Student questions: Raymond Jeanloz colloquium on "From Earth to Stars: Planetary Interiors and a New Chemistry"

12/2/15

Question 1: As a member of the National Academy of Sciences Committee on International Security and Arms Control who is researching kilovolt chemistry, how do you field the questions voicing concern regarding your published results being misused?
All of the studies my research group pursue are in basic, academic science, and not related to weapons, so we have no expectation of the results being misused. However, we do have to acknowledge that some future, unforeseen application of our work might be put to harmful use (this is true in biological and medical sciences, as well as in physical sciences), and the only protection against this possibility is to teach and promote ethical behavior among scientists.

Question 2: How much political interest in your research have you noticed regarding the exploration aspect it provides instead of national security concerns?
The research as completely basic, so is both motivated by and appreciated for its exploratory nature.

Question 1: What's the significance of studying high presssure states of elements and ice?
Our hope is to understand the chemical and physical properties of materials as they exist deep inside planets, both to understand the interiors of those planets and to understand how those interiors have evolved over time.

Question 2: How can lasers generate such high pressure (GPa) for your studies? What is the theory behind?
Our samples absorb the laser light (or are coated with a material that absorbs the laser light) that comes in pulses about 1-20 ns in duration and containing roughly 1-1000 kJ of energy. Even if only a fraction of that energy is absorbed, the temperature in the part of the sample hit by the laser pulse increases by an amount given by the specific heat, about 25 J/K/mole of atoms: say 1-1000/25 = 0.04-4 K/ mole of sample, assuming 0.1 percent of the energy is absorbed. As the volume of the region heated by the laser is about 1 mm x 1 mm x 10^-4 mm = 10^-7 cm^3, and the molar volume of materials is of order 1-10 cm^3/mole of atoms, this means we are only heating about 10^-7 mole of sample, meaning temperatures of order 0.04-4/10^-7 ≈ 4 x 10^5 to 4 x 10^7 K are reached almost instantaneoulsy (in under a picosecond) inside the sample, and this generates a local pressure that can be calculated according to the thermodynamic relation ∂P/∂T)_V = alpha K ≈ 10^-5 x 10^11 = 10^6 Pa/K, where alpha and K are thermal expansion coefficient and bulk modulus (incompressibility). The result is a calculated pressure pulse of order 4 x 10^11 to 4 x 10^13 Pa, or about 4-400 million atmospheres, the pulse then progating through the rest of the sample as a high-pressure wave.

Question 1: You showed some diagrams that appear to be taken from Seager et al. (2007). One of the conclusions from that paper was that mass-radius relationships cannot distinguish between planets with high vs. low C/O. However, your work seems to assume implications for silicate planets. What are the implications of diamond-anvil experiments for carbonate planets? Presumably, the core can still be primarily iron-rich, but the mantle would not?
I think carbon-rich planets, including those with carbonates, are very interesting, and much more work needs to be done on these materials so as to be able to reach more definitive conclusions.

Question 2: You showed some diagrams regarding H2-He mixtures, and mentioned that there is a range of pressure and temperatures where they are unmixed. What does this mean for estimates of hydrogen within the earth? Hydrogen is the most abundant element in the universe, but is unconstrained for planetary interiors?
Hydrogen metallizes at pressures in Earth's core, and there is considerable research on the possibility that there is hydrogen in the core. Even if there is, Earth has lost most of its hydrogen… yet the small amount left behind is still important, because it makes up water which is thought to be important for sustaining life.

Question 1: In your work to achieve higher pressures, what are the greatest restraints to be overcome? Are they solely in the equipment being used?
Good question – the equipment is a limitation, but calibrations and standards are needed, so have to be established, as we go to more extreme conditions. In the end, the main limitation is good imagination and the need for hard work…

Question 2: What pressures and for what durations do you expect to develop in the near future?
We are barely getting to the 100 million atmosphere pressure range, and hope to get to a few (2-5?) times this value in the near future for planar experiments. We can go to higher pressures by using spherically converging waves.

Question 1: You mentioned that you have not been able to collect any of the material produced during the experiments. Would minerals created at these extreme pressures even be able to exist at the low pressures created by our atmosphere?
You are correct that the states formed at the high pressures we're exploring are very unstable (high energy), and we're not sure if we could recover these materials to ambient conditions. Still, it's worth trying – after all, diamond is an high-pressure form of carbon that is unstable at ambient conditions, yet can survive for billions of years.

Question 2: Is there a natural process that is similar to the series of "love taps" that you do in lab that don't produce a lot of heat with the extreme pressure, or are they all extremely energentic events such as two bodies colliding?
I think a bolide with a gradient in density and stiffness might come close – say an asteroid with a very fluffy regolith overlying fractured rock, overlying less fractured rock.

Question 1: If there is liquid metal at the core of massive planets, would this leave a modified magnetic signature that could be observed? Alternatively, could the magnetic signal be used to prove an ionic core?
Yes, the configuration of liquid metal layers (how many layers, how thick, etc.) can determine the nature of the magnetic, and this is something that might be observable from great distance (say, if the magnetic field interacts with particles around the planet, such as in making an aurora).

Question 2: How do you know the structure is ionic at extremely high pressure? What mechanism is used to determine this?
The transition in sodium from metallic to "ionic" (electride) is documented through a combination of x-ray diffraction and spectroscopy interpreted based on (or augmented by considering) results of first-principles quantum mechanical calculations.

Question 1: In high pressure experiments, how exactly is ramp compression achieved?
In laser-driven experiments, this is done by increasing the laser intensity continuously and gradually (albeit for only ns to tens of ns time periods). For mechanical impact experiments, this is done by creating an impactor with graded density or stiffness (i.e., density or stiffness increase quasi-coninuously across the impactor).

Question 2: Under extreme pressures, why does iron become hexagonally packed?
Hexagonal packing provides one of the most compact geometric arrangements of equal-sized spheres, and Fe transforms to this packing arrangement at about 100,000 atmospheres. What is surprising is that at even higher pressures, a few hundred million atmospheres, iron is predicted from first principles quantum mechanical calculations to become slightly less efficiently packed (body-centered cubic arrangement) because of the core electrons deep inside the atom become involved in the chemical bonding between atoms.

Question 1: Is 2 million atmospheres the universal measurement of pressure where the structure of a metal deviates from the expected trend or are there metals that deviate at completely different pressures?
The pressures vary a lot from one metal to another, we think.

Question 2: When will there be experimental data available to compare to the theoretical prediction of the compounds that were shown in your phase diagrams?
Soon in some cases (next few years), and much longer as one looks to higher-pressure states.

Question 1: What differentiates liquid metal SiO2 and liquid magma SiO2?
Magma is liquid silicate inside a planet, so liquid SiO2 could be a magma but is normally not a metallic liquid until one gets to the high pressures of large planets such as super-Earth's are thought to have.

Question 2: If the super giant planets have extremely high pressure is the core likewise an extremely high temperature in comparison to the Earth?
Yes, temperatures are higher inside the giant planets, perhaps to tens of thousands of K (Earth's central temperature is thought to be under 7000 K).

Question 1: One of your slides showed that at high PT the cooling temperature of Fe is higher than SiO. Does that mean that some planets could have a rocky inner core and an outer iron core?
Rock will remain less dense than iron, at least over the range of conditions we have been considering, so rock will tend to lie above iron. However, it might be possible to have a layer of liquid rock above a core of solid iron deep inside a large super-Earth (contrast with the configuration for Earth of a solid rocky mantle above a liquid iron-alloy core).

Question 2: how would the above scenario affect the habitability of the planet?
We're not at all sure, at the present time, but can speculate that such a configuration could alter the structure or presence of a magnetic field that could in turn affect the habitability of the planetary surface (a magnetic field can protect a planetary surface from incoming radiation and/or charged particles). This is in the realm of speculation or future research, however.

Question 1: How do the pressures in giant impacts and at the cores of giant gas exoplanets compare to the pressures in shock fronts of supernovae?
The observed shock waves emerging from exploding supernovae are propagating in space, where the density of gas and dust is low. Therefore, these shock pressures are low in absolute value (way less than 1 atmosphere) but can involve relatively large increases in the local density and pressure of the interstellar medium.

Question 2: Why does the sound velocity increase as a function of pressure?
Because the closer one packs atoms together the harder it is is to push them even more closely together, the slope of the pressure-volume curve typically increases in absolute value with increasing compression. For a fluid, that slope is equal to the sound velocity squared.

Question 1: Did any of the planets in our solar system not form from 'late stage' giant impacts?
We're not sure about Jupiter and Saturn, which may have avoided late-stage giant impacting, but it is thought that the other planets may all have experienced one or more late-stage giant impacts.

Question 2: In your H2-He fluid mixture slide, you mentioned 'solar system environment' or 'jovian environment'. Could you explain what you mean by Jovian environment?
[I don't recall this and don't see this in my slides].

Question 1: Besides applications to planetary interior, do your experiments contribute to new understandings of other related fields?
Yes, because we can test predictions made using first-principles quantum mechanical calculations we can improve the quality of such calculations (though "first principles" they do involve some approximations). Such improved theory can then help predict the existence and properties of new materials, perhaps with some interesting technolgical properties.

Question 2: Do you collabrate with modeling researchers? How?
Much of our work involves collaboration with theorists who either model material properties using quantum mechanics, or planetary interiors or show-wave processes using fluid dynamics approaches.

Question 1: Do you have a philosophy that has led you through your career?
Our opportunity or role, if we are lucky enough to pursue it, is to leave this a better place than we found it.

Question 2: How much variety in composition (and thus material properties) do you expect to see in exoplanets, especially giants?
The most honest answer is "I don't know." Many in the research community are just starting to think about this, so it's an excellent question that is worthy of deep thought!

Question 1: You mentioned the laser driven compressions were accomplished by very large lasers. What type of lasers do you primarily use, and where do you house them?
We typically use Nd-doped glass lasers, such as those at the National Laser User Facility at University of Rochester or the National Ignition Facility at the Lawrence Livermore National Laboratory.

Question 2: What was the name of the recent experiment that demonstrated the "ionic bond" formed by high pressure on bound electrons?
Several groups have worked on the transition of Na to the electride ("ionic") state, with Ma, et al.'s work providing the picture I showed of transparent sodium: *Nature*, 458, 182 (2009).

Question 1: I had difficulty following the significance of viscosity in the context of your presentation. Could you explain what that meant?
Yes, I went over this very quickly. Most materials appear to show a viscosity that decreases with incresing strain rate, sometimes called "shear thinning," but it is not well understood why this is so. The consequence is that materials may behave in a more fluid like manner at high strain rates (shock compression) than at lower strain rates ("ramp" or quasi-isentropic compression).

Question 2: You said rocks are quasi-fluid like in planetary impacts. Is there some time-scale or condition for this state that separates it from the physics of normal rocks? How do we make the distinction when rocks are and aren't quasi-fluid like, in simulations and such?
The stresses are so huge in many shock experiments that they are well above the dynamic strength of rock or metal, so our samples behave in a fluid-like manner and much of our analysis therefore uses a version of fluid dynamics.

Question 1: Can you elaborate more on constant action?
Action seems to play an important role both in classical mechanics and quantum mechanics (see Feynman Lecture v. 2 Ch. 19 on least action), and Dennis Grady has suggested (concluded?) it may offer a unifying principle for understanding the mechancal response of materials at high strain rates. We don't understand how or why.

Question 2: How is it that water on the moon is preserved?
Water on the Moon seems to be preserved as ice that survives in shaded regions of the crust, such as regions in permanent shadow in/around craters.

Question 1: At what point does kilivolt chemistry coverge with nuclear chemistry?
When the temperatures are high enough (say millions of K, keV in temperature) to induce thermonuclear reactions. There are speculations that at super-high densities it may be possible to induce nuclear reactions at low temperatures ("pycnonuclear fusion"), but there is no confirmation of this idea so far (as far as I know).

Question 2: Besides pressure and heat, what are other conditions that may foster the new form of chemical bonding?
Good question – I'm not sure, but perhaps some other fields (e.g., electromagnetic) might play a role if intense enough.

Question 1: Why wouldn't we use the same method of determining Earth's core/mantle boundary on super Earths?
The Earth's core-mantle boundary involves a change from solid to liquid, from dielectric (insulator) to metal, and from a silicate (rock) composition to iron alloy. The bottom of the rocky (silicate) shell for a super-Earth may consist of liquid, metallic silicate – so is this the mantle-core booundary, or perhaps at shallower depths where there may be a transition from crystalline non-metallic silicate to liquid metallic silicate?

Question 2: Why does helium settling out of hydrogen in a liquid create luminosity?
Imagine two fluids, light and dense, mixed together and then allowed to settle. The dense fluid sinks relative to the lighter fluid, and goes toward the center of the planet. That sinking process involves frictional heating, which is what gives the extra luminosity.

Question 1: Why do you use the stishovite phase and not coesite? Are these stishovites synthetic?
Good question – the stishovite is synthetic, and we used that in order to get the highest initial density possible for our starting material (coesite has a much lower density than stishovite – 2.91 vs. 4.29 g/cc).

Question 2: In reference to the Temperature vs Pressure diagram (of H2-He fluid mixtures) what attributes to the plateau on the Saturn trend (that the Jupiter trend doesn't exhibit)?
The plot I showed is a combination of others' models, and the plateau does not make sense where it is shown – it should be where the temperature profile intersects the unmixing region (and the same for Jupiter). Good observation!

Question 1: Could you please elaborate on your point regarding the excess luminosity of Saturn?
The energy that Saturn emits, measured as infrared radiation, exceeds the amount of energy the planet gets from the Sun. This difference between emitted and absorbed radiation is the "excess" luminosity of the planet.

Question 2: In your opinion, what will be the most important applications of your ramp loading laser technique? (will this be more important in some analyses than others?)
This will be important for testing quantum-mechanical predictions and for simulating the conditions inside planets (which, to a large degree, are isentropic – constant entropy – due to convection).

Question 1: For the ramp method, would a higher number of shocks correspond to a lower change in entropy?
Yes, exactly so – well put.

Question 2: What are the intenisities of the lasers used to produce the shocks? What are the limitations that keep the timescales at nanoseconds?
The largest lasers put out kJ to 2 MJ of energy over time periods of 1-20 ns, corresponding to 1-100 TW of power, and this is sent into an area less than 1 cm^2.

Question 1: What exactly is the core-metal boundary and why is it important to understand for super-Earth exoplanets?
For Earth, the boundary separates the dense metallic (iron-alloy) core at the planetary center from the less dense rocky shell above it.

Question 2: You breifly mentioned potentially compressing materials to scales below the deBroglie wavelengh in the distant-ish future. What kinds of new observations might result from this? Where do you cross the boundary between chemistry and nuclear physics?
We're not entirely sure but this is a regime of completely quantum behavior. A similar condition can be achieved at low temperatures, where the particle wavelength can become large and causes Bose-Einstein "condensation."

Question 1: Does shocked material that is flung into space undergo an "unshocking" process after being exposed to a no-pressure environment?
Yes, absolutely.

Question 2: Could the changed chemical interactions due to extreme pressure inside supergiant extrasolar planets lead to the production of new elements, or variations or elements?
New elements can be made when thermonuclear processes take place, at conditions inside stars rather than planets.

Question 1: How accurate or indicative can the planetary pressure estimations be when using only a central pressure? This seems like a large approximation, especially when considering terrestrial planets with a sharp density cutoff between surface and atmosphere.
Yes, the central pressure is simply used to give an idea of how extreme the conditions can be inside a planet, and lower pressure exist at shallower depths and in the atmosphere. The central pressure can be calculated relatively precisely if one knows the mass and diameter of the planet, although one needs to know the actual variation of density with depth to get completely accurate estimates.

Question 2: What are some geochemical implications for high pressure, late occurrence (I.e. After some planetary formation) impacts on the planets, especially when rock becomes liquid? It could severely disrupt the entire planet's geochemical activity or might it be more localized, depending on the size of the impact?
This is still an area of research, so the answer is uncertain but it does seem plausible that a large (planetary-scale) impact can influence the geochemistry of the entire planet whereas smaller impacts (say under 1000 km diameter) mainly have a local effect on geochemistry (yet may splash geoechmically altered material around the planet, as with Earth's K-T impact).

Question 1: How do you determine/estimate the masses of exoplanets?
From orbital dynamics determined by sensitive measurements of the star's motion (caused by the gravitational pull of the orbiting planet), observed by the time-varying Doppler shift of the star's spectrum.

Question 2: What conditions do impacting late during planet formation create that otherwise wouldn't exist?
We're not entirely sure. Modeling does suggest that late-stage giant impacts are common, and this is consistent with our understanding of early Solar System planets where the consequences range from loss of Mercury's mantle (material pulled into the Sun) to formation of Earth's Moon.