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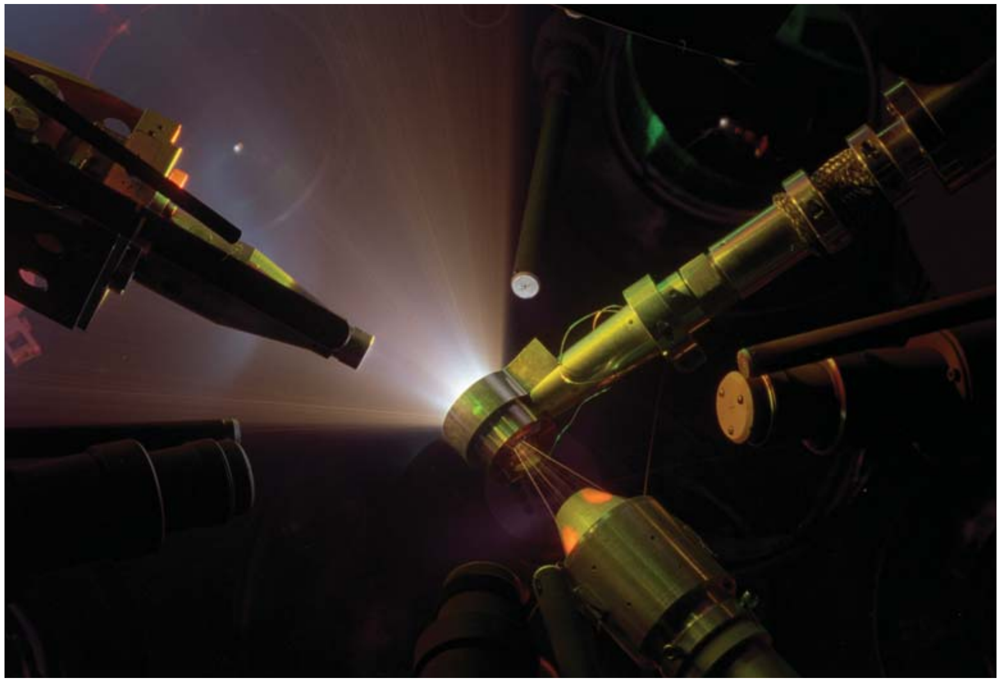

FIGURE 1. COMPRESSION EXPERIMENTS. At the University of Rochester's Laboratory for Laser Energetics, researchers uncovered new phase behavior in a mixture of hydrogen and helium gas. The cylindrical diamond anvil cell in the center of the photo compressed the gas sample statically before a laser-induced shock wave propagated through the sample and squeezed it dynamically to the pressure and temperature range of Jupiter's interior. (Photo courtesy of OMEGA Laser Facility.)

By mass, the giant gaseous planets Jupiter and Saturn consist of about 75–85% hydrogen and helium. (Uranus and Neptune, by contrast, are ice giants and contain far greater proportions of ammonia, methane, and water.) Researchers have hypothesized that the remaining composition of Jupiter and Saturn could be a few other gases, ice, and rock. Determining what those exact fractions are and how the planetary structures evolved over time depends critically on the H–He equation of state.

On the surface of gas giants, hydrogen and helium form a homogeneously mixed layer. In the 1970s, physicists predicted that at the high temperatures and pressures inside gas giants, the two lightest elements may separate and form a region of demixing, or immiscibility.[1] Today scientists know that at some depth in the planet's interior, molecular hydrogen dissociates and ionizes to form metallic fluid hydrogen. The helium is expelled from the mixture and is predicted to rain down from the immiscibility region to another layer, in which the conditions allow hydrogen and helium to mix again. Jupiter's central core is suspected to be solid.

Since that first prediction, many scientists have sought to better describe where in the planet's interior the H–He phase separation occurs and how gas giants are structured. Condensed-matter models based on density functional theory, for example, begin from the basic principles of quantum mechanics to approximate the system's electron density (see the article by Andrew Zangwill, PHYSICS TODAY, July 2015, page 34).

Despite such efforts, uncertainties remain. Models of H–He mixing in planetary interiors are highly dependent on the particular functional form a researcher chooses, and no model reliably describes the range of experimental results. Another challenge is accounting for the entropy within a mixed system of hydrogen and helium, which makes the calculations difficult.

Laboratory measurements are also challenging. Researchers studying H–He mixing with standard static compression methods using a diamond anvil cell must contend with the hydrogen's reactivity with the diamonds. On the other hand, dynamic compression with a laser-induced shock wave demands an initially homogeneous H–He mixture with a density three times that of cryo-liquid hydrogen to span the pressure conditions of a planetary interior.

Fifteen years ago, Stephanie Brygoo and Paul Loubeyre of the French Alternative Energies and Atomic Energy Commission; Raymond Jeanloz of the University of California, Berkeley; and their colleagues began blending the two types of high-pressure experiments. Their recent results not only support the existence of an immiscibility region in Jupiter but also provide experimental evidence for a four-layered planetary structure that's consistent with indirect spacecraft observations.[2]

Shining hydrogen

Jupiter's interior temperatures span thousands of kelvin, and its pressures span hundreds of gigapascals, about 1 million to 40 million times that of Earth's atmosphere. To reach such high pressures and temperatures in the lab, Brygoo and colleagues subjected samples of homogeneously mixed hydrogen and helium to static compression followed by dynamic compression. The researchers modified the apparatus so that one diamond window was only 300 μm thick, far thinner than the typically millimeters-thick walls of the anvil.

In the experiment, a diamond anvil cell first squeezed the samples to 4 GPa. The modifications allowed a laser-induced shock wave to propagate through the diamond window without deteriorating. Using the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics, the researchers compressed the samples further, to pressures up to about 200 GPa.

Figure 1 shows the experimental apparatus at the moment that the laser shock wave propagated through the hydrogen and helium sample, which was squeezed first by the diamond anvil cell. Sébastien Hamel of Lawrence Livermore National Laboratory says that "compressing hydrogen to such a degree without cracking the diamonds used to apply pressure, combining the static compression with laser-based shock waves to reach the required conditions, and building the diagnostic tools necessary to make the observations were incredible challenges that this team overcame."

During the experiment, Brygoo and her colleagues observed a sudden change in reflectivity of the laser light bouncing off the H–He mixture as the shock front passed through the sample. *Ab initio* calculations and theory predict that as the H–He mixture becomes conductive, insulating helium separates from metallic hydrogen. The effect increases reflectivity, a measurable signature of the phase separation. Loubeyre says that he and his colleagues "were not expecting such a clear discontinuity. It was expected to be smaller than what we observed."

Figure 2a shows the H–He mixture's phase diagram with the predicted demixed region colored in pink. The data, which are similar to previously published theoretical predictions,[3] indicate that the samples reached the temperature–pressure conditions of Jupiter's interior as the shock wave propagated through the system. "Phase separation has started rather recently in Jupiter, so the distribution of helium is not completely perturbed," says Loubeyre. Therefore, if the helium distribution is constant, the researchers estimate that about 15% of Jupiter's radius—the pink shaded region in figure 2b—forms an immiscibility region.

Reconciling observations and theory

The new laboratory results help tie together different spacecraft observations of Jupiter. In 1995, NASA's *Galileo* probe collected measurements of the helium abundance in Jupiter's atmosphere and found it smaller than the presolar value—the abundance thought to be present at the formation of the solar system.[4]

NASA's *Juno* probe, however, recorded measurements of a high gravitational moment in 2016 that indicated a model discrepancy.[5] The observations suggest that the planet's interior density should correspond to a high helium abundance in the outer layer. To reconcile the *Galileo* observations with the *Juno* measurements, modelers had to make modifications to the H–He equation of state.

The results reported by Brygoo and her colleagues appear to resolve the issue by providing experimental support for a Jupiter with four distinct layers. The immiscibility region lies between the homogeneously mixed H–He outer layer observed by *Galileo* and the deeper, well-mixed metallic H–He layer compatible with the *Juno* measurements. A fourth layer—a dense core of mostly heavy elements—lies at the center of the planet.

According to planetary scientist Christopher Mankovich of Caltech, observing the separation of hydrogen and helum "is a pretty big deal. The existence of this immiscibility region is an approximately 40-year-old idea that has shaped much of our thinking about the structures of Jupiter and Saturn. Finally there is a modicum of compelling experimental evidence."

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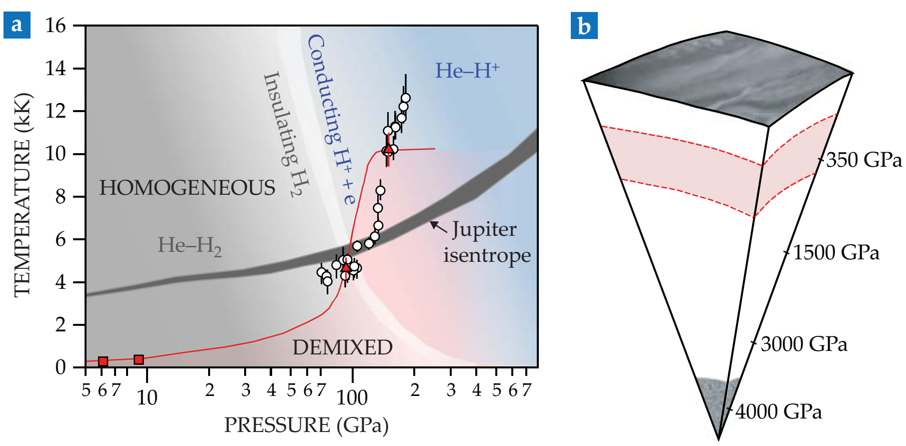

FIGURE 2. JUPITER'S IMMISCIBILITY REGION. (a) Previously collected reflectivity data from static compression experiments (red squares) and new dynamic compression measurements (red triangles) suggest a boundary (red line) between the predicted homogeneous and demixed regions of the H–He phase diagram. The white circles indicate that the samples span a region of phase space where hydrogen and helium separate. That Jupiter's temperature–pressure conditions cross the demixed region means that an immiscibility layer likely exists in the planet's interior. **(b)** With a constant helium distribution, the immiscibility layer (pink shading) spans about 15% of the planet's total radius. (Adapted from ref. 2.)

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