The Solar System: A Panorama

8

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Contents

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Abstract

The closest and most extensively studied planetary system, our solar system provides the foundation for understanding the characteristics of planetary and sub-planetary bodies and the processes that shape them. This chapter surveys the diversity of objects orbiting our Sun and what they tell us about the origins and evolution of the solar system. The numerous small bodies populating specific orbits, from the asteroid belt to the far reaches of the Oort cloud, encode information on the solar system's age and the initial conditions in the solar nebula. The surfaces and atmospheres of the planets and their satellites reveal how the same fundamental physical processes produced bodies with vastly different characteristics, from the dry, metal-dominated composition of Mercury through the storm-wracked hydrogen atmosphere of Jupiter. Finally, the search for liquid water and temperate climates elsewhere in the solar system, past or present, provides context for understanding the origin of life on Earth and the potential for life's existence elsewhere in the Universe.

Introduction

Our solar system consists of a diverse and dynamic collection of objects spanning many orders of magnitude in scale. From the Sun through the smallest atoms and electrons, all components play a role in the complex gravitational, chemical, and electromagnetic interactions that govern the evolution of the system as a whole. Although it is not yet clear whether our own solar system is representative of planetary systems elsewhere in the Universe, or even within our stellar neighborhood, it is the only system that we are currently capable of studying in detail. We study the solar system through a combination of spacecraft missions, ground-based and Earth-orbiting telescopes, and laboratory analysis of samples brought back by missions or delivered to Earth's surface in the form of meteorites. Such studies have shown us the complexity and diversity of solar system bodies, from the giant planets and their satellites down to asteroid fragments and minute ring particles.

Through studying the solar system today, we try to piece together the story of the planets' formation and subsequent evolution. The goal is to understand how the initial conditions, acted on by fundamental physical processes, led to the system we see today. We seek to explain why we have the number of planets we have in the orbits in which we see them and to understand the similarities and differences between them. What differences in the initial conditions of the terrestrial planets, or in their subsequent processing, produced the stark variations in atmospheric temperature and pressure between Earth, Venus, and Mars? Answering questions like these also sheds light on the occurrence and longevity of habitable environments on planets and satellites.

Figure 1 shows an inventory of our solar system, where the size of each body is plotted as a function of distance from the Sun (the orbital and rotational properties of the planets are given in Table 1). The eight planets stand out with respect to

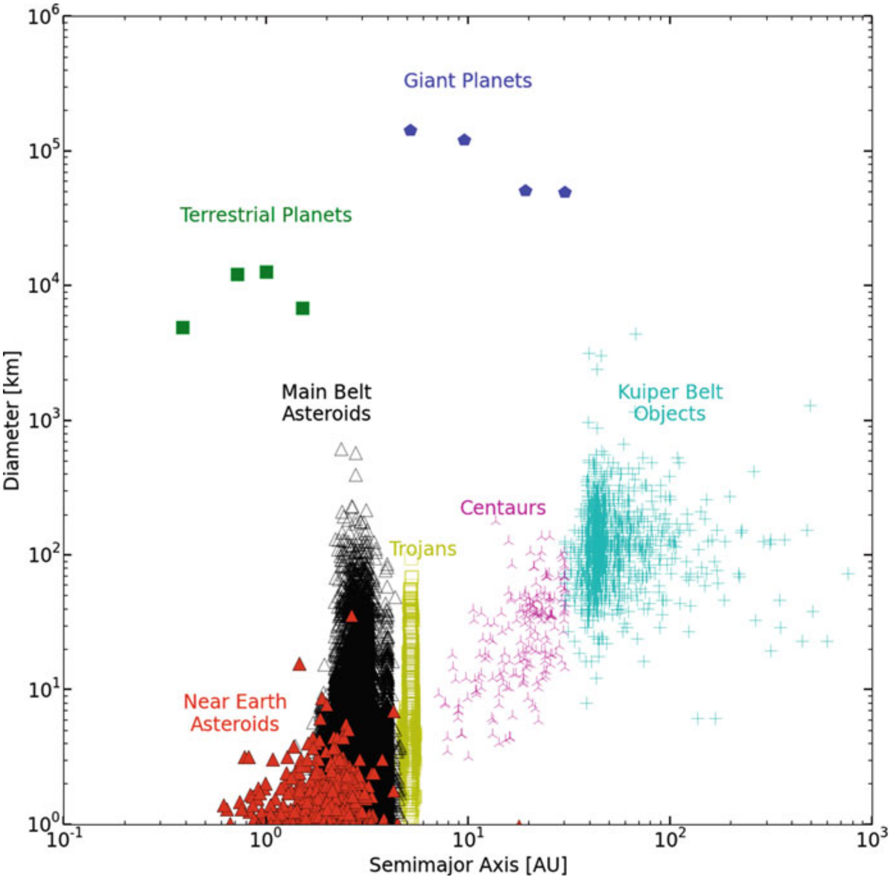

Fig. 1 Inventory of solar system objects. Note that the apparent increase in the minimum size of bodies with heliocentric distance is an observational bias, because it is much harder to find small bodies at large geocentric distances. Data provided by the International Astronomical Union's Minor Planet Center (Figure after Spencer)

size; Jupiter, followed closely by Saturn, is by far the largest body. Two orders of magnitude down in size from the terrestrial planets, we find a multitude of objects. Some of these are on stable orbits, including the main-belt asteroids between the orbits of Mars and Jupiter, the Trojan asteroids at Jupiter's L4 and L5 Lagrange points, and the Kuiper belt out beyond the orbit of Neptune. Other bodies are on chaotic or unstable orbits. Near-Earth asteroids may ultimately be on a course to hit a terrestrial planet, the Moon, or the Sun, and the Centaurs, in transit from the Kuiper belt into the inner solar system, will be transformed into comets when ices on their surface start to sublimate under increased solar heating. At roughly 10,000–50,000 AU, our solar system is enveloped by a shell populated by several billion icy bodies that is referred to as the Oort cloud.

Table 1 Orbital and rotation parameters of the solar system planets

Planet	*a* [AU]	*e*	*i* [deg]	Obliquity [deg]	P_{orbit} [Days]	P_{rotation} [Hours]
Mercury	0.387	0.205	7.0	0.01	88.0	1,407.6
Venus	0.723	0.007	3.4	177.4	224.7	5,832.5
Earth	1.000	0.017	0.0	23.4	365.2	23.9
Mars	1.523	0.094	1.9	25.2	687.0	24.6
Jupiter	5.203	0.049	1.3	3.1	4,331	9.9
Saturn	9.543	0.057	2.5	26.7	10,747	10.7
Uranus	19.192	0.046	0.8	97.8	30,589	17.2
Neptune	30.069	0.011	1.8	29.3	59,800	16.1

Data from the NASA National Space Science Data Coordinated Archive: http://nssdc.gsfc.nasa.gov/

In order to connect the current state of the solar system to its formation and evolution, we need to understand the processes at work on planetary bodies and calibrate our understanding of measurable signatures in terms of what they reveal about the past. The study of small solar system bodies – asteroids and comets – has taught us the age and initial conditions of the solar system. Computer simulations demonstrate potential evolution scenarios, and studies of planet-forming nebulae and disks around other stars provide the context into which to place our own stellar system.

A Brief History of the Solar System

Our Sun is a fairly typical star, and our understanding of the origin and formation of the solar system is based on studies of other systems in the galaxy that we believe represent the preliminary stages of stellar and planetary formation, calibrated to match the observed composition and architecture of our solar system.

We believe that the Sun was formed under similar conditions as other similar stars, in a dense core within a giant molecular cloud composed of molecular hydrogen, helium, more complex molecules, and dust grains. This core contained the inventory of volatiles and heavy elements present in our solar system today. At a specific point in time, an external trigger initiated the gravitational collapse of the dense molecular core. The core began to collapse under self-gravity, releasing gravitational potential energy that heated the central regions. Collisions between grains in the increasingly dense central region damped out vertical motion, resulting in a disk of material that spun in conservation of the initial random angular momentum of the core. Through a process that is still not well understood, the small grains agglomerated into large grains, which grew into kilometer-sized bodies known as planetesimals. Gravitational interactions then accreted the planetesimals into larger-sized embryos, or protoplanets.

The cores of the giant planets likely formed early via runaway solid-body accretion. Once these cores reached masses of order ten times the mass of the Earth, these protoplanets grew rapidly through runaway accretion of gas from the protoplanetary disk. The giant planets likely formed in the first 10 million years, while the terrestrial planets took about ten times longer. Formation stopped when the gas in the protoplanetary disk was cleared away by the strong solar wind during the Sun's T Tauri phase. Since the abundance of solid material in the disk decreased with heliocentric distance beyond the "ice" line, it took much longer for proto-Uranus and proto-Neptune to form than Jupiter and Saturn, and hence these planets have much less hydrogen and helium than Jupiter and Saturn.

Models for the evolution of the solar system during and after formation must be able to explain the sizes, locations, and compositions of the planets and the small body populations. Most models postulate that the giant planets have migrated significantly since their formation, although the timing of this migration, as well as the planets' formation locations and migration paths, vary significantly. Migration of the giant planets scattered some planetesimals inward toward the Sun and ejected others into the distant Oort cloud. Those that were scattered into the inner solar system were responsible for the bombardment of the terrestrial planets evident in these planets' cratering records. The heavily cratered surfaces of most rocky bodies in our solar system, together with the high porosities of many asteroids, suggest that the planets formed in a violent environment in which numerous bodies continued to impact the forming planets and collide with each other, often shattering proto-asteroids or planets to pieces. Unless completely dispersed, such fragments accreted to form a new body, sometimes leaving fragments behind in the form of small moonlets. Proto-Earth is thought to have been hit by a Mars-sized object, leading to the formation of our Moon.

The gradient in temperature from the hot Sun-forming region to the cold outer reaches is responsible for many of the broad-scale differences between the terrestrial and gas giant planets. Refractory metals and silicates condensed throughout the protoplanetary disk, while the cool temperatures in the outer solar system permitted the condensation of volatiles in the form of water (H_2O), ammonia (NH_3), methane (CH_4), and other species. Since the volatile elements are much more abundant than rock-forming elements (e.g., Si, Mg, and Fe), there was much more material available for planet formation in the outer regions of the planetary disk where the giant planets formed, than in the inner solar system where the terrestrial planets formed. These differences are reflected in the sizes and bulk densities of the eight planets, given in Table 2.

Bodies over $\sim$100 km in size are typically differentiated. That is, their cores consist mostly of the heaviest elements like Fe, while their mantles consist of lighter rocky material that may be overlain, depending on the body's composition, with an icy outer layer. The differentiation of bodies hints at a molten state early in their formation history, caused by the heat of formation and the decay of radioactive isotopes. Both of these heat sources remain active today, although their magnitude has been decreasing over the solar system's history. Figure 2 shows the interior structures of the eight planets, which is the product of early interior differentiation.

Table 2 Physical parameters of the solar system planets

Planet	Mass [10^{27}g]	Radius [km]	Density [g/cm^3]
Mercury	0.33	2,440	5.427
Venus	4.87	6,052	5.243
Earth	5.97	6,378	5.514
Mars	0.64	3,396	3.933
Jupiter	1,898	71,492	1.326
Saturn	568	60,268	0.687
Uranus	86.8	25,559	1.271
Neptune	102	24,764	1.638

The Sun

In many respects, the characteristics of our solar system are dominated by the Sun itself. The Sun is the only feature of our solar system that would be visible from a neighboring star. It dominates the mass of the solar system (99.86%), and the solar radiation and solar wind are responsible for radiative and chemical processing of the surfaces and atmospheres of objects out to the farthest reaches of the solar system.

Our Sun is a fairly typical G2V-type star; it has a mass of 2×10^{30} kg, and its luminosity of 3.8×10^{26} W places it squarely within the main sequence on the Hertzsprung-Russell diagram. The bulk composition of the Sun is representative of the original composition of the molecular cloud from which the solar system formed and is dominated by hydrogen (70% by mass) and helium (28%), with the remaining amount dominated by oxygen, carbon, and nitrogen. Studies of stellar evolution indicate that our Sun has an expected main-sequence lifetime of 9–10 Gyr and that it will then pass through a red giant phase and eventually become a white dwarf.

Today, the amount of solar energy incident on the planets matches or exceeds their intrinsic energy production. By comparing the total power emitted by planetary bodies with the solar power at their orbital distances, we can calculate the amount of internally generated energy in each of these bodies and gain insight into their thermal states and histories. The intrinsic heat flow of the terrestrial planets is nonzero but is negligible in comparison with the solar energy they absorb. Of the giant planets, Jupiter, Saturn, and Neptune emit twice the energy they receive from the Sun, while Uranus appears to lack an internal heat source for reasons that remain a mystery.

The Terrestrial Planets

Four planets orbit the Sun within 2 AU and constitute the terrestrial planets of the inner solar system: Mercury, Venus, Earth, and Mars (shown in Fig. 3). They are characterized by solid surfaces and dense compositions, in contrast to the

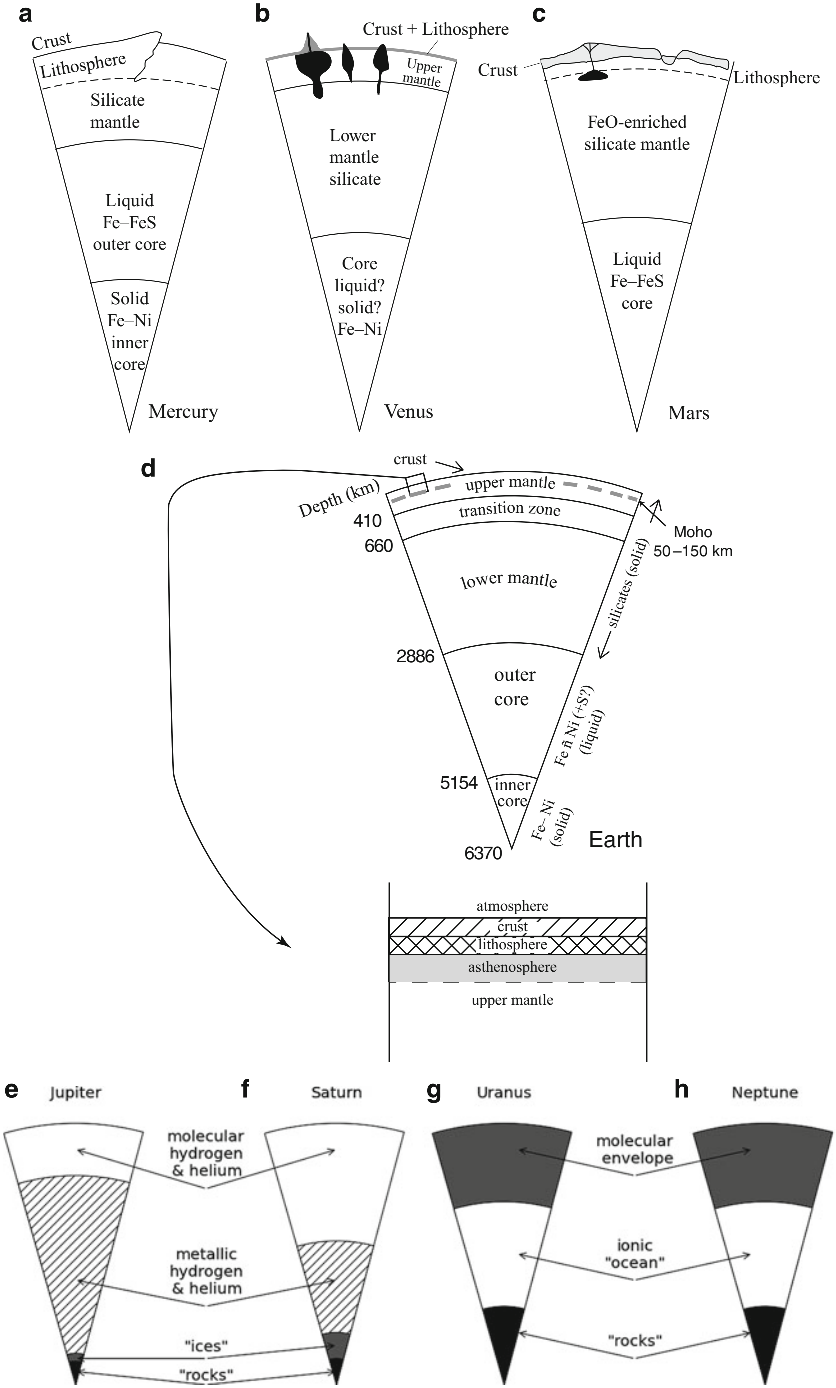

Fig. 2 Interior structures of the planets. The exact composition of the layers and the locations of their boundaries are still not precisely known; the figure represents our current understanding (Terrestrial planet schematics reprinted with permission from de Pater and Lissauer 2010)

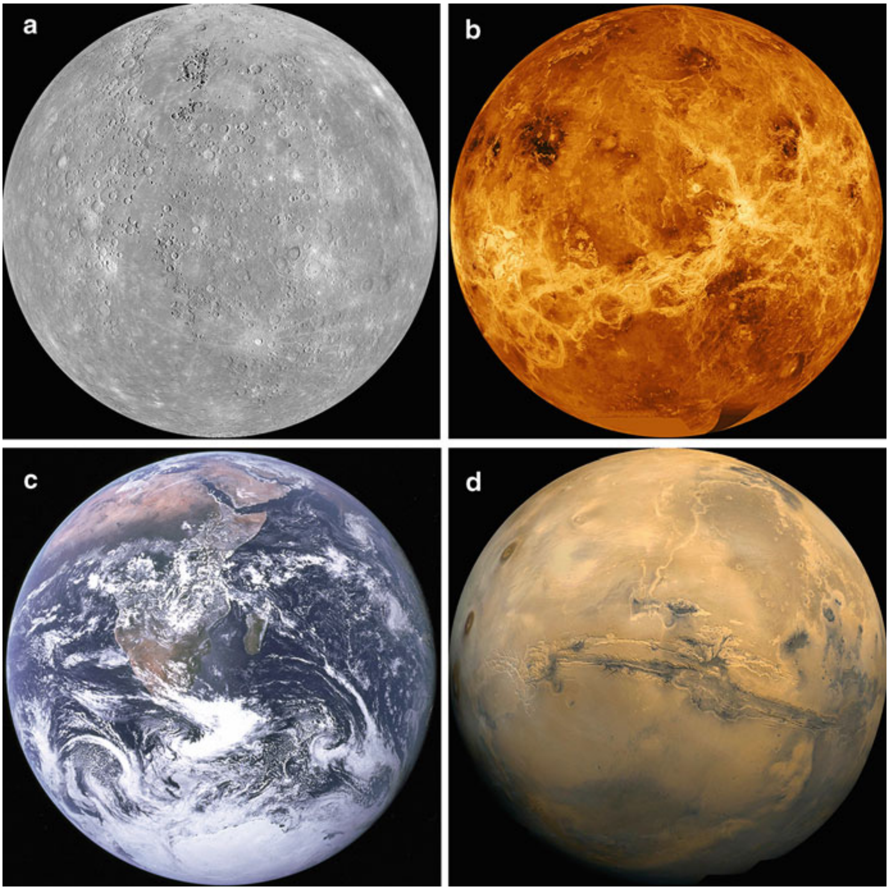

Fig. 3 The terrestrial planets. (**a**) Mercury (Source: NASA/JHU APL/Carnegie Institute of Washington). (**b**) Venus global view mosaicked from *Magellan* and *Pioneer* observations (Source: NASA/JPL). (**c**) Earth, as viewed by *Apollo 17* (Source: NASA). (**d**) Mars as viewed by the *Viking* Orbiters in the 1970s (Source: NASA)

volatile- and gas-dominated giant planets. The densities of the inner three planets indicate predominantly rocky compositions, roughly in the range of 5.2–5.5 g/cm^3, while the density of Mars is a markedly lower 3.94 g/cm^3 (see Table 2).

Due to the proximity of Mars and Venus to Earth, as well as their rough similarity in size, studies of these planets have included investigations into their past and current habitability. In addition, while Mars' cold, dry climate and tenuous atmosphere contrast starkly with Venus' hot, dense atmosphere, both planets represent possible phases through which Earth may have passed and end-members that it may ultimately reach.

Surfaces

The surfaces of the terrestrial planets and their satellites are silicate-dominated and have been processed by numerous mechanisms that provide a record of the evolutionary history of the bodies themselves and of the objects that impacted them. New crust was repeatedly created early in the solar system's history by the emplacement of massive lava flows and was subsequently modified by numerous processes. External processes include sputtering and chemical and radiation weathering, while intrinsic processes include tectonics and atmospheric weathering. Craters on planetary surfaces record the bombardment history as a function of solar distance but can be erased by surface processes and hence provide a tool for dating surface ages.

The surface of Mercury is dominated by tectonic features and heavy cratering; the lack of atmosphere and proximity to the Sun led to a high impact rate throughout its history. Mars' surface, while also heavily cratered (at least in the southern hemisphere), shows evidence of erosion by wind and liquid water. The appearance of Venus' surface is dominated by volcanism. Impact craters are randomly distributed over its surface, which may only be 300–600 million years in age; debates continue as to the mechanisms of its apparently global resurfacing. Earth's tectonic features are primarily related to its tectonic plate activity and include trenches at divergent plate boundaries and mountain ranges at interacting plate edges. Although Mars has substantial polar ice deposits of both water and CO_2 ice, Earth is the only planet in the solar system with stable liquid water on its surface.

Atmospheres

Although all of the planets likely accreted hydrogen and helium envelopes from the solar nebula, the rocky planets lacked the mass to maintain these primary atmospheres. Secondary atmospheres were formed by a combination of large-scale outgassing from early molten interiors and delivery from farther out in the solar system via comet and asteroid impacts. There is evidence that the climates of Earth, Venus, and Mars have evolved significantly over their histories, passing through phases of vastly different atmospheric temperature, density, and composition from what we see today.

Mercury's atmosphere is negligible and is composed of atoms sputtered from the surface and captured solar wind ions. Although both Mars and Venus have CO_2-dominated atmospheres with N_2 present at the few percent level, Mars' atmosphere is cold (218 K) and extremely tenuous ($\sim$6 mbar), while Venus' dense (93-bar) atmosphere produces a greenhouse effect that heats the surface to a mean temperature of 735 K. On Venus, the time variability of atmospheric SO_2 points to ongoing volcanic activity. Some evidence indicates that Mars' past atmosphere may have been warm and dense enough to permit liquid water on the surface. Such an environment may have had all the conditions to support life, but the question of Mars' climate history is still under active investigation. In contrast, Earth has a moderately dense (1 bar) atmosphere composed predominantly of molecular nitrogen (78% by volume) and oxygen (21%), with contributions from argon, carbon dioxide, water vapor, and other trace species. Earth's atmosphere is unique in its abundance of free oxygen, which is converted from CO_2 by organisms.

Interiors and Magnetic Fields

The interior structure of all four terrestrial planets is characterized by a dense core, a mantle, and a crust (see Fig. 2). Both Earth and Mercury have a solid Fe-Ni inner core, a liquid outer core, a silicate mantle, and an outer crust. The core of Mars is likely liquid Fe-FeS throughout, while we still do not know the state (liquid or solid) of Venus' core. Mercury's core comprises a strikingly large fraction of its total volume. One of the many hypotheses that attempt to explain the unusual core size postulates that a planetesimal impacted Mercury after its differentiation, stripping off much of its mantle and leaving behind an object dominated by core material.

Currents in the liquid outer cores of Earth and Mercury generate these planets' intrinsic magnetic fields. Earth's magnetic field protects its surface from the solar wind, which it holds off at a height of $\sim 10R_E$, the location of the bow shock. The ions populating this field originate both in Earth's ionosphere and in the solar wind. Mercury's magnetic field is strong enough to protect the surface from solar wind particles under typical conditions but is insufficient to hold off the solar wind at times of increased pressure. During these times, the solar wind impinges directly on Mercury's surface.

Although Mars lacks a magnetic field today, areas of localized remnant crustal magnetism indicate that it possessed a strong magnetic field during the first few hundred million years after its formation. The dynamo was likely shut off when Mars' interior cooled to the point that turbulent convection ceased in the core. Like Mars, Venus does not currently possess an intrinsic magnetic field, although an induced field is produced by interactions between the solar wind and Venus' ionosphere.

Satellites

The Earth is the only terrestrial planet with a large, regular satellite. It is generally accepted that the Moon was formed by the collision of a Mars-sized object with the proto-Earth, at a late enough stage that differentiation into a metallic core and silicate mantle had already occurred. The cores of the two objects merged to form Earth's core, while the mantle material was thrown into Earth's orbit and eventually accreted into the Moon. This process resulted in a body without a significant core and with a bulk composition similar to that of Earth's mantle. The only other terrestrial planet to host satellites is Mars, whose moons Phobos and Deimos are small in size and irregular in shape. Their compositions appear similar to carbonaceous chondrites, suggesting that they may be captured asteroids. However, various other properties (e.g., their close-in orbits) are difficult to reconcile with such a scenario.

The Giant Planets

Exploration of the giant planets by spacecraft began with the *Pioneer* missions in the 1970s. In 1989, *Voyager 2* became the first spacecraft to complete a visit to all four of the giant planets and still remains the only spacecraft to have visited Uranus and Neptune. Subsequently, both Jupiter and Saturn were visited by orbiters (the *Galileo* and *Cassini* spacecraft, respectively). The data resulting from these missions, as well as from ground- and space-based telescope observations (Fig. 4), have shown us the dynamic atmospheres, the intricate ring and satellite systems, and the complex neutral and plasma environments of the giant planets.

The giant planets can be separated into two categories – the gas giants (Jupiter and Saturn) and the ice giants (Uranus and Neptune). Within each category, the two bodies are of comparable size and mass (within a factor of 2), yet the gas giants have ∼10 times the mass of the ice giants. All four have some form of metallic/rocky core, a convecting conductive layer that generates a magnetic field, and an intricate system of rings and satellites.

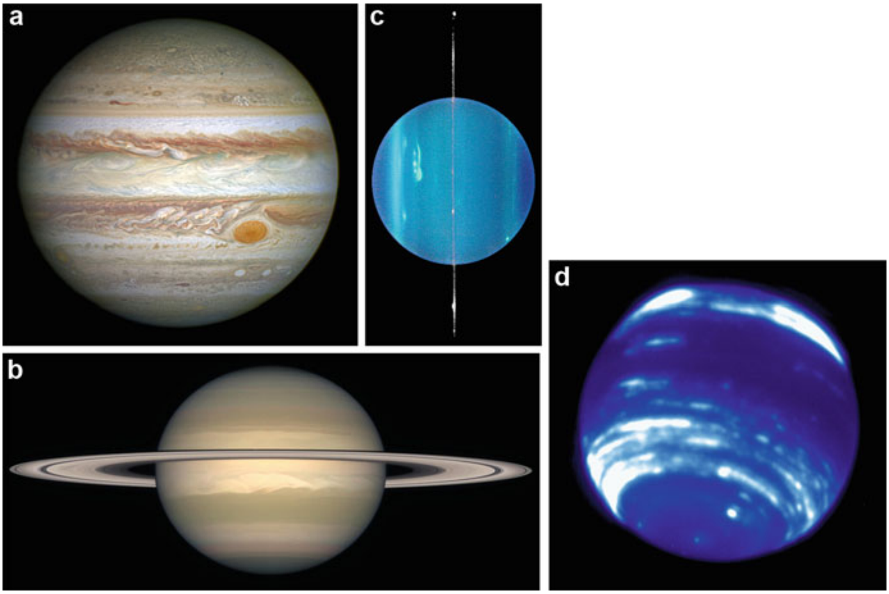

Fig. 4 The giant planets. (**a**) Jupiter and (**b**) Saturn viewed at optical wavelengths by the Hubble Space Telescope (Source: NASA/ESA/A. Simon). False-color images of (**c**) Uranus (Source: I. de Pater, H. Hammel, L. Sromovsy, P. Fry) and (**d**) Neptune (Adapted from de Pater et al. 2014) viewed at near-infrared wavelengths by the Keck telescope

Atmospheres

The atmospheres of all four giant planets exhibit decreasing temperature with depth down to $\sim$0.1 bar (the tropopause), below which temperature increases with depth, following an adiabat below roughly 1 bar. All four atmospheres are dominated by hydrogen (80–90% by volume) and helium (10–15%) captured from the solar nebula during formation, with trace amounts of C, O, N, S, and P in the form of methane, water, ammonia, hydrogen sulfide, and phosphine.

Most of the information we have on the giant planets' atmospheres has been determined by remote sensing. However, the *Galileo* probe, which was sent directly into Jupiter's atmosphere, determined the composition of this planet's "deep" (10–20 bar) atmosphere. It found that all elements, C, N, and S, as well as Ar, Kr, and Xe, were enhanced by a factor of $\sim$4 over the solar elemental values. Water, however, was measured at a factor of 3 below the solar O abundance, which was attributed to the fact that the probe descended into an anomalously dry region. Clearly, our understanding of atmospheric composition is limited to the depths probed by the observations, which are limited to the upper few bars for optical and infrared wavelengths. Radio wavelengths extend the observational reach significantly but still leave a large portion of the atmosphere untapped. Remote sensing data of all four planets indicate that the abundances of CH_4 and H_2S gases, relative to hydrogen, increase from Jupiter (factor of 4 over solar values) out to Uranus and Neptune (factor of 30–60 over solar values).

Within a planetary atmosphere, a gas rises from the deep atmosphere adiabatically until it reaches its condensation temperature and condenses to form a cloud. Such clouds vary from tenuous, localized features to global, optically thick layers. A water-solution cloud is expected to be present at the deepest levels, topped by a water-ice cloud. Above the level of the water cloud, we expect an NH_4SH cloud on all four planets. Jupiter and Saturn's upper atmospheres contain a top cloud layer of ammonia ice particles, while Uranus and Neptune's contain a methane-ice cloud at the highest levels with a somewhat deeper (yet above the NH_4SH layer) H_2S cloud.

The appearance of Jupiter and Saturn is characterized by massive storm systems and distinctive zonal wind patterns with multiple jets in each hemisphere. Neptune lacks the diverse, distinctive storm patterns of Jupiter but is spotted with omnipresent (but constantly evolving) bright cloud features and an occasional large storm. In contrast, Uranus typically appears free of bright cloud features; this difference may be due to a lesser degree of convective activity, perhaps connected to Uranus' apparent lack of internal heat production. An excess of CO in the atmospheres of Jupiter, Saturn, and Neptune (as high as $\sim$1,000× the equilibrium abundance in the case of Neptune) may indicate external delivery from comets or from materials originating on their icy moons.

Interiors and Magnetic Fields

Information on planetary interiors is difficult to obtain and relies on indirect information such as a planet's oblateness, rotation rate, and heat flow, as well as its magnetic and gravitational fields. Properties of the body's shape and structure can be inferred from its gravity field, as measured in situ by spacecraft or indirectly by its effect on the orbiting moons and rings. Models to match the observed properties of Jupiter and Saturn indicate relatively small, dense cores dominated by iron and silicate, roughly five to ten Earth masses for Jupiter and somewhat larger for Saturn. The bulk of each planet's volume is dominated by hydrogen and helium, in metallic form for the high-pressure interior and in molecular form in the shallower atmosphere (see Fig. 2 for interior diagrams of these planets).

The layer of metallic hydrogen and helium generates the powerful magnetic fields of Jupiter and Saturn. Saturn's magnetic field is somewhat weaker than Jupiter's and is distinctive in that it is the only known magnetic field that aligns with its planet's rotation axis. Jupiter's magnetosphere is home to vast, dynamic systems of ions and electrons, including radiation belts and a torus of plasma that is sourced from volcanic by-products in Io's atmosphere. As with Jupiter, Saturn is surrounded by a torus of plasma that is sourced by its satellites and rings, including material jetting out of Enceladus' geysers.

Uranus and Neptune have a larger relative abundance of heavier elements than Jupiter and Saturn and hence contain larger cores (out to perhaps ~1/3 of their radii). Their interior pressures are too low for metallic hydrogen to exist, yet the presence of magnetic fields indicates a convecting conductive material, which is thought to be an ionic "ocean" between about 0.3 and 0.7 planetary radii. Although little is known about the magnetic fields of Uranus and Neptune, these planets' magnetic axes appear to be not only tipped significantly (60° and 47°, respectively) relative to their rotation axes, but the magnetic dipole centers are also displaced from their centers by one third of the radius in the case of Uranus and over half the radius in the case of Neptune.

Satellites and Rings of the Giant Planets

A system of satellites and ring particles orbiting a central planet resembles a miniature planetary system, with bodies spanning a range of sizes, compositions, and orbital parameters interacting through diverse processes. The giant planets host a small number of large, regular satellites and a network of smaller satellites (more than 60 in number in the case of Jupiter). Nearly all regular and close-in satellites orbit in a prograde sense, in an orbital plane that aligns with the planet's equatorial plane to within a few degrees. They are also typically in synchronous rotation, so that the orbital and rotation periods are equal. In contrast, many of the small, outer satellites are in retrograde orbits and/or are not synchronously rotating, suggesting that these populations are dominated by captured comets, asteroids, or planetesimals. Several groups of small satellites follow similar orbits around Jupiter, suggesting that these satellites are fragments of larger bodies that were disrupted after capture.

All four of the giant planets are also encircled by ring systems, although the appearance of the rings is strikingly different between planets. Most rings can be thought of as failed satellites: the tidal forces close to the planet are sufficiently strong to prevent debris from coalescing into a satellite or to tidally disrupt a satellite in such an orbit if the satellite's mechanical strength is weaker than the tidal forces. Indeed, most rings are found within or near the Roche limit. Collisions between particles dissipate energy but conserve angular momentum, resulting in the flat, annular appearance of the rings. The dynamical, chemical, and even electromagnetic processes at work in planetary ring systems can be studied as small-scale analogs to the processes that shape the early disks in which planets form.

In addition to these "classical" rings, some planets also have tenuous, dusty rings. While cm-m-size ring particle orbits are governed by the planet's gravitational field, micron-sized dust is influenced by solar radiation, plasma, and electromagnetic forces, which limit their lifetimes to $\sim 10^3$ to 10^5 years (for a 1 μm size grained in Jupiter's rings). Such dusty rings must therefore be young and continuously replenished by new material.

Rings

Saturn's ring system is the most dramatic and well-studied in the solar system. Its appearance is dominated by the two main (A and B) rings, which are separated by a distinctive gap. Interior to the main rings are the C and the tenuous D rings, while 3,000 km beyond the A ring are the narrow, seemingly intertwined, F ring and the dusty G and E rings. The G ring is red due to light scattered off the dust, while the E ring appears blue, indicative of a ring composed of only tiny grains. Enceladus' water ice geysers are likely the source of the E ring material.

The main rings exhibit a wide range of dynamic features caused by complex gravitational interactions between the particles themselves, as well as between the particles and Saturn and its moons. The particles are predominantly pure water ice; slight contaminations of the ice have been used to infer a particle age of <150 Myr. Extensive and time-variable radial and azimuthal variations in the rings have been seen (Fig. 5). Numerous gaps between discrete rings are maintained by small moonlets, while resonant perturbations introduce waves. Spiral density waves reveal the surface mass density of the rings and have led to a total mass estimate for the rings roughly equal to the mass of the satellite Mimas. Transient clumps of particles form by self-gravitation and are sheared out along their radial extent leading to azimuthally extended features, while distinctive propeller-shaped features indicate numerous undetected bodies 20–250 m in size.

Jupiter's rings are extremely tenuous and composed mainly of dust originating from micrometeorite impacts on the small inner moons and collisions between larger-sized material in the rings. The dust is transported inward by Poynting-Robertson drag and kicked into higher-inclination orbits at the 3:2 Lorentz resonance, resulting in a halo of dust closer to the planet.

Uranus' ring system includes nine narrow (1–10 km wide) main rings. The outer (epsilon) ring is by far the brightest and varies in width from 20 to 95 km. The rings are composed of 10 cm–10 m sized dark particles, and dusty material is

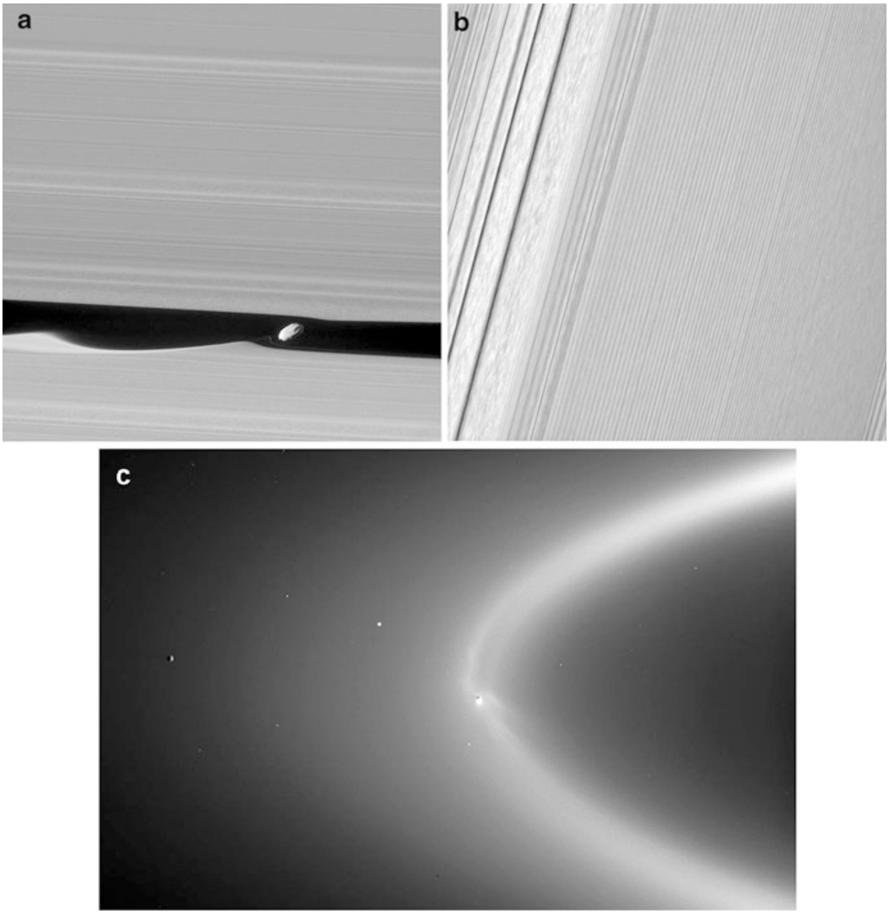

Fig. 5 Structure in Saturn's rings. (**a**) Waves in the edges of the Keeler gap raised by Saturn's small moon Daphnis. (**b**) Structure in Saturn's A ring as viewed in visible light by the *Cassini* spacecraft. A density wave is seen at the left of the image and is caused by the moons Janus and Epimetheus. (**c**) Enceladus orbiting within Saturn's E ring, which is likely made up of icy particles ejected from Enceladus' south polar jets (Source: NASA/JPL-Caltech/Space Science Institute)

interspersed between the rings. Beyond the main rings are the outer blue-colored mu ring, perhaps sourced from the moon Mab, and the dusty red-colored nu ring.

Neptune's rings, while also narrow (~15 km wide) and dark, contain a set of striking ring arcs which are grouped together within a narrow (40-degree) longitude range, where the extent of each individual arc in the azimuthal direction is only 1–10°. Several large moons orbiting within the ring system may be responsible for this unusual structure. While the trailing arcs appear to be quite stable, the two leading arcs have faded to invisibility since *Voyager's* visit to Neptune in 1989.

Major Satellites

The set of solar system satellites exhibits an astonishing diversity of surface and atmospheric features (Fig. 6). In addition, the subsurface oceans that now appear to be a common feature of large icy satellites are the current best candidates for other habitable environments within our solar system. Surface features reveal information on the thermal histories and external environments of the satellites, while gravity, magnetic field, and topography measurements provide glimpses into these bodies' interior structures.

All of the large satellites are broadly of silicate composition, with a volatile fraction that varies substantially between objects. They range in density from $\sim$1.75 g/cm^3 up to $\sim$3.5 g/cm^3 and are often differentiated into a core of heavy elements and a mantle of lighter materials. Their surfaces may be composed of pure water ice or be coated in dark materials that are either deposited from

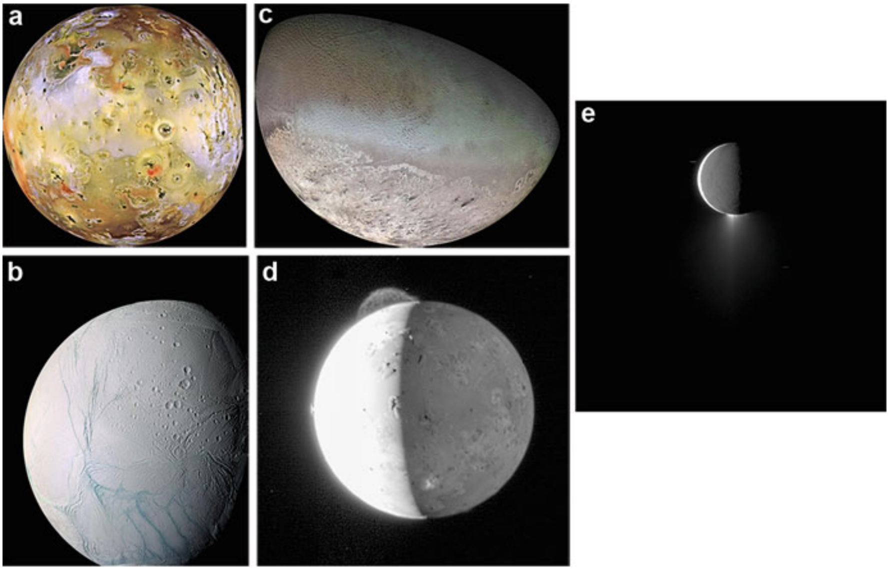

Fig. 6 Satellites. (**a**) Color image of Io constructed from near-infrared and optical images obtained by the *Galileo* spacecraft. Dark lava flows, colorful plume deposits, and yellow SO_2 surface frosts are all clearly distinguished (Source: NASA/JPL/University of Arizona). (**b**) Color image of Enceladus, mosaicked from frames spanning 338–930 nm obtained by the *Cassini* spacecraft. The blue linear features are thermal sources known as the "tiger stripes" and are the source of Enceladus' plumes (Source: NASA/JPL/Space Science Institute). (**c**) Triton's cryovolcanic landscape as viewed by *Voyager 2*, the only spacecraft to visit the Neptune system (Source: NASA/JPL/USGS). (**d**) Volcanic plumes on Io, viewed by the *New Horizons* spacecraft (Source: NASA/JHU APL/SwRI). (**e**) *Cassini* image of Enceladus' south polar plumes (Source: NASA/JPL/Space Science Institute)

external sources or brought up from the interior. Although all of the large satellites have atmospheres, such atmospheres are often extremely tenuous. For a body without a substantial atmosphere, the surface temperature is close to the equilibrium temperature. Satellite surfaces may be processed externally by sputtering and impacts or disrupted and recoated by past or ongoing geological processes.

The four Galilean satellites of Jupiter – Io, Europa, Ganymede, and Callisto – compose the largest system of major satellites in the solar system. These moons exhibit a monotonic compositional trend with Jovian distance, with the bulk density decreasing from Io (3.53 g/cm^3) out to Callisto (1.94 g/cm^3). Io, Europa, and Ganymede are locked into a 4:2:1 Laplace orbital resonance with one another, resulting in tidal heating that is strongest at Io and decreases outward through Europa and Ganymede. As a consequence of their thermal histories, all three satellites are differentiated and likely contain iron-dominated cores and rocky mantles. In contrast, Callisto is relatively unprocessed and has an undifferentiated interior composed of ice and rock. The surfaces of Europa, Ganymede, and Callisto are dominated by water ice and are likely underlain by salty subsurface oceans of liquid water. Io is volatile-depleted due to its ongoing active volcanism and volcanically sourced sulfur dioxide frost coats much of its surface, shown in Fig. 6a.

Titan is the largest satellite of Saturn and is comparable in density to Callisto ($\rho_{\text{Titan}} = 1.88$ g/cm^3). It is likely differentiated into a rocky iron core and an ice-rich mantle. Titan hosts the only atmosphere in the solar system comparable to Earth's in terms of its atmospheric pressure ($\sim$1.5 bar); its composition, which is dominated by nitrogen gas; and its wide range of weather patterns, which include a methanological cycle analogous to the hydrological cycle on Earth. A wide variety of complex hydrocarbons is present in Titan's stratosphere, produced by photolysis of methane gas at these high altitudes followed by a chain of chemical reactions.

One of the most exciting discoveries to come out of the *Cassini* mission to Saturn was the detection of extreme cryovolcanic geyser activity on Saturn's moon Enceladus. Plumes of water vapor mixed with molecules including methane, ammonia, and complex hydrocarbons emanate from a collection of long, warm tectonic features ("tiger stripes") near Enceladus' south pole (shown in Fig. 6b). The plumes are likely sourced from a global subsurface ocean, and the detection of ice particles containing salts suggests that the ocean is salty. The presence of a saltwater ocean containing most of the fundamental elements from which nucleic acids are made, combined with the heat source evidenced by the relatively high temperatures in the tiger stripes, suggests that Enceladus may have all the basic requirements to support life.

Triton is the largest satellite that orbits an ice giant planet. It orbits Neptune in a retrograde sense, indicating that it may have been captured from the Kuiper belt. It undergoes a complicated cycle of seasons, due to the large (28.5°) inclination of Neptune relative to its orbital plane, combined with the relatively large inclination of Triton's orbit. Its surface features (shown in Fig. 6c), as well as direct detection of "nitrogen-ice volcanoes" by *Voyager 2*, indicate ongoing geological activity.

Small Body Populations

Much of our knowledge about the age and formation of the solar system comes from the study of small bodies, which include asteroids, comets, and trans-Neptunian objects (TNOs). Hundreds of thousands of such objects have been identified, studied, and classified by their composition and the orbital populations to which they belong. The locations of these populations within the solar system are plotted in Fig. 1 and are shown graphically in Fig. 7. The composition and surface features of the objects in a given population provide information on how far from the Sun the objects were formed, as well as the degree of processing they have undergone since formation. The orbital parameters of specific small body populations therefore place important constraints on the migration of bodies throughout the solar system's history and hence provide a test on formation theories. The most primitive bodies – objects that have been minimally processed since their formation in the solar nebula – are found in the outer asteroid belt and among comets. The detailed composition of these bodies provides the most direct information on the composition of the primitive solar nebula. While such objects typically reside too far from Earth to permit detailed studies, we have gleaned information from those that pass periodically into the inner solar system (comets) or impact Earth's surface (meteorites).

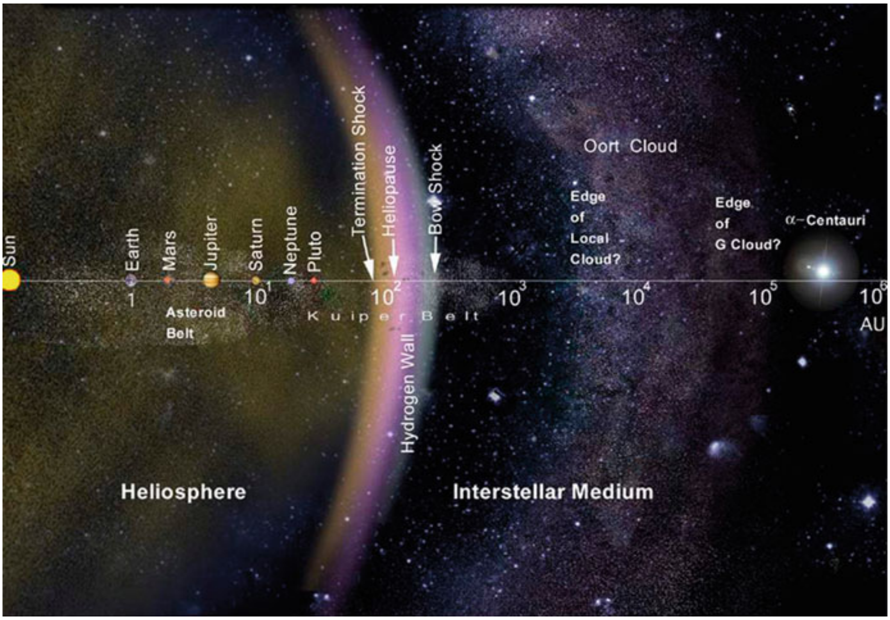

Fig. 7 Solar system schematic. The figure indicates the solar distance of the planets and small body populations on a log scale. The Oort cloud, and the outer Kuiper belt, falls well outside the heliosphere (Source: NASA/JPL-Caltech)

The Asteroid Belt

The asteroid belt, located at roughly 2.1–3.4 AU, resides between the orbits of Mars and Jupiter. The distribution of asteroid inclinations and semimajor axes is shown in Fig. 8, which demonstrates the groupings of individual asteroids into families of bodies that cluster in both orbital and color space.

The largest object in the asteroid belt, Ceres, is almost 1,000 km in diameter and is the only main-belt asteroid classified as a dwarf planet. The *Dawn* spacecraft, which studied Ceres in detail, revealed a heavily cratered surface composed of a mixture of rock, ice, and clays, as well as localized mid-latitude water vapor sources.

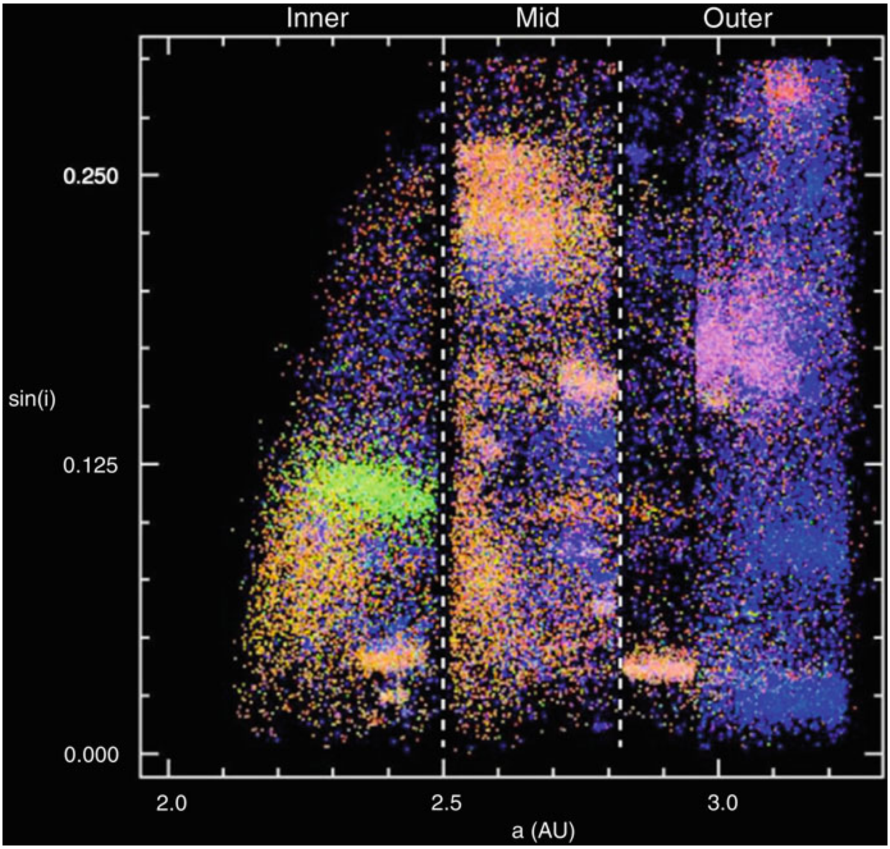

Fig. 8 Asteroid populations. The sine of the inclination (i) is plotted as a function of semimajor axis (a) for ~45,000 asteroids listed in the SDSS Moving Object Catalog 4. The color of each object reflects its optical color from SDSS measurements, using the coloring scheme described in Parker et al. (2008). The clustering of objects into asteroid families is apparent in both orbital and color space. The dashed vertical lines indicate the Kirkwood gaps, where the dearth of objects is due to orbital resonances with Jupiter (Reprinted with permission from Parker et al. 2008)

The next largest asteroids, Vesta and Pallas, are only half the size of Ceres, with diameters of ∼500 km. The overall asteroid size distribution roughly follows an inverse cube law, indicative of a collisionally evolved population. The fact that asteroids appear to be very porous, and are sometimes themselves orbited by one or more small satellites, is also suggestive of a violent past in which bodies were ripped apart via collisions. Metallic asteroids may be remnants of the cores of larger differentiated bodies that were shattered by impacts.

The structure and dynamics of the asteroid belt are heavily influenced by gravitational interactions with Jupiter. Pronounced gaps in the asteroid belt (the Kirkwood gaps, seen in Fig. 8) occur at mean-motion resonances with Jupiter, whose gravitational influence perturbs and removes asteroids from these orbits. Asteroids in other resonant orbits are protected, such as the Hildas in the 3:2 mean-motion resonance with Jupiter and the Trojan asteroids in the 1:1 resonance. The Trojans librate around the pseudo-stable L4 and L5 Lagrange points, 60° ahead of and behind Jupiter in its orbit. Small numbers of objects in 1:1 resonances have also been seen in the orbits of Earth, Mars, Uranus, and Neptune.

The objects in the asteroid belt span a wide compositional range; the majority are silicate-dominated (inner belt) or of volatile-rich carbonaceous composition (outer belt), while a small number are dominated by metals. The asteroid belt is the source of most meteorites that have been discovered on Earth (some meteorites are of lunar and martian origins), and laboratory analyses of meteorite compositions have given us some of the most detailed information on the age of our solar system and the composition of the primitive solar nebula. Of particular interest are the carbonaceous chondrite meteorites, which are rich in volatiles and appear to be of very primitive composition. Samples of these meteorites enable a characterization of the environment in which the planets formed.

Near-Earth Objects

Asteroids (and inactive comets) that pass close to Earth are known as near-Earth objects. The population of near-Earth asteroids is shown in Fig. 1; these objects are on unstable, chaotic orbits and have dynamical lifetimes of less than ∼10 Myr before they impact a terrestrial planet or the Sun or are ejected from the solar system altogether. The population is continuously resupplied from regions such as the Kirkwood gaps mentioned above. These regions themselves are likely resupplied with material, including small asteroids and collisionally produced asteroid fragments, through orbital migration likely caused by solar radiation (via the Yarkovsky effect).

Trans-Neptunian Objects

Beyond the orbit of Neptune, the outer solar system contains an extended reservoir of small bodies, many of which are likely remnant icy planetesimals from the solar

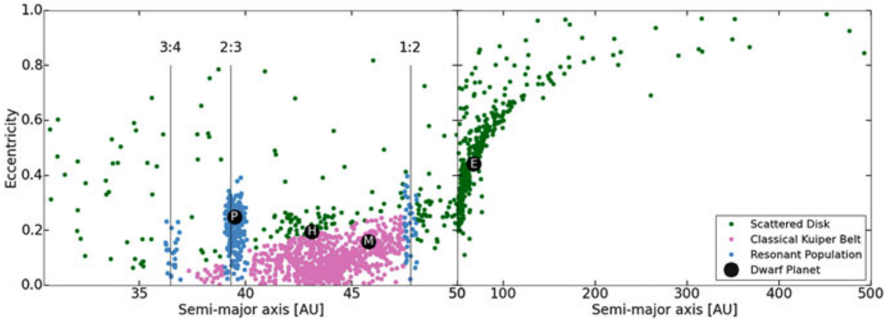

Fig. 9 Trans-Neptunian object populations. Eccentricity as a function of semimajor axis for small bodies beyond 30 AU. Classical Kuiper belt objects are in *purple*, scattered disk objects in *green*, and objects in or near resonance with Neptune in *blue*. The locations of mean-motion resonances with Neptune are indicated by *vertical lines* in the *left panel*. The *large black circles* are the dwarf planets Pluto, Haumea, Makemake, and Eris, labeled with the first letters of their names. Data provided by the International Astronomical Union's Minor Planet Center (Figure after Morbidelli and Levison 2014)

system's formation. Objects orbiting the Sun beyond 30 AU are known as trans-Neptunian objects. These make up the classical Kuiper belt, which extends from the orbit of Neptune out to 50 AU, as well as the scattered disk, which extends to much larger distances and contains a population of bodies with high eccentricities, inclinations, and semimajor axes. Figure 9 shows the eccentricities and semimajor axes of different TNO populations and demonstrates that the majority of these objects reside in the classical Kuiper belt, between 39 and 46 AU. The classical population appears to have a sharp outer edge at the 1:2 orbital resonance with Neptune. In the scattered disk, eccentricity correlates with semimajor axis due to gravitational interactions with Neptune, which increase the semimajor axes of objects without altering their perihelion distances. Clusters of objects are also found in mean-motion resonances with Neptune, where they are protected against scattering despite occupying similar orbital phase space as the planet. The Kuiper belt population includes dynamically hot and dynamically cold components, but it is still unknown whether these populations have distinct origins or whether the objects in the hot population have been dynamically excited out of the cold population. The number and orbits of the objects in the classical Kuiper belt constrain solar system formation scenarios and generally support a model in which Neptune has migrated outward by multiple AU since its formation. However, no existing model can currently explain all characteristics of the trans-Neptunian object populations.

Four trans-Neptunian objects have now been confirmed as dwarf planets: Pluto, Haumea, Makemake, and Eris. The first three of these objects orbit in the classical Kuiper belt, while Eris resides in the scattered disk. Eris is the most massive of the dwarf planets, with a mass nearly one fourth that of Earth's moon. In 2015, Pluto became the first trans-Neptunian object to be visited by spacecraft; the *New*

Horizons Pluto flyby revealed a complex atmospheric structure and surprising evidence for recent geological activity.

The detection of several TNOs with high eccentricities that cluster implausibly in orbital space has led to the hypothesis of a ninth planet with a mass of >5 Earth masses orbiting on an inclined, eccentric orbit out at hundreds of AU. Such a planet could have been ejected from an orbit closer to the Sun early in the solar system's formation or could have been captured from and/or perturbed by a nearby star. The chase is still on to actually find Planet Nine and confirm its existence; only then can we say that our solar system has nine planets (again).

The Oort Cloud

Out past the scattered disk, beyond even the reaches of the heliosphere (see Fig. 7), resides a population of roughly a trillion objects that constitute the Oort cloud. Extending from ∼10,000 AU out to 50,000 AU or more, the Oort cloud resides far enough from the Sun that objects are perturbed by passing stars as well as the galactic tide. Such interactions often result in highly eccentric and inclined orbits. The dynamical lifetime of objects in the Oort cloud is estimated at about half the age of the solar system. The classical Oort cloud may occasionally be replenished with objects from an unseen inner Oort cloud, between ∼1,000 and 10,000 AU.

Comets

Objects originating in the Oort cloud or Kuiper belt whose orbits are perturbed such that they pass through the inner solar system become known as comets. Short-period comets (<200 year periods) typically originate in the Kuiper belt, while long-period comets (>200 year periods) come from the Oort cloud. The composition of comets, including condensed silicate grains and volatile ices, resembles the composition of dense cores within interstellar clouds, and the species present do not indicate significant subsequent processing by the solar nebula. Comets are therefore believed to be the most primitive bodies in the solar system, preserving a record of the initial conditions in the solar nebula and providing insight into the first few hundred million years of the solar system's history. Comet nuclei have very low material strength and are likely made up of loosely bound material that impacted at low temperatures and velocities and stuck together. Their volatile-rich compositions reflect their formation in the cold outer reaches of the solar system. The volatile components are dominated by water ice but also contain ices involving CO, CO_2, CH_4, and NH_3. Complex molecules, such as methanol, formaldehyde, and even ethylene glycol, have been detected in some comets' comae.

The study of comet composition also has astrobiological implications. Bombardment of the inner solar system by icy planetesimals early in the solar system's history may have delivered significant quantities of water and/or organic molecules to the surfaces of Earth and the other terrestrial planets. Although it is still unclear what fraction of Earth's water was delivered from external sources, such impacts may have played an important role in creating the life-sustaining environment that set the stage for life on Earth.

Conclusions

Our exploration of the solar system we live in is still ongoing. Despite decades (and in some cases, centuries) of observation, many aspects of the planets and other bodies have eluded our understanding. The structure and composition of planetary interiors encode information on planetary histories yet can only be studied through indirect means. Investigations into outer solar system small body populations are in an exciting era of discovery due to emerging telescope technologies; the results of these investigations have the potential to discriminate between solar system formation models and reveal the processes of planet formation and subsequent orbital evolution. The hypothesized Planet Nine, orbiting many times farther out than Neptune, forces us to reevaluate our conception of the solar system's scope. Finally, recent discoveries have revealed the prevalence of geological activity and subsurface oceans on the outer solar system's icy worlds, paving the way for us to answer the question of whether life could have evolved, or could exist today, elsewhere in our solar system.

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