Metallic helium in massive planets

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The most abundant planetary constituents in the universe are hydrogen and helium. In our own solar system, it is estimated that >70% of the planetary mass is of this form, with most of it residing in Jupiter and most of it in a metallic state. The likely metallic state of hydrogen at high pressure has long been recognized (1), although the exact nature of this state and its properties continue to be debated (2). Helium, on the other hand, is generally thought to be a reluctant partner to hydrogen at high pressure because its expected metallization pressure at low temperature is very high, perhaps around 100 Megabars (Mbar) or more. In comparison, the highest pressure in the hydrogen–helium part of Jupiter is perhaps only 40 or so Mbar (3). This suggests that most of Jupiter's interior consists of a mixture of metallic hydrogen fluid (protons in a degenerate electron sea) and neutral helium atoms, with the latter making up about a quarter of the mass but only 7% of the nuclei by number (Fig. 1). In this issue of PNAS, Stixrude and Jeanloz (4) show that band closure in pure helium occurs at lower pressures than previously thought, provided the effect of high temperatures is taken into account. This suggests that helium behaves as a metal, at least at the highest pressures encountered in Jupiter and perhaps over a wider range of pressures in the many, often much hotter, planets of Jupiter's mass and larger that are now evidently common in the universe (5). The full thermodynamic and transport properties of the relevant mixtures cannot be deduced from the behavior of the end members (pure hydrogen and pure helium) and are therefore an area of ongoing research.

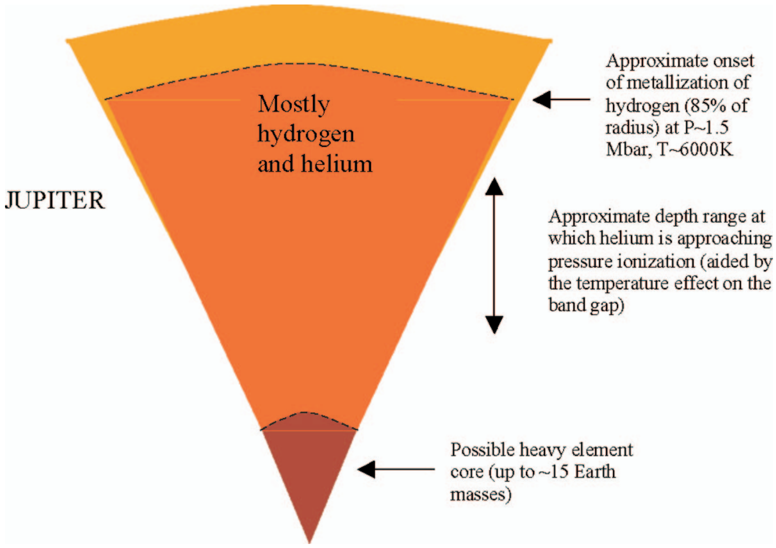

Fig. 1. Cross-sectional view of Jupiter.

Planets are "cold" in the sense that the energies of the electrons, either as bound states or as a degenerate electron gas, are large compared with thermal energies. For example, a typical internal temperature of Jupiter is 10,000 K, corresponding to $k_BT \sim 1$ eV, whereas the low-pressure band gap in helium is ~20 eV. However, planets can be hot compared with the melting point or Debye temperature. All giant planets, inside and outside our solar system, are likely to be in a fluid state throughout (with the possible exception of a central core of heavier elements). For many years it has been assumed that this enormous difference in energy scales would justify seeking guidance from low-temperature or zero-temperature results, so that the insulating state of $T = 0$ K helium at high pressure could be assumed to have relevance, even though the planet was in a fluid state. In retrospect, this was not a particularly good assumption. We have long known that the sharply defined band gap of a crystal becomes an often much smaller mobility gap (or no gap) in a liquid or amorphous material. The interplay of structure with electronic character is thus intimate and not easily understood by a simple comparison of k_BT with typical electronic energies, even though the underlying assumption of electron degeneracy still holds firm. As Stixrude and Jeanloz (4) discuss, experiments over the past decade had already cast doubt on a simple picture in which finite temperature effects are merely a small correction to the zero-temperature electronic structure and equation of state. Hydrogen is one such example, given that its electrical conductivity rises dramatically at around 1 Mbar or so (2) and at a temperature of a few thousand degrees, whereas room-temperature hydrogen is insulating at the same pressure. However, hydrogen has the additional complication of molecular dissociation, whereas helium should be comparatively simple.

These latest calculations use molecular dynamics but with the electronic structure determined through density functional theory. Although density functional theory is not first-principles quantum mechanics, it has a well established ability to produce accurate results if carried out with sufficient computational power. Indeed, this area of computation is advancing at an impressive rate, not so much through fundamental breakthroughs as through the growth of computational resources. (Molecular dynamics has been around for many decades, and density functional theory has also existed for several decades). Stixrude and Jeanloz (4) argue convincingly that their results represent a marked improvement over previous work.

What are the consequences for giant planets? Certainly the authors' results are of greatest relevance for planets more massive, or with higher specific entropy, than Jupiter, and there are many such planets. The cooling of giant planets from their initial hot state is affected by their size (3) (more massive planets have higher specific entropy at a given age, other factors being equal) but also by their external environment ("hot Jupiters" are close to their parent stars and are thereby prevented from cooling efficiently). But even in Jupiter, the results may have significance for the behavior of the deeper regions, where

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the temperature is perhaps 15,000 K and the pressure is >10 Mbar (much deeper than the conventional definition of where Jupiter becomes metallic). Metallization will modify the thermodynamics through the pressure–density relationship but also through the way in which temperature increases with density along an isentrope—the expected state for a convecting planet. The latter is characterized by the Gruneisen γ, a dimensionless parameter typically of order unity. One might expect a significant decrease in γ should an increase in temperature promote pressure ionization (in effect soaking up energy to change the electronic state rather than the motion of the atoms). Stixrude and Jeanloz (4) see only a modest effect in γ. Of course, the actual consequences for a giant planet can only be assessed by calculating the properties of a hydrogen–helium mixture; they cannot be determined from study of the end members alone (notwithstanding the time-honored practice of such attempts in planetary modeling). Recent research (6) has examined hydrogen–helium mixtures at a similar computational level, and more work is in progress.

Perhaps the most interesting issue raised by Stixrude and Jeanloz (4) is the solubility of helium in hydrogen. Salpeter (7) proposed that the formation of helium raindrops in planets such as Jupiter and Saturn might provide an ongoing source of energy release in addition to that provided by secular cooling from an initial hot state. In the first serious attempt to calculate the thermodynamic properties of hydrogen–helium mixtures (8), it was assumed that each helium atom contributed both its electrons to a nearly uniform Fermi sea, and it was found that limited solubility is driven by the difference in nuclear charge, not by the possibility that helium is neutral.

Band closure in pure helium occurs at lower pressures than previously thought.

Indeed, subsequent work (9) confirmed that in the asymptotic high-pressure limit, helium and hydrogen should phase-separate at sufficiently low temperature, perhaps around 5,000 K or so. This limit can be thought of as a classical "plasma" of protons and alpha particles in a uniform neutralizing background of electrons. However, it subsequently became common practice to appeal to the likelihood that helium insolubility was driven by the electronically unfavorable environment of neutral helium atoms in an electron sea provided by metallized hydrogen. Indeed, the low solubility of noble gases in metals can be thought of as arising from a repulsive pseudopotential (10) (the cost of orthogonalizing the itinerant electronic states to the bound states on the helium atom). Stixrude and Jeanloz provide a basis for the unlikely applicability of this view—at least at the highest temperatures in the giant planets—but because the estimates for insolubility are at lower temperatures, it is unclear whether this answers the question. As for the planets themselves, there is some evidence of insolubility operating in Jupiter, although the effect on composition, evolution, and structure is weak at best. The best evidence (11) is indirect: Neon was observed by the Galileo probe to be depleted in the atmosphere of Jupiter by an order of magnitude relative to solar abundance, and this is most reasonably explained by the partitioning of neon into helium raindrops. Certainly there is a need to understand neon better—not so much as pure neon but as a dilute mix of neon atoms in the environment provided by metallic hydrogen. Saturn may still the best case for a large effect of helium rain-out, but there is currently no direct and reliable means of measuring helium in Saturn's atmosphere by remote sensing. We need the equivalent of the Galileo probe, planted in Saturn.

The past decade has seen a remarkable upsurge in information about planets outside our solar system, along with the recognition that Jupiter may hold clues to many aspects of the origin and structure of our own system, including the existence and nature of Earth. We can look forward to additional contributions to these important scientific questions through first-principles (or nearly first-principles) quantum mechanical calculations, and also through experiments and space exploration.

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