort of giant planets observed by Doppler spectroscopy must be a remnant of a larger population, some of which remain in larger undetected orbits, whereas others have been destroyed. To infer the original population of giant planets from that detected today requires an explicit model of migration and its termination.

Trilling *et al.* (31) constructed such a model, placing Jupiters with a range of masses at or beyond 5 AU and allowing them to migrate through disks with varying lifetimes, masses, and levels of turbulence (which affect migration times). For simplicity, they assumed no special stopping mechanism except dissipation of the disk itself. The result of their study was that, to match the observed incidence of giant planets as seen by Doppler spectroscopic studies, roughly 10% of solar-type stars must possess giant planets today, but most are in orbits with semimajor axes beyond the reach of Doppler spectroscopic studies. Further, they conclude that most giant planets formed are lost to consumption by the parent star during the gaseous disk phase, and hence giant planet formation must be a common phenomenon among solar-type stars to account for the statistical occurrence of planets. Of course, variants of the model can be envisioned that would decrease or increase the mortality of young giant planets. Adding stopping mechanisms at the inner edge of the disk, for example, would reduce the loss rate. Including migration of giant planet cores during formation (28) as well as later migration of planets in particulate disks and by multiplanet interactions would have the opposite effect. Ultimately, completing the observational census of giant planets in all possible orbits around solar-type stars would allow the problem to be inverted, placing constraints on what happens to giant planets (and by implication, terrestrial planets) during formation.

Does observational evidence exist supporting the notion that stars sometimes do consume young giant planets? Some solar-type stars show an enrichment of metals (defined in astronomical parlance simply as all elements heavier than helium) in their atmospheres. It is commonly accepted that the Sun's observed complement of metals is close to, but slightly enriched, relative to the average value for nearby G-type stars (32, 33). There is a statistically significant relationship between stars with enhanced metallicity in their observable atmospheres and the occurrence of planets around those stars. Giant planets, which during formation tend to build up high metallicity associated with their sweep up of large amounts of solid material, are a potential source of stellar enrichment.

The stellar interior consists of an inner region in which radiative transport of photons carries the energy of thermonuclear fusion outward, without turbulent mixing. Atop this zone is a region of turbulent mixing—the stellar convection zone—which ranges from 30% of the Sun's volume to 100% of the volume of the very lowest mass stars (34). Because of the steeply decreasing density of the interior as one approaches the surface, the Sun's convection zone is of order only a percent of the total mass of the star. The significance of a convection zone of restricted extent is that limited mixing of material occurs through and below the base of the zone. Therefore, material of different composition—e.g., higher metallically—injected into the zone will tend to remain there and have an effect on the *observed* composition well out of proportion to its contribution in terms of the total mass of the Sun. The same applies for other solar-type stars.

Fig. 2 shows the enrichment in metallicity in a star of one solar mass, as a function of the mass fraction of the star in the well-mixed layer. I calculate the enrichment for four cases, corresponding to the introduction into the star of 1, 5, 10, and 15 Jupiter mass planets, respectively. From mapping Jupiter's gravitational field and modeling its interior, we know that it contains perhaps 15–30 Earth masses of heavy elements (18). That is an enrichment of 5–10 relative to solar and clear evidence for the significance of core and planetesimal accretion. However, we do not know well the relative enrichment among the various

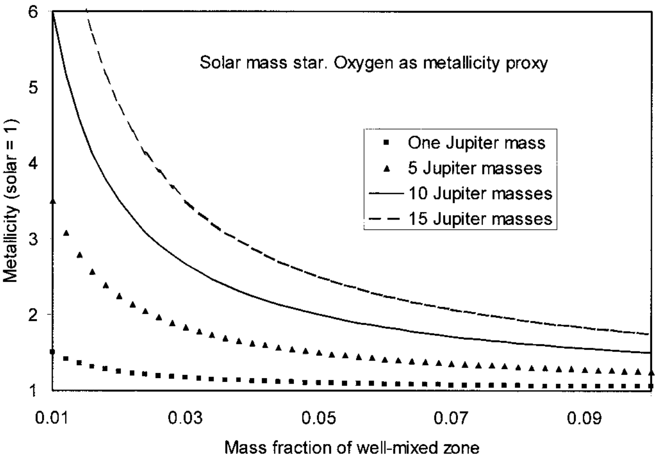

Fig. 2. Metallicity enrichment in a one-solar-mass star versus the thickness of its well-mixed zone, expressed as mass fraction of the star. The lines are labeled with the number of Jupiter masses deposited in the star through planet migration. The metallicity enrichment is expressed through oxygen abundance; oxygen is assumed to be five times solar in the giant planets.

different elements, except for the lightest elements carbon, nitrogen, oxygen, and the noble gases (35, 36). This is a problem for comparison with stellar metallicity in which iron is the standard—and for which we know nothing for Jupiter apart from the bulk metallicity. The major heavy element—oxygen—is enriched in Jupiter by a factor of 2–10 times solar. We take a value of five times solar for oxygen, and we use it as the proxy for metallicity in Fig. 2. The results seem consistent with the detailed numerical modeling of Sandquist *et al.* (37).

I have shown in Fig. 2 a range of masses for the mixing zone much larger than expected for F-, G-, and K-type stars to emphasize an important caveat. During the formation of stars, when planets are migrating, the zone of mixing may be much deeper. Indeed, I deliberately do not call it the convection zone, because several processes may lead to mixing of planetary material well below the traditionally regarded convection zone. This includes penetration by the planetary core (37), temporary increases in accretion rate onto the star forcing advective mixing, and transient changes in stellar structure during accretion. Although these are difficult to quantify in a uniquely defined historical model of a particular star–planet system, it is important to recognize that there may not be a direct one-to-one correlation between the metallicity of a star today and the number of companions it swallowed. For this reason, the very modest enrichment of heavy elements in the Sun relative to the average for stars of comparable vintage in the galactic neighborhood need not necessarily imply that the Sun consumed few or no giant planets during the formation of our own planetary system.

The Effect of Giant Planets on the Formation and Volatile Inventory of Terrestrial Planets

In this section, I discuss how the presence of Jupiter and Saturn, but especially the former, has profoundly shaped the volatile inventory of Earth. The conclusion of this section is that the spatial location and mass distribution of giant planets will predetermine the existence and habitability of terrestrial planets. I define terrestrial planets as those bodies made primarily of rock (including metals, such as iron–nickel), with solid surfaces capable of holding volatiles in liquid and gaseous (as well as solid) form. The possible variations on the theme of terrestrial planets have been thoroughly discussed elsewhere (38), as has the complexity of physical processes leading to continuous habitability of Earth through time (39).

Although dynamical simulations of terrestrial planet formation have appeared previously in the literature (40), little effort has been made to look at the stability of terrestrial planets in systems with giant planet configurations other than our own and specifically at orbital configurations like those in observed systems. Very recently, J. Chambers[§] simulated the orbital evolution of planetesimals and planetary embryos (larger aggregations approaching the size of the terrestrial planets) for a broad spectrum of giant planet orbits. He concludes that terrestrial planets could form and exist stably at 1 AU in the presence of Jovian-mass planets in circular orbits as tight as 3 AU or with masses several times that of Jupiter (but residing again at 5 AU).

Giant planets on eccentric orbits, on the other hand, make terrestrial planet formation more difficult by increasing the eccentricities of the orbits of the planetesimals themselves. However, Chambers points to systems with detected giant planets on moderate-period eccentric orbits, 14 Herculis and Epsilon Eridani, as being potentially habitable. Both the stars in this case are K-2 dwarfs with luminosities nearly three times less than the Sun's. For those systems, the habitable zone (where liquid water is stable) resides closer to the star than for our Sun, and it turns out that the inner edge of these compact habitable zones is dynamically stable against perturbations by the giant planets in both systems. The possible existence of these stable habitable zones illustrates the complexity involved in drawing conclusions about the potential for habitability of terrestrial planets in systems with diverse architectures.

It is possible that the first Earth-sized planet we detect and study around another star, perhaps with a facility like *Darwin* or *Terrestrial Planet Finder* (41), will have no atmosphere or no atmospheric water vapor (and, by inference, no surface water) at all. There are strong (but not fully conclusive) arguments that Earth's oceanic and crustal water budget was not derived locally, i.e., from planetesimals formed at 1 AU. The principal such argument is compositional: the water content of asteroids in the main belt appears to decline with decreasing semimajor axis, from the carbonaceous chondrites (10% by mass) to the enstatite chondrites (as low as 0.05% in mass). Because Earth formed inward of the asteroid belt, and temperatures in planet-forming disks rather generally must increase with decreasing semimajor axis, the planetesimals at 1 AU could have been dry. Other arguments pro and con have been offered (42), but there is some consensus that our volatile budget reflects significant contributions from distal orbits.

The strongest constraint on the source material of Earth's crustal water comes from the oceanic deuterium-to-hydrogen ratio (D/H). Here one must distinguish between crustal water and deep mantle water, because there is disagreement whether the deep reservoir has a different D/H value or even exists (42). The oceanic [Standard Mean Ocean Water (SMOW)] D/H ratio, 150 parts per million, is 5 to 6 times the solar system's primordial value measured in Jupiter (43). The SMOW value is also a factor of 2 to 3 times lower than that obtained for D/H in water in three long-period comets, all of which come from the Oort Cloud (44), thus ruling out Oort Cloud comets as the sole or even principal source of Earth's ocean water (44). Chondritic meteorites, while exhibiting large variations in D/H in hydrated minerals, on average have D/H close to SMOW. Because carbonaceous parent bodies are generally thought to reside in the asteroid belt, it is compelling to consider whether most of Earth's water came from the

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[§] American Astronomical Society Division for Planetary Sciences Meeting 2000, Pasadena, Talk no. 31.02.

primordial asteroid belt. Models addressing this hypothesis must account for both the total mass of crustal water, which is perhaps several times the mass of the ocean itself, and the SMOW value of D/H.

A very recent model for the origin of Earth's oceans provides a mechanism for deriving Earth's water budget from the asteroid belt (19). The model, unlike previous ones, quantifies in a chronological fashion the supply of terrestrial water from multiple sources that wax and wane in importance at different times keyed to the gravitational scattering of planetesimals by Jupiter and Saturn. Because it tracks the accretion of the terrestrial planets as well as the scattering of planetesimals, the model predicts when, during Earth accretion, different sources of water become available. Before the time that the Earth reached half its present mass, icy bodies from the Jupiter–Saturn region as well as small bodies from the primordial asteroid belt supplied water to the Earth. This water would have been trapped deep in the planet as well as lost through subsequent very large impacts.

Late in the accretional history of Earth, the dynamical environment of the primordial asteroid belt as shaped by Jupiter evolved to the point where large planetary embryos existed there. These embryos, by virtue of being built from objects in the 2–4 AU region, were rich in water with D/H of the carbonaceous chondrites. The presence of Jupiter pumped up the eccentricities of the embryo orbits so that they crossed the orbit of the growing Earth. The model predicts high collision probabilities between Earth and embryos originally on distal orbits, so that as much as 10 times the current oceanic inventory of water could have been delivered to Earth with appropriate D/H (19). Finally, after accretion of the Earth was complete, a late infall of icy material, essentially comets scattered from the Uranus–Neptune region and the Kuiper Belt, impacted Earth to contribute no more than 10% of Earth's water. This "late veneer," previously proposed (45) to be the source of most of Earth's water (46), cannot be a primary source according to the dynamical calculations. Although we do not know the D/H for Kuiper Belt comets, it plausibly is no less than that of Oort Cloud comets, having been derived from outer solar system material little processed from the nascent molecular cloud. The very small contribution of comets to Earth's oceans derived from the dynamical calculations is fully consistent with the relative D/H values for comets versus SMOW.

From the point of view of the present survey, the details of the story for Earth in particular are not important. Indeed in the study described above, assumptions were made about the length of time over which Jupiter formed; different assumptions might lead to different outcomes in terms of water abundance and timing of delivery to Earth (19). The key point is a general one: the timing of delivery and amounts of volatiles delivered depend on the masses, orbital configurations, and timing of formation of the giant planets in a given system. The complexity of the story implies that it is difficult to extrapolate from one case study to another without running a full numerical simulation. However, some general inferences can be made (sketched in Fig. 3). Define the "snowline" of the protoplanetary disk as the orbital distance beyond which water ice is stable and modestly inward of which water can exist in hydrated minerals. The presence of Jupiter near the snowline of our protoplanetary disk was crucial to pumping up the orbital eccentricities of relatively proximal hydrated ("wet") embryos in the primordial asteroid belt, making them potentially available to deliver large amounts of water to Earth.

In systems that lack a large giant planet at or near the snowline, pumping of orbital eccentricities among wet embryos was limited to mutual gravitational interactions among them. Numerical simulations suggest this is not sufficient to create embryo orbits that would cross the orbits of terrestrial planets in the habitable (liquid water) zone (47). Conversely, in a system where a giant planet formed inward of the snowline, terrestrial planets should be relatively bereft of water, because wet embryos would be scattered outward very efficiently by the forming giant planet. On terrestrial planets in such systems, some amount of water will be available from distant comets but not much, given the difficulty of scattering the latter inward. The extrapolations given above depend, of course, on the assumption that giant planets form before terrestrial planets. Indeed, there is no reason why a terrestrial planet cannot form quickly during the time the gaseous disk is still present, but migration of such planets inward to the parent star could be quite rapid (28).

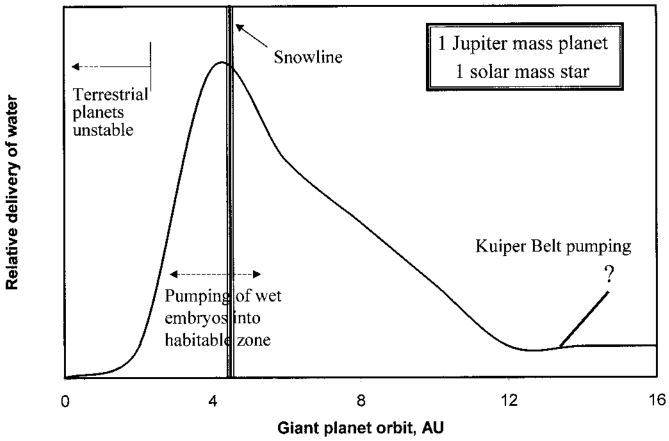

Fig. 3. Conceptual dependence of the supply of water to a terrestrial planet in the habitable zone for a system with a Jupiter-mass giant planet. The curve is drawn under the assumption that the solar system's configuration, with Jupiter near 5 AU, is close to the peak efficiency of delivery of water from hydrated ("wet") embryos in a primordial asteroid belt. The snowline is drawn in between 4 and 5 AU, but this is approximate. For a Jupiter with orbital semimajor axis of 3 AU or smaller around a solar-mass star, terrestrial planets in the habitable zone may not be stable,§ so water accreted is set to zero inward of that point. For a Jupiter at large semimajor axes, large numbers of icy planetesimals might get perturbed inward to collide with terrestrial planets (question mark on figure).

The main point, that the water budget delivered to the habitable zone depends sensitively on the existence and properties of giant planets, can be extended to other volatiles as well, including organics. However, there is a potentially interesting twist: the organic and volatile content of solid bodies is a sensitive function of temperature and other conditions of formation. Although most of Earth's water may have come from asteroids, it is possible in principle that most of the organic molecules came instead from comets (48). Therefore the composite-volatile picture of a habitable terrestrial planet—water plus life-forming elements and monomers—will be an even more complex function of the distribution and properties of neighboring giant planets.

Future Prospects

Prospects for the future study of extrasolar giant planets seem bright. Transit searches from ground and space will allow characterization of the properties of a fraction of the planets detected by Doppler spectroscopy. Astrometry from interferometers on the ground and in space will fill in the statistics of the occurrence of giant planets in orbits extending to 5 AU or so, for planets down to 10 Earth masses (49). Direct imaging searches implemented on 8-meter or larger telescopes and culminating in spaceborne imaging interferometers (41), will allow giant planets in orbits beyond 5 AU around nearby stars to be detected and atmospheric properties studied through spectroscopy. Microlensing surveys are capable of mapping the mass distribution of planets around stars in distant regions of the observable galaxy (but without detailed study of individual planets) (50). Space does not permit a more detailed analysis of the outcome of such future studies. However, the ability to search for and characterize giant planets by a variety of techniques certainly bodes well for a time, perhaps two decades hence, when we will thoroughly understand the frequency, nature, and dynamical effects on terrestrial planets of giant planets around other stars.

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