1. Briefly describe how differences in composition among the Jovian planets can be traced to their formation.

- The Jovian planets were all formed from similar planetesimals made of hydrogen compounds mixed with rock and metals. But Jupiter and Saturn captured more hydrogen and helium than Uranus and Neptune, which is why Jupiter and Saturn are larger and richer in those gases, while Uranus and Neptune are composed of a much higher fraction of hydrogen compounds.

2. Why is Jupiter so much more dense than Saturn? Could a planet be smaller in size than Jupiter but greater in mass? Explain.

- Jupiter is denser than Saturn due to the "pillow effect." As extra mass is added to the planets, the lowest layers of gases compress more under the added weight. So as we add gas to the Jovian planets, they can grow denser.
- If a planet were to grow more than about three times more massive than Jupiter, adding more gas would actually result in making the planet shrink in radius in order to accommodate the extra weight.

6. How do the cloud layers help explain Jupiter's colors? Why are Saturn's colors more subdued? Why are Uranus and Neptune blue?

- The different cloud layers are made of different chemicals and therefore apparently reflect light differently. This explains why Jupiter has different-color clouds in its atmosphere. Saturn's clouds also vary in color, but because they are deeper in the atmosphere and under more haze, the differences are more subdued.
  
  In contrast to colorful Jupiter and subdued Saturn, Uranus and Neptune are both blue. This is because the methane in these planets' atmospheres absorbs red light. So any light that enters the atmospheres, hits the clouds, and reflects back to us will lose most of its red light along the way, leaving us with blue-looking planets.

8. Why does Jupiter have such a strong magnetic field? Describe a few features of Jupiter's magnetosphere.

- Jupiter has a strong magnetic field because it has a fast rotation and a very large volume of metallic hydrogen by which to generate its field. Jupiter's magnetosphere is similar to Earth's in many ways, but there are some very important differences. One of these is that the charged particles in Jupiter's field come not from the solar wind, but from the volcanic moon Io. Because of this source embedded inside the magnetosphere, there is a donut-shaped region of charged particles in the magnetosphere called the Io plasma torus, something Earth does not have. The magnetosphere also interacts with other moons, bombarding them with high-energy particles and creating thin atmospheres.
10. What are the key features of Jupiter’s four Galilean moons? Explain the role of tidal heating and orbital resonance in explaining these features.

- The key feature of Io is that it is extremely volcanically active due to tidal heating. Europa, Ganymede, and Callisto all seem to have subsurface oceans. Europa’s surface is young, with many features indicating geological activity. Ganymede’s surface is young in places and much older in others, which also indicates that tectonic and volcanic processes may have recently been active. Callisto, by comparison, looks heavily cratered and appears to be geologically dead.

   The inner three of these moons (Io, Europa, and Ganymede) get their heat from tidal heating. This comes about because their orbits are not quite circular, which means the moons are constantly being flexed by changing tidal forces as they orbit. While the tidal heating tries to circularize their orbits, they are trapped in an orbital resonance with each other that keeps their eccentricities larger than they would otherwise be. This explains why these moons show geological activity when we expected them to be quiet and nearly dead.

11. Describe the atmosphere of Titan. What did the Cassini/Huygens mission learn about Titan’s surface?

- The atmosphere of Titan is the only other one in the solar system that is made of nitrogen gas like Earth’s. The surface pressure is also comparable to Earth, at 1.5 bars. However, Titan’s atmosphere is also very cold (well below the freezing point of water) and contains no oxygen. It also has dense methane clouds, which may create methane, or ethane rain, which could fall onto the surface.

   The Huygens probe has shown us that Titan appears to have valleys carved by rain, a sort of dirt on the surface (which is probably precipitated smog particles), and a slush of water, ice, and ammonia that functions like lava on Earth.

14. Briefly explain why icy moons can have active geology at much smaller sizes than rocky worlds.

- Ice moons can have geological activity at smaller sizes than rocky worlds because the ice of which they are made melts at much lower temperatures. Because of this, it takes much less heat to create geological activity. Combined with the heat source of tidal heating, this has allowed for a surprising amount of geological activity in the outer solar system.

15. What are planetary rings made of, and how do they differ among the four Jovian planets? Briefly describe the effects of gap moons and orbital resonance on ring systems.

- Planetary rings are made up of countless small icy particles on similar orbits. Saturn’s rings are the most impressive, being visible from Earth. Jupiter’s rings are dusty and almost invisible. Uranus and Neptune both have narrow, bright, and dense rings with very sparse, dusty rings in between. Neptune’s dense, brighter rings also appear in arcs around the planet rather than making complete circles. Gap moons are small moons that orbit inside the rings. Their gravity nudges the ring particles away from themselves, clearing gaps in the rings. Other, more distant moons also affect the rings via resonances. Resonances can cause the ring particles to clear large gaps from their repeated nudges on the ring particles. Resonances can also launch waves in the rings.

Test Your Understanding

Suppose someone claimed to make the discoveries described below. (These are not real discoveries.) Decide whether each discovery should be considered reasonable or surprising. Explain clearly; not all these have definitive answers, so your explanation is more important than your chosen answer.

17. Saturn’s core is pockmarked with impact craters and dotted with volcanoes erupting basaltic lava.
The discovery is unexpected. The core lies below tens of thousands of kilometers of dense gas and even metallic hydrogen. No impactors reach that depth, and the conditions at the core are so extreme that nothing resembling familiar basaltic volcanism could occur.

18. Neptune’s deep blue color is not due to methane, as previously thought, but instead is due to its surface being covered with an ocean of liquid water.

This discovery is not plausible. Neptune does have a great deal of water, but temperatures at the visible surface would be far too cold for it to be liquid.

19. A Jovian planet in another star system has a moon as big as Mars.

This is plausible. We know of no reason why larger satellites could not exist around extrasolar planets. After all, some of them are much larger than Jupiter.

21. A new small moon orbits Jupiter outside the orbits of other known moons. It is smaller than Jupiter’s other moons but has several large, active volcanoes.

It is not plausible. Tidal forces are too weak on objects so far away, and they are not forced into elliptical orbits by resonances. It would also be too small to have volcanoes from radioactive heating.

Process of Science

37. Europan Ocean. Scientists strongly suspect that Europa has a subsurface ocean, even though we cannot see through the surface ice. Briefly explain why scientists think this ocean exists. Is the “belief” in a Europan ocean scientific? Explain.

The evidence for a Europa ocean is strong, but all indirect. It’s scientifically acceptable to believe that Europa has an ocean, as long as one retains an open mind to the possibility there’s just “mushy ice.” Although we can’t test this hypothesis, I wouldn’t call it a “belief”, with current technology, in principle, it is something we can empirically test. So it is scientific.

38. Breaking the Rules. The geological “rules” for the terrestrial worlds tell us that a world as small as Io should not have any geological activity. However, the Voyager images of Io’s volcanoes proved that the old “rules” had been wrong. Based on your understanding of the nature of science, should this be seen as a failure in the process of the science? Defend your opinion.

It is obviously a success of the scientific method. Io “breaks the rules” for terrestrial planet geology because those rules were based on planets where only radioactivity, accretion, and differentiation were important heat sources. Tidal heating was an unknown process when those “rules” were figured out. The failure of the old rules to “predict” Io’s appearance required the rules to be revised, which is at the core of the scientific method.