REVIEWS

The four hundred years of planetary science since Galileo and Kepler

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For 350 years after Galileo's discoveries, ground-based telescopes and theoretical modelling furnished everything we knew about the Sun's planetary retinue. Over the past five decades, however, spacecraft visits to many targets transformed these early notions, revealing the diversity of Solar System bodies and displaying active planetary processes at work. Violent events have punctuated the histories of many planets and satellites, changing them substantially since their birth. Contemporary knowledge has finally allowed testable models of the Solar System's origin to be developed and potential abodes for extraterrestrial life to be explored. Future planetary research should involve focused studies of selected targets, including exoplanets.

Our ancestors' first organized attempts to make sense of their surroundings were observations of the night sky. Astronomy is therefore considered to be the most ancient of all the sciences. For the first nine-tenths of recorded history, and long before, astronomy was concerned solely with positional measurements of the planets—but for the occasional threatening omen, whether eclipse, nova, comet or meteor shower. All else appeared static except for those 'wanderers' that we now know to be the Earth's siblings.

A quick start for planetary science

In the winter of 1609–1610, planets became much more than the few luminous specks that drifted before the celestial backdrop. During the preceding summer, and just weeks after learning about the Dutch invention of a 'spyglass', Galileo Galilei constructed his own by attaching concave and convex lenses at opposite ends of a metre-long cardboard tube. On lifting an improved, but still primitive, telescope heavenward, he beheld "the most beautiful and delightful sights… matters of great interest for all observers of natural phenomena… first, from their natural excellence; secondly, from their absolute novelty…" as he excitedly exclaimed that March in *Sidereus Nuncius*. This 24-sheet pamphlet announced several revolutionary findings, such as the Earth-like nature of the Moon's surface (Fig. 1a); others came later in the same year. Galileo's startling discoveries provided pivotal support for Nicolaus Copernicus's heliocentric model (in 1543) of the Solar System[1,2].

Throughout scientific history, observational findings and theoretical advances have often marched hand-in-hand. It is thus most fitting that astrophysics also began four centuries ago with Johannes Kepler's *Astronomia Nova* (1609; see Fig. 2a). Curiously, this anniversary received considerably less attention than Galileo's achievements during the just-ended International Year of Astronomy. Perhaps observational facts are favoured over theoretical constructs, or perhaps Galileo's story, culminating with his often-chronicled confrontation with the Church, provides better copy.

Today, four centuries after these revolutionary masterworks, and just fifty years after rockets were first launched towards a Solar System neighbour, the Earth's emissaries have explored every planet designated by the International Astronomical Union. Of those classically known, all but Jupiter have been under recent surveillance by our space probes. Meanwhile spacecraft swarm about the Earth routinely taking the scientific pulse of our home planet's surface, atmosphere and magnetosphere. And the indefatigable Voyager spacecraft, having reached the distant fringes of our Solar System, are now slipping into interstellar space.

The time of telescopes

Galileo's initial 'observing runs' recast essentially everything previously believed about our cosmic neighbourhood. By that high standard, subsequent progress in astronomy over the next three-and-a-half centuries proceeded sluggishly indeed. Advances usually arose as a direct consequence of improved telescopes or their attached instruments[1]. During this period, various Solar System bodies were identified at an accelerating rate, and their mechanical properties (for example, orbits, sizes and rotations) and photometric (brightness) characteristics were refined[3]. But their chemical and physical attributes (for example, composition and atmospheric conditions) remained obscure until the last third of the twentieth century.

Increasingly precise positional measurements of Solar System bodies—which, until 1717, were the only celestial targets noted to move—stimulated mathematicians throughout the seventeenth, eighteenth and early nineteenth centuries, culminating in the elegant dynamical theories of Lagrange and Laplace[2]. This work was primarily motivated by its usefulness in determining longitudes for maritime navigation. As remarkable as this may seem today, astronomy has across much of history been the most practical and financially rewarding of all the physical sciences[2]. Moreover, if astronomy were once again to include astrology (ever-lucrative), this would still be true today.

Solar System discoveries steadily accumulated in the seventeenth and eighteenth centuries, with five Saturnian moons found between 1655 and 1684. Well before this time, Tycho Brahe established (through visual observations) that comets were celestial bodies and not atmospheric phenomena. Edmond Halley's orbital calculations (in 1682) of his eponymous comet demonstrated that one of these previously mysterious interlopers periodically visited the Earth's neighbourhood on its 75-year stroll about the Sun. More significantly, this analysis dramatically demonstrated the predictive power of the Newtonian world view.

In the late eighteenth century William Herschel sighted four additional satellites. Of much greater consequence, in 1781 this amateur chanced upon Uranus while systematically scrutinizing the sky visible

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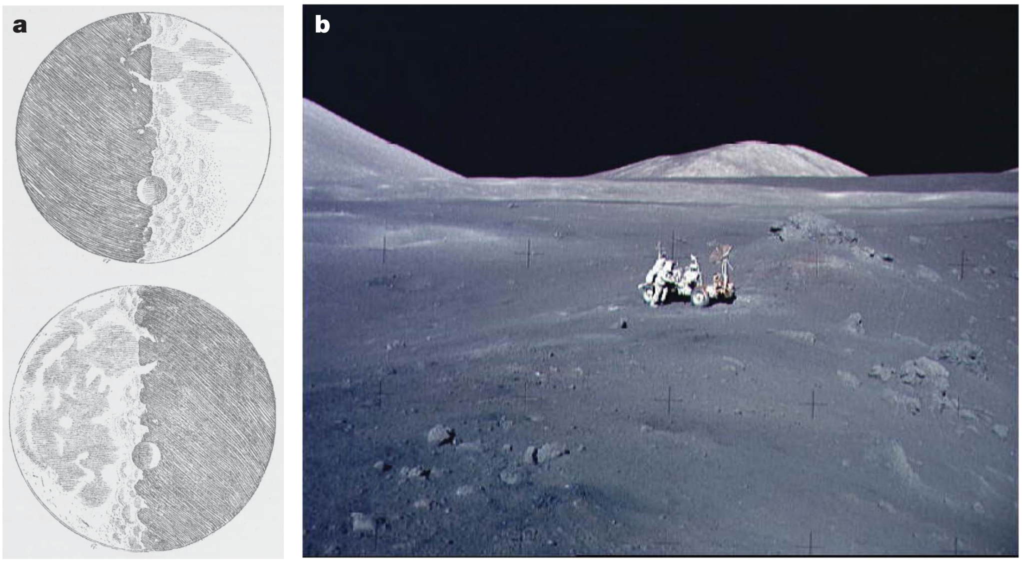

Figure 1 | The 'magnificent desolation' of the Earth's Moon. a, Galileo's wash drawings (of 1610) portray our Moon as possessing a "rough and uneven" surface that, "just like the face of the Earth itself, is everywhere full of vast protuberances, deep chasms, and sinuosities". **b**, Harrison Schmitt, the only scientifically trained astronaut, works alongside the Lunar Rover with Family Mountain behind and Shorty Crater to the right (NASA image AS17-137-21011). When Apollo 17 lifted off the Moon 38 years ago, manned lunar exploration abruptly ceased. Lunar exploration in the 1960s provided major scientific findings[70], including a wealth of geology[41] and laboratory cosmochemistry[40]; the latter prompted new models of the Moon's origin[62] (see Fig. 2 and ref. 63) and still underpin our understanding of truly giant impacts, which can destroy some planets but also create others[61]. Equally importantly, the lunar programme developed and refined the crucial infrastructure of launch, guidance, telemetry and navigation. The technologies that took astronauts to the Moon became our stepping-stones into deep space, where innovative mission designs (such as gravity-assists, orbital manoeuvres and sensitive communication protocols) were devised to ensure that spacecraft could operate for decades in hostile environments. More vigorous lunar studies since 2007 have found the Moon to be less dry than once believed, making human colonization more plausible. This has re-ignited heated political and scientific debate about the pace and value of human exploration of the Solar System.

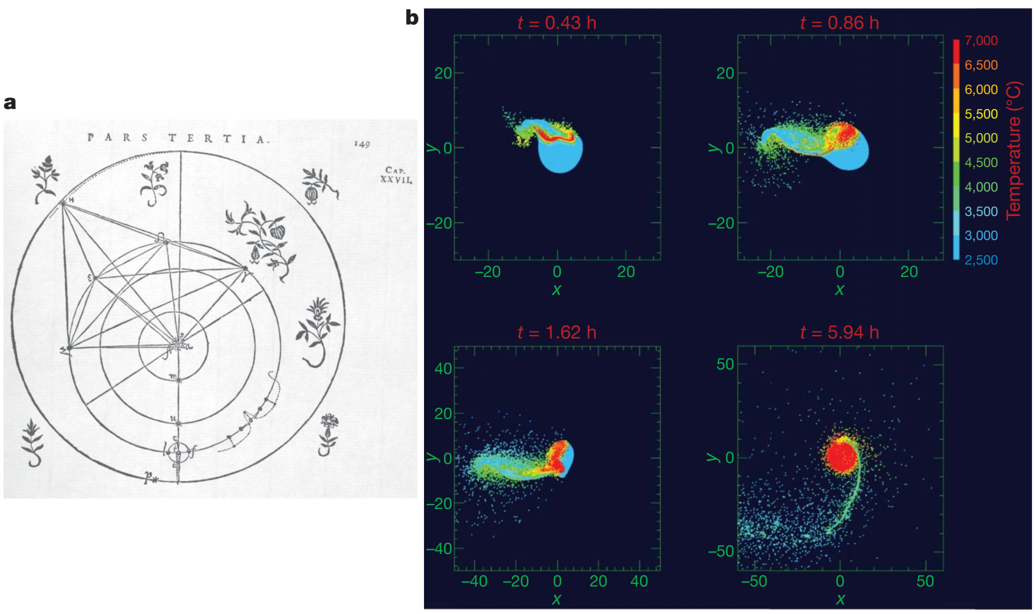

Figure 2 | Dynamical studies complement the Solar System's exploration by spacecraft. a, With this diagram from *Astronomia Nova* (1609), Johannes Kepler demonstrated how Mars' position, as observed from the Earth, changes when both planets trace elliptical orbits. Published just before Galileo's landmark observations, Kepler's book announced equally revolutionary findings, namely two laws governing planetary motion: planets move along ellipses about the Sun, and their paths sweep out equal areas in equal times. **b**, This smoothed-particle-hydrodynamics simulation (reprinted from figure 9 in ref. 63 with permission from Elsevier) shows four time-steps in the emplacement of a disk after a Mars-mass impactor strikes the proto-Earth at slightly above mutual escape speed. This generates a disk of about 1.3 lunar masses that is almost devoid of iron and baked free of volatiles, and that has the angular momentum of the present Earth–Moon system. The colour scale indicates temperatures in degrees kelvin. By permitting celestial simulations that test how various complex scenarios evolve, enormous enhancements in computer speed and memory have been midwives to the current renaissance in celestial mechanics[71–73], which began as the Space Age opened. Through such numerical 'experiments', computers have become astronomy's primary 'laboratory', enabling theoreticians to explore better how the Solar System's extant structure came to be. Consequently we currently understand how orbits and spins tidally evolve, how meteorites are delivered to the Earth, where comets originate, what imprints the intricate morphologies of planetary rings, and so on. The influence of theoretical studies on present understanding of the Solar System's formation and operation matches that of spacecraft exploration and telescopic surveys.

from his backyard for close stellar pairs. This unexpected detection of a planet not visible to the naked eye effectively doubled the Solar System's size and toppled the belief that the nearby Universe (at least) was charted territory.

Astronomy changed profoundly in the nineteenth century. The first invisible (infrared and ultraviolet) radiations were sensed in 1800 and 1801. In the same period Ceres, the first-discovered asteroid, was spied and turned out to be located precisely where the empirical Titius–Bode law (of 1772) predicted that the missing fifth planet should reside. Once meteorites were demonstrated to have a cosmic origin, chemists began to analyse extraterrestrial materials[2]. By correctly inferring the cause of Uranus's orbital irregularities, celestial mechanicians guided observers to Neptune (in 1846), now classified as our Sun's eighth and final planet (Pluto is categorized as a 'dwarf' planet).

Several mid-nineteenth-century developments—the long-sought detection of stellar parallax, and the inventions of spectroscopy and photography—transformed the practice of, and the results derivable from, telescopic observations. These redirected astronomical attention from the planets to the much more distant stars. This trend accelerated during the early twentieth century, when modern advances transformed astronomy into astrophysics, the physics of heavenly bodies. With stellar and galactic studies so attractive, the investigation of planets and moons slipped into relative obscurity. According to conventional wisdom[2], the professional status of planetary research plummeted primarily in reaction to Percival Lowell's aggressive promotion of possible intelligent life on Mars, but recent scholarship questions this historical interpretation[4]. Planetary science's stature improved when two influential texts[5,6] appeared in mid-century.

Ground-based astronomical studies dominated our understanding of the planets until the mid-1960s. Even twenty years later, terrestrial telescopes remained the principal tool for investigating many Solar System targets. And today, observational surveys of comets and asteroids have arguably contributed as much to our understanding of these classes as do infrequent spacecraft fly-bys.

Box 1 | Sociology

In 1958, shortly after deciding to embark on the sustained scientific exploration of the Solar System, NASA "looked around for ... people to do the science and found nobody."[77]. Thus NASA had to "cajole ... and provide enormous incentives for people to... work on planetary science."[77]. This strategy succeeded: many students and young researchers, including me[11], were lured to Solar System exploration in the 1960s. But it was scientific excitement and the 'future' that attracted us, not money. Concurrently NASA enticed universities to establish planetary science departments by constructing buildings and funding faculty, 'soft-money' scholars (researchers supported solely by government funding) and students. As a planetary historian observed[2], the American space programme galvanized the field of planetary astronomy, revitalized it and reformed it. Other Western-bloc nations soon joined the parade.

Because planetary science amalgamated bits of knowledge from several traditional disciplines, it started without professional homes in scientific organizations, academic departments or journals. In the USA, both the American Astronomical Society and the American Geophysical Union vied to represent the discipline. Responding to a persuasive group of planetary leaders, in 1969 the American Astronomical Society spun off its first sub-speciality[79] in part to accommodate this "young community of irreverent and promiscuously interdisciplinary scientists."[79]. Nowadays, the Division for Planetary Sciences with fifteen hundred members is by far the American Astronomical Society's largest, most active and most independent section.

Once planetary measurements had been obtained close-up from space platforms, in addition to ground-based observatories, Solar System science expanded from traditional astronomical techniques, such as photometry and spectroscopy, into descriptive and messy scientific specialties like meteorology, geology and occasionally even biology. This transformation demanded new publication outlets, and several journals (for example, *Icarus*) emerged to serve this burgeoning, multi-disciplinary field.

Planetary observations redefined

Planetary exploration is quite unusual in the history of science: a subject that was born almost instantaneously when an esoteric research speciality was abruptly elevated to prominence by events far beyond its control (Box 1). During the Space Race, the American and Soviet governments funded planetary science to demonstrate military prowess and to enhance national prestige[7–9]. Many citizens, including scientists, were simply captivated by "the irreducible wonder and allure of exploring other worlds"[7]. Meanwhile, the industrial sector was motivated instead by profit and technological challenge.

The Earth's atmosphere absorbs many forms of electromagnetic radiation, and its turbulence blurs resolution across wide swathes of the spectrum. Accordingly, simply moving instruments into space permits sharper images across all wavelengths. Moreover, the Solar System differs from more remote astronomical targets in actually being reachable by interplanetary vehicles, whose small telescopes can enlarge what had been pinpoints of light into marvellous worlds worthy of exploration in their own right. For typical orbiting instruments at Mars and Saturn, resolution improves by $\sim 10^5$ and 10^6, respectively, so that the number of pixels on a scene is $\sim 10^{10}$ and 10^{12} greater. 'Being there' additionally opens up the possibility of landing on a surface, chipping away at selected rocks, sniffing the atmosphere, and—especially—finding the unexpected. Physical samples of extraterrestrial materials can then be delivered to well-equipped terrestrial laboratories, where mineralogy and isotopic composition can be analysed in detail. The advantages of space missions for planetary exploration are aptly illustrated by how the Cassini spacecraft's observations have improved our knowledge of Titan (see Fig. 3).

Steps into space

Few citizens today realize how poorly known the Solar System's members, including the Earth, were before the space era. Simply put, astonishingly few facts were available. Consider the following evidence: as late as 1966, reputable scientists argued over whether vegetation might cover Mars[10]. Ten years before, scientific opinion was split on whether Venus was covered by a desert, a swamp or an ocean[10]. Lunar craters, the only such structures observed in the Solar System but for a handful of terrestrial examples, were believed to be volcanoes until 1950 (ref. 2). Natural satellites were considered to be dead chunks of rock or ice…dull, dull, dull. Findings from space missions have radically altered the Solar System that our children know: "it isn't Kansas anymore," to paraphrase Dorothy in *The Wizard of Oz*.

The exploration of the Earth's neighbours proceeded at a blitzkrieg pace shortly after Sputnik's 1957 launch. Within six months, the Earth's radiation belts—the first space-age surprise—were identified. In January 1959, Luna 1 escaped the Earth's gravity altogether and skimmed past the Moon, discovering the solar wind along the way. By mid-September Luna 2 had crashed into the Moon. Only three weeks afterwards Luna 3 transmitted grainy photographs of the heavily cratered lunar far side. In 1962, Mariner 2's fly-by of Venus, the first successful planetary encounter, measured that planet's searing heat. Thirty months later Mariner 4 viewed a bombarded, uncharacteristically bland region of Mars.

During the late 1960s and 1970s, when my career was beginning[11], a new expedition to inner Solar System destinations seemed to depart every few months (Box 2). The Earth's Moon was a primary target (Fig. 1). I became addicted to space exploration by the gradual and seductive disrobing of all the inner planets—Mercury (the *three* Mariner-10 fly-bys in 1974–75); Venus (Mariners 5 and 10, Pioneer Venus in 1978, the productive Venera and Vega series, and the radar-revealing Magellan); and Mars (Mariners 6 and 7, the revolutionary Mariner 9 in 1971, and finally the Viking landers that sought life during the mid-1970s)[2].

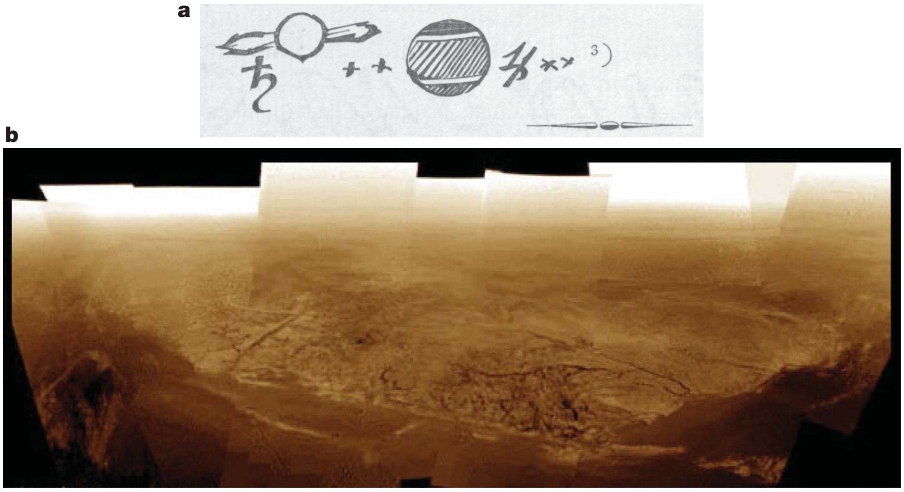

Figure 3 | Titan: a new world is uncovered by space missions. a, Using his newly built, state-of-the-art telescope, in 1655 Huygens drew Jupiter (right) and Saturn (left) in order to contrast Jupiter's satellite system with the apparent absence of moons about Saturn; two nights later he sighted Titan. **b**, Following this discovery, the next milestone was Kuiper's 1944 identification of a methane atmosphere[2]. But this now-most-intriguing satellite remained basically a fuzzy orange ball to Earth-bound observers until the brief Voyager-1 fly-by[25] indicated that Titan had a thick smog-filled atmosphere topped by rich organic hazes, and that atmospheric conditions might prompt methane rain to fall[14,25,30]. After Cassini's more than seventy close overflights of this moon, a complex and arresting world has been revealed[14]. Examinations of the satellite's surface with radar, and through infrared and visual windows, have glimpsed a geologist's delight: globe-girdling, hydrocarbon sand dunes, apparent dendritic valley systems and regional-scale methane lakes. Subdued surface relief and few craters, each markers of a youthful surface, signal active land erosion. The European Space Agency's Huygens probe, while parachuting through the dense atmosphere to a landing on methane-rich plains sprinkled with assorted ice boulders, snapped this image of river-valley networks debouching into dark smooth basins (mosaic prepared by R. Pascal and reproduced with permission). Meanwhile, plasma, gravity and magnetic field observations[14] suggest that Titan has an internal, liquid water–ammonia ocean. None of these discoveries—which show the real satellite to be as fantastic as those Titans imagined by science fiction authors—could have been achieved from the ground or from Earth orbit.

But, by thirty-five years ago, humankind's heady rush into space had slowed. The USA abandoned the Moon in the early seventies (Fig. 1), and few American planetary missions were being approved. In this same period, the Soviet exploration programme experienced a string of mishaps, and thus lost funds and influence. Fortunately, with their launches in 1977, the American Voyager spacecraft were already speeding along their ambitious 'Grand Tour': first, both spacecraft visited Jupiter in 1979 (Fig. 4), then Saturn in 1980 and 1981; Voyager 2 ventured past Uranus in 1986 and met its Neptune appointment (Fig. 5) three years later. During an otherwise unexciting period, humanity's space programme was sustained by these inspirational flights, and many of today's leaders in Solar System exploration matured as scientists involved in these missions.

Throughout the 1980s, but for Voyager's triumphs, the US exploration programme languished: the Reagan administration considered eliminating all planetary research, missions failed or were cancelled, and the Challenger disaster reduced launch capability and reprogrammed funding. In the mid-1990s, the Discovery programme—a continuing line of smaller, more focused missions—partially resuscitated planetary science. These flights have performed diverse investigations of the inner Solar System, emphasizing small bodies and the Moon, and also sought exoplanets[12]. However, missions under NASA's mantra of 'faster, better, cheaper' unfortunately rarely fulfilled all three adjectives simultaneously.

Flagship missions (Galileo to Jupiter in 1989 and Cassini-Huygens to Saturn in 1997) were dispatched to furnish extended follow-up observations to Voyager's reconnaissance of the gas giants and their environs. In extraordinary engineering triumphs, the Galileo spacecraft dropped an atmospheric probe through about ten bars of Jovian gases[13], and the Huygens capsule parachuted safely to a soft landing on Titan's surface (Fig. 3) to return an hour's scientific measurements[14]. Despite a jammed antenna that stanched data transmissions, the Galileo spacecraft returned astonishing images that concentrated on Io's volcanoes and Europa's cracked ice shell[13]. Currently at the start of its seventh year, Cassini is circling arguably the most beautiful planet (Saturn) (see Fig. 6) and the most interesting system. Titan[14] (see Fig. 3) has been disclosed as a remarkable world in many respects and the rings as local dynamical archetypes of astrophysical disks[15,16].

The mid-1990s also witnessed a major redirection of planetary science, and much of NASA's astronomy portfolio, towards the study of origins. Several new findings fuelled this rebirth: the discovery[17,18] of increasingly common exoplanets[12,19], many in multiple systems; the then-plausible (but now discredited) identification of fossil life forms in the Martian meteorite ALH84001 (ref. 20); and the realization that terrestrial life could survive, and perhaps even arise, in

Box 2 | Early missions

Planetary science rapidly developed into a socially cohesive discipline with fiercely loyal practitioners. Among reasons, the nature of the planetary missions that furnish the fundamental results was key. Especially for the early space missions, the selected scientific teams often lasted decades and required long hours together to determine priorities, to devise observational strategies, then to retrieve the data and, finally, to sort out interpretations. By demanding an individual's undivided devotion, missions created tightly knit, elite cadres. Considering the long hours toiling in isolation towards 'sacred' goals and the scarcity of female planetary scientists early on, team membership somewhat resembled a monastic calling. Grand celebrations accompanied the launches and encounters of space missions, producing camaraderie not often matched elsewhere in the sciences.

During these years, many of us were surely driven by the flood of surprising findings as well as by ambition and competition. But, best of all, we felt part of something bigger than ourselves: the exhilarating exploration of our corner of the Universe[11]. This phalanx of dedicated explorers, many of us in our twenties when the program started in earnest, have reached their sixties and seventies, or are no longer alive. After a glorious half-century during which the Solar System was disclosed, the torch is passing to a new generation.

The dominance of large flagship teams in planetary science has, however, changed. Nowadays, the typical 'soft-money' planetary scientist is usually supported by numerous small grants, rather than a single huge fund. This requires more 'overhead': writing proposals, reviewing them, sitting on selection panels and choosing directions. Surely this is more democratic, but sadly it is much less efficient.

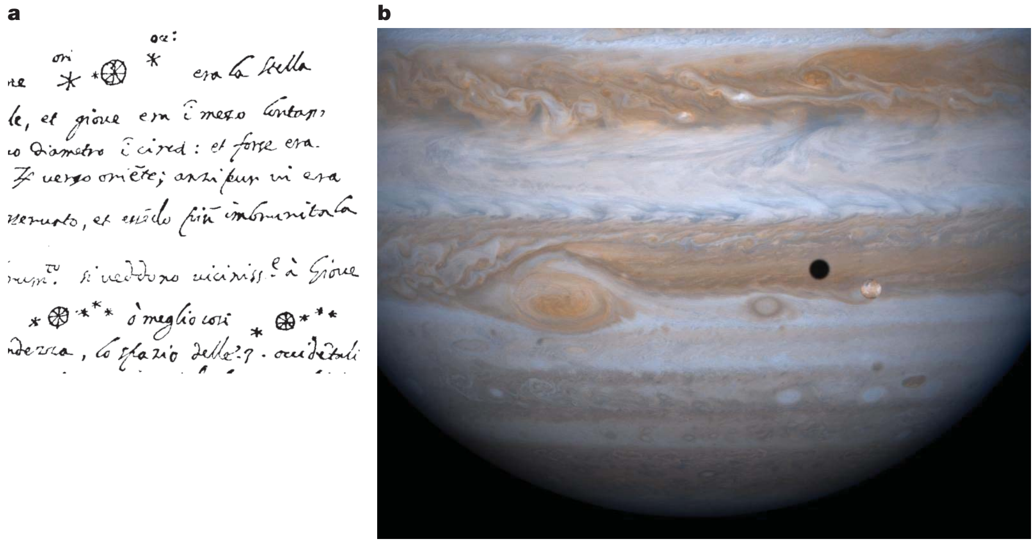

Figure 4 | Jupiter's Galilean satellites and other moons of the giant planets. a, Galileo's graphical chronicle shows three configurations of his "Medicean planets" in January 1610. The Tuscan physicist reported "that which will excite the greatest astonishment by far": four satellites "wander around Jupiter as does the Moon around the Earth, while all together trace out a grand revolution about the Sun in the space of twelve years"; he thus overturned the idea that the Earth was the centre of all celestial motion. **b**, Io, Jupiter's innermost Galilean satellite, floats in front of the planet's tumultuous atmosphere, to the right of the Great Red Spot and its own shadow. (Cassini image PIA02860, resolution ~100 km, NASA/JPL/SSI). During Voyager-1's flight past Jupiter, most planetary experts were stunned when Io displayed towering sulphuric volcanic plumes, with activity dwarfing the Earth's[74]. The other Galilean satellites of Jupiter, each roughly Moon-sized, are dramatically distinctive[13,25]: Europa is neatly encased in a thin, cracked ice shell overlying its global ocean; Ganymede exhibits geological complexity and a magnetic field, indicating a liquid interior; outermost and sombre Callisto is densely pocked with craters. Saturn's celebrities[26] include two-faced Iapetus[75], Titan[14] (see Fig. 3), and Enceladus[76]; improbably, the latter satellite, which should be inconsequential given its tiny size, spews jets of water vapour into space. Neptune's Triton somehow fuels geysers that squirt from fissures in its frozen cantaloupe-like skin. A planetary geologist has claimed that Uranus' Miranda, with its patched-quilt surface, is "all the strange places rolled into one"[77]. In sum, satellites are astonishingly active and as fascinating as are the planets.

extreme environments. Questions of planetary origins, and life itself, began to be addressed with vigour and funding. Astrobiology, helped in part by finally having a name, became an accepted scientific discipline[21]. In short order, NASA's planetary budget blossomed and was divided roughly equally between Mars and other targets.

Nations other than the USA and the USSR have also ventured into the cosmos. An international armada, including the inaugural missions from Europe (the European Space Agency) and Japan, greeted Halley's comet in 1986. During the last few years, the European Space Agency, India, China and Japan joined America to drop in on the Earth's satellite, signalling a worldwide resurgence of interest in the Moon (Fig. 1).

Ground-based and Earth-orbiting telescopes today supplement space missions and are contributing relatively more to planetary science than they had twenty years ago. Large telescopes combine adaptive optics with sensitive detectors and powerful computers. These sighted the first Kuiper belt object (besides Pluto) in 1992 (ref. 22), and have continued the census of these intriguing bodies. Moreover, high-quality, yet low-cost, systems permit amateurs and small academic observatories to supply valuable data for comprehensive surveys and the systematic monitoring of selected targets. Our improved inventory of the Solar System's inhabitants now includes additional classes of celestial objects (for example, binary asteroids and trans-Neptunian objects[23] (including Kuiper belt objects, the scattered disk and Oort-cloud comets[24]), comet/asteroid transition objects[24], irregular satellites and families within various groups).

Insights into planets and origins

Among the findings about our celestial neighbourhood during the Space Age, I have five favourite areas: (1) our modern understanding of the Solar System's constituents; (2) the vigorous activity of many planets and satellites; (3) astrobiology; (4) the Solar System's origin; and (5) other planetary worlds.

An informed census of the Solar System's inhabitants. Figures 5, 6, 7 and 8 illustrate how several planets (Neptune, Saturn[25,26], Venus[27] and Mars[28,29], respectively) are perceived today compared to when Sputnik was launched. Now I mention some revised perspectives about satellites and small bodies.

The exploration of natural satellites[13,14,26,30] by space missions has revealed them also to be distinctive worlds. The Earth's Moon (Fig. 1) was, of course, the first extraterrestrial destination to be scrutinized, initially by the kamikaze Rangers and instrumented orbiters, then with landers and eventually humans. Today unmanned sentries have returned to improve human understanding of the Earth's celestial neighbour, perhaps as a prelude to a more intensive human exploration programme. As captured in images that are emblematic of space's desolate beauty, the Moon—though undoubtedly alien—was no surprise: a heavily cratered, inert world. Other satellites were naturally expected to be similar, with smaller moons even less interesting. However, Mars' Phobos, the next satellite target, was truly otherworldly, a 25-kilometre-long potato crisscrossed with grooves and global-scale craters[31]. With more surface area per unit volume, small bodies should cool faster than large ones and should accordingly be dead and boring. But spacecraft visits have found many of the supposedly cold bodies in the outer Solar System to be surprisingly active (Figs 3 and 4).

Numerous, relatively diminutive Solar System bodies (asteroids, comets, meteoroids, and so on) have been examined by telescope, and a few visited by spacecraft. Asteroids—previously considered to be inert chunks of rock that do little more than occasionally collide with one another—are instead ephemeral rubble piles: the Yarkovsky effect[32,33] inexorably modifies the orbits and spins of the smaller bodies, occasionally generating binaries through tidal and centrifugal break-up. Comets are not dirty snowballs but icy dirtballs[34], blackened by tarry organics[24]. Surprisingly, grains within these visitors from the coldest reaches of space have experienced greatly elevated temperatures at some time[35].

The frigid fringe of our Solar System contains a fascinating menagerie—small to large bodies; some primitive, others melted; and tribes of different colours and orbital patterns—all tossed together as

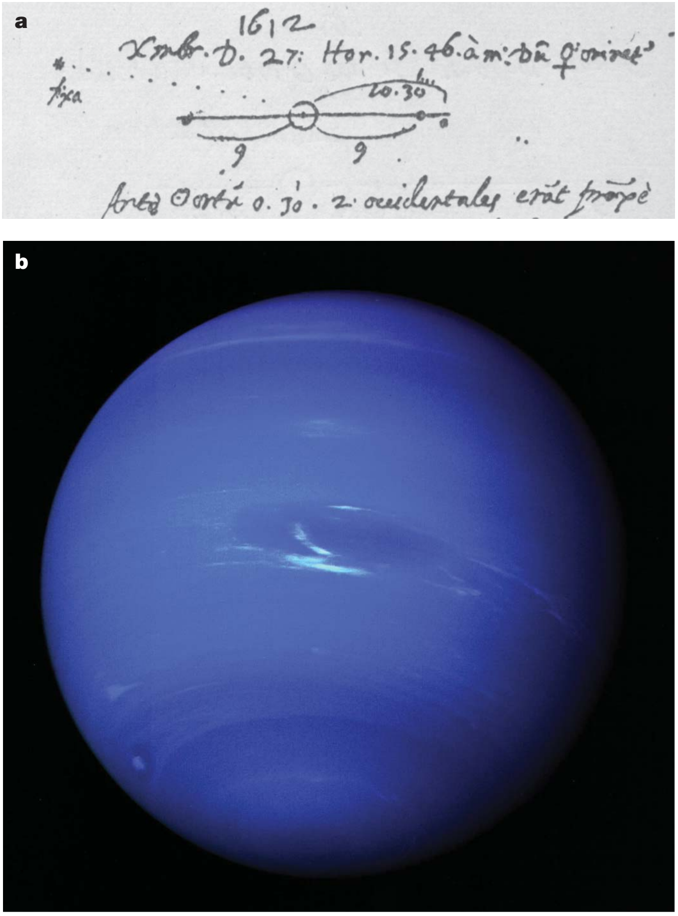

Figure 5 | The allure of the outer Solar System. a, In 1612–13, while observing Jupiter, Galileo noticed the motion of a nearby object, now recognized to be Neptune. Indeed, some historians suspect that the Italian observer realized that he had spied a new planet. **b**, A Voyager-2 false-colour image (PIA01492, resolution a few hundred kilometres, NASA/JPL) displays Neptune, an ice-giant planet, including its Great Dark Spot with some attendant white cirrus clouds, as well as other atmospheric storms. The outer Solar System, so unlike our rocky terrestrial neighbourhood in composition and setting, challenged our models when the Voyager spacecraft transmitted their first data. Consisting principally of hydrogen and helium, the gas giants Jupiter and Saturn dwarf the Earth. Their elaborate rings and satellites are diverse and often active despite limited thermal sources (Figs 4 and 6). A *Science* reporter captured the excitement of the Voyager flights: "for sheer intellectual fun, there has never been anything quite like the Voyager encounters. Volcanoes on Io, ringlets around Saturn, braided rings—the observations are outrageous". In addition to these features, the planets themselves are spectacular, with turbulent atmospheres, powerful thunderstorms and energetic aurorae. Neptune, the solar-system planet farthest from the Sun, has the strongest zonal winds, despite its meagre supply of solar energy; the massive moon Triton and three shimmering ring arcs orbit it. Uranus, the other ice giant, features a system of interlaced rings and moons, a highly distorted magnetic environment and the bizarre satellite Miranda.

the Solar System assembled aeons ago. Kuiper belt objects[23], excluding Pluto, were unknown two decades ago but today more than a thousand of these distant, large, icy bodies are being tracked. They present a local population the radial span and orbital architecture of which resemble the debris disks exterior to recently born stars[36]. This region houses at least three dwarf planets (Haumea, Eris and Makemake) besides the demoted dwarf planet Pluto, which is currently recognized as being even less distinguished among the trans-Neptunian objects than Ceres is among asteroids.

The final outcome of humankind's exploration of the Solar System has been to recognize our Earth as a planet. The iconic Apollo image of Earthrise over the Moon changed everyone's view of our watery blue marble, sparking the global ecological movement of the 1970s. Our habitat is not isolated from space. Instead, our cosmic surroundings profoundly affect us. Violent collisions by asteroids and comets have demonstrably punctuated life aboard our planet over and over, and will yet again.

A changing and often violent Solar System. As the space era opened, heavenly motions were thought to be entirely predictable. However, it is a clock-like Universe no more: many of today's archetypes of chaos involve celestial dynamics: Hyperion's spin[37], Mars' obliquity[38] and planetary orbits over millions of years[39].

When particles are nudged onto chaotic orbits, their paths can vary significantly, delivering them into regions where collisions may eliminate them, thus clearing swathes through orbital space. Accordingly chaos had a determining role in the Solar System's accumulation and evolution, sculpting much of its architecture visible today. A corollary to chaos is that the contemporary Solar System is continually changing. Orbits can be destabilized when—owing to perturbations, such as the Yarkovsky effect[32,33]—they drift into resonances (places where a mass's relative position repeats over simple fractions of forcing periods).

Even as the stochastic nature of our celestial backyard has been disclosed, regularities have been simultaneously identified. Sometimes bodies are preferentially eliminated from the ubiquitous resonant locales: indeed, vacant gaps are prominent in ring systems (see Fig. 6), as well as permeating the asteroid and Kuiper belts. In other circumstances, masses may be driven onto resonant paths: some asteroids share such arrangements with Jupiter, and satellites commonly reside in resonant pairs. These configurations signify evolution, and are not relics of birth.

Once the episodic events (visiting comets, eclipses, and so on) in the Earth's neighbourhood were recognized as natural phenomena, but before chaos became common knowledge, the Sun's realm was believed to be serene and unchanging. That viewpoint adjusted gradually as craters—the dominant geological form on most solid Solar System surfaces—came to be understood as resulting from impacts[4]; such collisions naturally ensued from the orbital chaos that induces trajectories to cross. Many believe that the Late Heavy Bombardment[40,41], an intense pulse of cratering events, pummelled the inner Solar System about 3.9 billion years ago. Impacts became terrestrially relevant once the Cretaceous–Tertiary period extinction was interpreted[42] as a consequence of a climatic cataclysm following the crash of a 10-kilometre-across extraterrestrial visitor into the Earth. In 1994 humanity witnessed a variant of this devastating event when twenty-plus remnants of the tidally ruptured comet Shoemaker-Levy 9 bombarded Jupiter[43].

The bicentenary of Darwin's birth emphasized the idea that slow modifications can also produce life-altering consequences. The Solar System's exploration began just as the 1960s plate-tectonics revolution[44] was establishing quantifiable global processes that concomitantly explained various regional and local geophysical features. Because many early planetary researchers trained as geologists, modern geophysics immediately informed their interpretations of features visible on the other terrestrial planets.

Although planetary scientists were receptive to indications of global planetary transformations, evidence for change was scant at first. The early images of Mars misled our community into expecting that every solid celestial body would appear like the Earth's scarred Moon. But in 1971 Mariner 9, the initial spacecraft to orbit another planet, instead revealed a Martian landscape that in places was familiar to Earthlings: having ancient river valleys, volcanoes, deep canyons and weather[31]. Obviously the Red Planet had changed at least twice from its original heavily cratered appearance: once to a more benign, terrestrial-like environment and then to today's dry, cold state. Moreover, contemporary surveillance of Mars has documented a rich, extended sedimentation history[45], and also witnessed fresh craters, cascading landslides and erupting rivulets[46], all happening over the missions' lifetimes. Similarly, once Magellan's radar could peer through

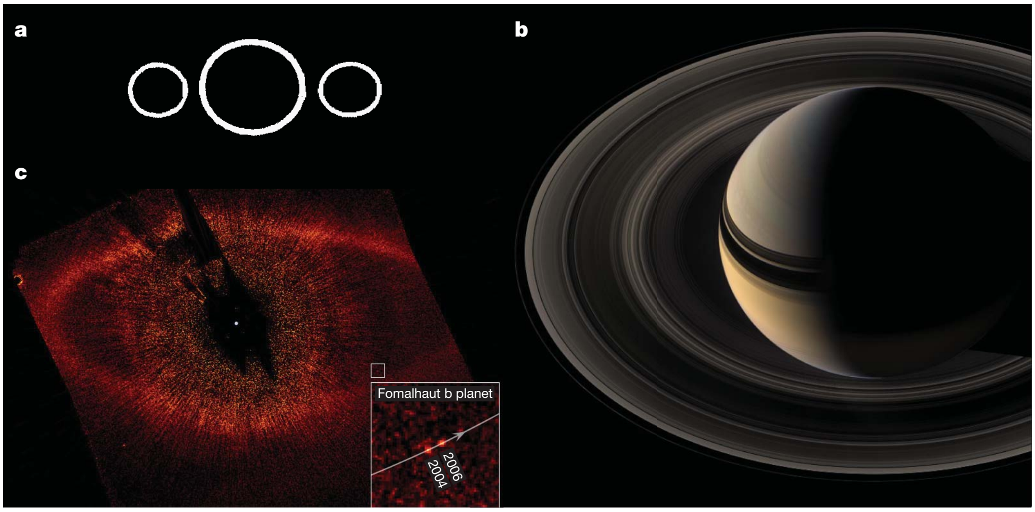

Figure 6 | Saturn's rings provide analogues to protoplanetary disks. **a**, Galileo's sketch of Saturn (late 1610, shown by Christiaan Huygens in *Systema Saturnium* in 1659), led him to comment, "to my very great amazement, Saturn was … not a single star but three together." Instead, the first astronomer had simply misinterpreted an out-of-focus view of the rings. **b**, This image (PIA08388, NASA/JPL/SSI) shows Saturn's rings as unusually dark because the Sun lights them from below. Neutral-colour haze enshrouds the planet's northern hemisphere—cooler, with less direct sunlight—while the ring's shadow creates sharp dark central bands across the planet's mid-section. Uncountable centimetre-to-metre icy particles in Saturn's rings[16,26] form a thin, almost opaque, disk that changes on timescales ranging from days to aeons. Considerable radial structure is induced through periodic forcing by exterior moons that circle just outside the main rings. Elsewhere, two tiny, embedded moons have cleared gaps in the outermost ring; numerous, even smaller, moonlets, invisible here, disturb the ring. The dynamical behaviour of Saturn's disk, with its embedded masses, exhibits many similarities to (but some differences from) protoplanetary disks[16]. **c**, Fomalhaut b, a Jupiter-size exoplanet (in white box), carves a path along the inner edge of a debris ring that surrounds a young A3 star at about 115 astronomical units in this false-colour image from the Hubble Space Telescope[68] (STScI image PRC 2008-39a). As with the moons embedded in Saturn's rings, the exoplanet's existence was originally inferred from the belt's shape and the belt's crisp inner boundary. Detailed information from our Solar System's exploration can inform our understanding of extrasolar planets and their formation, and vice versa.

Venus's thick clouds, the Earth's inward (towards the Sun) neighbour was observed to have erased the record of its birth (Fig. 7). That planet's surface is blanketed by volcanic plains and is relatively youthful, with few craters[27]. The giant planets also vary, not only as manifested in their obvious churning atmospheres (for example, colourful flows past Jupiter's Great Red Spot; see Fig. 4), but also by their continued cooling over the ages[47].

Ongoing geological activity has been detected as well on several outer-planet satellites (see above, and Figs 3 and 4). Selected features in Saturn's rings[16,26] (Fig. 6) and in other ring systems have been observed to materialize, evolve or vanish over days to decades. Thus, the activity in some Solar System precincts rivals that of our terrestrial surroundings.

Ruminations on life's beginning. Conversations about the likelihood of extraterrestrial life stretch back millennia. Such debates became spirited during the mid-1990s, driven partly by provocative scientific findings (see above) but also in response to the creationists' attack on life's origin and subsequent evolution.

Astronomers have detected increasingly complex, but still relatively simple, organic molecules throughout the interstellar medium and circumstellar environments of our own galaxy and beyond. Similar molecules have been uncovered in planetary (and satellite) atmospheres, and on the surfaces of airless moons, comets and Kuiper belt objects; more elaborate organics are found within carbonaceous chondrites. Thus, a common chemistry apparently links the living entities on the Earth with the cosmos. Hence, the observational evidence prompts one to consider life in a framework far vaster than Darwin envisioned.

Questions about extraterrestrial locales where life might develop and then persist into the present have suddenly become approachable. The prevailing opinion is that life requires energy, organic matter and a solvent, probably water, motivating NASA's present exobiology strategy to "follow the water".

Potential exobiological habitats[10,21] in the Sun's realm that satisfy these putative requirements include ancient Martian river basins and that planet's subsurface, cracks that penetrate Europa's icy shell, and the source regions for Enceladus' warm plumes. Titan, with its rich organic environment but numbing cold, remains of astrobiological interest primarily to exhibit the complexity that organic molecules might achieve before life's emergence. The preceding list of potential targets demonstrates a substantial broadening of biology's 'habitable zone'[48]. If extraterrestrial life is found, probably it will not be where or what scientists currently forecast.

The last decade's focused campaign of Martian global mapping and rover excursions[28,29] has furnished abundant evidence for scattered ancient shallow lakes and for a currently active Mars. Hydrated salts, sulphates and perhaps carbonates are preferentially located along cracks through Europa's surface[21] but arguments rage about the accessibility of the underlying ocean. Much of the material exiting Enceladus is sodium-rich, suggesting that the deep interior is warm[49]; however, the mechanisms to generate such heat and the moon's jets remain controversial. If, after comprehensive searches, biological molecules are absent at all these destinations, we will have tightly constrained how terrestrial life originated.

Considerations of the Solar System's origin. Starting with the myths of ancient civilizations, and extending through Immanuel Kant's nebular hypothesis to the tidal and encounter theories of a century ago, considerations of the Solar System's origin were historically often just philosophical musings, suited to exploit the available mathematics of the day[6,50]. Scientific facts that could constrain speculations were simply unavailable. That is no longer true.

The ages of millimetre-sized and smaller specimens of meteorites[51,52], cometary dust[35] and lunar samples[40] have been determined to within less than a million years, by comparing isotope ratios. Such age-dating sharply restricts possible processes and orders the sequence of pivotal events throughout the Solar System's infancy $(4.5–4.6) \times 10^9$ years ago.

Insights from Solar System exploration and from the avalanche of observations of protoplanetary disks[36,53,54] and exoplanets[12,19,55] have advanced our understanding of how planets originate. The former contributes enlightening details about nearby planets that have (obviously)

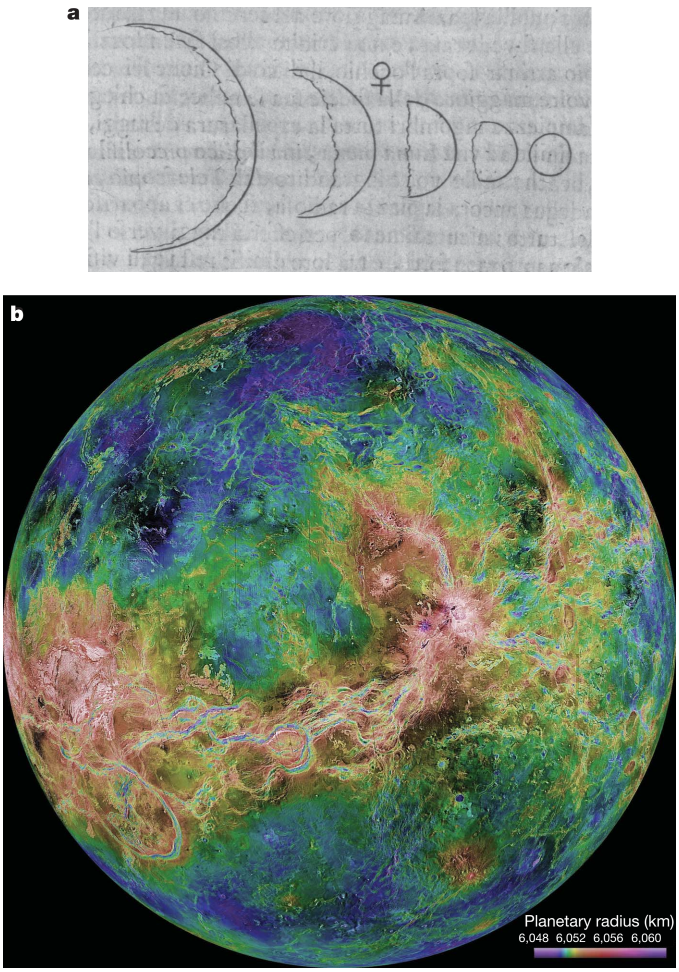

Figure 7 | Radar observations unveil Venus' hellish landscape. **a**, Galileo's sketches (late 1610) of the phases of Venus disclosed that the planet's apparent shape—like the Moon's—varied with orbital phase, as did its size. Remarkably, the Tuscan physicist concluded "with absolute necessity…that Venus revolves about the Sun just as do all the other planets", thus discrediting geocentric cosmologies. **b**, Magellan's radar has penetrated the Venusian clouds (image PIA00159, NASA/JPL) to furnish this 100-metre-resolution, false-colour image that is centred at 180° east longitude. Once considered the Earth's twin because of its similar size and mass, Venus is now known to be strikingly different[27]. A dense carbon dioxide atmosphere caused a runaway greenhouse effect that today produces scorching temperatures that induced nearly all of the planet's water to escape. Venus' clouds are made of sulphuric acid, not water droplets like ours. The planet's surface is surprisingly young and volcanoes are widespread. Lava flooding is thought to have obliterated most surface features only 800 million years ago. The Earth's nearest sibling presents a sobering example of how a planet's surface conditions are sensitive to its atmospheric content. Some newly discovered, mostly gaseous exoplanets have superheated atmospheres owing to their close proximity to their central stars. The thermal structures of these are surprising and presumably require additional heat sources such as tidal warming[55,74].

successfully been born, whereas the latter furnishes broad information about hundreds of this celestial species.

Because many formation processes are hidden deep within extrasolar disks, and all contemporary observations have fairly coarse resolution, events must often be inferred. Thus parallel theoretical advances[15,56,57] are essential to guide such observations. Nonetheless, within the last decade, the Solar System's origin—like cosmology—has moved from speculation into a full-fledged science in which hypotheses now face observational testing.

Our Solar System was born when a dense molecular cloud collapsed. As our protostar accreted its mass over $\sim 10^5$ to 10^6 years, a flattened and evolving protoplanetary nebula of gas and dust surrounded it.

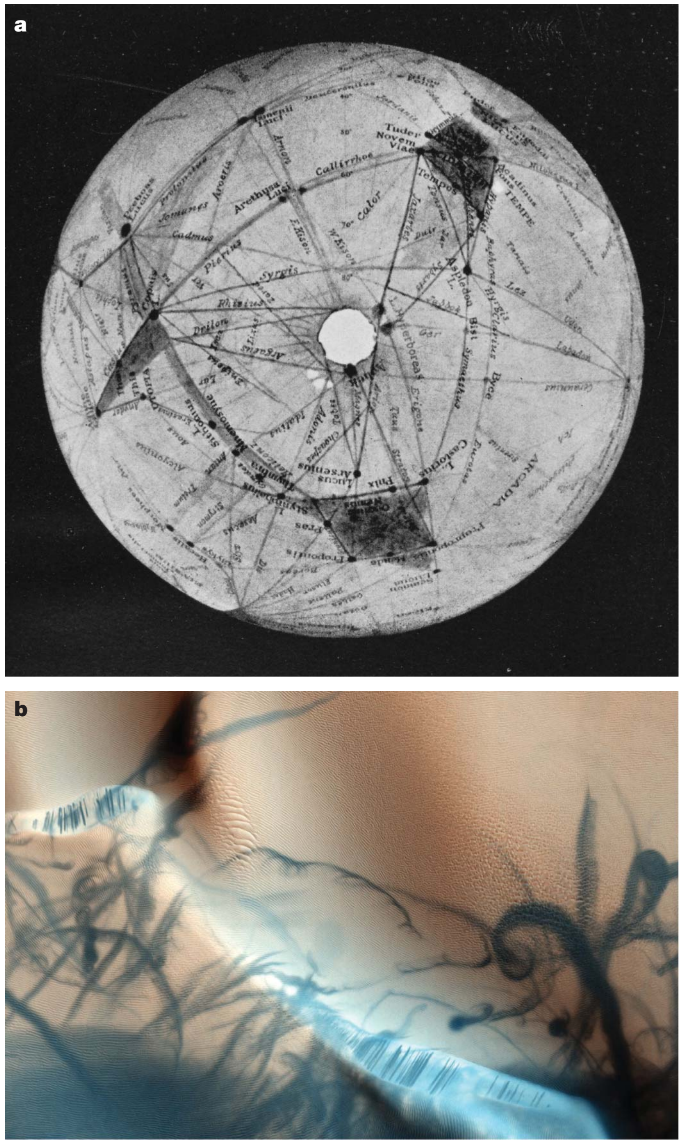

Figure 8 | The Earth's sibling, Mars. **a**, Early telescopic observations established that Mars' polar caps varied with the seasons, and that the planet's features varied, even occasionally being obscured by global dust storms; this Earth-like behaviour stimulated popular interest in Mars. Lowell's 1905 sketch of the north pole of Mars displays many roughly linear features ("canali") that he interpreted as evidence of intelligent habitation. **b**, Dark ground tracks record the paths of numerous dust devils that criss-cross light-coloured sand dunes in a crater west of Isidis Planitia; the comb-like arrays are landslides from ridge crests. (Mars Reconnaissance Orbiter HiRISE image ESP_014426_2070, ~0.8 km × 1.2 km, NASA/JPL/University of Arizona.) Much of Mars' variability, including that highlighted by Lowell, is caused when carbon-dioxide ice sublimes and when dust is transported over global distances. Mars has been revealed as the richest planet, except for the Earth, in the phenomena it displays[28,29]. It is, of course, the ultimate target of the human exploration programme and is among the most likely to harbour extraterrestrial life. Accordingly, the Red Planet has stayed the centrepiece of the Soviet/Russian and American space programmes[77]. Investigations of Mars compare its processes to the Earth's, in the belief that synergistic studies of both planets may unlock their secrets. For example, layered deposits encircling Mars' poles may record the effects of the substantial orbital/rotational oscillations that Mars undergoes[78]; this could substantiate the Milankovich model of terrestrial climate change. Our understanding of Mars has fluctuated wildly on two questions: whether freely flowing water was ever abundant and whether Mars ever sustained life.

Early on, dust coagulated to form pebbles that then, through an as-yet obscure mechanism, swiftly agglomerated into kilometre-sized planetesimals[57,58]. These bodies were probably loose rubble piles, as we infer from the low densities measured for asteroids and comets[59]. But the 500-metre-across near-Earth asteroid Itokawa[60], a bifurcated jumble of different-sized boulders, cautions that today's models of spherically symmetric accumulation may be simplistic. Then, via runaway accretion taking approximately 10^5 to 10^6 years, these bodies aggregate into thousand-kilometre-across planet-embryos.

In heated regions closer to the Sun, only refractory materials (for example, silicates and metals) can condense. There, energetic collisions between embryos produced the terrestrial planets[61]. As this final stage ended, no more than 30 to 50 million years after the nebula started collapsing, a Mars-scale projectile struck the proto-Earth, splaying portions of the Earth's mantle into a circumplanetary disk from which our Moon rapidly accumulated[62,63] (Fig. 2).

Meanwhile, in the giant-planet region, substantial cores—with masses and compositions augmented by more volatile ices—initiated runaway accretion of the nebular gases that now constitute their envelopes[47]. A vocal minority advocates global gravitational instabilities in the nebula, rather than the traditional core-accretion scenario above, to produce the giant planets. According to observations of massive exoplanets, this accumulation took merely 10^6 years, much less time than previously surmised. Throughout this period, the giant planets drift orbitally owing to interactions with the neighbouring disk[15,56]. A similar migration has putatively brought many exoplanets near their stars[64]; Saturn's rings display comparable processes[16]. Subsequently, the giant planets evolve radially by flinging any remaining planetesimals[65] into the Oort cloud from whence some ultimately return as today's comets[66].

The now-favoured "Nice model"[67] contends that, following a half-billion-year migration from a more compact configuration, the giant-planet orbits were dramatically rearranged, wreaking havoc (including the Late Heavy Bombardment[40]) and producing much of the Solar System's unique structure. Although we have recently learned much about the Solar System's origin, the next decade should witness considerably greater progress.

Exoplanets are today's 'wanderers'. A short eighteen years after the startling discovery of three planets tugging at a pulsar[17], a diverse zoo of exoplanets[12,19,55,64] has been revealed within disparate settings. Orbital solutions, like those available for our planets in 1700, are known for the almost 500 exoplanets sensed to date by ground-based[19] and space-based[12] instruments. The first planets have been sighted (see Fig. 6; refs 68, 69). Exoplanets range from 'hot Jupiters', through 'super-Earths', to massive objects hundreds of astronomical units away. Transit observations[55] have provided a preliminary characterization (mass, radius, density and some composition) of scores of these bodies, permitting a new phase of planetary studies to begin. The measured variety furnishes fertile targets to which planetary subdisciplines (for example, dynamics, meteorology and cosmochemistry) can be applied. Such exercises will enlighten us about exoplanets, but will disclose as much about our proximate planets. Simply put, planetary research has thus become relevant far beyond the Sun's environs (Box 3).

The past becomes the future

When recalling another scientific revolution, a character in Tom Stoppard's *Arcadia* remarks, "A door like this has cracked open five or six times since we got up on our hind legs. It's the best possible time to be alive, when almost everything you thought you knew is wrong…". And so it has been for planetary science since the space age began. These five decades, a relatively brief interlude between planetary ignorance and knowledge, have been very special indeed for us, fortunate explorers of our environs.

Few scientists envisaged that the neighbouring worlds explored by space missions would be so diverse, nor how entrancing many are. It is difficult to choose a favourite among Saturn's austerely beautiful rings, Venus's tortured volcanic plains or Triton's icy elegance. These worlds, all following the same laws of physics and chemistry, are so different. Yet all are the Earth's siblings, born from the same interstellar cloud at a similar time.

When the first exoplanets are viewed in detail, the Earth's residents—like Galileo in 1610—will doubtlessly recognize them as "most beautiful and delightful sights". Our planetary exploration will then have come full circle, as subsequent discoveries gradually transform these extrasolar beacons into worlds as familiar to our descendants as Mars and Saturn are to us today.

Box 3 | Future planetary exploration

Through its latest decadal survey, the United States National Research Council is vigorously debating the future for Solar System exploration. Advocates have prepared white papers on nearly 200 available planetary opportunities[80]. This comes as the reconnaissance of the Solar System has been completed and we are moving into a new chapter of deliberately exploring the Earth's companions in space, a time when specific scientific questions must be addressed.

Some policymakers consider that the early twenty-first century is the time to develop outposts on Mars, but such action seems premature for various reasons—financial, technical and sociological. I judge that the human space exploration program will advance slowly, meaning that the Earth's residents will colonize Mars much later. In the meantime, we will learn the most about our Solar System as well as our place in it, through deepening our understanding of the Solar System's origin and of exoplanets. The latter bodies today are much like the 'wanderers' were to Galileo: mere specks of light.

With numerous exoplanets tabulated[19,64] and the properties of some measured[55], astronomers and planetary scientists should work together to benefit from one another's accumulated wisdom. One community possesses detailed understanding about a handful of bodies, whereas the other has broadly surveyed many extrasolar planetary systems. Perhaps, after a half-century, planetary science will reunite with astronomy, as both disciplines seek to comprehend planetary systems in the broadest terms.

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