Future Space Travel and Technologies: Metallic Hydrogen To Make The Unknown Known

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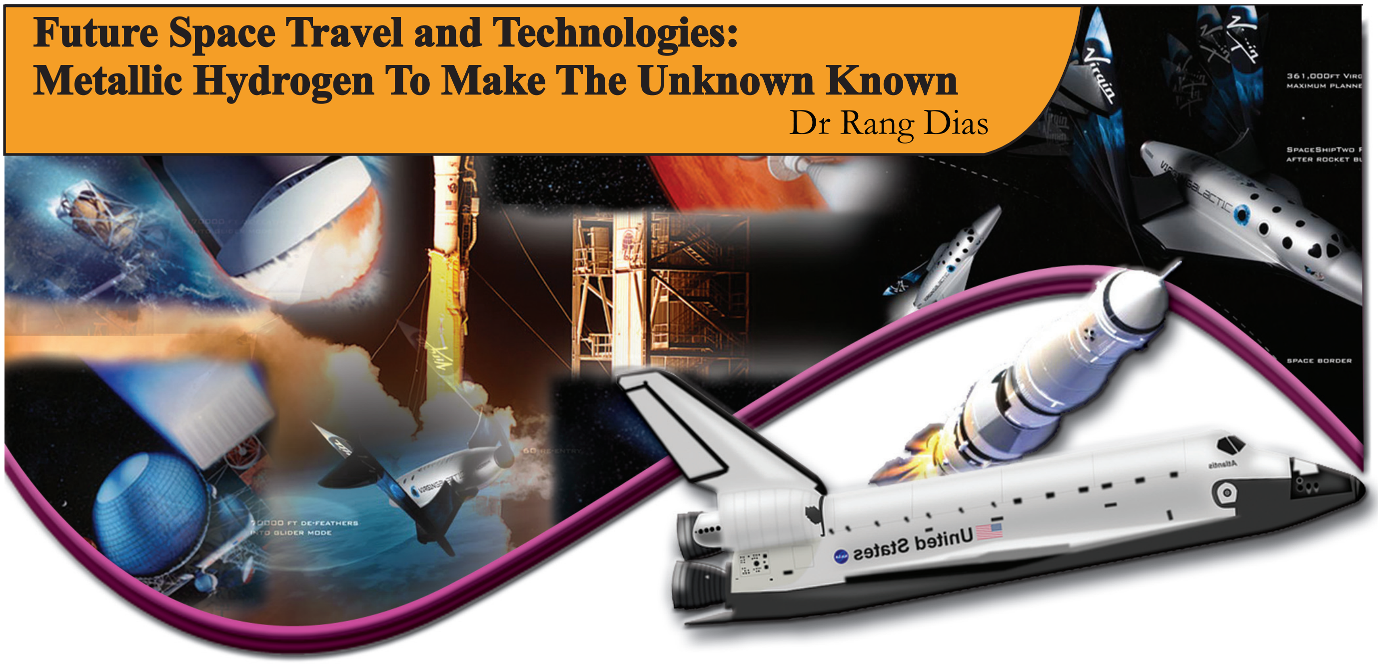

Hydrogen is the simplest and most abundant of elements. Composed of one proton and one electron, it makes up 90% of our universe. On earth, hydrogen is commonly found as a diatomic molecular gas. But on Jupiter/Saturn, where interior pressure is millions of times greater than that at our planet's surface, the hydrogen molecule is theorized to exist as a superhot liquid. Of course, it is no ordinary liquid, even if it is the most common element in the universe. Despite its simple atomic structure, hydrogen has proved to be much more complicated than scientists had imagined. Ordinarily a gas consisting of diatomic (two-atom) molecules, hydrogen can be cooled to a liquid (below 20 kelvins, or –253 degrees Celsius) and to a solid (below 14 kelvins). In all these states, hydrogen is normally an electrical insulator, but in the 1930s it was first predicted by Wigner and Huntington that subjecting hydrogen to extreme pressure found deep inside Jupiter, would cause the molecules to dissociate (break apart into atoms) thereby turning hydrogen to behave as a metal that can conduct both heat and electricity.

What is more, in 1968 Neil W. Ashcroft of Cornell University suggested that, under certain combinations of pressure and temperature, hydrogen atoms would rearrange themselves into a new kind of quantum liquid with attributes of both superconductors, which conduct electricity without resistance, and superfluid, which flow without resistance. Such exotic behaviors become particularly interesting if some of these phases of hydrogen turn out to be metastable where the phases could retain their high pressure forms for an indefinite period once external forces are removed, similar to diamonds formed by high temperatures and pressures deep inside Earth remaining diamonds even after they reach the surface, instead of immediately reverting back to carbon's more stable form, graphite. It might be used as a room-temperature superconductor, a material that physicists have been seeking for decades. It might also serve as a compact energy source and as a lightweight building material. This lightweight high energy density material can be used as rocket fuel that packs nearly four times as much propellant power per kilogram as the liquid hydrogen used in the most powerful rockets today. This would certainly revolutionize rocketry, allowing single stage rockets to enter orbit and chemically fueled rockets to explore our solar system. Production of metallic hydrogen in the laboratory is one of the great challenges of high-pressure physics.

Although efforts to metallize hydrogen have increased extensively in recent decades, prompting numerous experiments at high pressure, and uncovering increasing complexity, daunting experimental challenges have left researchers in the field on a constant quest to observe this elusive state of the element.

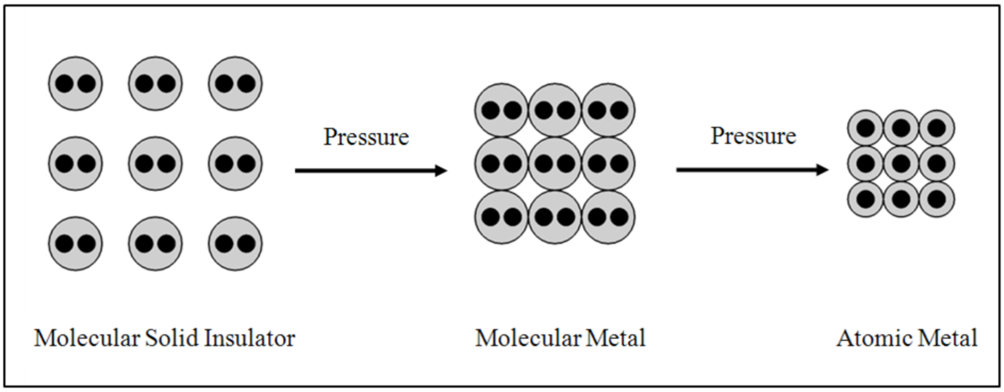

Fig. 1 : Schematic production of solid hydrogen at low pressure (left) and high pressure (right). Molecules in ordinary hydrogen (left) are well separated, and the electrons—shown as clouds of negative charge—stay close to the pairs of protons. But high pressure pushes the molecules so close to one another that the electrons can easily hop from one molecule to the next, thus creating an electric current when a voltage is applied to the liquid (right).

Since the work of Wigner and Huntington, there have been numerous calculations of the critical pressure needed for the dissociative transition from molecular to solid atomic metallic hydrogen. On the atomic scale, what happens during metallization is that some of the hydrogen's electrons are freed from their molecules. At low pressures, the tendency for two hydrogen atoms to form a molecule is extremely strong, so the liquid hydrogen contains only molecules. Each molecule contains a pair of protons surrounded by a cloud of negative charge. Because it takes a relatively large amount of energy (15 eV)— to remove an electron from a hydrogen molecule, the molecular hydrogen fluid cannot carry a current: it is electrically insulating. This situation changes however, as the hydrogen molecules are pushed together. The electronic mobility gap, that is, the energy required to remove an electron from a molecule so that it can conduct an electrical charge— decreases as the molecules move closer together [see figure 1]. However, phase transition calculations that seek the structure with the lowest lattice energy, have difficulty in handling the zero-point energy contribution to the total energy. As a result, the predicted critical transition pressures have an enormous variation, from as low as 0.25 Mbar to over 20 Mbar, while recent predictions are in the 400 to 600 GPa range [see figure 2].

The metastability of metallic hydrogen depends on temperature and pressure. Above some temperature there will be sufficient thermal energy in the atomic lattice for the atoms to rise above the potential barrier and recombine into hydrogen molecules, releasing the energy of recombination, 216 MJ/kg (note: the dissociation energy of a hydrogen molecule is 4.68 eV). This is more than twenty times the specific energy released by the combustion of hydrogen and oxygen in the Space Shuttle's main engines, 10 MJ/kg. Because of this very large potential specific energy, it is interesting to explore the possible use of metallic hydrogen as an energy source for rocket powered launch vehicles. A rocket engine is fundamentally a quite a simple device. Liquid fuel and oxidizer are injected into a reaction chamber where combustion releases the chemical energy producing a hot gas. The hot combustion products exit the chamber at fairly high pressure through a throat and then expand out of a nozzle. In rocketry one of the characteristics of a propellant is its specific impulse, related to the thrust (specific impulse represents the number of seconds that a thrust of one kilogram of force (Newtons) can be sustained by one kilogram mass of propellant). Liquid (molecular) hydrogen-oxygen used in modern rockets has a specific impulse of ~460s; while metallic hydrogen has a theoretical specific impulse of 1700s. Such a fuel would allow single-stage rockets to enter into orbit or carry economical payloads to the moon. The metallic hydrogen can be carried in a small spherical tank inside the liquid hydrogen diluents tank. Therefore metallic hydrogen propelled vehicles clearly can revolutionize rocketry. If pure metallic hydrogen is used as a propellant, the reaction chamber temperature is calculated to be greater than 6000 K, which is too high for currently known rocket engine materials. By diluting metallic hydrogen with liquid hydrogen or water, the reaction temperature can be reduced, yet there is still a significant performance improvement for the diluted mixture.

Despite the promise of this material, several challenges must be overcome before they can be used in applications. The metallic

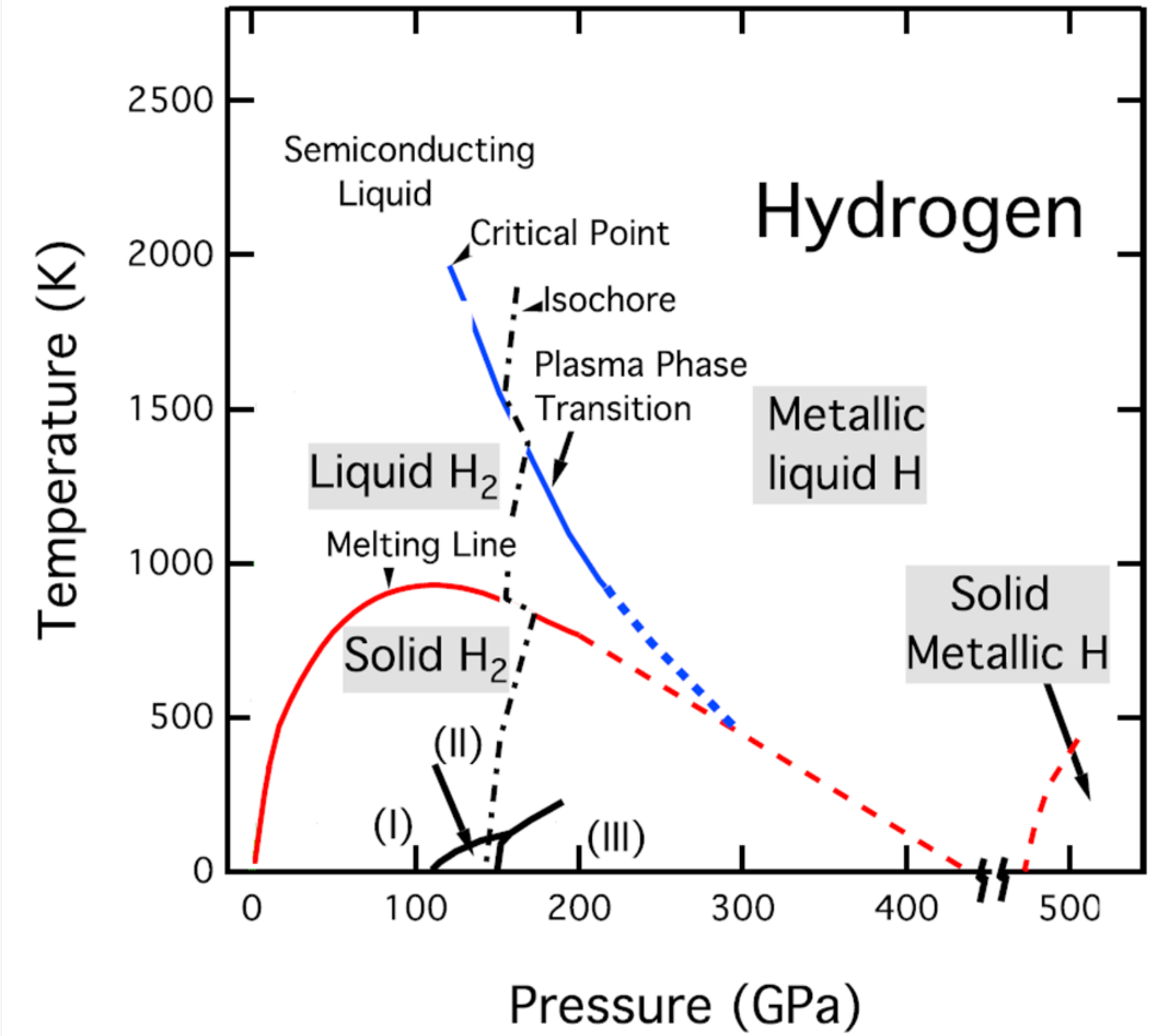

Fig. 2 : Phase diagram of hydrogen. The blue line represents the molecular-to-monatomic liquid transition (Plasma Phase Transition) and red line shows the melting line. Black lines are solid phase boundaries separating I, II and III.

hydrogen formed under extremely high pressures and temperatures entails conditions beyond the reach of current techniques for large-scale synthesis. Furthermore, despite being metastable over a large pressure and temperature range, it is often not stable at ambient conditions. Nevertheless, the quest is to generate materials with properties that exceed those of the materials that currently exist. Mixtures of molecules allow for the possibility of tuning properties and even generating novel properties. These can occur due to the incorporation of small atoms or even extra electrons within the lattice, possibly generating internal or chemical pressure and thus "pre-compressing" the material. Although metallic hydrogen has not yet been produced, it can revolutionize rocketry, in which case the world as we know would be dramatically changed and certainly unlock the secrets of the universe to make the unknown known.

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