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Jupiter's Interior as Revealed by Juno

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Abstract

Jupiter is in the class of planets that we call gas giants, not because they consist of gas but because they were primarily made from hydrogen-helium gas, which upon gravitational compression becomes a metallic fluid. Juno, in orbit about Jupiter since 2016, has changed our view: The gravity data are much improved, and the simplest interpretation of the higher order even harmonics implies that the planet may have a diluted central concentration of heavy elements. Jupiter has strong winds extending to perhaps ~3,000-km depth that are evident in the odd zonal harmonics of the gravity field. Jupiter's distinctive magnetic field displays some limited local structure, most notably the Great Blue Spot (a region of downward flux near the equator), and some evidence for secular variation, possibly arising from the winds. However, Juno is ongoing; it has not answered all questions and has posed new ones.

- Juno's mission reveals Jupiter's interior.
- A core exists but is diluted by hydrogen.
- The mission revealed wind depth and magnetic field.

1. INTRODUCTION

Jupiter is the most massive planet in our Solar System and may well have played a key role in determining the architecture of our planetary system and the delivery of water to Earth (e.g., Raymond & Izidoro 2017). Current evidence from exoplanets suggests that these are not the most common kinds of planets in the universe, but they are common and likely to be key in understanding the planet formation process (see **http://exoplanet.eu/**). In 2016, NASA placed a spacecraft called Juno in orbit about Jupiter (Bolton et al. 2017, 2019). Unlike earlier missions that flew by the planet or orbited the planet, this spacecraft was designed in large part to focus on the most important questions about Jupiter's interior structure. Does Jupiter have a core (defined to be a central concentration of heavy elements, not necessarily solid)? How are the constituents distributed within the planet? What is the nature of Jupiter's magnetic field? And, very importantly, what is the water abundance within Jupiter? Juno attempted to answer these questions and others to shed light on how Jupiter formed and evolved and thereby constrained the formation and early evolution of our Solar System. The mission has been a success, but it is ongoing, so not all the questions can be answered yet and many answers are partial.

Juno has an orbit that brings it close to the planet's atmosphere every 53 days; this orbital period is about four times longer than originally intended, and the timetable for the mission has accordingly expanded. The intent of this review is to explain why the questions are important, how we go about tackling them, and the progress that has been made in answering them. It is often true in science that when we seek answers, we find more questions, and Juno has been no exception. In major part, the success of the mission can be defined in terms of the surprises it provided.

I structure this review as follows. First, I provide a historical context and an introductory-level explanation of those aspects of Jupiter that are readily understood even without spacecraft data. Second, I explain the questions we wish to answer and the approach to seeking their answers. Third, I describe the key results for the three most important scientific investigations on Juno: the gravity field, the magnetic field, and the microwave radiometer (MWR). I also provide an overview of how Jupiter and Saturn compare, motivated by the contemporaneous Cassini results, and offer some suggestions on how we might progress in future decades.

This review is not the right place to find a detailed description of how interior models are constructed or how material properties (equations of state) are formulated, but the reader is pointed to places for those things.

2. HISTORICAL PERSPECTIVE

2.1. Early Days

The pioneering paper on the internal structure of giant planets was Jeffreys (1924). This paper highlights three central ideas in thinking about these bodies, ideas that still persist as guiding principles: constraints from gravity, thermodynamics of possible constituents, and energy balance. Jeffreys begins by making use of the data then available for the precession of the orbits of Jovian satellites. When a satellite moves in a $1/r$ gravitational potential, the orbits are closed (and expressed by Kepler's laws). But when the central body rotates, it is distorted from a sphere and this leads to a quadrupole moment and a contribution to the gravity potential that scales as $1/r^3$. The orbits are no longer closed if they are eccentric, and we can describe them by a precession (that is, a rotation) of that ellipse. From this, we can estimate the moment of inertia of the body, using the classic results obtained by Radau (1885) and Darwin (1899). Jeffreys thereby obtains for Jupiter a polar moment of inertia of

$$C = 0.264Ma^2, \quad 1.$$

where M is the mass and a is the equatorial radius. Remarkably, our current best estimate differs only slightly in the third decimal place. Recall that the coefficient in that equation is 0.4 for a uniform density body and about 0.33 for Earth. Together with the known mean density, this constituted a powerful constraint on the nature of Jupiter. But of course any further analysis requires an understanding of material properties since the self-gravity of Jupiter ensures very high internal pressures. Although Jeffreys inferred that the outer region of Jupiter must be hydrogen, he was unable to progress further through lack of knowledge at that time about the behavior of materials with pressure. He also lacked adequate data to assess the energy balance and thermal state.

Following the quantum mechanical evolution of the 1920s, it became possible to assess the behavior of materials under compression. A key idea was proposed by Wigner & Huntington (1935): Hydrogen undergoes transition to a metallic state (a lattice of protons in a sea of degenerate electrons) at high pressure. They determined that such a state could arise at a pressure as low as 0.25 megabars but acknowledged that the actual required pressure might be much higher. From hydrostatic equilibrium, a typical internal pressure of Jupiter is

$$P_{\text{int}} \sim \frac{GM^2}{4\pi R^4} \sim 10 \text{ megabars}, \qquad 2.$$

where G is Newton's gravitational constant and R is the mean radius. This is well in excess of estimates for metallization (Dias & Silvera 2017). The idea of a metallic state is not a speculation—it arises naturally from well-understood principles of condensed matter physics. It is also not contingent on the idea of a lattice—the key idea is the degenerate sea of electrons, not the disposition of the protons, which form a fluid within Jupiter. No knowledgeable worker contests the existence of this state, and there are no substantial uncertainties in the pressure-density relationship. The uncertainties that are of greatest concern are in the transition to this state. It is accordingly not surprising that an early major modeling effort (Demarcus 1958) was able to do moderately well in describing the internal structure of Jupiter; indeed, he got a central core of heavy elements ~10 Earth masses, although this was as much to ease the computation (avoid a central singularity) as it was physically motivated (D.J. Stevenson, personal communication). However, Demarcus did assume that the helium abundance would vary with radius, based on the erroneous notion that heavier elements naturally migrate toward the center. In fact, diffusive settling driven by molecular weight differences takes longer than the age of the Universe for Jupiter's gravity and radius (even without consideration of homogenization by convection).

2.2. The Adiabatic Assumption

At that time, there was no understanding about internal temperatures, but this was not a huge problem because temperature is only a perturbation, not key to the density. In other words, planets are degenerate. Of course, the outermost part of the planet is an ideal gas, but that is a negligible part of the mass. A key advance in understanding internal temperatures came with the observation that Jupiter emits more energy than it receives from the Sun (Low 1966). The delivery of this luminosity from the interior is not possible by radiation except near optical depth unity in the infrared (where the energy escapes to space). The preference for convection at deeper levels, where the luminosity is not much reduced, is understood by asking whether the temperature gradient needed to carry the observed heat flow is less than or greater than the isentropic temperature gradient ($T \sim P^{0.31}$ for an ideal gas of hydrogen and helium). For a frequency-independent opacity source arising from the collision between hydrogen molecules, the opacity increases almost linearly with pressure and the predicted profile for radiative transfer is $T \sim P^{0.5}$, which is superadiabatic and unstable. Accordingly, convection is preferred in these planets, except that there may be a window in molecular hydrogen opacity at around 1200 K (discussed later and not appreciated at that time). Conduction is never important in most of the planet. Convection implies a nearly isentropic internal state provided the planet is homogeneous, since the needed convective motions are highly subsonic and the fluid is everywhere of low viscosity. This adiabatic assumption (Hubbard 1968, 1969) enables one to estimate a typical interior temperature (of order 10^4 K) simply by knowing the temperature in the observable part of the atmosphere (the low pressure end of the assumed isentrope). Isentrope and adiabat are used interchangeably here; it is perhaps best to use the word isentrope since that is in fact how models are constructed. The thermal energies associated with 10^4 K are small compared to electronic energies.

The isentropic approximation also allowed us to make a model of thermal evolution, which simply matches the luminosity to the rate of change of internal heat content, in accord with the virial theorem. Since the luminosity scales as fourth power of temperature, the loss of heat from an early hot, puffed-up state of Jupiter is fast and the exact initial condition of the planet is forgotten, meaning that one can estimate the time it takes for the planet to reach its current observed effective temperature without knowing the precise initial condition. That time is compatible with the age of the Solar System (Fortney & Nettelmann 2010) and assuredly also the age of Jupiter (Kruijer et al. 2017). This model is of course in the spirit of Kelvin (i.e., the age of the planet is directly related to the Kelvin time, defined as the planet heat content divided by the planet luminosity). The irony here is that Kelvin got the wrong age for both Earth and the Sun, a famous controversy of Victorian science, but could have correctly estimated the age of Jupiter if he had had the data.

2.3. Parsimony

This early work was parsimonious: The assumption of homogeneity (except for a likely core of heavy elements) was driven primarily by the absence of a need to assume otherwise and not by some well-established understanding of internal structure. Parsimony is often referred to as Ockham's razor (see Wikipedia at **https://en.wikipedia.org/wiki/Occam's_razor** for the complex history).

Interior modeling in the 1970s and 1980s was stimulated by the new data provided primarily by the Pioneer spacecraft (because they got so close to the planet) but also by Voyager (Hubbard & Smoluchowski 1973, Stevenson 1982a). But at this point the basic outline of a reasonable interior was widely accepted: a mostly homogeneous planet of hydrogen and helium, with the exception of a central core of perhaps 10 Earth masses. Here and throughout this review, the word core is only used to mean a central concentration of heavy elements (metals in the language of astrophysicists) and implies nothing whatsoever about whether it is sharply defined or solid or liquid or exactly what elements are present in that region. Analogy with Earth is completely inappropriate. For most interior modeling, detailed attributes of any core are invisible from detection and the presence of the core is expressed only through its gravitational influence.

3. A SIMPLE PICTURE OF THE INTERIOR

3.1. The $n = 1$ Polytrope

The predominance of hydrogen and helium in Jupiter points to the need to understand those constituents well. The protosolar mix was near 27% helium by mass (relative to hydrogen), a value that is not in fact directly measured but inferred from solar models (and consistent with our understanding of Big Bang nucleosynthesis). There is no known way of fractionating hydrogen from helium during the formation of Jupiter (when both are in ideal gas form), so the bulk composition of Jupiter preserves that mass fraction even if there is later fractionation inside the planet. The behavior of pure helium is simple, so the need to understand hydrogen is central to formulating

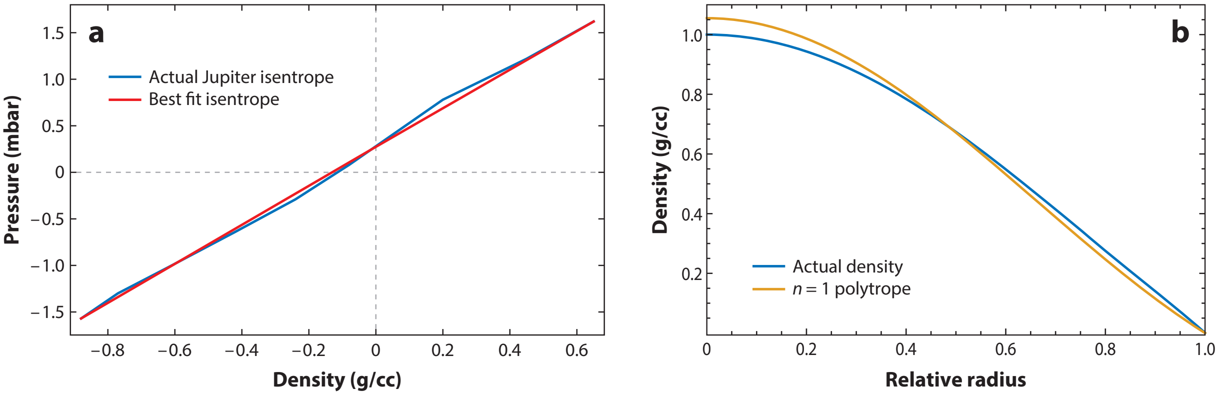

Figure 1

Two curves designed to demonstrate why the $n = 1$ polytrope is a good approximation for a coreless Jupiter. (*a*) Hydrogen-helium log-log plot of pressure versus density. The blue line is the actual isentrope for Jupiter (French et al. 2012), and the red line is the best fit isentrope with $P \propto \rho^{2.05}$. (*b*) Resulting density distributions within Jupiter, scaled to the same total mass and outer radius. The blue line is the actual density, and the orange line is the $n = 1$ polytrope discussed extensively in the text. The vertical axis is density, and the horizontal axis is radius scaled to the outer radius.

interior models. Here, we encounter a fortuitous circumstance: Cold molecular hydrogen is quite stiff—that is, $d\ln P/d\ln\rho$ is of order 3 or 4, where ρ is the density. However, the region where this applies is also the region where the thermal contribution to the equation of state dominates, and that part is soft. As we go up in pressure, transitioning to a degenerate electron gas (the metallic phase), the cold part softens but becomes more dominant. The net effect is that the equation of state is very close to $d\ln P/d\ln\rho = 2$ over a very wide range (French et al. 2012) (see **Figure 1**).

The equation of hydrostatic equilibrium (ignoring rotation) is

$$\frac{dP}{dr} = -\rho g(r). \qquad 3.$$

Based on **Figure 1**, if we take as a good approximation $P = K\rho^2$, known as the $n = 1$ polytrope [cf. Chandrasekhar 1958 (1939)], then the solution to the equation of hydrostatic equilibrium (ignoring rotation) is

$$\rho(r) = A\frac{\sin x}{x} + B\frac{\cos x}{x}; \; x \equiv kr, \qquad 4.$$

$$k^2 \equiv \frac{2\pi G}{K}. \qquad 5.$$

In the case of no core, B must be identically zero since the density must be finite at the origin. In that limit, $kR = \pi$, where R is the outer radius (first zero of the density). We thus encounter the first important result of this model: The radius of a coreless hydrogen-helium planet is independent of its mass. This assumes constant entropy, but it immediately tells us that the reason Saturn has a smaller radius than Jupiter is not because it has less mass but because it contains a higher fraction of heavy elements. The predicted radius of a coreless hydrogen-helium planet is slightly less than the observed mean radius of Jupiter, but that is because Jupiter is rapidly rotating. In fact, the observed radius of Jupiter is close to the largest possible radius for a planet of that composition and entropy irrespective of mass. (Hot jupiters have larger radii because of much higher entropy.)

In the presence of a core, B is finite and can be determined by requiring that Equation 3 is satisfied just outside the core:

$$\frac{d\rho}{dr}|_{r=r_{c+}} = -\frac{GM_c}{2Kr_c^2} = -\frac{k^2 M_c}{4\pi r_c^2}, \qquad 6.$$

and from Equation 4 it follows that B is a measure of the core mass. At the surface, we can write $kR = \pi(1 - \delta)$ so δ is the fractional change of radius due to the core. Since $A\sin(\pi\delta) - B\cos(\pi\delta) = 0$, we have

$$\delta = \frac{1}{\pi}\tan^{-1}\left(\frac{B}{A}\right) \cong \frac{B}{\pi A} \qquad 7.$$

and in a few straightforward steps conclude that the fractional decrease in the radius is the ratio of core mass to total mass. This explains the smaller radius of Saturn relative to Jupiter; Saturn would have the same radius as Jupiter if it had the same fractional abundance of heavy elements, but it is actually much enriched.

Consider instead the addition of heavy elements throughout a uniform hydrogen-helium planet. To a very good approximation, the density of a mixture can be well estimated by assuming volume additivity (Militzer & Hubbard 2013). Accordingly,

$$\frac{1}{\rho\,(P)} = \frac{(1-y)}{\sqrt{\frac{P}{K}}} + \frac{y}{\rho_Z\,(P)}, \qquad 8.$$

where $\rho(P)$ is the density of the mixture at pressure P, y is the heavy element mass fraction, and the heavy element density is ρ_Z. In the case of very large ρ_Z, this predicts a polytrope $P = K_{\text{eff}}\rho^2$, where $K_{\text{eff}} = K(1 - y)^2$. From Equations 4 and 5 but with $B = 0$, we now have a planetary radius that is reduced by the factor $(1 - y)$, which says that the decrease in radius is the same whether heavy elements are concentrated in a core or distributed uniformly throughout the planet. Of course, this is only approximately correct; in practice, adding heavy elements outside a core leads to a planetary radius reduction factor that is more like $1 – 0.8y$.

A mean moment of inertia I can also be calculated. (This differs from C in Equation 1 because of oblateness.) The result is

$$\alpha \equiv \frac{I}{MR^2} = \frac{2}{3}\left[1 - \frac{6}{\pi^2}\left(1 + \frac{2M_c}{M}\right)\right], \qquad 9.$$

even if the envelope is enriched in heavy elements. This result ignores the direct effect of the core on the moment of inertia (which is of order $0.3M_c r_c{}^2$) because that is very small, at the level of typically 0.1% for a 10-Earth-mass discrete (and therefore small radius) core. The effect of the core on the moment of inertia is overwhelmingly through its effect on $g(r)$ outside the core, which affects the density profile in the hydrogen-rich region through the term $B\cos x/x$. Notice that this is a very different consideration than what one encounters for terrestrial planets. Only the mass matters. Fortuitously, the value of $\boldsymbol{\alpha}$ for no core is 0.263, very similar to the coefficient in Equation 1 and the observed C/MR^2. But this shows that the detection of a core for Jupiter is not straightforward (and there is no intention or prospect of doing so with this simple model).

We see then that with only two parameters, the radius of the planet and the moment of inertia, one could derive two properties of the interior: the mass of the core and the extent to which the mantle (everything that is not core) is enriched in heavy elements. If these were the only observables, this is the most you could ever hope to learn. Of course, if atmospheric observations could be used to infer the enrichment of the mantle, then this model is also disprovable, an essential feature of any good model. That is why parsimony (Ockham's razor) is a valuable benchmark. Qualitatively, these comments agree with the trends observed in detailed models, for example, those of Guillot (2005) showing that the core mass is anticorrelated with the heavy element abundance in the envelope and the total mass of heavy elements does not change much, as required to keep the mean density constant. But in practice, nothing is so simple and there is no requirement that the entire region external to the core is homogeneous.

3.2. Gravitational Moments

The moment of inertia can be determined in principle from the spin axis precession rate of the planet (the same method we use for Earth), and this is being attempted by Juno (Le Maistre et al. 2016). But the long-standing practice in planetary science, plausible for rapidly rotating fluid bodies, relies instead on the gravity field. In the absence of any dynamical effect (e.g., convection or tides), the external gravitational potential can be written as

$$V(r,\theta) = \frac{GM}{r}\left[1 - \sum_{n=1} J_{2n}\left(\frac{a}{r}\right)^{2n} P_{2n}(\cos\theta)\right], \qquad 10.$$

where the J_{2n} are dimensionless numbers called gravitational moments, the P_{2n} are Legendre polynomials, and θ is the colatitude. There is no dependence on longitude, and there are only even harmonics because it is assumed that the only perturbation from a $1/r$ potential arises through the uniform rotation of the planet (which does not distinguish between north and south).

By equating Equation 10 to V evaluated directly from the density distribution within the planet, we find that

$$J_{2n} = \frac{-1}{Ma^{2n}} \int \rho(r,\theta)\, r^{2n} P_{2n}(\cos\theta)\, d^3r. \qquad 11.$$

In the case of $n = 1$, $J_2 = (C - A)/MR^2$, where C and A are the unequal polar and equatorial moments of inertia, Radau and Darwin found an approximate formula linking the value of J_2 to the value of C. It is remarkable (and far from obvious) that this approach is in fact exquisitely accurate in the case of Jupiter, unless one considers pathological models (Helled et al. 2011, Gao & Stevenson 2013). In other words, J_2 determines the moment of inertia and vice versa to the level of perhaps a few parts in 10^4. This can be explicitly demonstrated for the quadratic equation of state considered here, even with the density discontinuity at a possible core surface. The relationship might begin to break down if the core is diluted; we will test that.

It is evident from the r^{2n} weighting in the integrand of Equation 11 that the higher Js contain information about the outer regions of the planet. Note, however, whereas J_2 is trivially nonzero, J_4 (for example) is nonzero only to the extent that the density distribution has a P_4 component or the extent to which the volume integral extends to a boundary that is nonspherical. If rotation were a very small perturbation on the planet, then we would expect only J_2 and no higher order moments since the centrifugal force [the rotational correction to $g(r)$] is proportional to P_2. However, rotation is not so small, and necessarily there are higher order terms (e.g., terms in ${P_2}^2$, part of which is proportional to P_4). It is tempting to suppose that there is some extension of Radau-Darwin to the higher Js, but that is not the case—the relationship of J_4 to the density distribution is not at all straightforward other than the qualitative inference that it is linked to the outermost regions of the planet. For a rigidly rotating planet $J_{2n} \propto q^n$ (Hubbard 1999), where $q \equiv \Omega^2 R^3/GM$ is the dimensionless measure of the centrifugal effect (Ω is the planetary rotation).

If we thought (for some physical reason) that we understood the outermost region of the planet very well (for example, that it sat on a known isentrope and had a known composition), then our ability to decouple J_2 and J_4 or even J_6 becomes a game of playing with large changes in the deep interior rather than small changes in the near surface. In effect, this is the strategy largely employed now: Change things that are intrinsically unsuited to the parameters of focus (J_4, J_6) in the belief that we know the outer envelope (other than its precise entropy and composition). Of course, there is never any strict decoupling, so the favored models are not intuitive generally.

3.3. Satisfying the Constraints

Even before Juno, it was evident that the simplest kind of model, one with a core and mantle of variable heavy element enrichment, had trouble fitting J_4. There are two possible reasons: The interior could be more complicated, or our understanding of the underlying equation of state (by far the most important thing) is imperfect. But a simple model gets close to satisfying gravity data, so before pursuing those avenues, we should consider how well the simple model does on other attributes. We shall consider three: (*a*) the magnetic field, (*b*) the heat flow and inferred thermal history, and (*c*) the atmospheric composition.

The magnetic field of Jupiter has been inferred through radio emission since the early days of radio astronomy (Burke & Franklin 1955). In the usual, very simplified characterization, it is a tilted dipole with a characteristic field strength of 4.2 Gauss, about an order of magnitude larger than Earth's surface field. Pioneer data told us that it had substantial higher harmonics. If these arose from a current distribution that existed out to about 75% of the planet radius, then one could readily understand the relative magnitudes of the dipole, quadrupole, and octupole (an approach that enables us to understand that Earth's field arises from currents confined to Earth's core). Accordingly, a region of field generation was inferred that was at least 75% of the radius and perhaps more (Connerney et al. 1996). The only known way of explaining large magnetic fields in bodies is a dynamo, which arises through complex fluid motions in an electrically conducting medium. A liquid metal suffices (as in the case of the liquid iron alloy outer core of Earth, for example), although in fact a somewhat lower conductivity may suffice (Stevenson 2003). In this context, complex means that very simple kinds of circulations may not work but convection in a rotating body may suffice. In practice, one needs a magnetic Reynolds number defined as $R_m \equiv vL/\lambda >$ some critical value, perhaps 10 or 100, where v is a typical fluid velocity (relative to a rigidly rotating frame) and includes a substantial vertical component, L is a characteristic length scale for the flows, and $\lambda \equiv 1/\mu_0\sigma$ is the magnetic diffusivity where μ_0 is the permittivity of free space and σ is the electrical conductivity. Substantial rotational effect arises through the importance of the Coriolis force in large-scale motions (i.e., a small Rossby number), an easily satisfied criterion in Jupiter. Simple models of Jupiter have no difficulty meeting these requirements, even for flows as slow as 0.1 cm/s, typical or less than what would be predicted by commonly used scaling laws for thermal convection (Stevenson 2003). Complicated models (those with superadiabaticity and a compositional gradient) do have trouble with explaining the observed field.

The observed excess luminosity requires convection below about optical depth unity in simple models (but see Section 4.3 below), and this implies isentropy for the interior. Simple models can then adequately explain the observed heat flow for an age of around 4.5 Ga. In the spirit of Ockham, this argues for simplicity, but it is not a strong argument against more complex models (Nettelmann et al. 2012).

Finally, we should consider the atmospheric composition, based on both remote and in situ (Galileo) measurements. Although there is still some disagreement, these data support a roughly threefold enhancement of the atmospheric abundance over the solar value, except for helium, neon, and possibly water (Owen & Encrenaz 2003, Guillot 2005). Let us first talk about the threefold enrichment. It is remarkably constant for materials as diverse as ammonia and methane on the one hand and heavy noble gases on the other hand. This is surprising given that heavy noble gases are expected to condense (if at all) at very low temperatures, perhaps of order 40 K or less, as clathrates or on amorphous ice. However, the traditional view of Jupiter itself is that it perhaps formed not far outward of the water ice (snow) line, perhaps at 150 K or as low as 100 K. Lower temperatures would provide a puzzle for the observed properties of the Galilean satellites (especially Callisto, which is far out but clearly volatile depleted relative to Titan). These observations have led to the idea that very cold planetesimals were delivered from far out in the nebula, inward to the Jupiter-forming region at a late stage of Jupiter formation when the dominant effect was infall of nebular gas (Owen & Encrenaz 2003). Alternatively, the nebula was depleted in hydrogen and helium so that the gas that accreted onto Jupiter was enriched relative to solar (Grasset et al. 2017). Notice that in either case, the atmospheric composition is attributed to pollution—the addition of material late in accretion that differs from the original solar nebula. The alternative of dredging of material from a primordial core is seldom mentioned, perhaps sensibly, since that material would not be expected to be enriched in heavy noble gases.

The abundances of helium and neon are depleted relative to solar, presumably because of interior processes described in Section 4.2. The water abundance is a different problem. There is no compelling evidence that this is greatly modified by interior processes (Soubiran & Militzer 2016), although much thought has been put into that possibility by this author and others. The Galileo probe saw a water mixing ratio that is much (approximately an order of magnitude) lower than solar, and this was attributed to the unfortunate circumstance that the probe entered a dry downwelling part of the atmosphere. Additional deeper probe measurements were advocated as a result. A new concept, developed and applied to microwave radiometry, offered a method to globalize the measurements and was considered as an additional method. Practical limitations led to the Juno choice of microwave radiometry without additional probes (Section 5.1). In any event, the available evidence points to a nonuniform distribution of water vapor or ice, even at levels below the conventionally defined cloud deck [the place where $P_v(T) = fP$; P_v is the vapor pressure of water, either as ice or liquid, whichever is lower; f is the molar mixing ratio of H_2O; and P is the total pressure]. There is a well-based suspicion that water is twice solar, although with a large error bar (C. Li et al., unpublished article) perhaps not too different from the observed enrichment of other elements except for helium and neon. The abundance of water is of central importance to understanding Jupiter's formation.

Simple models of Jupiter suggest a gravity field that is incompatible with the likely enrichment because they tend to give a lower density for the outer envelope than we would infer for the observed isentrope and heavy element enrichment. A lower water abundance or higher temperature would help reduce the gap between the simple models and the observations. However, even complicated models (below) seem to encounter a likely mismatch between observations and models. This all suggests problems with our understanding of the planet. A three-layer model would seem to be the minimum (see **Figure 2**). We turn next to complications, some of which are motivated by this difficulty.

4. COMPLICATIONS

4.1. The Molecular-Metallic Phase Transition

At absolute zero, and even allowing for quantum effects of the protons, it is widely accepted that molecular hydrogen transforms to metallic hydrogen as a first order phase transition.

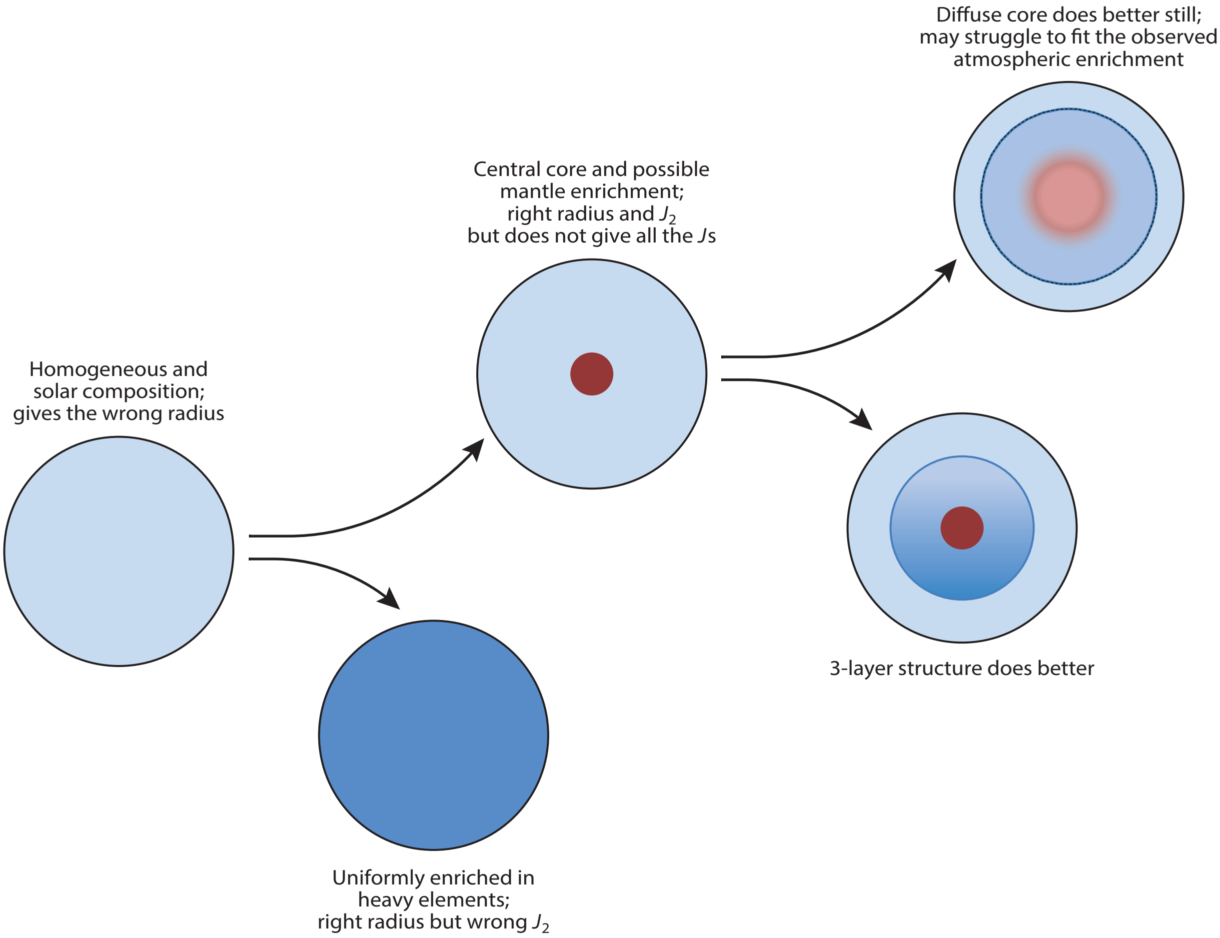

Figure 2

A sequence of progressively more complicated models. A homogeneous model can give the right radius but wrong J_2 (moment of inertia). A two-layer model (core and homogeneous mantle) gives the right radius and moment of inertia but wrong higher Js. A more complex model is needed.

It is useful to formulate a precise understanding of what it means to have a first order phase transition from the perspective of Gibbsian thermodynamics. Consider a Gibbs free energy $G(P,T;x)$, where x denotes the mole fraction of free protons relative to a mix of free protons and molecules. For each pressure P and temperature T, we can then minimize G with respect to x. When there are two or more minima with respect to x at fixed P and T, then the one that is lowest determines the thermodynamic equilibrium state (the others are metastable by definition). If the minimum jumps in x abruptly at some pressure P, then that determines the first order phase transition (see **Figure 3**). There will be an associated volume discontinuity and latent heat, both of which will tend to zero as one approaches the critical temperature T_c from below. Above $T = T_c$, there is only one minimum of G with respect to x and no first order transition (i.e., the preferred state will change gradually from x near zero to x near unity as pressure increases). **Figure 3** displays this concept for a simple two-component phase diagram of the functional form

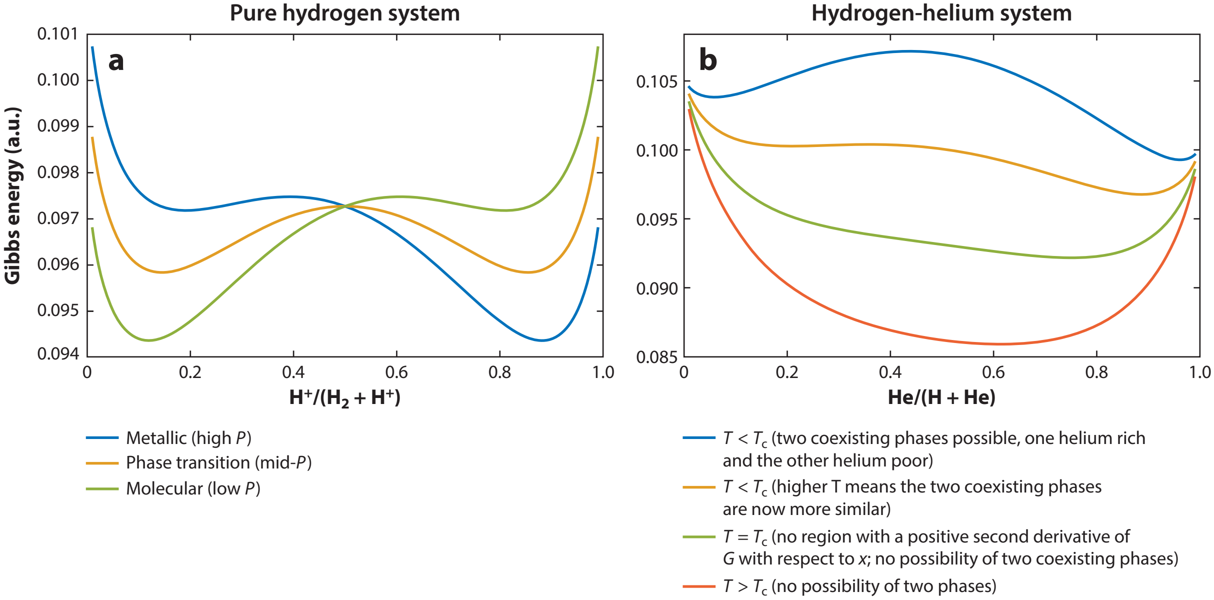

Figure 3

Gibbsian thermodynamic description of phase transitions, all based on Equation 12. (*a*) Three curves at different pressures for pure hydrogen, all showing a first order phase transition defined by the choice of *x* that minimizes the Gibbs energy as pressure is changed. Green (low *P*) is molecular, orange (mid-*P*) is right at the phase transition coexistence of two phases, and blue (high *P*) favors metallic (large *x*). (*b*) Representation of the hydrogen-helium system or the pure hydrogen system at coexistence. The curves are at almost fixed *P* but varying *T*, and we see four curves. Blue and orange are at *T* low enough to have a first order phase transition (two minima). Green is the critical *T* (T_c), and red is clearly above the T_c (no phase transition possible).

$$\begin{aligned} G(P,T;x) &= xG(P,T;x=1) + (1-x)G(P,T;x=0) + x(1-x)\Delta G(P,T) \\ &\quad + kT[x\ln x + (1-x)\ln(1-x)]. \end{aligned} \qquad 12.$$

The first two terms are obvious: They represent the contributions from the two end-member states (e.g., pure molecular hydrogen and pure metallic hydrogen). The third term represents the interactions between the two species, here represented as binary collisions with $x(1-x)$ being a measure of the likelihood of disparate species being adjacent, and ΔG expresses the repulsive interaction of unlike species (relative to the interactions of like species). The last term is the standard ideal entropy of mixing term predicted by statistical mechanics, again assuming randomness of the locations of the species. This is a simplification, but the general features of this functional are preserved even when one goes to a more complicated model. For this simple case, the critical *T* (above which $\partial^2 G/\partial x^2$ is positive for all *x*) is given by $T_c = \Delta G/2k$. This model illustrates the central idea, which is that entropy counteracts the tendency toward a first order transition so an abrupt jump can therefore occur only below a certain specified critical temperature.

A first order phase transition can have important consequences for the evolution of a planet, although those consequences are widely misunderstood. If it exists, then there must indeed be a discontinuity in density in pure hydrogen alone, but this is actually quite subtle in interior models (i.e., typically the overshoot in density on the metallic side is largely canceled by the undershoot on the molecular side). There is indeed a discontinuity in entropy at constant temperature (i.e., the latent heat), and this has important implications for the interior thermal structure. However, the latent heat release (positive or negative) that arises as the planet cools is a small effect (Stevenson & Salpeter 1977a,b). Importantly, the Gibbs phase rule dictates that there must be a compositional discontinuity across the phase transition, and this could have large consequences for the observed composition of the envelope, potentially reconciling observed and inferred abundances of heavy elements. But in the end, all of this amounts to rather little since the overwhelming evidence is that Jupiter (and Saturn) is too hot to encounter the low-temperature first order nature of the phase transition (Dias & Silvera 2017). Data on this question are somewhat inconsistent, but there are no data for pure hydrogen that compel the presence of a first order change under the conditions encountered in Jupiter today. In short, when people talk about molecular and metallic layers in Jupiter, they are essentially correct, but there is absolutely no implication in such language that you go abruptly from one layer to the other as you change radius or pressure—there is instead a region where you are neither one nor the other and the transition is gradual. The thermodynamic properties may be anomalous but without discontinuities or interfaces. In the next section we see how helium may complicate that picture.

4.2. Helium Immiscibility

The same model Gibbs energy as Equation 12 (with x now interpreted as a helium abundance) describes the binary phase diagram of hydrogen and helium. There is no doubt that hydrogen and helium phase separate at low P and T (it is experimentally observed), and there is no doubt that they phase separate at very high P (where all the electrons form a Fermi sea and the positive ions are protons and alpha particles). There is, however, no direct experimental verification of the phase separation under the conditions of most interest to Jupiter, which are P is approximately a megabar and T is approximately 5000–8000 K. The pressure is set by the expectation that the phase transition is driven by the insolubility of a species that prefers bound electronic states (helium) in a species that has (or is becoming) a state with copious free electrons (Stevenson 1979, Morales et al. 2013). Higher pressures are unlikely because the actual temperature inside the planet continues to rise on the isentrope needed for heat transport, while the critical temperature for immiscibility is likely to be rather insensitive to pressure once the relevant conditions have been satisfied. Theory for the critical T is uncertain to perhaps 20%, a large enough error to preclude a strong theoretical prediction about helium insolubility in Jupiter. The best evidence for the phase transition is actually atmospheric observations by Galileo, which show perhaps a 10% depletion in helium (relative to primordial solar) but, very importantly, a factor of six depletion in neon (Owen & Encrenaz 2003). It is perhaps ironic that the original motivation for helium immiscibility was the observed luminosities of Jupiter and Saturn, since we now recognize that these are not a good way of determining the existence of immiscibility. But the atmosphere dictates that a discontinuity in helium abundance should occur in Jupiter, albeit not very large. The situation for Saturn is unclear.

In Jupiter, any hydrogen-helium phase separation must be limited in pressure, happening at neither very low P nor very high P. In this picture, helium rain forms once the hydrogen is largely metallized and then falls as droplets to greater depths (higher temperature), where it redissolves. Saturn could be different because of the lower pressures. This helium evolution has a modest effect on thermal evolution but a readily detectable effect on interior models (because the Js are known with such high precision; see Section 6.1). The modesty of this effect would appear to be coincidental.

4.3. Is It Adiabatic?

An adiabatic interior has formed a key assumption in standard (simple) interior models. Strictly speaking, it means that in a multilayered planet, each homogeneous layer is close to isentropic, but there can be discontinuities in entropy but negligible discontinuity in temperature across interfaces that correspond to discontinuities in composition. However, isentropy everywhere else demands two additional nontrivial conditions: a failure of microscopic heat transport (thus enforcing a convective state) and the absence of broad and stable compositional gradients. The former would enforce subadiabaticity, and the latter would enforce superadiabaticity.

Molecular hydrogen is homopolar and is only opaque in the infrared to the extent that molecules collide. Thus, the opacity is roughly proportional to pressure, and this is what guarantees a convective state deeper than roughly optical depth of approximately unity. However, the proportionality constant in the opacity depends on temperature because it depends on the characteristic temperatures for molecular rotation and vibration. It so happens that the opacity is low at around 1200 to 2000 K despite the high pressures corresponding to that location in Jupiter. Coincidentally, water, methane, and ammonia all (as vapor) have low opacities in this temperature range. This led to a crisis in the opacity of the deep envelope of Jupiter (Guillot et al. 1994) that has as its solution the likely presence of alkali metals (e.g., Na in elemental form) just as is observed in hot jupiters (Guillot 2005, Fortney et al. 2011). At present, there is no observational verification of the presence of this opacity source, and it is plausible that Jupiter manages to convect all the way from the observed atmosphere to the deep interior (but see Section 6.1 and Debras & Chabrier 2019). Subadiabaticity would imply a higher density at depth than the standard models, and this is the opposite of what the gravity data seem to require.

Parsimony drives the common practice of assuming homogeneity. The tendency toward well-mixed layers in Earth (the planet we know best) arises for a reason that has no relevance to Jupiter: the strong phase separation of an iron alloy from silicates. As the planet forms, compositional gradients (and possibly small-scale layering) would seem to be highly likely in giant planets (Leconte & Chabrier 2012). In a degenerate fluid, where αT is much smaller than unity (perhaps $\sim$0.05 at great depth), it is easy to create a compositional gradient that overwhelms convection and forces the fluid to be superadiabatic yet stable overall in the Ledoux sense (see also Bodenheimer et al. 2018). Double-diffusive convection may ensue, a state that looks (at the large scale) like a smooth compositional gradient. This can have a large effect on interior models and thermal evolution (Leconte & Chabrier 2012, Debras & Chabrier 2019).

4.4. More Layers?

I have already identified the puzzle of reconciling observation with models. By far the simplest way to solve this puzzle is to invoke additional layering. In its simplest form, this modeling consists of three layers: a core (a region of heavy element concentration), a mantle (metallic hydrogen but enriched in helium and in heavy elements), and a molecular envelope (still enriched but less so than the mantle and slightly depleted in helium). Consistent with the discussion in Sections 4.1 and 4.2, the mantle-envelope boundary (it need not be sharp) is recognized as the location where helium rain forms and not necessarily with the molecular-metallic transition, but of course the expected radial location is about the same.

Most published models have been of this kind (Guillot 2005, Nettelmann 2012, Miguel et al. 2018). These kinds of models take liberties with what we understand about these planets because they invoke a rather large change in heavy element abundance between envelope and mantle that is not derived from any kind of thermodynamic modeling and may be too large to be readily compatible with our understanding of helium immiscibility. With the notable exception of neon, all other heavy elements partition less effectively than helium between metallic and molecular hydrogen-rich phases. However, this heavy element partitioning might be merely an increase of heavies as one goes inward toward the center and could then be the outcome of an accretion process that tends to put heavy elements near the center of the planet in a way that creates a stable compositional gradient, not because the heavies are more dense but because the ratio of the flux of accreting gas to the flux of accreting solids (i.e., heavy elements) increases as time passes in the planet formation epoch. This is the picture favored by Helled & Stevenson (2017). This must not be confused with the atmospheric enrichment discussed above, which presumably arose from even later accretion that was Rayleigh–Taylor unstable (i.e., the accretion of dense solids onto a hydrogen-rich envelope).

Figure 4 suggests a currently favored picture for the interior of Jupiter. Note the lack of any sharp boundaries in composition or material properties with depth.

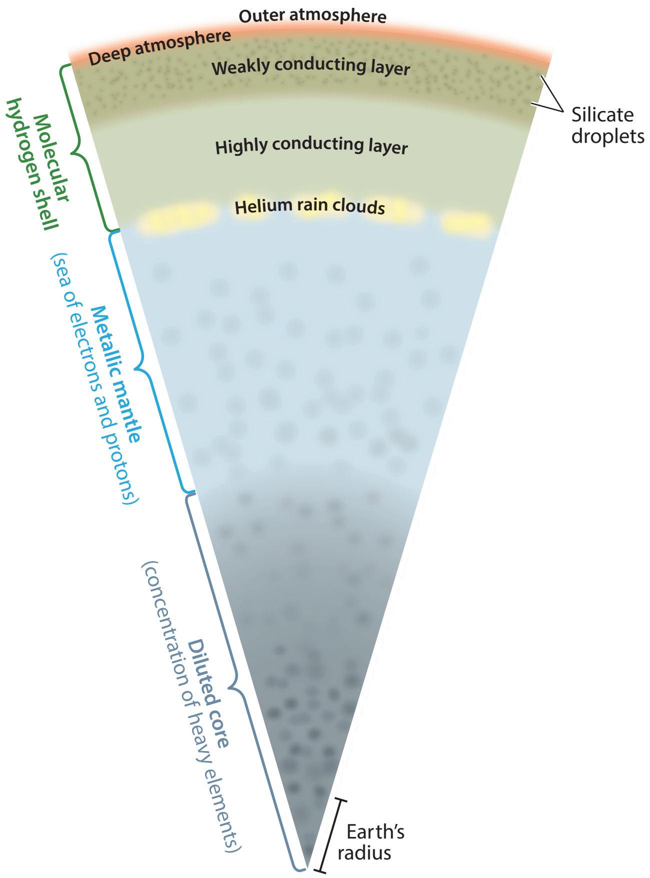

Figure 4

A current view of the interior of Jupiter. From the outside inward, we encounter ammonia cirrus at less than one bar of pressure (the observable aspect of Jupiter in the visible), water clouds at tens of bars, and silicate clouds presumed at tens of kilobars. At ~3,000 km, less than 5% of the radius, the temperature is thousands of degrees and the conductivity of molecular hydrogen is similar to that of salty water (1 S/m). Helium phase separates as the hydrogen approaches metallization (pressure not known but plausibly 1–3 Mb). A diluted core (heavy elements mixed nonuniformly with hydrogen and helium) is present deeper still.

5. THE PATH TO JUNO

5.1. The Scientific Motivation

Planetary science has a decadal survey every 10 years, including a scientific rationale and description of acceptable billion-dollar (New Frontiers) missions. In addition, there are Discovery-class missions at half the cost. After Galileo (mid-1990s) it was widely recognized that a mission to Jupiter, focused on interior science, was a desirable goal, and this was expressed in the decadal survey. This could be either Discovery or New Frontiers. Several unsuccessful proposals were made for Discovery missions to Jupiter. However, Juno (named after a Greek goddess) with Principal Investigator Scott Bolton was successful in 2003 (Bolton et al. 2019) by combining the virtues of the previous Discovery proposals and most of the science teams and by including an MWR from one of them. Juno advocated that an MWR was a better way to understand the atmospheric composition than the previously favored atmospheric probes. The mission has proved that view to be correct, as the atmosphere is complicated and heterogeneous, so getting water abundance is not at all straightforward—even a deep probe to 100 bars would not have worked. This review does not cover the MWR results in detail, although it is likely that they will eventually have something important to say about the interior.

5.2. The Winning Proposal

Juno is a solar-powered spacecraft with three primary objectives related to the formation of Jupiter and the deep interior as well as many instruments and objectives related to the magnetosphere and atmosphere. Our focus here is on those three primary considerations: the gravity field (measured by precise tracking), the magnetic field (measured by a magnetometer), and the atmospheric thermal and compositional structure down to hundreds of bars (measured by an MWR).

Gravity is the primary means to determine internal structure, not because it is the best way but because it is achievable. With the essential aid of the Italian space agency, it was possible to include Ka band and X band with both uplink and downlink, enabling determination of the gravity field to typically a part in 10^7 or 10^8. The gravity field shows evidence of being spin axisymmetric even at levels approaching this accuracy, which greatly aids the confidence with which conclusions can be drawn, since determination of a fully tesseral field out to a harmonic degree of approximately the number of orbits would be very challenging. At the time of the proposal it was appreciated that the major new accomplishment of gravity data would be the nature of the winds rather than the nature of the core.

The magnetic field measurements have two main challenges: the very wide dynamic range from nanotesla to perhaps 0.01 tesla and the expected nonsymmetry of the spatial structure; the latter in particular defined a mission that extended over at least 32 orbits. The results were surprising from the outset because the first science pass was fortuitously close to a feature in the field that was not detected previously and corresponded to a cloud top field that was perhaps 70% larger than previous models predicted. However, the rest of the mission revealed that the field exhibits spots (regions of anomalously high or low field strength) in spatially localized and infrequent locations; in this sense the mapping of the field has proved to be possible in a largely predictable way.

The microwave data were advertised as the means of getting the water abundance even though we knew that the dominant opacity source was ammonia. This claim rested on the expectation that ammonia would be uniformly distributed once we got below the relevant cloud deck at around 1 bar pressure and that the temperature distribution would prove to be easy to understand. Neither expectation, but especially the expected uniformity of ammonia, turned out to be true. However, the MWR measurements have proved to be an invaluable guide to the nature of the atmosphere.

5.3. Accomplishment

It is a truism that missions are successful to the extent that they surprise. Juno surprised us. Everything worked as expected except that the mission stayed in a long, 53-day orbit because of concern about valves on the engine. This was a scientific boon, although of course it has added to the cost. The spacecraft is achieving the same coverage and proximity of a shorter mission but with the benefit of time to consider and react to the results and see changes.

In gravity, we achieved what we proposed but more because it proved possible to say something important about the nature of the differential rotation. In the magnetic field, we found out (yet again) that each planet is unique in the nature of its field; previous superficial similarities to Earth (after allowing for the difference in the levels at which the field is generated) proved to be incorrect. Comparisons with past data have also enabled us to infer something about secular variation (changes to the field on decadal timescales), and it has also been possible to develop some ideas about how gravity, winds, and magnetic field may be interrelated, something that some suspected prior to the mission. And MWR has proved confounding but revolutionary. One could not ask for more! It is clear that our simplistic ideas of meteorology in Jovian atmospheres are in need of revision.

6. JUNO GRAVITY

6.1. The Even Harmonics

A hydrostatic Jupiter should only exhibit even zonal harmonics (even values of the J coefficients) of the gravity field. To a first approximation, the data are consistent with this expectation. Although there were some uncertainties in the wind profile and how that affects the gravity field, this partly nonhydrostatic effect turned out to be a relatively small concern for the even harmonics (unlike Saturn, where the very large symmetric differential rotation affects the even harmonics quite strongly; Iess et al. 2019).

Before Juno there were two main kinds of uncertainties for the interior models: those due to the error bars in the Js and those due to the uncertainties in the equation of state. Juno resolved the former, and parallel work in the previous decade largely resolved the latter. Models were largely of the three-layer kind (even before Juno): a central "core" of heavy elements, a "mantle" that is enriched in heavy elements, and an "envelope" that is less enriched in heavy elements (quotation marks are used here to remind the reader that you must not think of these boundaries as sharply defined). These models were (and are) parsimonious in the sense that they match the number of observables with the number of degrees of freedom in the model. They have sufficient flexibility that they should fit the data, but even so, two issues have arisen: The models typically require a diffuse core, and they overpredict the density in the envelope. We now discuss each attribute in turn.

The core expresses itself in the gravity field primarily through its mass, not its size or (equivalently) composition. However, that simplification breaks down once the core becomes sufficiently large (or, equivalently, sufficiently poorly defined). In most current modeling, the envelope is rather well defined (specified entropy and homogeneous) although with an uncertain composition. Given this enforced simplicity, the only remaining degree of freedom concerns the mass distribution of the core. This corresponds to small changes in J_4 and J_6 given that you have already forced the model to agree at J_2. This is the basis for the diffuse core models of Wahl et al. (2017), and it seems to have been confirmed by Debras & Chabrier (2019), although there are models that merely increase the heavy element abundance deep down (Nettelmann et al. 2012, Miguel et al. 2018). It is debatable as to whether the latter are readily distinguishable from a diffuse core.

The idea of a diffuse core makes some sense in planet formation. In the classic works Bodenheimer & Pollack (1986) and Pollack et al. (1996), it was assumed that a core of heavy elements would form overlain by the hydrogen-helium envelope. In fact, this has never made sense (Stevenson 1985) for two reasons: First, the temperatures and densities during formation are sufficient to disrupt planetesimals and then vaporize incoming ice or rock before that material reaches a central core, at least for cores exceeding a few Earth masses (much less core than interior core models currently favor). Second, ice and rock are soluble in metallic hydrogen fluid under Jupiter conditions (Soubiran & Militzer 2016). Note that the latter is completely different from the way we think about layering in Earth. What is not clear, however, is whether the diffuse core picture that is currently favored is quantitatively consistent with current ideas of Jupiter formation (Helled & Stevenson 2017) and subsequent evolution that may dredge up core material. If one takes the output of highly detailed accretion models such as Bodenheimer et al. (2018), they predict a postaccretion heavy element distribution that is smooth (i.e., diluted) but not anywhere near to the same extent as the models favored by fitting the current gravity (Wahl et al. 2017; Debras & Chabrier 2019; B. Militzer, unpublished work, 2019). Giant impacts are also a possibility (Liu et al. 2019) and have the potential to make the core even more diffuse, but of course such models are imperfectly understood and it is not at all certain that they can be invoked.

Given these difficulties, it is natural to look back at older, less favored models such as a direct Jeans collapse (analogous to the instability that might initiate star formation). It is therefore important to remind the reader that those models introduce a host of other difficulties beyond those of explaining the right kind of core (or even the existence of a core). Direct collapse requires a disk that approaches the threshold for instability without first redistributing the high surface density (the cause of the instability) through density waves. Instability models offer no straightforward interpretation of exoplanets or the prevalence of cores in giant planets and the striking similarity of the hypothesized core of Jupiter to the actual planets Uranus and Neptune. It is of course always possible that Jupiter was somehow special, so one must maintain an open mind in the face of the evident theoretical difficulties.

Even with the diffuse core or mantle enrichment, a problem persists: Models tend to yield a required envelope density that is lower than that observed. This can be interpreted in one of four ways: (*a*) The envelope heavy element enrichment is actually very low, despite observation; (*b*) the temperature of the deep envelope is higher than inferred from models of the atmosphere; (*c*) the envelope is more complicated (nonisentropic and nonhomogeneous) than previously supposed; and (*d*) we have the wrong equation of state. Let us consider each in turn (the reality may of course be a mixture).

Juno was motivated in part by the desire to determine water abundance. It has not yet succeeded because the atmosphere is complex, but the interpretation of ammonia and the MWR data suggest water is 2 ± 1 solar (C. Li et al., unpublished article). Since water is the most abundant condensate, the low end of this estimate (a solar value) would be marginally compatible with interior models, especially if the rock component is solar or subsolar. We have no direct information on the rock component, although channel 1 of the MWR could be interpreted as an absence of the rocky component (this would be a major surprise).

The usual assumption for the isentrope sets it at 165 K at 1 bar. (This is a fictive value and must not be interpreted as the actual T at 1 bar.) MWR allows for some superadiabaticity at depths associated primarily with the molecular weight gradient that arises in a convecting system that has both ammonia and (especially) water condensing. Still, the superadiabaticity required to reconcile observation with interior models is of the order of 15 K, not the 5 K that seems more likely as an upper bound for a meteorological effect.

Debras & Chabrier (2019), taking this problem seriously, have proposed the most elaborate changes in the compositional and thermal structure in the envelope. Their proposal is tied to the nature of the hydrogen-helium phase diagram, especially the partitioning as helium rain forms and how this evolves over time.

At present, nobody seriously contemplates a change in the equation of state even though it has not been fully tested against data. It is worth remembering that the behavior of hydrogen near a megabar and at a few to ten thousand degrees is not well understood at the 1% level, as interior models may require.

6.2. The Odd Harmonics

We see latitudinal dependence of wind speeds at the cloud tops, and for over 50 years there have been sharply differing opinions about whether these are the surface expression of a deep-seated flow (i.e., a differential rotation) or merely a surficial atmospheric flow. The truth has proved to be intermediate. The essential observation for this inference is the amplitude of the odd zonal harmonics (J_3, J_5, J_7, J_9). These can be present only for a nonhydrostatic planet, and they require an asymmetry in the atmospheric flows between the hemispheres, as is indeed observed. The interpretation is nonunique (that is, the actual flow could in principle be different in depth and strength from the favored interpretation) but is bolstered by the remarkable ability to explain both the amplitudes and relative signs of these odd *J*s.

The interpretation of the odd *J*s is mainly done by considering the thermal wind equation (Kaspi et al. 2018):

$$2\Omega \cdot \nabla (\rho_0 u) = \nabla \rho \times g, \tag{13.}$$

where Ω is the rigid body rotation of the deep interior, ρ_0 is the unperturbed density (the spherically symmetric hydrostatic solution), u is the zonal flow, ρ is the resulting small density perturbation responsible for the observed odd *J*s, and g is gravity. The three most important things to understand about this equation are (*a*) it is only approximate; (*b*) it is not dynamical—that is, it does not explain where either ρ or the associated flow field u actually comes from; and (*c*) it is highly nonunique in its inference about the flows and *J*s. Let us consider each in turn. Concerning this equation's approximate nature, much has been written about this (Kaspi et al. 2018), and the summary is that for the accuracy of the current data and in the absence of a fully dynamical explanation, there may be no substantial benefit in being more careful. Both of these issues may change in the future and merit a more careful assessment, just as has been done for the even *J*s. The nondynamical nature of the equation can be seen from the fact that one can derive an equivalent equation (e.g., see Liu et al. 2008) that avoids ρ_0 inside the divergence term but explicitly invokes the entropy anomalies. We do not know these, and we would need a full theory of convection in a rotating sphere with magnetohydrodynamics (MHD) to compute them. Concerning perhaps the most important issue, nonuniqueness, it is important to note the structure of the equation: You could have small u where ρ_0 is large or large u where ρ_0 is small and get similar contributions to the left-hand side of the equation (depending, of course, on their gradients). The background density ρ_0 changes by orders of magnitude between the atmosphere and the region where the flow may become small. A priori, there is nothing you can do to offset this huge nonuniqueness.

Despite this, Juno showed us something very remarkable and perhaps unexpected (Kaspi et al. 2018): The pattern of the observed flow (specifically the north-south asymmetric part) explains the pattern (signs and magnitudes) of the odd *J*s. This, combined with their typical amplitude, leads to a plausible (although still nonunique) interpretation for the depth of the flow. We then find a depth of about 3,000 km, which happens to be the depth at which the electrical conductivity is around 1 S/m. By a completely unrelated approach, based on Ohmic dissipation (Liu et al. 2008), a predicted depth of 2,800 km was found for the level at which the flow drops to a low value. Liu et al.'s (2008) theory was also nondynamical and concerned only energy dissipation (the requirement that the total Ohmic dissipation not exceed the planetary luminosity by a large factor). The lack of a fully dynamical theory should lead one to be cautious about all of this, but the correspondence to Saturn (where the flows are stronger but decay at a similar electrical conductivity, at around 10,000-km depth) lends support to the interpretation that the zonal flows are confined by MHD effects (the finite conductivity of molecular hydrogen) rather than by some simple notion of an envelope that is convectively isolated from a metallic region or a simple notion that the flows are purely meteorological (Iess et al. 2019). The region of interest is one where clouds occur (for example, rock clouds; Markham & Stevenson 2018), so there may be other important fluid dynamic effects that have not been considered.

6.3. What Else?

The determination of the moment of inertia for Earth and Mars is not done in the approximate scheme provided by Radau and Darwin but by detection of the planetary precession of the rotation axis. We expect to do the same for Jupiter (Le Maistre et al. 2016) once we have a sufficient time base. Current observations are also providing hints for the Love numbers, specifically the response of Jupiter (change in its gravity field) because of the tides raised by Io. This is of interest because tides, unlike rotation, are dynamic, so there should be a difference between the Love number predicted for purely static tides (Wahl et al. 2016) and the Love number that arises from actual, dynamic tides. At present, the evidence suggests a small difference at most. Finally, the issue naturally arises of tesseral gravity. Is the gravity field of Jupiter truly spin axisymmetric? Even if it is, is it time dependent? Jupiter may exhibit normal modes, although the expected amplitude is controversial and not understood (Markham & Stevenson 2018). With the multitude of orbits and high precision available, it may be possible to demonstrate that Jupiter, like Saturn (Iess et al. 2019), exhibits a more complex gravity field than we have discussed thus far.

7. JUNO MAGNETIC FIELD

7.1. Static Field Structure

Unlike Earth, the outer boundary of the dynamo region for Jupiter is diffuse. Not only is the electrical conductivity a smooth (although rapidly changing) parameter, but also the fluid viscosity is smooth (no sudden jump in behavior, as for Earth's core-mantle boundary). We also suspect that the strength of the zonal flow (important for creating the nonobservable toroidal field) varies strongly in Jupiter in accordance with the MHD effect (see Section 6.2). For all these reasons, it is a mistake to think of Earth as a close analog to Jupiter. Even so, pre-Juno observations suggested a field that is somewhat Earthlike. Juno observations suggest otherwise: The field is different in structure, and any inference for the outer boundary of dynamo action is unclear.

The results (Moore et al. 2018) show that Jupiter's magnetic field is different from all other known planetary magnetic fields (**Figure 5**). Within Jupiter, most of the flux emerges from the dynamo region in a narrow band in the northern hemisphere, some of which returns through an intense, isolated flux patch called the Great Blue Spot near the equator. Elsewhere, the field is much weaker. The nondipolar part of the field is confined almost entirely to the northern hemisphere, where the field is strongly nondipolar. In the southern hemisphere it is predominantly dipolar. This suggests that Jupiter's dynamo, unlike Earth's, does not operate in a thick, homogeneous shell, and it is proposed that this unexpected field morphology arises from radial variations, possibly including layering, in density or electrical conductivity, or both. Interestingly, this complexity is also suggested in the complex gravity models discussed earlier (Section 6.1).

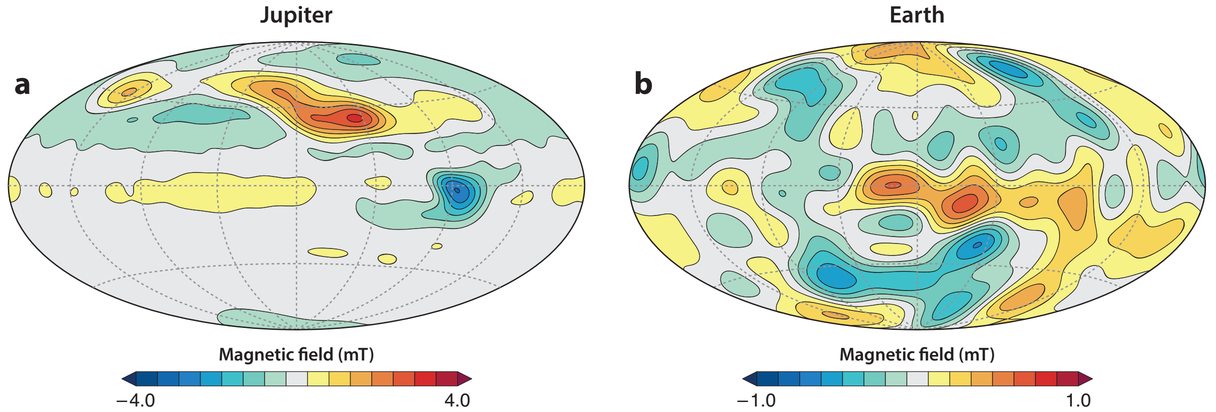

Figure 5

(*a*) The nondipolar part of Jupiter's radial magnetic field at $r = 0.90\ R_J$. (*b*) For comparison, the nondipolar part of Earth's radial magnetic field at the core-mantle boundary ($r = 0.55\ R_E = 3{,}485$ km, where R_E is Earth's radius). Almost all of Jupiter's nondipole radial field is concentrated in the northern hemisphere, whereas Earth's field is evenly distributed throughout. Figure adapted from Moore et al. (2018).

7.2. Secular Variation

The first clue to the dynamic character of Earth's field emerged from considering how the field changes over geologic time. We call this secular variation, and it is sometimes visualized as a rotation of the field relative to a frame fixed to the mantle (so-called westward drift) but is in fact more complex. Comparison of the magnetic field from Juno data with observations from the Pioneer 10 and 11, Voyager 1, and Ulysses spacecraft indicates a consistent, systematic change in the field over this 45-year time span that cannot be explained by changes in the magnetospheric field nor by changing the assumed rotation rate of Jupiter (Moore et al. 2019). Furthermore, the inferred change in the field is consistent with advection of the field by Jupiter's zonal winds, projected down to between 93% and 95% of Jupiter's radius, a depth range at which electrical conductivity of the hydrogen envelope becomes sufficient to advect the field. The fact that a simple zonal wind model, determined independently from atmospheric and gravity-field observations, explains much of the inferred secular variation of the field not only lends independent support to the determination of the secular variation of the field but also demonstrates that zonal wind interactions with the magnetic field are likely to be an important process within Jupiter.

8. JUNO MICROWAVE OBSERVATIONS

8.1. The Big Surprise

In the usual notion of how atmospheres work, we expect the mixing ratio of a condensable in a convecting atmosphere to be uniform up to the level at which the partial pressure of the condensable equals the locally determined vapor pressure. Above that level, clouds form and a lower temperature then leads to a lower mixing ratio. Previous ground-based infrared and radio-wave observations (de Pater et al. 2016) indicated ammonia depletion to 4 bars. Surprisingly, Juno's MWR results (Bolton et al. 2017, Li et al. 2017) have shown that, contrary to expectations, the concentration of ammonia is still variable down to pressures of tens of bars in Jupiter, far deeper than the level of condensation. The proposed explanation is exotic (mushballs!).

8.2. Mushballs

While mid- and high latitudes show a general depletion of ammonia, the equatorial zone of Jupiter has an abundance of NH_3 that is nearly uniform. In parallel, Juno determined that the equatorial zone is peculiar for its absence of lightning, which is otherwise prevalent everywhere else in the planet (Brown et al. 2018). T. Guillot et al. (unpublished article) show that a model accounting for the presence of small-scale convection, water storms, and large plumes originating in Jupiter's deep atmosphere can explain the observations by invoking mushballs: fist-sized aggregates of water ice and very cold water-ammonia solution (**Figure 6**). At midlatitudes, where thunderstorms powered by water condensation are present, ice particles may be lofted high in the atmosphere, in particular into a region located at pressures between 1.1 and 1.5 bar and temperatures between 173 and 188 K, where ammonia can dissolve into water ice to form a low-temperature liquid phase containing about one-third ammonia and two-thirds water. T. Guillot et al. (unpublished article) estimate that, following what occurs for hailstorms on Earth, this liquid phase enhances the growth of hail-like particles (mushballs). Their growth and fall over many scale heights can effectively deplete ammonia and by consequence water in a large fraction of the atmosphere. In the equatorial zone, the absence of thunderstorms shows that this process is not occurring, implying that small-scale convection can maintain a near homogeneity of this zone. This view requires that the abundance be of order solar or greater, and C. Li et al. (unpublished article) find water to be 2 ± 1 solar.

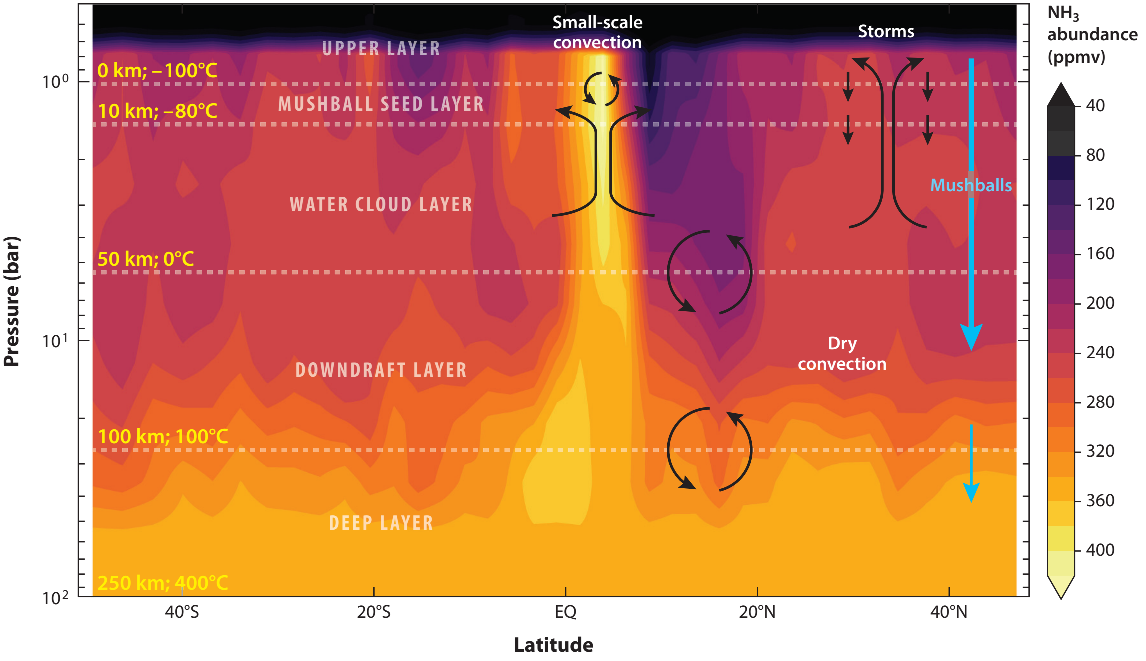

Figure 6

A schematic suggestion for the dynamics of the atmosphere of Jupiter. This shows the average map of ammonia abundance in Jupiter retrieved by the Juno spacecraft during perijove 1 (PJ1) to PJ9 as a function of latitude and pressure. Overlaid are indications of altitude and temperature as well as the layers and mechanisms (small-scale convection and/or storms in the water condensation region, dry convection deeper) considered. Water vapor condenses to ice particles at the 5-bar level (0°C), ~50 km below the 1-bar level.

9. COMPARISON WITH SATURN

At the same time we have gathered information using Juno, the Juno Principal Investigator suggested that Cassini enter into a Juno-like orbit to enable similar-quality data for the gravity and magnetic fields of Saturn. This opportunity highlighted an already-known difference between the planets: The magnetic field of Saturn is exceptionally spin axisymmetric, so much so that it is not possible to discern a dipole tilt or a deep-seated rotation rate (Cao et al. 2019). Jupiter, by contrast, has a complex field, initially thought to be Earthlike but now seen to be unique (see Section 7.1). The striking character of the Saturnian field is not yet understood, although certainly the presence of strong winds and static stability (cf. Mankovich et al. 2019) could aid the axisymmetrization (Stevenson 1982b).

The most striking new difference between the two planets was in the effect of the differential rotation on their respective gravity fields. In Jupiter, differential rotation shows up in the odd harmonics and is not a significant player in the even harmonics. In Saturn, the differential rotation shows up weakly in the odd harmonics but so strongly in the even harmonics that it may confound attempts to get a much more precise picture of the interior (unlike Jupiter). Why are these differences so striking? The answer lies in something explained early in this review: Despite being over a factor of three less massive, Saturn is almost as large as Jupiter. Accordingly, one must go three times as far down into the planet to encounter the equivalent thermodynamic conditions (pressure, temperature, electrical conductivity). The zonal flows are accordingly stronger and more nearly axisymmetric in Saturn because the shell of non-MHD flow is much thicker. This fits with the much larger and even gravity field signal of Saturn's winds.

Did Jupiter and Saturn form in the same way? It is too soon to say. If we can get a better understanding of the density structure of Saturn, perhaps through kronoseismology (Mankovich et al. 2019), we might be able to decide this and discern the dilute core feature that emerged for Jupiter. It is unlikely to come straightforwardly from the usual even harmonics of static gravity for the reasons explained above. There is no guarantee, however, that Jupiter and Saturn formed by the same mechanism.

10. PUTTING IT ALL TOGETHER

Juno has surprised us, and in large part that defines its success. It has also clarified and improved our understanding of Jupiter. The very high precision gravity data support a view that also emerges from our understanding of formation: Jupiter has a central concentration of heavy elements, but that core may be diffuse, a legacy of the planet formation and evolution. It is not yet clear whether the claimed diffuse core is consistent with formation ideas, although the wild card of a giant impact may permit agreement. Juno gravity has enabled determination of the structure of the zonal winds so that for the first time we know something about how deep the differential rotation extends, suggesting a possible MHD connection between the magnetic field and the flow. The odd gravity harmonics were key, although the north-south asymmetry that allowed for this remains to be explained. Most probably, it can arise because the shell in which MHD effects are important is so thin that regions north and south of the equatorial belt do not communicate fluid dynamically with each other. Jupiter's magnetic field turns out to be unique for reasons that may well be related to the unusual internal structure. Time variation of the field suggests a connection between the winds we see and the field we measure. Most surprisingly, the deep atmosphere is not homogeneous, a possible consequence of the peculiar thermodynamics of the water-ammonia system, allowing for the presence of a liquid that is very cold and rich in ammonia. A key observation, the water abundance, has proved difficult to obtain as a consequence. This review does not do justice to what we have learned from MWR, even though it is suspected that here is a connection between our growing understanding of the interior and our still-incomplete understanding of the deep atmosphere. But emerging from all this is a perspective that Jupiter is central to understanding how planets in our Solar System formed: It is more massive than all the other planets combined, it is mostly an electrically conducting form of hydrogen, it has a large and complex magnetic field as a consequence, and it has secrets still to be unlocked.

DISCLOSURE STATEMENT

The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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