Study of liquid hydrogen provides important data for planetary models

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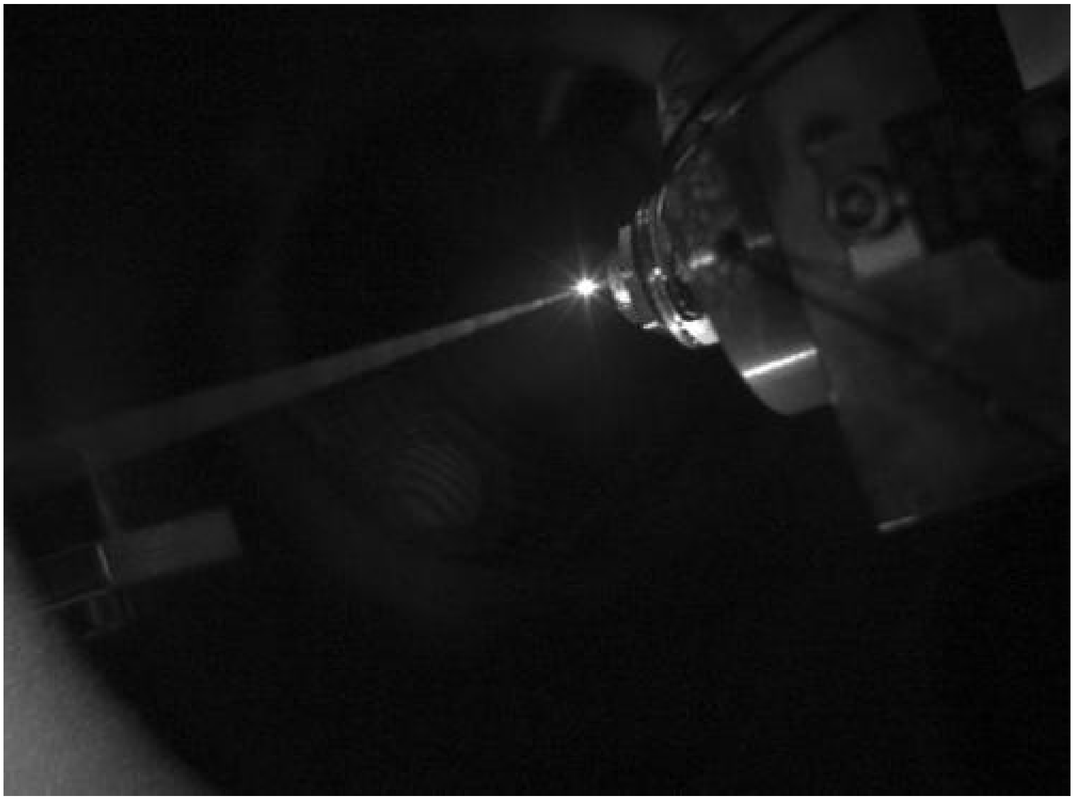
The gas giant Jupiter, captured by the US-European space ship Cassini-Huygens. Credit: NASA/JPL/Space Science Institute

Using DESY's X-ray laser FLASH, researchers took a sneak peek deep into the lower atmospheric layers of giant gas planets such as Jupiter or Saturn. The observations of the team around lead author Dr. Ulf Zastrau from the University of Jena reveal how liquid hydrogen becomes a plasma, and provide information on the material's thermal conductivity and its internal energy exchange, which are important ingredients for planetary models. The scientists present their experiments in Friday's issue of the scientific journal *Physical Review Letters*.

The atmosphere of gas giants consists mainly of hydrogen, which is the most abundant chemical element in the universe. "We have very little experimental knowledge about the hydrogen in the interior of such planets," says Zastrau. "This is despite our very good theoretical models." The researchers therefore decided to use cold liquid hydrogen as a sample of the planetary atmosphere. "Liquid hydrogen has a density that corresponds to that of the lower atmosphere of such giant gas planets," explains Zastrau. The scientists used DESY's X-ray laser FLASH to heat liquid hydrogen, almost instantaneously, from minus 253 to around 12,000 degrees Celsius and simultaneously observed the properties of the element during the heating process.

Hydrogen is the simplest atom of the periodic table, consisting of a single proton in the atomic nucleus, which is orbited by a single electron. Normally, hydrogen occurs as a molecule consisting of two atoms. The X-ray laser pulse initially heats only the electrons. These slowly transfer their energy to the protons, which are around 2,000 times heavier, until a thermal equilibrium is reached. The molecular bonds break during this process, and a plasma of electrons and protons is formed. Although this process takes many thousands of collisions between electrons and protons, the studies showed that the thermal equilibrium is attained in just under a trillionth of a second (a picosecond).

Astrophysics in the lab



The hydrogen jet inside the sample chamber. Credit: Sven Toleikis/DESY

"We are carrying out experimental laboratory astrophysics," explains Zastrau. Until now, researchers have relied on mathematical models to describe the interior of gas giants such as Jupiter. Important model parameters include the dielectric properties of hydrogen—for example, the thermal and electrical conductivities - which are crucial to correctly simulate the massive, outward-directed heat flows in giant gas planets.

"The study has revealed the dielectric properties of the liquid hydrogen," reports co-author Dr. Philipp Sperling from the University of Rostock. "When you know the thermal and electrical conductivities of the individual layers of hydrogen in the atmosphere of a giant gas planet, you can calculate the associated temperature profile." The researchers' experiments enabled them to locate a first point in the phase diagram of hydrogen. The experiments will have to be repeated at other temperatures and pressures in order to create a detailed picture of the entire planetary atmosphere.

The study requires a great deal of effort, in part because hydrogen does not normally exist in liquid form on earth. In order to liquefy hydrogen gas, it first must be cooled to minus 253 degrees Celsius. "We use extremely pure hydrogen gas and force it through a copper block that is cooled by liquid helium," explains DESY researcher Dr. Sven Toleikis, a member of the team. "The temperature must be very precisely controlled during this process. If the hydrogen gets too cold, it freezes and blocks the line," says Toleikis. In such cases, a small heater is used to re-liquefy the hydrogen as needed. At the end of the copper block, a nozzle projects like a finger into the experimental vacuum chamber. From its tip flows a fine jet of liquid hydrogen with a diameter of just one fiftieth of a millimetre (20 micrometres). This experimental setup has been developed in the course of many years of cooperation between the University of Rostock and DESY.

Super-slowmo

In order to study the properties of liquid hydrogen as it vaporizes, the researchers shot the intense pulses of DESY's FLASH soft X-ray laser at the fine jet. "For the experiment, we used FLASH's unique ability to split up the individual flashes," explains Toleikis. "The first half of the flash heats up the hydrogen, and we use the second half to investigate its properties." Using the Split-and-Delay Unit, which was developed in cooperation with the University of Münster and the Helmholtz-Zentrum Berlin, the second half of the flash is deliberately delayed by a tiny fraction of a second (up to 15 picoseconds, i.e. trillionth of a second). By studying the system in this way with slightly different delay times, the way in which a thermal equilibrium is established between the electrons and the protons in the hydrogen can be observed similar to a super-slow motion camera.

The interpretation of the observation data was not simple, however. "It took us a long time to understand what was actually happening in the experiment," says Prof. Ronald Redmer, who leads the Rostock working group. The researchers made use of density functional theory—a standard tool of quantum physics which is used to describe systems with many electrons—to model the process. However, this standard procedure does not work for systems with two different temperatures, as in the FLASH experiment. "Before we were able to correctly describe the observations, we had to extend density functional theory with a two-temperature model," reported Redmer.

"Our experiment showed us the way of how to investigate dense plasmas with X-ray lasers," says Dr. Thomas Tschentscher, scientific director of the European XFEL X-ray laser, at which experiments will be possible in 2017. "This method opens up the road for further studies, e.g. of denser plasmas of heavier elements and mixtures, as they occur in the interior of planets. Hopefully, the results will provide us among others with an experimentally based answer to the question, why the planets discovered outside our solar system do not exist in all imaginable combinations of properties as age, mass, size or elemental composition, but may be allocated to certain groups."

In addition to the universities of Jena and Rostock and DESY, researchers from the US research centres SLAC National Accelerator Laboratory and Lawrence Livermore National Laboratory, the Helmholtz Institute Jena, the University of Oxford, the GSI Helmholtz Centre for Heavy Ion Research, the Hamburg Centre for Ultrafast Imaging (CUI), the University of Münster and the European XFEL also participated in the study. The work was supported by the Federal Ministry of Education and Research (BMBF) as part of the research topics (FSP) 301 and 302 and by the VolkswagenStiftung by a Peter Paul

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