Cosmochemistry, 2nd Edition
End-of-Chapter Questions and Answers

Chapter 1

1. How does cosmochemistry relate to other, more well-known disciplines such as geology, chemistry, or astronomy?

   Cosmochemistry is the study of the chemical compositions of the universe and its constituents and the processes that produce those compositions. It is a mixture of all these other disciplines. It uses the principles of chemistry/geochemistry and nuclear physics to address fundamental problems in planetary geoscience and astronomy.

2. Distinguish between the following terms: lithophile, siderophile, chalcophile, atmophile.

   Lithophile (literally rock-loving) elements tend to form silicates or oxides, siderophile (iron-loving) elements combine with iron to form metal alloys, chalcophile (sulfur-loving) elements react with sulfur to form sulfides, and atmophile elements tend to occur as gases and reside in atmospheres. These terms describe the geochemical affinities of elements.

3. How do element behaviors in the solar nebula or in interstellar space differ from those in planets?

   The geochemical affinities described in the previous question determine the behavior of elements in geochemical (i.e. planetary) systems. Elements in the solar nebula were largely governed by their relative volatilities. Refractory elements formed solid phases at high (but not extreme) temperatures, whereas volatile elements were harder to condense and formed gas phases except at very low temperatures.

4. Who was Victor Goldschmidt and what role did he play in the development of geochemistry and cosmochemistry?

   Goldschmidt is often referred to as the father of geochemistry, determining how elements behaved in geologic systems, and coining the terms lithophile, siderophile, chalcophile, and atmophile. He also established cosmochemistry by first reporting the cosmic abundances of elements based on element proportions in meteorites.

5. What are some of the sample sets that are available to cosmochemists?

   Cosmochemists can take advantage of any of the following sample sets:
   - Samples returned to Earth by spacecraft, including (so far) samples of the Moon, several small asteroids, and a comet
   - Lunar samples collected and returned by the Apollo astronauts
   - Meteorites
   - Interplanetary dust particles (IDPs), mostly collected by high-flying aircraft
   - Remote-sensing measurements of the chemical compositions of planets and planetesimals by instruments on orbiting or landed spacecraft and rovers

6. List five techniques by which elements and/or isotopes can be measured.

Elements and/or isotopes can be measured by various analytical techniques in the laboratory:

- Mass spectrometers (stable and radiogenic isotopes, organic molecules)
- Inductively coupled plasma mass spectrometers (major/trace elements, isotopes)
- Electron microprobes (major/minor elements in minerals)
- Ion microprobes (trace elements and isotopes)
- Visible/infrared spectrometers (organic molecules, mineral identification)

Some other techniques available on spacecraft missions include:

- Gamma-ray and neutron spectrometers (selected elements, including hydrogen)
- Alpha-particle X-ray spectrometers (major/minor/a few trace elements)

Note: For a more complete listing of analytical techniques, see the Appendix.

Chapter 2

1. What is nuclear binding energy? What are the two main ways it can be released? Which of these is currently powering our Sun?

Nuclear binding energy is the energy that holds an atom together. It can be measured as the difference in mass between sum of the masses or particles that make up the nuclide and the assembled nuclide. This “mass defect” can be expressed in terms of energy using Einstein’s famous equation: $E = mc^2$, where m is the mass defect, and c is the speed of light.

2. When discussing stable and radioactive isotopes, what is meant by the “Valley of β Stability”?

The Valley of β Stability is the region of the Chart of the Nuclides where the stable isotopes plot. The stable isotopes have the lowest mass among the nuclides of a given atomic number (A). Unstable isotopes are less tightly bound and thus have a higher mass. A cross section as a function of mass through the Chart of the Nuclides at a given value of A will have a U-shaped profile with the stable isotope(s) at the lowest mass—at the bottom of the Valley of β Stability. Unstable isotopes can decay by β^- or β^+ emission or by electron capture, becoming more tightly bound and moving toward the bottom of the Valley of β Stability.

3. What are four different modes of radioactive decay?

- β^- decay, in which a neutron emits and electron and becomes a proton.
- β^+ decay, in which a proton emits a positron and becomes a neutron.
- Electron capture, in which a proton captures and electron and becomes a neutron.
- α decay, in which a nucleus emits an α particle (^{4}He nucleus).
- Fission, in which a heavy nucleus splits into two or more smaller nuclei.

Five modes are listed, but note that β^+ decay and electron capture have the same result, turning a proton into a neutron.

4. In order to use radioactive decay of an element for a chronometer, the decay constant must not have changed with time. How do we know that this is true?

    - Decay through different paths and mechanisms leads to consistent results.
    - Supernova light curves, which are driven by the decay of short-lived radionuclides, follow the same profile for supernovae that exploded at any time during the 13.2 billion-year history of the galaxy. For this to be true, the decay rates cannot have changed.
    - Our understanding of nuclear physics has revealed the conditions under which radioactive decay rates might change. In the interior of stars, where nucleosynthesis occurs, decay rates can be very different that they are outside of stars. Electron capture rates can be changed if an atom is squeezed hard enough to force an electron into the nucleus. The pressure at the core of the Earth is enough to increase the electron capture decay rates by a tiny amount.

5. What are the five main types of chemical bonds? Give two important properties of each type.

    - Ionic bond: an electrostatic bond between a metal, which donates an electron to become a positive ion, and a non-metal, which accepts and electron to become a negative ion. The exchange of electrons results in filled outer shells for both atoms and provide a strong electrostatic force that bind the atoms together. Compounds with ionic bonds tend to have high melting and boiling points and to be soluble in water.
    - Covalent bond: characterized by sharing of pairs of electrons between atoms. Sharing of electrons also produces more-stable electron structure in each atom. Substances with covalent bonds tend to be hard, to have high melting and boiling points, and tend not to conduct electricity. These compounds are not soluble in water.
    - Metallic bond: characterized by sharing of valence electrons among many atoms; the electrons are delocalized and can move around. Metals are malleable and ductile and conduct electricity.
    - Van der Waals forces: weak, short-range, electrostatic, attractive forces between uncharged molecules arising from the interaction of permanent or transient electric dipole moments.
    - Hydrogen bond: intermolecular bonds that form between molecules consisting of hydrogen and some of the most electronegative elements (N, O, F, Cl). The electrons in the molecule move to the end with the electronegative element giving it a negative charge. This negatively charged end is attracted to the positively charged hydrogen end of another atom. A hydrogen bond is about one-tenth the strength of a covalent bond. Hydrogen bonds are responsible for the distinctive properties of water.

6. Why is water such an important compound in geochemistry and cosmochemistry? What are some of its distinctive properties?

Water is an abundant compound, consisting of the most abundant (H) and third most abundant (O) elements in the solar system. It is known as the universal solvent—any substance that has a net electrical charge across a molecule will dissolve in water. Due to hydrogen bonding, water has a high boiling point and a wide temperature range over which it is a liquid. Water is the basic chemical for life, in large part due to the wide range over which it is liquid. Water has a high specific heat, which means that it acts as a thermal climate buffer on Earth. Water is one of very few compounds that expands when it freezes—the solid floats on the liquid. This is what keeps our oceans liquid. The oceans are cold at the bottom, so if ice would sink, it is unlikely that it would ever melt and the ocean would freeze from bottom up.

Chapter 3

1. What was the Big Bang? What is some of the observational evidence that supports this model?

The Big Bang is the currently accepted theory for the formation and large-scale evolution of the universe. According to the theory, the universe expanded from an initial state of extremely high density and high temperature. The details of the first ~ 3 minutes are given in the book. The main observations supporting this model are:

- Hubble's observed that the distance of receding galaxies correlates with their speed, as determined by the spectral red shift. This shows that the universe is expanding and that distance between galaxies is increasing.
- Penzias and Wilson's discovery of the cosmic microwave background also supports the big bang. The universe is pervaded by microwave radiation corresponding to a temperature of ~3 K. This is the primordial radiation, which decoupled from matter very early in the history of the universe. The temperature of the radiation has been decreasing since the beginning due to expansion of the universe.
- Models of Big Bang nucleosynthesis do an excellent job of explaining the relative abundances of the light elements. The models predict abundances of ^{1}H (~75% by mass), ^{4}He (~25% by mass), ^{2}D (0.01% by mass), and trace amounts of ^{3}He, ^{6}Li, ^{7}Li, ^{9}Be, and perhaps ^{10}B and ^{11}B. These match the initial composition of the universe to which the products of stellar nucleosynthesis were added.

2. What is a Herzsprung–Russell diagram and how is it used?

A Herzsprung-Russell diagram is a plot of stellar luminosity (variously plots as luminosity, absolute bolometric magnitude, apparent visual magnitude, etc.) versus effective surface temperature (plotted as temperature, color index B–V or spectral class). It is used primarily to display the different stages of stellar evolution.

3. What is the initial mass function (IMF) of stars and how and why is it different from the present-day mass function (PDMF).

The initial mass function of stars (IMF) describes the number of stars of each mass that form together in a single region of cluster star-formation. Many more low-mass stars form than high-mass stars, so the IMF plots as a line with a steep negative slope on a log stellar lifetime vs log stellar mass plot. Low-mass stars live much longer than high-mass stars, so over time the line becomes steeper. The present-day mass function (PDMF) described the number of stars as a function of mass in the galaxy today and reflects the depletion of short-lived, high-mass stars while the long-lived low-mass stars are still shining.

4. What are the main nuclear reactions that power Main Sequence stars? What happens when this energy source is exhausted?

   Stars are powered by hydrogen fusion reactions. These reactions include the proton-proton reactions and CNO-catalyzed hydrogen burning. While a star is on the Main Sequence, the energy released by hydrogen burning balances the force of gravity. When the hydrogen fuel is exhausted, the core of the star can no longer support itself against gravity and the star contracts and heats up. Soon, a hydrogen-burning shell ignites around the core, and later, when the contracting core gets hot enough, helium burning is initiated in the core. As helium is exhausted, a series of other elements are fused, with the details depending on the mass of the star. Eventually all of the fuels that can generate energy through fusion in the star are exhausted. Low-mass stars become white dwarfs. High-mass stars explode as supernovae.

5. What are the dominant processes that produced the elements heavier than iron? Give the basic outlines of how each one works.

   There are two dominant processes that produced the elements heavier than iron, the *s*-process and the *r*-process. The *s*-process is neutron capture on a time scale that is slow compared to the rate of β^- decay. The *s*-process is the mechanism that produces heavy elements in low-mass stars. A nuclide captures a neutron. If the resulting nuclide is unstable, it will β^- decay to a nuclide with one less neutron and one more proton. In a few weeks, the nuclide will capture another neutron. The nuclides move along the floor of the Valley of β Stability to make heavier and heavier nuclides. The *r*-process is neutron capture on a time scale that is fast compared to the rates of β^- decay. The *r*-process is actually covers a number of processes that include rapid production of large numbers of neutrons. This is the primary method of producing heavy nuclides in massive stars and in neutron-star mergers. In the *r*-process, a stable nuclide captures many neutrons almost simultaneously and moves up the slope on the side of the Valley of β Stability until it becomes so unstable that it can decay before capturing another neutron. After β^- decay the nuclide captures another neutron and then decays again. The nuclides are concentrated at the so-called drip line, where neutrons are captured rapidly, but each capture is immediately followed by β^- decay. The nuclides are driven to heavier masses until they become unstable to nuclear fission, or the free neutrons disappear. When the neutrons disappear, all of the nuclides β^- decay back to the bottom of the Valley of β Stability.

6. How would you identify a star that formed early in galactic history? List two important characteristics of such a star?

   Stars that formed early galactic history are very old. The lifetime of a star is a function of its mass, with massive stars having short lifetimes and low-mass stars surviving a long time (see Fig. 3.2). Surviving stars that formed early in the history of the galaxy (at 10-13 Ga) are low-mass stars, less the 1 solar mass. Stars formed early in galactic history will also have low metallicity. This is because they formed before the majority of the heavy elements were produced.

7. Why did massive stars dominate nucleosynthesis in early in the history of the galaxy?

   Nucleosynthesis occurs primarily during the last stages of a stars life. The lifetimes of massive stars are short, a few million years, while those of low-mass stars can be very long (Fig. 3.2). Thus the only stars that could have released newly synthesized elements into the galaxy during its early history were the massive stars.

Chapter 4

1. What are the three main ways of obtaining information about solar system abundances?

   Solar system abundances of elements and isotopes have been determined (1) by measuring abundances in the Sun (by spectroscopy), (2) by analyzing chondritic meteorites (especially CI carbonaceous chondrites), and 3) through the application of nucleosynthesis theory. A fourth way has become available recently, analyzing Genesis samples of the solar wind.

2. What are the advantages and limitations of spectroscopic measurements of the solar photosphere for determining solar system abundances?

   The Sun makes up >99.8% of the mass of the solar system. It is believed to have gone through a fully convective stage as it formed, so to first order it is expected to be well-mixed. So measuring the Sun directly through spectroscopy should be a good way to get compositional information about the Sun and the solar system. It is relatively easy to obtain precise and detailed spectra of the Sun, but transforming the solar spectrum into element abundances requires a realistic model of the stellar atmosphere and understanding how lines are formed and interact. Segregation of some elements below the surface convection zone may have affected photospheric abundances somewhat. Fractionation of elements as they are ejected in the solar wind changes the surface composition and must be corrected for theoretically. Finally, the Sun's composition has changed over time because of nucleosynthesis. For the most part, the products of nucleosynthesis have not been mixed to the surface and cannot be observed, but the earliest stages of nuclear burning affected deuterium, ^{3}He, and some other light isotopes, so in some instances the Sun's current abundances do not reflect its original composition.

3. Why are CI chondrites so important to cosmochemistry?

   CI chondrites provide the best match for the solar composition, at least for the least volatile elements, and thus their careful analyses in the laboratory can fill in data for elements or isotopes not easily determined from the solar spectrum.

4. What are some of the differences between the composition of the solar system and the composition of the galaxy? How might these differences have arisen?

Solar system abundances are not necessarily the same as in the galaxy or universe, which are termed cosmic abundances. The solar system composition is a snapshot of the region in which it formed – a region of active star formation where abundances of material ejected from massive stars by supernovae were enhanced over the galactic average. The Sun's surface layers preserve that original composition for most elements (the products of hydrogen burning that powers the Sun have not yet appeared at the surface). But the composition of the galaxy has continued to evolve. Stellar nucleosynthesis has added elements heavier than helium to the galactic composition, and the galaxy continues to grow through accretion of metal-poor gas and assimilation of other galaxies.

5. Why would you want to normalize chemical data obtained for a chondrule or a meteorite? What would you normalize the data to and why?

   There are two main reasons to normalize chemical data. 1) The abundances of the elements differ by many orders of magnitude, so a plot without normalization is overwhelmingly dominated by the abundance differences in the cosmic composition. If you divide the measured composition by the composition of the solar system (CI chondrites), the large abundance differences between elements are cancelled out and you can see the fractionations among the elements. 2) One can further highlight fractionations in a specific system by normalizing to the composition of the system. This will still eliminate the large differences in absolute abundances and will isolate the differences in composition for different parts of that system.

Chapter 5

1. What are presolar grains and why are they important?

   Presolar grains are grains that originated before the solar system formed and were part of the raw material for the solar system. Some presolar grains carry a direct record of nucleosynthesis in stars, and thus they provide ground truth for models of stellar nucleosynthesis. Others are the product of vaporization and condensation in interstellar space and provide constraints on models for the formation of the solar system and its constituents.

2. How are presolar grains recognized?

   Presolar grains are primarily identified by their isotopic compositions, which are often quite extreme compared to the isotopic composition of solar system constituents. This is because individual presolar grains carry the signatures of stellar nucleosynthesis in a specific star. The solar system bodies formed from average mixtures of very large numbers of those grains.

3. What are the important differences between circumstellar condensates and interstellar grains?

   Circumstellar condensates formed in the winds ejected from dying stars. Their compositions reflect the compositions of the stellar ejecta. Interstellar grains formed in interstellar space from atoms from many sources, including dust that was returned to the gas phase by supernova shocks and intense infrared radiation, and subsequently recondensed into dust in molecular clouds.

4. How can presolar grains tell us about stellar nucleosynthesis?

   Presolar grains formed from atoms that were ejected from the interiors of stars where nucleosynthesis was going on. Nucleosynthesis processes leave distinct isotopic signature in their products. As the atoms are ejected from the parent stars, they condense into dust grains, trapping the products so that we can analyze them in the lab. Comparing the resulting isotopic compositions with the predictions of nucleosynthesis models allows us to validate the models.

5. What can presolar grains tell us about the environment of their formation?

   Circumstellar condensates are typically mineral grains that condensed from the gas phase. The mineralogy tells us about the conditions under which they condensed. For example, a SiC grains formed in a carbon-rich environment, probably in the ejecta of a carbon star, which is a 1-3 solar mass star in its asymptotic giant branch stage. An Al_2O_3 grain formed in an oxygen-rich environment, perhaps in the same 1-3 solar mass star as the SiC grain, but earlier in its evolution, in the Red Giant phase before carbon was dredged up into the envelope.

6. What can presolar grains tell us about the environment and processes in interstellar space and in the early solar system?

   There are many types of presolar grains, each with its own mineralogy and chemical, physical, and thermal stability. Each reacts differently to the environments that it is exposed to. Cosmic-ray interactions in interstellar space can erode a mineral grain or cause some elements to be expelled from the grain. The temperature profile of the solar nebula would have different effects on different types of grains. High temperatures would be particularly hard of presolar graphite, but might not harm refractory organics or oxide minerals very much. Oxidizing conditions would be hostile to carbonaceous presolar grains but would not bother oxide minerals. Careful examination of presolar grains and their relative abundances can tell us about their journey through interstellar space, into the solar nebula, and then into the meteorites in which they are found.

Chapter 6

1. Describe the components of chondritic meteorites.

   Chondrites are composed of chondrules (quenched droplets of silicate melt, usually crystallized into olivine, pyroxene, sometimes with metal, and interstitial glass), refractory inclusions (CAIs and AOAs, made of minerals that would condense at high temperatures or occur as residues from evaporation), grains of iron-nickel metal and sulfides, and matrix (fine-grained mixtures of silicates, oxides, metal, sulfides, commonly with organic matter, and sometimes altered to phyllosilicates and carbonates).

2. Explain the classification system used for chondrites.

The chondrite classification system distinguishes groups of meteorites, each having the same bulk chemical composition (a primary characteristic). The groups are identified with abbreviations, based on the name of a prominent member (e.g. CV, CI, H, L, R, E). Then each group is subdivided into petrologic types based on relative degrees of thermal metamorphism or aqueous alteration (a secondary characteristic). Petrologic type 3 is unmodified; 4, 5, and 6 indicate increasing degrees of metamorphism, and 2 and 1 represent increasing degrees of aqueous alteration.

3. What is differentiation, and how does it cause chemical changes?

   Differentiation is chemical change resulting from melting and crystallization. Melting is rarely complete, and partial melting produces magmas and solid residues that differ in chemical composition. Dense phases like metal (either solid or immiscible metallic liquid) can segregate from silicate (either molten in a magma ocean or through a mesh of crystals), producing cores. Once magmas form and cool, fractional crystallization can segregate early-formed crystals from liquid, usually by gravity, resulting in further chemical changes. Not only major and minor elements are affected by differentiation; trace elements partition into preferred phases (compatible elements fit into the crystal structures of minerals, whereas incompatible elements do not and so remain in the liquid).

4. Distinguish between the origins of magmatic achondrites, primitive achondrites, and irons.

   Magmatic achondrites are crystallized silicate magmas or cumulates of crystals formed by fractional crystallization. Primitive achondrites are solid residues from partial melting. Irons are crystallized molten metals, containing not only iron but also nickel and accessory minerals composed of other siderophile elements.

5. How are oxygen isotopes in chondrites and achondrites illustrated graphically, and how are the isotopic compositions useful in classifying meteorites and recognizing relationships between them?

   Plots of the measured isotope ratios of $^{17}O/^{16}O$ and $^{18}O/^{16}O$, reported as deviations from a standard in parts per thousand (permil), are used as a classification scheme for meteorites. Chondrites normally plot as clusters of points on such a diagram, distinguishing different groups. Some chondrite components, like CAIs, plot on a line representing mass-independent variations due to mixing. Achondrites from the same body plot on lines with a slope of ~0.5, indicating mass-dependent fractionation of the isotopes. These variations can also be used for classification and recognizing different kinds of meteorites that might derive from a common parent body.

Chapter 7

1. What are the major processes that produce chemical fractionations of importance in cosmochemistry?

   Nebular and planetary processes that induce chemical fractionations include

   - Condensation or evaporation

- Nebular sorting of chondrite components
- Physical fractionation resulting from oxidation/reduction
- Partial melting and fractional crystallization
- Aqueous reactions, dissolution, chemical weathering
- Glancing impacts between large bodies
- Loss of pyroclastic material during eruptions on small bodies
- Aeolian sorting of components by wind on planets with atmospheres
- Core formation
- Gravity segregation of components in giant planets
- Separation of aqueous fluids in icy bodies

2. Describe the order of appearance of the important minerals that are calculated to condense from a cooling gas of solar composition. Would an evaporation sequence be similar?

   Thermodynamic calculations indicate that condensation of a gas of solar composition begins with highly refractory metal nuggets and aluminum, titanium, and calcium compounds (corundum, perovskite, diopside, melilite, anorthite, followed by magnesium compounds (forsterite, enstatite), and metal. Some previously condensed minerals react with the gas on cooling to form other minerals (e.g. forsterite to enstatite). See Figure 7.1.

   Evaporation is, in principle, the inverse of condensation. But evaporation is generally not an equilibrium process, so the details are different. The sequence of evaporation is controlled by the stability of individual mineral phases, and because all of a given element is not in a single mineral phase in a natural system, each element evaporates over a range of temperature.

3. How do we quantify the volatility of an element? Where do we see evidence of element fractionation according to volatility?

   Volatility is normally quantified by the temperature at which 50% of the element has condensed from a gas of solar composition. CAIs and AOAs are refractory materials depleted in volatiles. Bulk chondrites also show volatile element depletions, unrelated to lithophile, siderophile, or chalcophile behavior. Depletions of volatile elements in achondrites and in planets are more extreme than in chondrites, and the origin of this depletion is not known.

4. What is the evidence for metal-silicate fractionation? How and where might this have occurred?

   Various chondrite groups exhibit fractionation of metal from silicates, e.g. H, L, and LL chondrites. This fractionation occurred in the solar nebula, possibly by gravity or aerodynamic sorting of grains by density. In the parent asteroids of achondrites, metal-silicate fractionation likely occurred by gravitational settling of molten metal to the core. On a larger scale, metal-silicate fractionation can occur when glancing impacts among differentiated planetesimals and planets partly remove silicate crusts.

5. How and why are elements partitioned during partial melting? During fractional crystallization?

   During partial melting, combinations of minerals having the lowest melting points (eutectic or peritectic compositions) melt first, and separation of these melts from the solid residue produces fractionation. The low-temperature endmembers of solid solution minerals also melt first during heating, enriching the residue in the complementary compositions (e.g. iron-rich olivine melts before magnesium-rich olivine). During fractional crystallization, early-crystallizing minerals are separated from the liquid, forming cumulates and enriching the residual liquid in incompatible elements (including trace elements). Compatible trace elements follow the early-fractionated crystals.

6. What chemical fractionations are produced during the differentiation of rocky planets? Of the giant planets?

   The rocky planets are differentiated to produce metallic cores, silicate mantles having ultramafic compositions, and silicate crusts that are basaltic and/or andesitic. The crusts are formed from magmas produced by partial melting of mantles, allowing further fractionations. The giant planets have rocky cores overlain by ice mantles and, in the case of gas giants, envelopes of mostly molecular hydrogen. Models indicate that immiscibility between liquid helium and metallic hydrogen allows fractionation of those elements in the deep interiors of Jupiter and Saturn.

Chapter 8

1. What are isotopes? Why do the isotopic compositions of most elements only vary by a small amount among solar system materials? What are some different causes of isotope variation in natural materials?

   Isotopes are any of two or more forms of the same element having the same number of protons (the same atomic number, Z) but different numbers of neutrons (different atomic masses, A).

   The isotopes were produced over the ~13 Gyr history of the galaxy in a wide variety of stars. After ejection from their source stars, the elements and their isotopes were mixed through the galaxy by supernova shock and winds from massive stars. Circumstellar condensates, which retain the composition of their source star, are destroyed in the interstellar medium on timescales of 10^8 years, leaving the atoms to mix with other atoms in the galaxy. Eventually, the atoms from various sources were incorporated into molecular clouds. Dense cores of molecular cloud gravitationally collapsed to form new stellar system. This process involved mixing at all scales. The gas phase becomes increasingly homogeneous. Dust grains evaporate and their atoms mix through the gas phase. Accretion of planetesimals can generate melting, which further mixes the elements and isotopes. All of these processes worked to homogenize the isotopic composition of the galaxy. But some circumstellar grains survive this mixing and carry highly anomalous isotopic compositions into and throughout the galaxy and into new stellar systems. But these grains will not produce large scale isotopic anomalies unless a large number of similar grains are concentrated in a small sample relative to the other kinds of dust. In addition, the processes that mix the isotopes can result in mass-dependent and mass-independent isotopic fractionation (partitioning) among phases. Large isotopic fractionations can occur is a processes prevents a system from reaching equilibrium (kinetic fractionation).

2. Calcite, magnetite, and fayalite precipitated together from the same fluid. How do you use their oxygen-isotope compositions to determine the temperature at which they precipitated? Can you determine the isotopic composition of the fluid? How?

   There is an extensive experimental database that has determined the fractionation as a function of temperature between minerals and water during precipitation. Different minerals have different fractionations compared to water at any given temperature. If you know that two minerals precipitated from the same fluid, you can use the experimental data to determine the temperature of precipitation from the fractionation between the two minerals. Once you know the temperature of precipitation, you can use the temperature and the composition of either of the two minerals to determine the composition of the water from the literature database (both minerals will give the same answer).

3. What are the main differences between equilibrium and kinetically controlled evaporation? What conditions are necessary to generate large isotopic fractionations during evaporation? Why does evaporation from a solid typically not produce isotopic fractionation?

   In an equilibrium situation, the vapor and liquid exchange atoms across the interface and develop a steady-state relationship between the isotopic compositions of the liquid and the vapor. The light isotopes are typically slightly enriched in the vapor relative to the liquid. In the kinetically controlled situation, the isotopically light vapor is removed from contact with the liquid as soon as it is generated. As evaporation proceeds, the liquid becomes isotopically heavier. To generate large fractionations, the vapor must be efficiently removed from the interface with the liquid so that there is no back reaction the dampen the isotopic fractionation. The liquid will typically be well mixed by diffusion so that the whole volume of the liquid becomes depleted in light isotopes. In a solid, only the surface atoms are involved in the evaporation, leaving the rest of the solid unaffected.

4. A meteorite has a very high D/H ratio and that its oxygen is ^{17}O and ^{18}O rich. What can you say about where the meteorite or its constituents may have formed?

   If you were to interpret the oxygen data in terms of CO self-shielding, you would attribute the ^{17}O and ^{18}O-rich composition to water that was produced in a region where only ^{17}O and ^{18}O were dissociated from the carbon. Such water might be expected to accumulate in the outer solar system where water condenses to ice. Deuterium enrichments are expected to result from ion-molecule reactions in molecular clouds or in the outer solar system. Having both ^{17}O and ^{18}O rich oxygen and D-rich hydrogen thus implies an outer solar system origin. Is the meteorite aqueously altered?

5. We now know that the majority of elements with more than one isotope show mass-independent isotope variations that can be attributed to nucleosynthetic processes. Describe how such "isotopic anomalies" could have survived to be incorporated into solar system objects. In spite of these anomalies, why are the isotopic compositions of most objects so similar?

   Isotopic anomalies are carried in dust grains and will survive so long as the dust grain survives. If a solar system object forms from dust grains that have, on average, a slightly different composition than that of the bulk solar system, that object will be isotopically anomalous. In general, the larger the object, the closer the mix of dust grains will approximate the solar system average. This is why most objects have compositions similar to the bulk solar system. But if a nebular process can change the mixture of dust grains compared to the solar system average, an anomalous object of almost any size could be produced. Consider dust that is heated to a temperature where one or two of the major dust components evaporate. If the evaporating and surviving dust have different bulk isotopic compositions, an isotopically anomalous body will form from that processed dust.

Chapter 9

1. Radiometric dating is one way to get age information. What are some of the other ways of measuring time? How do radiochronometers complement these methods?

   There are a variety of ways to determine relative time (is this older than that?). Any process that recurs on a regular basis can be used to measure time.

   - The geologic concept called the Principle of Superposition is very useful for determining relative ages. The lava flows on the surface of Mars can be put into chronological order by recognizing that the oldest flow is on the bottom and that the flows get younger as you go up the section. This principle is used all the time in different contexts. For example, a chondrite must be younger than the chondrules it contains. The aqueous alteration that affected a meteorite must have occurred after the meteorite formed. The relative chronology that is generated by this reasoning can be put onto an absolute timescale through radiometric dating of one or more of the objects in the sequence.
   - Cosmic rays can break atoms into two or more smaller atoms in a process called spallation. One can count the number of spallation nuclei to estimate how long an object has been exposed to cosmic rays. The cosmic ray exposure ages can be put on an absolute scale through a knowledge of the cosmic ray flux in the solar system.
   - Crater counting is used to estimate the age of planetary surfaces. A heavily cratered surface is older than a lightly cratered surface. The timescale determined from crater counting can be calibrated in an absolute sense using radiometric dating. Crater counting is first discussed in Chapter 10.

2. Why is it necessary for an object to be dated by a radiochronometer to have been isotopically homogeneous when it formed?

Determining a radiometric date depends on identifying the daughter isotope produced by radioactive decay. If the daughter isotopes are produced in an object in which the daughter element has a homogeneous composition, the daughter isotopes can be recognized, particularly if their abundance correlates with the abundances of the parent element. On the other hand, if there are isotopic variations in the rock due to other causes, there is no clear way to determine which atoms were produced by the radiochronometer.

3. Which radiochronometer(s) would be best suited to determine the crystallization age of a basaltic meteorite? What are some of the complications that might result in an incorrect age determination?

   Basaltic meteorites (e.g. eucrites) are made up of pyroxene (pigeonite) and plagioclase, with minor tridymite, ilmenite, chromite, and other accessory minerals.

   - They can be measured using the ^{87}Rb-^{87}Sr system. Although the parent-daughter elemental ratios are low, there is a reasonable spread among different phases and the Sr isotopic composition can be measured with high precision. Initial ratios give more-precise formation ages than do isochrons.
   - ^{147}Sm-^{143}Nd can be used on basaltic meteorites. Again, the parent-daughter elemental ratios are not high (both elements are REEs) and the spread in elemental ratios among phases is not great, but the Nd isotopic composition can be measured precisely. This system is robust against thermal metamorphism.
   - The U-Pb system can also give information on the formation time of basaltic meteorites. This system is subject to disturbance by thermal metamorphism.
   - Two short-lived radiochronometers, ^{26}Al–^{26}Mg and ^{53}Mn–^{53}Cr, provide information of the differentiation of basaltic achondrites.

4. What are the best radiochronometers to use to determine the formation times of CAIs and chondrules? Why?

   CAIs and chondrules both formed very early in solar system history. Thus, high precision chronometers are needed to sort out their chronology. The ^{26}Al–^{26}Mg system and the ^{207}Pb–^{206}Pb system are the most widely used. The ^{26}Al–^{26}Mg system has the highest resolution, but it is a relative chronometer and cannot give absolute ages. The ^{207}Pb–^{206}Pb system is the most precise long-lived system and gives an age resolution of better than a million years, sufficient to determine the relative formation times of chondrules and CAIs.

5. What radiochronometers are best suited for dating aqueous alteration in chondritic meteorites? Why?

   In order to directly date aqueous alteration, it is necessary to date minerals that precipitated from the fluid. The ^{53}Mn–^{53}Cr system is well suited for this work because minerals that commonly precipitate from the fluid (carbonates, fayalite, hedenbergite) tend to have very high Mn/Cr elemental ratios. An extensive chronology of aqueous alteration has been built up using the ^{53}Mn–^{53}Cr system. The ^{60}Fe–^{60}Ni system also has potential for this work because fayalite and hedenbergite have high iron abundances and effectively exclude nickel. But the initial $^{60}Fe/^{56}Fe$ ratio was very low and so far the ^{60}Fe-^{60}Ni system has not proven useful for dating aqueous alteration.

6. Which radiochronometers use nuclear reactions as part of the analytical procedure? What are the advantages of this approach?

   The ^{40}Ar–^{39}Ar and ^{129}I–^{129}Xe systems use nuclear reactions to convert some of the parent element into an isotope of the daughter element so that parent and daughter can be measured at the same time (as noble gases). This makes the measurements easier to make. Using a stepped pyrolysis technique, the parent element can be directly associated with the daughter isotope.

Chapter 10

1. How accurately do we know the age of the solar system? What is the largest uncertainty in the age? Why can we determine the sequence and timing of events in the early solar system with higher precision that we know the absolute age?

   The absolute age of the solar system comes from the U-Pb system. This system has two chronometers ^{235}U-^{207}Pb, ^{238}U-^{206}Pb, which gives it both an internal check for isotopic disturbance and high precision when dating early solar system objects. The biggest uncertainty in the absolute age of the solar system comes from the half-lives of the uranium isotopes of ~0.2%, which translates to ±9 million years at the age of the solar system. Other isotope systems can also provide estimates of the age of the solar system, but their absolute uncertainties are large than that for U-Pb.

   Short-lived radionuclides such as ^{26}Al and ^{53}Mn can give a precise relative chronology at the beginning of the solar system. This is because with short half-lives the clocks run much faster. But to get absolute ages, we must tie the short-lived chronometers to a long-lived chronometer, and as just discussed, the long-lived chronometer has a larger error.

2. Summarize the evidence that chondrules are younger than CAIs. Hint: Several lines of evidence do not involve radionuclides.

   CAIs have older radiometric ages than do chondrules.
   CAIs are found within some chondrules, but not the other way around.
   CAIs are made of higher temperature minerals than chondrules, as appropriate for the earlier formation of CAIs in a cooling nebula environment.

3. Give two lines of reasoning to support the idea that differentiated asteroids accreted before chondritic asteroids.

   The ages of accretion and of core formation for differentiated asteroids, as determined from Hf-W systematics in their samples, are older than chondrites.

4. Describe cosmic-ray exposure ages of meteorites and summarize what they tell us about the history of meteorites.

   Cosmic rays impacting a solid object break atoms of the object into smaller fragments in what are known as spallation reactions. The process is random, producing roughly the same abundances of isotopes of similar mass. The contribution of spallation products is easiest to see in isotopes that have low natural abundances. The spallation products can be either stable or radioactive. The concentrations of stable spallation products increase linearly with time, assuming a constant flux of cosmic rays. Radioactive spallation products build up, but decay according to their half-lives. Over time, as steady-state abundance is reached where production of new nuclides is balanced by the decay of nuclides that are already present. When a body of a few meters in diameter is broken out of its parent asteroid, it is exposed to cosmic rays, spallation reactions begin, and cosmogenic nuclides begin to build up. When the meteorite falls to Earth, the Earth's atmosphere shields the meteorite from exposure to cosmic rays and the production of cosmogenic nuclides stops. Cosmic ray exposure ages of meteorites can be inferred from a knowledge of the cosmic ray flux and the measured abundances of rare stable isotopes such as ^{3}He, ^{21}Ne, and ^{38}Ar and from the relative abundances of radioactive nuclides such as ^{14}C, ^{10}Be, ^{26}Al, ^{36}Cl, ^{81}Kr, etc. The radioactive nuclides can give additional information as well. When a meteorite falls to Earth, the production of radioactive spallation products stops and the accumulated species begin to decay. This decay give information about how long the meteorite has been shielded from cosmic rays. The time of this shielding is the terrestrial age of a meteorite.

5. What is the evidence that martian meteorites came to Earth as a result of a limited number of discrete impact events on the martian surface?

Martian meteorites were exposed to cosmic rays on the journey to Earth. When they arrived on Earth, the cosmic-ray exposure ended, and the radioactive spallation isotopes began to decay. For each meteorite, one can determine the cosmic-ray exposure age (the time the object was exposed to cosmic rays on its journey to Earth) and it terrestrial age (how long the object has been shielded from cosmic rays by the Earth's atmosphere (see answer to question 4)). When summed together, the so-called "launch ages" cluster into distinct groups. Those with similar launch ages also tend to have similar mineralogies an crystallization ages, implying the same source rock. The ~140 martian meteorites define about a dozen distinct combinations of crystallization age, mineralogy, and launch age (Fig. 10.16), which can be interpreted as about a dozen distinct impact events that launched meteorites to Earth.

Chapter 11

1. How much water ice, relative to rocky minerals, is potentially condensable from a solar gas?

The relative proportions (by weight) of water ice (37%) and rock materials (34%) that can condense from a solar gas are comparable. The amount of H_2O is limited by the hydrogen combined with carbon (23%, expressed as CH_4) and with nitrogen (6%, expressed as NH_3 ice). See calculations in Box 11.1.

2. What makes noble gases so useful in cosmochemistry?

Noble gases are useful in understanding planetary differentiation and atmosphere evolution. What makes them so useful is their many isotopes and the fact that they do not normally participate in chemical reactions. This lack of chemical reactivity means that noble gas abundances are very low in most solid, making it possible to identify contributions from radioactive decay and spallation reactions.

3. What noble gas components have been identified in meteorites, and what are their origins?

   Noble gas components, identified by their distinctive mixture of isotopes, are
   - Nuclear components, which are produced by radioactive decay, spontaneous fission, and cosmic-ray irradiation
   - Solar components, representing solar wind gases implanted into surface samples (regoliths) on airless bodies
   - Planetary components, which are carried in presolar grains and organic matter; the name "planetary" is a misnomer, attributed to their similarity of their elemental abundance patterns to noble gases in planetary atmospheres

4. Explain the difference between extractable and insoluble organic matter in chondrites, and note why this distinction is significant.

   Organic matter in chondrites is a complex mixture of molecules that are either soluble or insoluble in liquids. Soluble molecules can be separated and characterized; these are highly variable in terms of structure, composition, and size (molecular weight). Insoluble organic matter consists of complex, macromolecules (kerogen) that are dominantly aromatic (ring) compounds. They are difficult to characterize, and can be studied by breaking them apart with harsh acid treatments.

5. What elements are found in organic molecules, and how can their isotopes help constrain their origins?

   Besides carbon and hydrogen, organic compounds can contain oxygen, nitrogen, sulfur, and phosphorus (the so-called biogenic elements). All of these elements occur in more than one isotope, and isotopic anomalies in bulk organic matter and in specific compounds can constrain their formation conditions. For example, the extremely high deuterium/hydrogen ratios of the organic matter in carbonaceous chondrites imply formation by ion-molecule reactions under cold conditions in molecular clouds. Another example stems from the observation that $^{13}C/^{12}C$ ratios decrease as the number of carbon atoms in an organic molecule in a chondrite increases. This finding is taken as evidence that larger molecules formed by combining smaller molecules.

6. What observations or properties of organic molecules suggest that they formed in the interstellar medium, in the solar nebula, or in planetesimals?

   The evidence supporting different formation locations for organic matter in chondrites is conflicting, perhaps because these molecules formed or were modified in multiple locations. Ring structures, the survival of strained molecules, the identity of functional groups, chirality, and regular patterns within mixtures of organic molecules all help constrain the conditions of formation and storage. Isotopes are perhaps the most reliable indicators of formation conditions. Available data suggest that organic compounds form in the interstellar medium or in the protoplanetary disk. These compounds are then likely modified by reactions in the interiors of planetesimals, or by cosmic-ray irradiation on their surfaces.

Chapter 12

1. How are spectroscopic observations used to relate various kinds of meteorites to asteroid parent bodies?

   Asteroids are classified based on their reflectance spectra. Telescopic or spacecraft spectra of asteroids can be compared with laboratory spectra of meteorites to find plausible matches. Although such comparisons are not definitive links between meteorites and their parent bodies, they do identify asteroid types with the appropriate mineralogy (adjusted for space weathering effects).

2. What are plausible heat sources for planetesimals, and how does heating manifest itself in ice-free and ice-bearing bodies?

   The rapid decay of short-lived radionuclides, especially ^{26}Al, was the most potent heat source for small bodies in the early solar system. Impact heating was also effective for large bodies, but was probably not consequential except for localized heating. Long-lived radionuclide heating and electromagnetic induction heating have also been considered but were probably not effective heat sources for planetesimals. Heating caused thermal metamorphism and/or melting in ice-free bodies. Aqueous alteration occurred in ice-bearing bodies, which limited heat excursions until ice was exhausted.

3. What are onion shell and rubble pile structures for asteroids, and how do they form?

   Onion shell structure refers to the configuration of highly metamorphosed chondrite in the center of an asteroid, grading outward to relatively unmetamorphosed chondrite at the surface, i.e. a concentric progression of petrologic types from type 6 to type 3. This thermal structure is a natural consequence of radiogenic heating and the conduction of heat from the interior to space. When a collision disrupts an onion shell asteroid and then it reaccretes, a rubble pile structure of chunks of varying petrologic type, where interior and surficial materials are mixed haphazardly, is produced.

4. How are the various classes of planetesimals distributed in the solar system, and what can we infer about their origin from their distributions?

   The asteroid belt shows a roughly concentric pattern, with melted/differentiated and/or thermally metamorphosed (S-class) and aqueously altered (C-class) bodies concentrated closer to the Sun, and relatively unaltered (P- and D-class) bodies farther outboard. This pattern may reflect, in part, a thermal gradient caused by earlier accretion of objects closer to the Sun, where the density of material was higher; early accreted bodies had more live ^{26}Al. The pattern may also reflect the transfer of objects from the outer solar system, possibly caused by migration of giant planets, and implantation of these small bodies into the outer main belt.

5. What do we know about the compositions of KBOs and the processes that have affected them?

The spectra of KBOs are somewhat limited, but the largest known bodies have surfaces dominated by ices (CH_4, N_2, CO, H_2O, H_2S), stabilized by the very low temperatures at these great solar distances. Pluto and its moons are the nearest KBOs, and it is dominated by nitrogen and methane ices. All these bodies also contain organics (tholins). Comets are also KBOs, and their rocky components can be identified in chondritic porous IDPs and samples returned by the Stardust spacecraft. These consist of unaltered silicates (mostly olivine and pyroxene), oxides, and other phases similar to those in chondritic meteorites.

6. It has sometimes been said that there is a compositional continuum between asteroids and comets. What does this mean, and what are the implications of this statement?

   Carbonaceous chondrites that have experienced aqueous alteration are derived from asteroids that once contained water ice, probably in smaller amounts than in comets, which are basically dirty snowballs. In the early solar system, carbonaceous chondritic asteroids may have exhibited cometary behavior, expelling jets of gas and dust. Ceres still contains appreciable ice and possibly liquid brines in its interior. Thus, the distinction between asteroids and comets, in terms of volatile contents, is gradational.

7. How have collisions affected planetesimals?

   The main asteroid belt consists of collisional rubble, and only a few intact planetesimals remain. Even many of the larger asteroids are reaccreted rubble piles. Asteroid families, consisting of disrupted chunks still in similar orbits, are common. Glancing collisions have stripped silicate crusts and mantles from metallic cores, leaving naked core M-class asteroids and selectively grinding olivine-rich mantle material into dust.

Chapter 13

1. What kinds of bulk chemical variations are exhibited by the various classes of chondrites?

   Non-carbonaceous chondrites show varying degrees of volatile element depletion, as well as differences in oxidation state which are reflected in the relative proportions of iron as metal versus oxidized silicates, oxides, and sulfides. Carbonaceous chondrites show enhanced contents of refractory elements, reflecting refractory inclusions. And, like other chondrites, they exhibit varying depletions in volatile elements.

2. Briefly explain how the various kinds of spacecraft instruments used to measure chemical composition work. What elements can be measured?

   Orbiting spacecraft have used X-ray fluorescence and gamma-ray and neutron spectrometers to analyze asteroids. XRF depend on fluorescent spectra generated by X-rays from the Sun, and only a few elements can be measured. Gamma rays can be generated by the natural decay of a few radioactive elements (K, U, Th) or produced by nuclear spallation reactions caused by high-energy galactic cosmic rays. Characteristic gamma-ray emissions are detected and used to identify a number of elements, if they are in high enough concentrations. Neutrons are also generated by cosmic rays, and the flux of escaping neutrons can be used to identify hydrogen (usually thought to indicate water) and a few other elements. (More details are presented in the Appendix.)

3. Compare the chemical compositions of IDPs to carbonaceous chondrites.

   Interplanetary dust particles come in two varieties: chondritic porous IDPs, which are thought to derive from comets, and chondritic smooth IDPs, which are samples of carbonaceous chondrite asteroids. The chemical compositions of these small particles are unrepresentative, but in aggregate the chondritic smooth IDPs' chemistry resembles that of CM and CI chondrites. Their mineralogy, consisting of phyllosilicates and other alteration phases, also connects them with carbonaceous chondrites.

4. What processes can lead to chemical variations in achondrites and irons? How can we determine exactly what processes occurred in a given set of samples?

   Achondrites are either partial melts (magmatic achondrites) or solid residues from partial melting (primitive achondrites). Varying degrees of partial melting produce liquids and complementary residues having different compositions. Fractional crystallization of melts produce evolved liquids and crystal cumulates with different compositions. The compositions of iron meteorites are also controlled by the degree of melting and fractional crystallization.

5. When a chondrite begins to melt, what is the composition of the first melt and how does it evolve with further melting?

   The first melts are mixtures of minerals with low melting temperatures. For an ultramafic starting composition, these melts are typically basaltic. However, for chondrites that do not lose volatiles during melting, the first melts can be andesitic. In any case, magmas undergoing fractionation become more iron-rich and silica-rich.

Chapter 14

1. Describe some analytical tools used on orbiting and landed spacecraft to analyze materials on the surface of the Moon and Mars.

   A gamma-ray/neutron spectrometer is an especially useful tool for orbiters, and it has found wide use on both Moon and Mars. A multi-spectral reflectance spectrometer is not specifically a geochemical tool, but spectral data have been used to estimate Fe and Ti contents of the lunar surface. Likewise, an orbiting thermal emission spectrometer has provided mineral modes for Mars which have been converted to chemical data, although it is not very accurate.
   XRF and APXS instruments have directly measured the chemical composition of samples on the martian surface.

2. Briefly describe the major groups of lunar rocks returned by Apollo astronauts and how they relate to groups determined from orbital measurements.

   The major lithologies returned by Apollo missions to the Moon are mare basalts, highlands rocks that include ferroan anorthosite, and impact breccias, often containing

KREEP components. These rocks can be readily distinguished and mapped by orbital GRS measurements of FeO and Th (see Fig. 14.3). The mare basalts are further classified by their TiO_2 contents, which can be distinguished and mapped using orbital visible/near-infrared spectra.

3. What are the major geochemical characteristics of the lunar mantle and crust?

   The lunar crust is rich in cumulus calcic plagioclase, so it is Ca- and Al-rich. These rocks are also Fe-rich. The lunar mantle composition is complementary to the crust, so it is depleted in those elements enriched in the crust. The complementarity is especially noticeable in rare earth element patterns, in which the crust has a positive Eu anomaly and the mantle is opposite.

4. How does the chemical composition of the martian crust differ from that of the Moon?

   The composition of the martian crust is basaltic, because it is formed from partial melts of the ultramafic mantle. The lunar crust is a plagioclase cumulate, as noted in question 3 above.

5. How has water affected the surface of Mars?

   Water, which has existed periodically on the surface of ancient Mars, and probably throughout Mars history in the subsurface, has altered rocks, producing a variety of clay minerals and other phases from basalts, and serpentine from ultramafic rocks. Various evaporite minerals, especially sulfates and halides, have also precipitated from fluids on the surface, and as veins in subsurface rocks. Despite the widespread occurrence of sedimentary rocks, they typically have compositions resembling their basaltic protoliths, implying that alteration has been nearly isochemical.

6. What are the major geochemical characteristics of the Martian mantle and crust?

   Martian crustal rocks have mostly basaltic compositions, and their chemistries reflect fractional crystallization. Older rocks are alkaline, and younger rocks are sub-alkaline. The composition of the mantle has not been measured directly, but from its melting products is inferred to be more Fe-rich and more highly oxidized than the Earth's mantle.

Chapter 15

1. What is the evidence that our Sun formed in the vicinity of other stars and was influenced by a nearby supernova?

   Astronomical observations indicate that most star formation occurs in regions with a high density of gas and dust, forming clusters of stars. The occurrence of short-lived radionuclides in the early solar system, as found in meteorites, requires that other stars occurred in the solar neighborhood. These nuclides, produced in the nearby stars and ejected in supernovae, would not have been incorporated live if the distances between the stars were great.

2. Discuss the evolution of ideas about temperatures in the solar nebula, and how that relates to the formation of CAIs.

   Early models envisioned at hot nebula, with temperature decreasing outward from the protosun. Such a nebula would have evaporated all solid materials, which then condensed on cooling, producing refractory inclusions and other solids depleted in volatile elements. Newer models are not consistent with such a hot nebula, except very near the protosun. The occurrence of nucleosynthetic isotope anomalies in meteorites, which are carried by presolar grains, indicates that all the infalling solid materials were not melted or evaporated, thus limiting the maximum temperatures in the nebula within a few AU from our star. Instead, localized heating (by an unresolved mechanism) produced chondrules by melting and refractory inclusions by partial evaporation.

3. What constraints do we have on the bulk chemical compositions of planets?

   The basic observations that constrain the bulk compositions of planets include mean density (corrected for self-compression in larger bodies) and moment of inertia. The uncompressed mean density provides insight into the relative proportions of dense metallic core versus silicate mantle plus crust. The moment of inertia factor constrains how density varies within the body. Once the mass of the core is estimated, chemical (usually chondritic, but subtracting the core composition) models are constructed that calculate mineralogical changes with depth (increasing pressure and temperature). This integrated mineralogy is then used to calculate a mean density and moment of inertia for comparison with measured values. The procedure can be reiterated until a reasonable match is obtained.

4. Describe the building blocks that accreted to form the terrestrial planets, and explain how that may relate to their observed volatile element depletions.

   The building blocks for the terrestrial planets were originally thought to be chondritic planetesimals. However, the ages of chondrites are younger than those of differentiated meteorites and irons, so current thinking is that the planetary raw materials were already differentiated. The bulk compositions of differentiated bodies would still be broadly chondritic, with similar ratios of refractory elements to chondrites, but would have been more depleted in volatile elements. Additional volatile elements and compounds, like water, may have been added by late accretion of carbonaceous chondrite bodies.

5. How do the chemical compositions and internal structures of the giant planets differ from those of the terrestrial planets, and from each other?

   The giant planets include gas giants (Jupiter and Saturn) and ice giants (Uranus and Neptune). The gas giants began with solid rocky cores but grew rapidly enough that they captured gas directly from the nebula. However, they do not have solar compositions, as the abundance of elements heavier than H and He are somewhat enriched. The outer layers of Jupiter and Saturn are depleted in He relative to H, caused by raining out of He at high pressures in the interiors of these bodies (He, as well as Ne, is not soluble in H, once pressures are high enough to form metallic H.

Uranus and Neptune also have rocky cores, but accreted mantles of solid ices rather than nebular gas. They do not show the depletion of He (and Ne) relative to H, because their internal pressures are not high enough to form metallic H.
The atmospheres of all the giant planets contain an array of volatile compounds, including CH_4, NH_3, H_2O, and H_2S, as well as hydrocarbons and noble gases.

6. What aspects of cosmochemistry are used to infer the compositions and internal structures of exoplanets?

   We cannot directly measure the chemistry of exoplanets, but cosmochemical reasoning can be used to infer their compositions. Mean densities, determined from measurements of their sizes and masses, are used to infer the proportions of gas/ice, rock, and metallic core. Internal structures are based on these compositions. Exoplanets span the range of planets in our solar, and extend to even larger and smaller bodies with a bewildering array of structures.