Solar System

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INTRODUCTION

Planetary Science is the branch of knowledge benefiting most as a result of the space age. In less than half a century, the field has been revolutionized by the influx of new images, observations, and other forms of data. Most planets and their larger satellites have been transformed from telescopic objects to individual worlds. Each has revealed a distinctive geological pedigree. New twists on well-known evolutionary processes are seen, and totally unanticipated phenomena are revealed every time a spacecraft visits a planet. What was ''planetary astronomy'' in one generation has become ''comparative planetology.''

Technological developments such as adaptive optics, large-mirrored telescopes, and infrared (IR) array detectors have revitalized our observatories. These new tools enable significant, but parallel, progress to be made from the ground. Computers allow numerical experiments to test theories and to run simulations where a solution of the analytic equations is impossible.

OVERVIEW

As a result of our newfound knowledge and tool kits, increasingly detailed studies of the beginnings of our solar system are being undertaken. Planets—albeit giant, Jupiter-class ones—are being discovered around other stars, extending the reach of Planetary Science beyond its grasp. Astronomical observation is still a major player in the study of the solar system. The Kuiper Belt, a region of our solar system only suspected a decade ago, now has over 700 catalogued members; it took 110 yr to discover that many asteroids. Distant Pluto is the only planet not yet visited by a spacecraft. It likely will remain a ''telescopic'' object for years to come, with the recent cancellation of the Pluto–Kuiper Express mission.

The status of our knowledge of the planetary system is summarized in the following pages. The treatment of each body is brief and up-to-date as of the turn of the millennium. However, rapid progress continues. In the time it took to prepare this article, 16 new satellites, 390 asteroids, and what may be ancient shorelines on Mars were discovered. For an inventory of planets and satellites in the solar system, see Table 1.

FORMATION

Our solar system began when a large cloud of gas and dust began to collapse. Comprised of a solar mixture of elements (Table 2), the mix is mostly hydrogen and helium, with a few percent sprinkling of compounds containing carbon, oxygen, nitrogen, and even lesser quantities of silicon and metals. The preponderance of hydrogen in this mixture means that most of the carbon (C), oxygen (O), and nitrogen (N) present react to form ices: mainly methane (CH_4), water (H_2O), and ammonia (NH_3), with some carbon monoxide (CO) and N_2. To conserve the angular momentum, motions in the cloud became accentuated as collapse continued, much as an ice skater spins faster as her arms are drawn to her body. The cloud fragmented into several hundred subclouds, each destined to form a separate stellar system.

As the subcloud continued its collapse, compression of the gas component caused heating. The gas component tends to obey the hydrostatic equation, while small solid particles undergo Keplerian orbits around the barycenter. This difference in kinematics causes a drag force on the particles as they orbit the protosun. This drag force has several effects: elliptical orbits are circularized, inclined orbits damp down toward the equatorial plane, and particles tend to spiral inward. Because drag on a particle is proportional to its cross-sectional area and mass, different sizes and mass particles are affected to varying degrees. The result is low-velocity collisions. A non-negligible percentage of the particles stick together, beginning the inexorable process of protoplanetary accretion.

The cloud has become disk-shaped. Temperature and density gradients increase toward the equatorial plane and radially inward to the center of the disk. At a given position in the disk, solid particles will vaporize if the local temperature is warm enough. Therefore particles residing in the inner regions of the disk are mainly refractory materials: high-temperature species like metals, oxides, and silicate minerals. Farther out, in the cooler regions, ices dominate solid particles, as ices are hundreds to

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Table 1 Inventory of planets and satellites in the solar system

Object	Equatorial diameter [km]	Mass [kg]	Rotation period [days]	Orbital period [days or years]
Sun	1,391,400	1.99×10^{30}	25.4	–
Mercury	4,879	3.30×10^{23}	58.6	89
Venus	12,103.6	4.869×10^{24}	243R	225
Earth	12,756.28	5.9742×10^{24}	1.00	365.25
Moon	3,476	7.35×10^{22}	Synchronous	27.321661
Mars	6,794	6.419×10^{23}	1.02	687
Phobos	26.8 × 22.4 × 18.4	1.063×10^{16}	Synchronous	0.31891
Deimos	15 × 12.2 × 10.4	2.38×10^{15}	Synchronous	1.262441
Asteroid belt				
Jupiter	142,984	1.899×10^{27}	0.41	11.9 yr
J1 Io	3,670 × 3,637.4 × 3,630.6	8.9316×10^{22}	Synchronous	1.769138
J2 Europa	3,130	4.79982×10^{22}	Synchronous	3.551181
J3 Ganymede	5,268	1.48186×10^{23}	Synchronous	7.154553
J4 Callisto	4,806	1.07593×10^{23}	Synchronous	16.689018
J5 Amalthea	262 × 146 × 134	7.2×10^{18}	Synchronous	0.498179
J6 Himalia	170	9.5×10^{18}	0.4	250.5662
J7 Elara	80	8.0×10^{17}	0.5	259.6528
J8 Pasiphae	36	2.0×10^{17}	?	735
J9 Sinope	28	8.0×10^{16}	?	758
J10 Lysithea	24	8.0×10^{16}	?	259.22
J11 Carme	30	9.0×10^{16}	?	692
J12 Ananke	20	4.0×10^{16}	?	631
J13 Leda	10	6.0×10^{15}	?	238.72
J14 Thebe	110 × 90	8.0×10^{17}	Synchronous	0.6745
J15 Adrastea	26 × 10 × 16	2.0×10^{16}	?	0.29826
J16 Metis	40 × 40	9.0×10^{16}	?	0.29478
S/1999 J1	?	?	?	736
S/2000 J1	?	?	?	130
S/2000 J2	?	?	?	766
S/2000 J3	?	?	?	606
S/2000 J4	?	?	?	661
S/2000 J5	?	?	?	618
S/2000 J6	?	?	?	703.5
S/2000 J7	?	?	?	626
S/2000 J8	?	?	?	733
S/2000 J9	?	?	?	652
S/2000 J10	?	?	?	591
S/2000 J11	?	?	?	289.7
Saturn	120,536	5.685×10^{26}	0.43	29.5 yr
S1 Mimas	418.2 × 392.4 × 382.8	3.75×10^{19}	Synchronous	0.942422
S2 Enceladus	513.6 × 494.6 × 489.2	7.0×10^{19}	Synchronous	1.370218
S3 Tethys	1,071.2 × 1,056.4 × 1,051.6	6.27×10^{20}	Synchronous	1.887802
S4 Dione	1,118	1.10×10^{21}	Synchronous	2.736915
S5 Rhea	1,528	2.31×10^{21}	Synchronous	4.5175
S6 Titan	5,150	1.3455×10^{23}	?	15.945421
S7 Hyperion	360 × 280 × 225	2.0×10^{19}	Chaotic	21.276609
S8 Iapetus	1,436	1.6×10^{21}	Synchronous	79.330183
S9 Phoebe	230 × 210	4.0×10^{17}	0.4	550.48
S10 Janus	194.0 × 190.0 × 154.0	1.92×10^{18}	Synchronous	0.6945
S11 Epimetheus	168 × 110 × 110	5.4×10^{17}	Synchronous	0.6942
S12 Helene	36 × 32 × 30	?	?	2.7369
S13 Telesto	30 × 25 × 15	?	?	1.8878

Orbital distance [10^3 km or AU]	Inclination [°]	Eccentricity	Escape velocity [km sec^{-1} or m sec^{-1}]	Known or probable surface composition
–	–	–	617	Ionized gas, H, He
0.387 AU	7.005	0.206	4.25	Basaltic dust and rock
0.723 AU	3.395	0.007	10.36	Basaltic and granitic rock
1.000 AU	0	0.017	11.18	Water, granitic soil
384.401	5	0.0549	2.38	Basaltic dust and rock
1.524 AU	1.851	0.093	5.02	Basaltic dust and rock
9.378	1	0.015	11 m sec^{-1}	Carbonaceous soil
23.459	0.9–2.7	0.0005	6 m sec^{-1}	Carbonaceous soil
5.203 AU	1.305	0.048	60	N/A
422	0.04	0.004	2.6	Water ice
671	0.47	0.009	2	Water ice, dust
1,070	0.21	0.002	3.6	Water ice, dust
1,883	0.51	0.007	2.4	Water ice, dust
181	0.4	0.003	0.13	Sulfur coated rock
11,480	27.63	0.15798	90 m sec^{-1}	Carbonaceous rock
11,737	24.77	0.20719	40 m sec^{-1}	Carbonaceous rock
23,500	145	0.378	40 m sec^{-1}	Carbonaceous rock
23,700	153	0.275	20 m sec^{-1}	Carbonaceous rock
11,720	29.02	0.107	20 m sec^{-1}	Carbonaceous rock
22,600	164	0.20678	20 m sec^{-1}	Carbonaceous rock
21,200	147	0.1687	16 m sec^{-1}	Carbonaceous rock
11,094	26.07	0.14762	4 m sec^{-1}	Carbonaceous rock
222	0.8	0.015	59.54 m sec^{-1}	Rock
129	0	0	10 m sec^{-1}	Rock
128	0	0	20 m sec^{-1}	Rock
23,562	143.49	0.20615	?	?
7,418	45.378	0.20554	?	?
24,200	165.792	0.31774	?	?
20,700	149.906	0.26862	?	?
21,920	160.909	0.34647	?	?
20,974	149.288	0.20027	?	?
22,870	165.039	0.28091	?	?
21,155	146.353	0.14582	?	?
23,500	151.7	0.52772	?	?
21,730	163.545	0.24604	?	?
20,354	165.62	0.15532	?	?
12,657	28.552	0.21521	?	?
9.537 AU	2.484	0.056	35.49	N/A
185.82	1.53	0.0202	0.2	Water ice
238.02	0	0.00452	0.2	Water ice
295	1.86	0	0.4	Water ice
377	0.02	0.00223	0.5	Water ice
527.04	0.35	0.001	0.7	Water ice
1,221.83	0.33	0.29192	2.7	Water, Methane ice
1,481.1	0.43	0.104	0.1	Water ice
3,561.3	14.72	0.02828	0.6	Water ice, soil
12,952	150.	0.16326	0.1	Carbonaceous soil
151.472	0.14	0.007	70 m sec^{-1}	Water ice
151.422	0.34	0.009	50 m sec^{-1}	Water ice
377.4	0	0.005	11 m sec^{-1}	Water ice
294.66	0	0	7 m sec^{-1}	?

(*Continued*)

Table 1 (*Continued*)

Object	Equatorial diameter [km]	Mass [kg]	Rotation period [days]	Orbital period [days or years]
S14 Calypso	30 × 16 × 16	?	?	1.8878
S15 Atlas	37 × 34.4 × 27	?	?	0.6019
S16 Prometheus	148 × 100 × 68	?	?	0.613
S17 Pandora	110 × 88 × 62	?	?	0.6285
S18 Pan	20	?	?	0.575
S/2000 S1	?	?	?	1288
S/2000 S2	?	?	?	690
S/2000 S3	?	?	?	791
S/2000 S4	?	?	?	889.6
S/2000 S5	?	?	?	448
S/2000 S6	?	?	?	452
S/2000 S7	?	?	?	1036
S/2000 S8	?	?	?	730.5
S/2000 S9	?	?	?	943
S/2000 S10	?	?	?	927
S/2000 S11	?	?	?	882
S/2000 S12	?	?	?	888
Uranus	51,118	8.685×10^{25}	0.72R	84.0 yr
U1 Ariel	1,160	1.4×10^{21}	Synchronous	2.520379
U2 Umbriel	1,190	1.2×10^{21}	Synchronous	4.144177
U3 Titania	1,600	3.4×10^{21}	Synchronous	8.705872
U4 Oberon	1,550	2.9×10^{21}	Synchronous	13.463239
U5 Miranda	484	7.0×10^{19}	Synchronous	1.413479
U6 Cordelia	26	?	?	0.335034
U7 Ophelia	31	?	?	0.3764
U8 Bianca	42	?	?	0.434579
U9 Cressida	62	?	?	0.46357
U10 Desdemona	54	?	?	0.47365
U11 Juliet	84	?	?	0.493065
U12 Portia	108	?	?	0.513196
U13 Rosalind	54	?	?	0.558459
U14 Belinda	66	?	?	0.623527
U15 Puck	160 × 150	?	?	0.761833
U16 Caliban	60	?	?	579
U17 Sycorax	120	?	?	1289
U18 Prospero	?	?	?	?
U19 Setebos	?	?	?	?
U20 Stephano	~80	?	?	?
S/1986 U10	40?	?	?	0.638
Neptune	49,528	1.024×10^{26}	0.67	164.8 yr
N1 Triton	2,705.2	1.3×10^{23}	Synchronous	5.876854
N2 Nereid	340	2.0×10^{19}	?	360.13619
N3 Naiad	58	?	?	0.294396
N4 Thalassa	80	?	?	0.311485
N5 Despina	148	?	?	0.334655
N6 Galatea	158	?	?	0.428
N7 Larissa	208 × 178	?	?	0.55654
N8 Proteus	436 × 416 × 402	?	?	1.122315
Pluto	2,302	$1.150\text{–}1.277 \times 10^{22}$	6.38725	247.7 yr
P1 Charon	1,186	$1.397\text{–}1.572 \times 10^{21}$	Synchronous	6.38725

Orbital distance [10^3 km or AU]	Inclination [°]	Eccentricity	Escape velocity [km sec^{-1} or m sec^{-1}]	Known or probable surface composition
294.66	0	0	9 m sec^{-1}	?
137.67	0.3	0	13 m sec^{-1}	Water ice
139	0.003	0	50 m sec^{-1}	Water ice
142	0	0.004	35 m sec^{-1}	Water ice
133.583	0.004	0	10 m sec^{-1}	Water ice
22,893	172.796	0.36658	?	?
15,101	46.18	0.45853	?	?
16,540	48.656	0.29345	?	?
17,887	34.97	0.6346	?	?
11,322	48.451	0.15783	?	?
11,386	49.329	0.36727	?	?
19,804	174.954	0.54392	?	?
15,685	148.561	0.21408	?	?
18,601	169.593	0.254	?	?
18,383	33.285	0.61436	?	?
17,784	34.886	0.38703	?	?
17,866	174.766	0.0866	?	?
19.191 AU	0.77	0.05	21.29	N/A
191.02	0.3	0.0034	0.7	Water ice, soil
266.3	0.36	0.005	0.6	Water ice, soil
435.91	0.14	0.0022	1.1	Water ice, soil
583.52	0.1	0.0008	1	Water ice, soil
129.39	4.2	0.0027	0.4	Water ice, soil
49.77	0.08	0.00026	14 m sec^{-1}	Ice and soil
53.79	0.1	0.0099	17 m sec^{-1}	Ice and soil
59.17	0.19	0.0009	23 m sec^{-1}	Ice and soil
61.78	0.01	0.0004	35 m sec^{-1}	Ice and soil
62.68	0.11	0.00013	31 m sec^{-1}	Ice and soil
64.35	0.07	0.00066	44 m sec^{-1}	Ice and soil
66.09	0.06	0	58 m sec^{-1}	Ice and soil
69.94	0.28	0.0001	31 m sec^{-1}	Ice and soil
75.26	0.03	0.00007	36 m sec^{-1}	Ice and soil
86.01	0.32	0.00012	126 m sec^{-1}	Ice and soil
7,169	139.2	0.082	?	?
12,214	152.7	0.509	?	?
?	?	?	?	?
?	?	?	?	?
?	?	?	?	?
76.416	?	?	?	?
30.069 AU	1.769	0.01	23.71	N/A
354	159	0	2.5	Nitrogen, Methane ice
5,515	27.6	0.75	0.2	Methane ice
48.23	4.74	0	74 m sec^{-1}	Ice and soil
50.07	0.21	0	84 m sec^{-1}	Ice and soil
52.53	0.07	0	48 m sec^{-1}	Ice and soil
61.95	0.05	0	26 m sec^{-1}	Ice and soil
73.55	<4	?	106 m sec^{-1}	Ice and soil
117.65	<5	?	222 m sec^{-1}	Ice and soil
39.482 AU	17.142	0.25	1.15–1.21	Methane, Carbon Dioxide ice
19.6	0	0	0.56–0.60	Water ice, soil

Table 2 Solar elemental abundances

Element	Number %	Mass %
Hydrogen	92.0	73.4
Helium	7.8	25.0
Carbon	0.02	0.20
Nitrogen	0.008	0.09
Oxygen	0.06	0.8
Neon	0.01	0.16
Magnesium	0.003	0.06
Silicon	0.004	0.09
Sulfur	0.002	0.05
Iron	0.003	0.14

thousands of times more abundant than metals or silicates. The biggest of the accreting ‘‘iceballs’’ (5–10 Earth masses, $M_{\oplus}$) are large enough that their gravity can gobble up vast quantities of the surrounding gas (mainly hydrogen and helium). They grow more massive still, allowing even more gas to be captured (i.e., runaway accretion).

This scenario explains several features of our solar system. Most objects orbit in a single plane about the Sun, called the ecliptic. The source of the compositional gradient seen in the present-day solar system is also explained. In the regions where water and other ices exist as solids, we find the Jovian, or Jupiter-like, planets. Hundreds of times more massive than the terrestrial ‘‘crumbs,’’ their composition largely reflects the original gaseous component of the nebula. Farther out, collision timescales were longer and building materials much more rare. The outermost planets did not grow to the runaway accretion stage and are depleted in H and He relative to Jupiter and Saturn.

Eventually, the center of the nebula reaches temperature and density conditions sufficient for the initiation of thermonuclear fusion. The protosun ignites and begins to produce its own internal energy. Heating and radiation pressure from the young Sun cause residual gas in the nebula to dissipate (T Tauri phase). Except for a sweeping up and a redistribution of the leftover crumbs, the formation of our planetary system is essentially complete.

MERCURY

Looking at the surface of Mercury, the innermost planet, one sees a heavily cratered surface interspersed with maria, impact basins subsequently flooded with basaltic lava. Mercury’s appearance is that of a slightly larger version of our Moon. But appearances are deceiving. To account for its density of 5.44 g cm^{-3}, the planet must have a huge iron–nickel (Fe–Ni) core, nearly 75% of the planet’s radius and 42% of its volume. The Moon’s core is only 2% or 3% of its radius; the Earth’s core is 45% of its radius.

Mercury orbits the Sun at 0.38 astronomical units (AU), in a decidedly elliptical path ($e = 0.206$). At aphelion, it is 63% farther from the Sun than at perihelion. Virtually airless, Mercury’s surface has the most extreme conditions of any terrestrial body. Thermal IR measurements from Earth-based telescopes show that daytime temperatures can peak at 700 K; at night, the minimum plunges to 90 K. But at a depth of only 1 cm in the dusty soil, the diurnal temperature pulse is ‘‘only’’ from 450 to 210 K. So molten lakes of lead or zinc, common to old science fiction stories, are not plausible. Nonetheless, the surface environment is extremely hostile to most materials. A robotic exploration of the surface is not likely in the near future.

Mercury is devilishly difficult to observe from Earth—it is never more than 27° from the Sun. Therefore it must be observed either at high airmass (just after sunset or before sunrise), or during daylight hours when the Earth’s atmosphere is very turbulent. In 1965, a radar beam was bounced off Mercury’s surface. The Doppler spread in the return demonstrated that the planet rotates in 58.6 days, not 88 days as expected. Mercury exhibits a 3:2 spin–orbit resonance wherein it rotates exactly three times on its axis for every two revolutions about the Sun. It is believed that the spin–orbit coupling is a result of tidal interaction, with the Sun removing the angular momentum, slowing its originally higher spin rate.

A ‘‘day’’ on Mercury is rather remarkable. The time between noons is 176 Earth days. However due to Mercury’s elliptical orbit, the Sun will rise in the east, stop, reverse its direction through the sky for a while, then resume its westward march. The apparent size of the Sun’s disk changes by about 62% during the course of 88 days. And, at perihelion, the Sun is directly overhead at one of only two points on the equator—180° apart—called ‘‘thermal’’ poles.

Recent observations have revealed ‘‘radar bright’’ regions near the eternally shadowy poles. Several candidate minerals are reflective at radio wavelengths. It is intriguing that subsurface water ice is a leading candidate. It may take a lander to determine the truth.

Mercury lies very deep in the Sun’s gravitational well. Mariner 10 is the only spacecraft to have flown past the planet (during 1974). In addition to craters and impact basins, the images show a global network of ‘‘compression ridges’’ (or ‘‘scarps’’), which is best explained by the cooling (shrinking) of the planet by some 15 km in radius. Yet Mariner’s magnetometer also detected a weak magnetic field—evidence that the interior is still molten. A jumbled, ‘‘chaotic’’ terrain antipodal to the Caloris impact basin is likely due to the convergence of seismic energy from the impact event half a world away. The region was kicked several kilometers skyward, then came crashing down.

VENUS

Venus' radius and mass are slightly less than those of the Earth at 0.95 $R_\oplus$ and 0.82 $M_\oplus$, respectively. Presumably, our planet's closest neighbor formed in the same general region of the solar nebula, and the interior composition and structure of both planets are similar. Venus orbits the Sun at a mean distance of 0.72 AU in the most circular of all planetary orbits. It has no moons. Long supposed to be Earth's ''twin,'' it is difficult to see any family resemblance in Venus upon closer inspection.

Venus is eternally and completely covered by thick clouds, which circulate around the planet in about 4 Earth days. The planet's true rotation period was determined in 1962, when radar was bounced off the surface. The Doppler broadening gave a value: 243 Earth days—retrograde. Too lazy for an internal dynamo to generate an appreciable magnetic field, the solar wind slams into the upper atmosphere, slowly but inexorably eroding it.

The atmosphere was discovered in 1761, but it was not until 1932 when the major constituent, CO_2, was identified via spectroscopy. In 1972, the composition of the clouds was determined—sulfuric acid. It may rain H_2SO_4, but it never reaches the surface. The application of Wien's law to far-IR and radio data showed the lower atmosphere to be ~750 K. The Soviet Venera 7 probe landed on the surface in 1970, confirming the high temperature and reporting a surface pressure of 90 bar. The greenhouse effect is responsible for the high temperature. The atmosphere is largely transparent to solar radiation (predominantly ~500 nm), which can penetrate to heat the surface. Energy is reradiated as heat (black body peak ~4000 nm). However, at these longer wavelengths, the carbon dioxide (CO_2) atmosphere is opaque and acts as a very efficient thermal blanket. Equator to pole, daytime or night, the surface would have a uniform temperature (±2 K), save for the effects of topography.

And it is dry heat. Most of the Earth is covered with several kilometers of water. Venus' surface is dry; the atmosphere contains only 30 ppm water. Did Venus originate with an Earth-like water inventory then lose it? Or was it born dry? This question is the key to understanding the planet's evolution.

Four of six Soviet landers have returned surface panoramas. Angular, platey rocks, gravel, and fine soils in varying states of erosion are revealed. Chemical analyses at all but one of the landing sites showed a basaltic composition comparable to terrestrial oceanic crust.

Although preceded by both Soviet and American radar mapping missions, the true oracle in our understanding of Venus' surface was NASA's 1991 Magellan mission. More than 98% of the planet was mapped at a resolution of 100–200 m/pixel. From the travel time of the radar, accurate altimetry was derived. The histogram of surface radii is narrow and bell-shaped, very different from the bimodal histogram for Earth. (Our planet shows peaks at oceanic and continental radii.) This argues against Earth-like global plate tectonics on Venus.

The Magellan images revealed regions of local tectonism (crustal folding and stretching), lava channels, and eolian features. The weathering processes on Venus seem to be extremely slow. Accurate impact crater counts were also made. The older a planetary surface, the more impact craters it will accumulate. The Apollo landing sites allowed absolute ages to be assigned to certain crater densities on the Moon; these can be extrapolated to Venus and other solar system bodies. The results for Venus are interesting, if not puzzling.

Earth-style plate tectonics results in a continual recycling of the crust at subduction zones and a regeneration at midoceanic ridges. It seems that Venus underwent a global resurfacing event about 500 million years ago, with craters accumulating ever since. Was Venus tectonically active for over 90% of its history, becoming inert only relatively recently? Unlikely. The Earth still has plenty of tectonic activity. Or is resurfacing on Venus a periodic process? Very un-Earthly. Understanding the disparate styles of tectonism on Earth and Venus is crucial to comprehending the differences between these two worlds.

EARTH

The third planet from the Sun shows several traits that make it unique among terrestrial (rocky) planets. Approaching Earth from space, we would first notice the presence of a large moon. An active magnetic field (~0.6 G) shields our planet from solar and galactic charged particles. Abundant water, in all three phases, coats the planet. Were aliens to drop 10 probes at random locations, about one-third would travel through water clouds and three-quarters of them would splash down into an ocean. A paucity of impact craters (~300 total) implies a very young surface. The atmosphere—78% nitrogen (N_2), 21% oxygen (O_2), 0.9% argon (Ar), and 0.05–2% water (H_2O)—is a mix far removed from chemical equilibrium with the surface materials; it betrays the existence of photosynthetic life-forms generating vast amounts of free oxygen. A layer of ozone (O_3) in the upper stratosphere screens the planet below from a large percentage of the solar ultraviolet (UV) radiation (shortward of 310 nm). Advanced life is no doubt the most unique feature of our planet.

The relatively rapid rotation (currently 23 hr, 56 min, 04 sec, 0.0989) allows diurnal temperatures to be moderated and supplies the Coriolis force that gives weather systems their characteristic size scale. The spin axis is inclined 23 1/2° to the orbit normal, causing seasons. Our Moon tends to stabilize this obliquity (i.e., axial tilt), thereby moderating climate on a timescale of several hundred million years. The time characteristic for continental driftis also about this size, as is the time characteristic for evolution. Plate tectonics (a.k.a. continental drift) is constantly renewing and rearranging the surface. It is known that evolutionary ''explosions'' have occurred coincident with the formation of new oceans, such as the Tethys Sea (now the Indian Ocean) and the Atlantic. Life originated (perhaps several times over) within the first few hundred million years of our planet's history, judging by the age of the oldest known fossils (3.5–3.9 Gyr). It is increasingly clear that evolution has been influenced, even shepherded, by geological processes.

Heat from radioactive decay led to the early melting of the Earth. Dense materials (metals, and elements that readily dissolve in them) sunk to the center, and less dense materials floated in a process called chemical differentiation. The interior structure we ''see'' by seismic monitoring became established. At the center is a solid Fe–Ni inner core, surrounded by an Fe–Ni liquid outer core (the phase change is largely due to a decreased pressure). The next layer is the mantle, with its base at just over 50% the Earth's radius. It is composed of dense, molten rock, and transports heat to the surface by convection. (We recently have learned that there is a significant topography at the core–mantle boundary.) Only in the outer several hundred kilometers does the mantle cool from fluid, to plastic, to the brittle (solid) top layer called the crust. The crust begins ~5 km below the seafloor and ~30 km below the continents. The ocean floor material is mainly basalt rock (common to terrestrial planets), while the continents generally are composed of a less dense rock type called granite.

The Earth's surface is divided into roughly 10 nearly rigid tectonic plates, which move relative to each other at rates of a few centimeters per year. Plates spread apart at midoceanic ridges. Trenches and island arcs occur at subduction zones (Japan, the Andes), where plates converge and one slips beneath the other. Horizontal slippage occurs at transform faults, such as California's San Andreas. Plumes carry hot, low-viscosity materials from the depths, and volcanic island chains (Hawaii) form where these hot spots puncture a plate. The hypothesis provides a unifying framework for solid Earth science in terms of thermal convection. The underlying dynamics of the process—the ''hows'' and ''whys''—is just beginning to be understood. Only recently have computers become capable of simultaneous numerical models of both physical and chemical aspects. The mystery of why the Earth has had vigorous plate tectonics throughout its history—but Venus has not—is far from solved. Until models can reproduce the difference, we cannot truly say that we understand either planet.

MOON

Our Moon likely was produced near the end of Earth's accretion phase 4.6 billion years ago, when a Mars-sized body crashed into Earth, knocking large chunks of the mantle into orbit. This ''Giant Impact Hypothesis'' explains many major characteristics of the system. It accounts for Earth's obliquity and rapid spin (initially 12–16 hr), the Moon's diminutive core, the apparent high-temperature chemistry, low density (3.3 versus 5.53 g cm^{-3} for Earth), desiccated state, and the spot-on oxygen isotope match with Earth found in the samples returned by Apollo.

The chunks rapidly coalesced, and heating by radioactive decay soon melted the early Moon. A magma ocean several hundred kilometers deep formed. Cooling ensued, and a 1000-km lithosphere of largely anorthositic rock formed. The surface suffered a period of intense heavy bombardment as Earth and Moon swept up their remaining building blocks. Large impact basins, several hundred kilometers across, were created on both worlds. Intense cratering ended about 3 Gyr ago. Darker, basaltic lava later erupted in many places, preferentially filling the low-lying, thinner-crusted, and heavily fractured basins.

This scenario of lunar evolution was pieced together from superposition relationships—an often used geological principle whereby ''newer stuff tends to cover older stuff.'' One of the foremost results from analyzing the 400+ kg of samples returned by six Apollo and three Soviet Luna probes was to apply radioisotopic dating to fix absolute ages to each step in the process. For lack of anything better, this timescale is extrapolated, with additional assumptions, to estimate ages for other planets and satellites in the solar system.

Small bodies have large surface area/volume ratios, so active lunar geology ended quickly. The only substantive geologic events in the last 2.5–3.0 Gyr have been occasional impacts. Luna's gravity (one-sixth that of the Earth; mass = 0.0123 $M_{\oplus}$) is too feeble to retain an atmosphere. Surface temperatures swing between 370 and 100 K. Impact gardening and intense thermal cycling comminute the ''soil'' (to misuse a term) to the consistency of talcum powder. Craggy peaks described in old science fiction novels are in reality mantled and muted.

The lunar far side is deficient in the dark, basalt-filled maria so common to the near side. It is largely covered with impact craters. Far-side crust is about twice as thick near-side crust. There is a 2-km offset toward Earth in the center of mass from the center of figure, due to the maria. Tidal forces tug on the ''bulge'' to keep this face oriented Earthward.

Seismometers left by the Apollo astronauts have been used to learn about the Moon's interior. A topmost layer (regolith) typically is 3–30 m deep, consisting of rubble created by impacts. While the seismometers functioned, they recorded the Moon being whacked by a number of things: grenade-sized explosives, lunar module upper stages, and spent rocket boosters. It rang like a bell, indicating a much less dissipative interior than the Earth's—further evidence for a largely solid interior. Passive monitoring showed moonquakes originate in two zones: the surface and ~1000 km deep. Surface events are ascribed to impacts; deeper ones hint at a transition zone from solid to partially molten. No core could be detected, although the magnetometer on NASA's 1998 Lunar Prospector mission detected a small metallic core 1–2% of the Moon's total mass.

Another interesting result came from Lunar Prospector's Neutron Spectrometer. Dips in the epithermal neutron energy spectra occurred at both poles. One interpretation of this is 10–300 million metric tons of water ice buried approximately 50 cm in permanently shadowed craters (water is an excellent moderator of neutrons).

Corner cube reflectors at the Apollo landing sites are still used to conduct laser-ranging experiments. The Moon currently is receding from the Earth at about 6 cm yr^{-1}.

MARS

Roughly half the diameter of Earth, diminutive Mars is nevertheless a world of ''big geology.'' Its southern hemisphere has ancient, heavily cratered uplands reminiscent of the Moon, complete with large impact basins. The northern half of the planet is relatively younger, with less cratered plains. Straddling the boundary is the Tharsis bulge, a construct of four major and several minor shield volcanoes, roughly half the area of the United States. The sheer size of Tharsis indicates that Mars has a very thick, rigid crust to support the load, estimated to be 100–200 km thick. Olympus Mons is the solar system's largest volcano, being 27 km high and having a base the size of Arizona. Although inactive, the paucity of impact craters betrays a young age, perhaps ~1 Gyr.

Downslope of Tharsis is Valles Marineris, a 5000-km-long canyon, in places hundreds of kilometers across and 6 km deep. This fracture is evidence that Mars' crust is thinner than the Moon's. Its eastern end branches out into a chaos of hundreds of outflow channels. There is global evidence for a past era when abundant water flowed on Mars. Dry riverbeds are seen in the ancient south. Classic groundwater sapping patterns, fretted terrain, and valley networks abound—and water is the only liquid in sufficient cosmic abundance to be the culprit. A stated goal of NASA's Mars program is to locate sequestered water.

Today, Mars' atmosphere is thin and dry: 6–9 mbar (600–900 Pa), comprised of 95.3% carbon dioxide (CO_2), 2.7% nitrogen (N_2), 1.6% argon (Ar), and only ~10 precipitable microns of water. Because this is below water's triple point, liquid water cannot exist on the surface for long. Mars does have polar caps, though. A substantial fraction of the atmospheric CO_2 condenses at the winter pole. The result is a semiannual fluctuation in the surface pressure, with seasonal sublimation winds predominantly away from the summer pole. Mars' orbit around the Sun is eccentric ($e = 0.0934$), resulting in asymmetric seasons. Presently, perihelion is at the end of southern spring: southern summers are hotter than northern summers. Global dust storms tend to initiate around the perihelion. Typical atmospheric optical depth due to dust loading is 0.3–0.6, but can reach 5 during dust storms.

The thin atmosphere is a poor thermal blanket. At the Mars Pathfinder landing site in Ares Valles, diurnal temperatures cycled between 197 and 263 K. Mars lacks an ozone layer to shield the surface from solar UV radiation. Chemical reactions between the atmosphere and surface rocks in the presence of UV produce a suite of superoxides and peroxides that become adsorbed onto the surface. These chemicals are very destructive to organic compounds. In effect, the surface of Mars is self-sterilizing.

The Mars Global Surveyor orbiter has discovered stripes of magnetized surface rock—bands of magnetic materials aligned in one direction, alternating with magnetic materials of the opposite polarity. This is somewhat reminiscent of the patterns seen at midocean rift zones on Earth. On our planet, the alternating stripes testify to plate tectonics. Earth's reversing magnetic field imprints in upwelling magma as it cools below the temperature at which a magnetic field is preserved. The movement of crust away from a spreading center creates a ''recording'' of the magnetic field versus time (or age). The simplest conclusion: Mars, too, might have had a strong internal magnetic field and might have experienced limited tectonic activity when the oldest southern terrain formed about 4 Gyr ago.

The size of Mars' core is constrained by the planetary mean density (3.9 g cm^{-3}) and dimensionless moment of inertia (0.365). At one extreme, a 1300-km-radius metallic iron (Fe) core fits the data. At the other, a 2000-km radius iron–sulfur (FeS) core also works. Petrochemical evidence from known Martian meteorites (the SNCs[a])

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[a] SNCs stands for Shergotty–Nahkla–Chassigny. These are the three prototypical members of the SNC class of meteorites, named after the towns nearest where they were found. The SNCs are thought to originate from the planet Mars.

shows that the upper mantle is depleted in siderophile (''iron-loving'') and chalcophile (''sulfur-loving'') elements. This implies that the latter model is preferred. In addition, FeS is less electrically conductive than pure Fe, possibly explaining the lack of a strong internal magnetic field in Mars today.

Mars has two small satellites, Phobos and Deimos. The party line is that these bodies are captured asteroids. However, recent near-IR spectra show that their surface materials are not matched by any of the common asteroid spectral types.

ASTEROIDS

In the late 1700s, astronomers were puzzled by the vast, seemingly empty region of the solar system between Mars and Jupiter, from 1.52 to 5.20 AU. They began a search for the ''missing planet'' in this region. On the first night of the 19th century—January 1, 1801—Giuseppe Piazzi discovered the ''missing planet.'' It was named Ceres, after the Roman goddess of the harvest. The mystery had been solved. Or had it really been? By 1807, three more asteroids had been discovered in similar orbits, what we now call the ''main belt.'' (The term asteroid means ''star-like,'' in reference to their telescopic appearance.) The official nomenclature for asteroids is a number (sequential, in order of discovery), followed by a proper name (typically chosen by the discoverer), hence 1 Ceres, 2 Pallas, 3 Juno, 4 Vesta, etc. Today there are about 53,000 numbered asteroids. The sampling of the main belt is likely complete down to $\sim$20 km diameter. It is estimated some 100,000 observable asteroids are yet to be discovered. Were all asteroids combined, they would comprise a single body less than 1500 km in diameter—about two-thirds the Moon's diameter. 1 Ceres is the largest asteroid, with a diameter of 960 km.

Main belt asteroids never accreted as a single body. The region is riddled with locations where an object's orbital period around the Sun is an exact ratio of Jupiter's orbital period, e.g., 2:1, 3:1, 8:3, etc. Any asteroid wandering into this region is removed in short order. These resonance regions, named Kirkwood Gaps after their discoverer, are very apparent now that the statistical sample of known asteroid orbits has grown so large. This gravitational sculpting by Jupiter is responsible for replenishing the population of ''near-Earth'' asteroids (NEAs). The primary source of meteorites, NEAs are continually swept up by the terrestrial planets. Apollo asteroids are those whose orbits cross the Earth's orbit; the Amor and Aten families comprise asteroids with perihelia less than Mars' or Venus' orbit, respectively. Asteroid ''families'' are named after the first-known member in a given class.

A third class of asteroids is the Trojans. These bodies (currently 1550 are known) orbit at Jupiter's distance from the Sun, 5.2 AU. Found roughly 60° ahead and 60° behind Jupiter along its orbit, they surround two gravitationally stable regions predicted theoretically by J.L. Lagrange. (Incidentally, Mars has two confirmed ''Trojans.'' Searches for Earth Trojans have been, to date, unsuccessful.)

While the asteroids never accreted as a single planet, it is also plain that in the past, there existed several bodies large enough to have undergone planetary differentiation. Spectra show various compositional types, or families, of asteroids. Some are metallic, others show silicate mineral composition, while some have spectral absorptions due to a few percent organic (carbon bearing) and/or hydrated minerals. The M-class (metallic) asteroids presumably are samples of the cores of these shattered, larger planetoids. 4 Vesta is of the rare basaltic achondrite class, and it probably represents a piece of the surface of an evolved body whose interior had melted and flooded its surface with lava flows. Most asteroids, however, are chemically undifferentiated. They represent relatively primordial relics from the time when the solar system formed.

Understanding asteroid compositions is complicated by several factors. The composition of the solid component of the protoplanetary nebula varied with temperature, i.e., radial distance from the Sun, and with time. In general, inner asteroids are composed of higher-temperature minerals than those further out. Somewhere within the present-day belt was the ''ice line,'' or the region where temperature dropped enough for water to condense. Water of hydration is seen in spectra of many outer belt asteroids.

Asteroids are the most energetically accessible bodies to the Earth because their gravitational wells are tiny. They represent a vast, untapped mineral resource for future generations, as human exploration of the solar system becomes a reality. We have only begun a detailed examination of this class of objects. The first asteroid orbiter, the NEAR spacecraft, has completed its examination of 433 Eros. Outer planet probes typically are targeted to fly by asteroids as they pass through the belt. It is clear that asteroids are important to our future, and to our past. The impact of a 10-km-sized asteroid into Mexico's Yucatán 67 Myr ago had significant effects on terrestrial evolution by killing off the dinosaurs.

JUPITER

Giant Jupiter is more massive (318 $M_\oplus$) and bigger (11 $R_\oplus$) than all the other planets combined. It is the first of four ''Jovian'' gas worlds—planets with no solid surfaces and compositions that are to first order similar to the Sun. By mass, the atmosphere is 78% hydrogen (H_2) and 19% helium (He). The remaining percent is mostly ''hydrated'' molecules of CH_4 (0.2%) and NH_3 (0.5%). Trace amounts of other species, many produced through UV photochemistry, give color to its clouds. Jupiter began as a ''seed'' of rock and ice, perhaps 12 Earth masses, onto which accreted a sizeable amount of its local solar nebula.

Many of the planet's characteristics are understood as consequences of this ''runaway accretion.'' Drawing in gas from far away caused Jupiter to spin rapidly due to a conservation of angular momentum. The Jovian day is a mere 9 hr, 55 min, 30 sec, short enough that the planet's polar diameter is 6.4% less than its equatorial span. Accretion caused much heating—the core is estimated to be about 30,000 K, although the cloud tops are a brisk 150 K. Today, Jupiter emits about twice as much energy as it receives from the Sun. The source of this energy is a slow, continued contraction of about 10 cm yr^{-1}. Jupiter is a bona fide planet and not a ''failed star.'' It would require 13 times its mass for the core to burn deuterium, and 75 times its mass for plain hydrogen fusion to initiate.

The rapid rotation and heating from below cause Jupiter's cloud structure to be very different from the Earth's cloud structure. Clouds are organized into bands parallel to the equator, called belts and zones. Convection causes rising, hot air parcels (zones) to cool, condensing out dissolved species when saturation vapor pressure is reached. Sinking parcels heat up, vaporizing larger (less backscattering, therefore darker) ice crystals. Jupiter rotates differentially, generally faster at the equator than at the poles. Weather systems remain confined to their original latitudes, blowing at up to 150 m sec^{-1}. The Great Red Spot is the most prominent of these generally oval features. About three times the size of Earth, it has persisted since at least 1665. Theoretical calculations give it a minimum age of 50,000 yr.

The atmosphere has many cloud levels. Topmost is ammonia (NH_3), then ammonium hydrosulfide (NH_4SH), with a thick H_2O cloud deck at about 10 bar of pressure. A probe released by the Galileo spacecraft unfortunately did not survive much deeper than this. Dozens of deeper layers are predicted but are obscured by higher layers. Deep convection of the atmosphere makes the planet self-sterilizing—any organic chemicals produced by UV photochemistry are destroyed when re-equilibrated at the bottom of a convection cell.

Interior models show that the atmosphere gives way to a layer of liquid molecular hydrogen. Pressure increases with depth until the electrons and nuclei become dissociated. The molecular layer transitions into liquid hydrogen metal, at the base of which presumably lies the original ''seed'' core of rock. Metallic hydrogen is an excellent conductor of electricity and, combined with the planet's rapid rotation and convection, gives rise to a magnetic field of 4.2G (14 times that of the Earth). Charged particles trapped in this field form intense radiation belts. This is the source of Jupiter's decimeter radiation. All six spacecraft to Jupiter were built of radiation-hard materials. A simple flyby gives a dosage similar to a billion chest X-rays. The aging Galileo spacecraft, in orbit since 1995, only briefly dips close to the inner satellites to minimize radiation damage. A human's body temperature would be raised by about 1 K at Io's distance from Jupiter due to radiation.

Jupiter has 27 satellites—10 of which were discovered as this article goes to press. Many of the outer satellites are in irregular or retrograde orbits, evidence (along with light curves and spectra) that they may be captured asteroids. The four innermost satellites are also small, odd-shaped, rocky bodies. Deep in Jupiter's gravity well, micrometeorite impacts and charged particle impacts sputter from their surfaces a steady supply of submicron particles (about the size of smoke particles) that comprise Jupiter's ring.

The four largest satellites, Io, Europa, Ganymede, and Callisto, qualify as planets in their own right (the latter two are larger than Mercury). Codiscovered by Marius and Galileo (the man) in 1610, they were pivotal evidence against Ptolemy's Earth-centered worldview. These worlds probably accreted in the Jovian subnebula, in some ways making Jupiter a smaller version of the solar system. As such, they exemplify many principles of comparative planetology, such as compositional gradients (more ice) with increasing distance from Jupiter. Outer Callisto is the most heavily cratered surface in the solar system, attesting to great age and little internal geologic activity. The inner three Galileans are in a resonance, one consequence of which is varying degrees of internal heating due to tides. Surface age correlates with distance from Jupiter, consistent with more tidal energy being deposited in the inner satellites. Totally desiccated by geological activity, innermost Io is the most volcanically active body in the solar system, complete with hot lava flows and sulfur dioxide geysers and snow. Europa and Ganymede have veneers of dirty water ice, overlying liquid oceans and rocky cores. Europa's surface is very young (few craters), while Ganymede has regions older than Europa but younger than Callisto. Lately, Europa's ocean has become a fashionable place to consider as an abode of life (joining Mars and Saturn's satellite Titan). The next mission to Jupiter likely will be a Europa orbiter.

SATURN

Save for its prominent ring system, Saturn might appear as just a slightly smaller Jupiter. Appearances are deceiving. Although 85% of Jupiter's diameter (9.5 $D_\oplus$), it has only one-third of Jupiter's mass (95.1 $M_\oplus$). Saturn's density is 0.69 g cm^{-3}: find a large enough bathtub and it would float. To understand the differences between Jupiter and Saturn, consider their relative positions in the solar system.

Saturn orbits the Sun at an average distance of 9.54 AU, nearly twice Jupiter's 5.20 AU. During accretion, there was less ''seed'' material per unit volume, and the local nebular gas density was less. There were fewer building blocks and a higher ice-to-rock ratio than closer to the Sun. Although, to first order, it is solar in composition, Saturn did not accrete sufficient mass to retain the full hydrogen inventory in its region of the nebula. ''Energy of assembly'' was far less than for Jupiter, resulting in less internal heat. Central pressure is also much less. Like Jupiter, Saturn emits more energy than it receives from the Sun, but it is not sufficiently massive for slow contraction to be the source. Rather, at Saturn's reduced interior pressure, helium is less soluble in hydrogen. Helium droplets ''rain'' onto the core, releasing gravitational potential energy as heat. Otherwise, the interior structure of the two planets is rather similar. A much deeper transition region from molecular H_2 to metallic H and a slower spin (10 hr, 39 min, 25 sec) result in a magnetic field only 5% that of Jupiter.

Less internal heat and only one-quarter of the incident sunlight has atmospheric consequences. The cloud structure is essentially similar, but the colder atmosphere means each cloud deck occurs lower on Saturn. Above the topmost ammonia clouds, methane photochemical haze forms. These two effects conspire to mute Saturn's cloud features relative to Jupiter's and to give it a higher albedo.

Saturn's spin axis is inclined 26 1/2° to the orbit normal, causing marked seasons (Jupiter's obliquity is a paltry 1°). Large equatorial storms tend to occur at 30-yr intervals, Saturn's period around the Sun. Equatorial winds typically exceed 500 m sec^{-1}.

To the dynamicist, Saturn's rings are every bit as beautiful as they are to the casual observer. Girdling the planet's equator, they span 274,000 km but are a mere 100 m thick. At each Saturnian equinox, the rings are edge-on to the Sun and apparently disappear for a few days. Ring spectroscopy reveals water ice at about 100K. Radar reflectivity and models of the scattering phase function yield a particle size distribution from house-sized down to dust. The most probable size is ~10 cm in diameter, although this varies with distance from Saturn. Gaps exist at several locations in the rings. The most prominent, the Cassini Division, lies at the 2:1 orbit resonance of the satellite Mimas. When Voyager arrived at Saturn in late 1979, the rings were resolved into literally thousands of ringlets and gaps. Other features, such as radial spokes, nonplanar warps, and braids, show that there is much more to ring dynamics than solely orbit–orbit resonances with satellites. Ring science is a field enriched by theories of spiral density waves, bending waves, shepherd satellites, and imbedded moons. Erosion by micrometeorite impacts, and radial ''spreading'' due to collisions imply that the rings are only a few hundred million years old—far younger than Saturn. Current thinking is they are ephemeral structures, perhaps produced when a small (few kilometers) satellite was shattered by a comet impact.

Saturn has 24 known moons. In general, they are small bodies, with albedos in excess of 90%. Densities, where known, are 0.90 g cm^{-3}, consistent with the water ice composition of the rings. One satellite, Iapetus, has an unknown dark surface material on its leading hemisphere. In general, the satellites are heavily cratered, ancient surfaces, with few signs of internal geologic activity (except Enceladus).

Then there is Titan. At 5150 km diameter (larger than Mercury), the satellite has a dense atmosphere [85% N_2, 3% CH_4 (methane), and up to 12% Ar, a spectrally inert gas]. Titan's surface pressure is about 1.6 times the Earth's. The N_2 likely was produced by the UV photolysis of NH_3 (ammonia) over the eons. Titan's surface is eternally shrouded in a thick smog of organic compounds. Unlike the self-sterilizing environments of Jovian planet atmospheres, however, photochemically produced organics can precipitate to the surface and accumulate. Oceans of primeval soup, hypothesized two decades ago, are unlikely based on recent radar observations, but Titan remains arguably the most profitable place in the solar system to search for life (excluding Earth). Its meteorology may be dominated by a ''hydrologic'' cycle where CH_4 takes the place of H_2O in forming clouds and precipitation. The Cassini spacecraft will enter orbit around Saturn in 2004, dropping the Huygens descent probe into Titan's atmosphere. Its 2-hr descent to the surface will open our eyes to this mysterious world.

URANUS

Of the four Jovian planets, Uranus is the least understood. The spin axis is tilted nearly into the orbital plane. The poles actually receive more solar energy than the equator, averaged over Uranus' 84.01-yr orbit. When Voyager 2 encountered Uranus in 1985, the southern hemisphere had been basking in the Sun for decades. Even considerable image enhancement revealed few distinct clouds, although atmospheric circulation is symmetric about the spin axis. Things have changed in the intervening decades. Recently, clouds appear increasingly frequently, consistent with visual reports made at the last equinox. This ''zebra'' changes its stripes with seasons. The temperature above the cloud tops (53 K) is uniform planetwide to within a few degrees, because the time constant for thermal equilibration is longer than the Uranian year. Odd for a Jovian, Uranus has almost no internal heat source.

At 14.54 $M_\oplus$, Uranus was unable to retain nearly as much hydrogen and helium as were the more massive Jovians. It is smaller (4 $D_\oplus$) and denser (1.19 g cm^{-3}) than Saturn. Above an Earth-sized rocky core lies a deep layer of high-pressure water, likely containing dissolved NH_3, CH_4, H_2, He, and various salts. Its upper boundary is at the H_2O critical point, 218 bar and 273 K. Sandwiched between this layer and the visible atmosphere is a region of molecular H_2. The planet lacks sufficient mass to reach the required internal pressure for metallic hydrogen.

Uranus has a strange magnetic field, tilted 60° to the spin axis, and offset from the planet's center by 0.3 radius. Its source is in the briny water layer. While the offset is understood, the tilt is not. It shows a 17.24-hr periodicity, betraying the planet's spin rate. This, and the observed oblateness (0.024), places strong constraints on the interior structure.

Methane and ammonia are enriched in the atmosphere relative to Jupiter or Saturn, although the composition is still mostly hydrogen and 15% helium. Cloud decks are similar to Saturn's, but are deeper due to a cooler temperature profile. The topmost cloud layer is methane (CH_4) ice crystals. Methane has an absorption band at 725 nm, giving the mostly whitish clouds a slightly blue tinge compared to Saturn.

On March 10, 1977, Uranus occulted a star. By monitoring the star's brightness as the atmosphere refracts its light, one can derive the ratio (T/μ) for Uranus, where T is temperature and μ is the mean molecular weight. However, the stellar flux also showed symmetric, sharp dips before and after planetary occultation. The cause is a series of narrow rings between 1.60 and 1.90 planetary radii. There are a total of 11 rings, 2–100 km in width. Ring particles are rather different from Saturn's: dark as coal (4% albedo) and larger ($\sim$1 m). Thought to be mainly water ice, the blackening probably results from the UV photolysis of a methane component in the ice. (Saturn's distance from the Sun is too warm for methane to condense, so its rings stay bright.) The outermost (epsilon) ring is elliptical and varies in radial width. Voyager imaged two small (< 25 km) ''shepherd'' satellites that serve to limit the radial spreading of this ring. Similar moonlets may confine the other rings, but they have not been seen. Postencounter Voyager images (in forward-scattered light) reveal a dust-sized component due to collision grinding. As with Saturn, it is difficult to believe that the rings are as old as the planet.

Uranus has 20 known moons. The five largest are tidally locked to Uranus, as our Moon is to Earth. They are darker, denser, and smaller than Saturn's major satellites. Surprisingly, they show indications of varying degrees of past internal activity, despite the colder environment. The secret probably lies in their composition: a mixture of water, methane, and ammonia ices has a much lower melting temperature than water alone.

Tiny Miranda—only 480 km in diameter—seems to have the most tortured history of all the satellites. Strange, square-shaped to oval-shaped features (coronae) contrast with the surrounding heavily cratered but muted terrain. Coronae are relatively dark and riddled with concentric, subparallel grooves. How did such a tiny world evolve?

An early hypothesis posited that after initial accretion and differentiation, Miranda was blasted apart in a collision. It then reaccreted piecemeal. However, ''joints'' between coronae and surrounding regions are geologically inconsistent with this scenario. An alternate theory is that Miranda underwent ''chaotic despinning.'' Normally, a satellite gradually despins at a certain rate, eventually pointing its long axis toward its primary. Eons ago, Miranda's orbit overlapped several other satellite resonance regions. In such an instance, the despinning rate is augmented by a factor of e^{-2}, where e is the orbital eccentricity, a small number. Rapid despinning deposited all of Miranda's rotational energy as internal heat in short order. This energy was enough to melt the planet and to fuel geologic activity.

NEPTUNE

Except for a ''saner'' axial tilt of 28.8°, the bulk properties of Neptune seem rather similar to Uranus. The interiors are thought to be analogous. Slightly smaller in diameter, and slightly more massive, Neptune's density is 1.66 g cm^{-3}. It orbits the Sun at 30.06 AU, half again as far as its neighbor does, every 164.79 yr. At Neptune's distance, the Sun has only 1/900 the intensity as seen from Earth. Neptune's magnetic field is weaker than that of Uranus. It is also offset from the planet's center and inclined some 50° to the rotation axis. The spin period is 16.05 hr. Unlike Uranus, Neptune has a substantial internal heat source. Consequently, cloud-top temperature is relatively balmy at 57 K, some 4 K warmer than its neighbor. Both planets have average albedos near 35%. While vertical cloud structure is quite similar, horizontal differences are substantial.

Voyager 2 observations in 1989 recorded abundant cloud features. There is a significant variation in both the latitude and the rotation rate of the clouds, from 450 m sec^{-1} westward at the equator to 300 m sec^{-1} prograde at latitude 70° south. The range of wind speeds is wider than on any other planet, and a substantial fraction of the sound speed. How such wind velocities can be maintained in the cold, low-energy environment is a mystery. Cyclonic features such as the Great Dark Spot (GDS) were seen to persist in Voyager images for over 8 months, but have long since disappeared. The GDS' overall lifetime could have been as long as 10 yr. A similar region appeared for a while in Neptune's northern hemisphere, but it has dissipated, too. Ephemeral cloud features have been monitored from Earth via disk-integrated photometry since about 1978. Recently, adaptive optics permits direct terrestrial observations of Neptunian clouds at a resolution similar to Voyager far-encounter images, although the entire planet is only about 2 sec of arc in apparent diameter. The changing face of the planet is a meteorologist's dream.

The search for Neptunian rings using stellar occultations was ambiguous. Symmetric events on both sides of the planet would have confirmed the presence of a ring, but this was not the case. Voyager resolved the dilemma. Neptune does indeed have a ring system, situated from 1.7 to 2.5 planetary radii. The optical depth of the six known rings ranges from 0.0045 down to 0.00008 or less. (Saturn's main rings have optical depths from 0.4 to 2.5.) Neptunian ring material is much more tenuous. The particles are dark (4% albedo) as for Uranus. The outermost ''Adams'' ring clumps into ''arcs'' instead of being evenly distributed about the planet in longitude. How these arcs (named Courage, Liberté, Egalité 1, Egalité 2, and Fraternité) are constrained from spreading is unknown.

Neptune's satellite system can be divided into two regions. The inner region comprises six small satellites, ranging from 58 to 208 km in diameter, with the exception of outermost Proteus. Proteus is somewhat larger, 418 km mean diameter, comparable to Uranus' Miranda. These inner satellites orbit in regular, prograde orbits of low inclination and eccentricity. The outer region contains two very irregular satellites, Triton and Nereid. Triton orbits in retrograde fashion, with an inclination 157.3° to Neptune's pole. Nereid's sense is prograde, but its inclination and eccentricity are 27.6° and 0.75, respectively. Triton is thought to be a captured body. The process whereby this large, Pluto-sized moon was captured probably disrupted any initial, regular satellite system. Nereid is a survivor of this time, but has been scattered in the process.

Triton is a bizarre world. Its surface temperature is a mere 38 K—the coldest planetary-sized body. The thin atmosphere, 16 μbar of mainly N_2, is in vapor equilibrium with surface frosts of N_2, CH_4, and CO. Few craters on the tan-colored to cream-colored surface attest to a young age (< 50–100 Myr). Voyager caught several geyser-like eruptions shooting dark particles to an altitude of 8 km, where prevailing winds turned the flows horizontally. Other presumably inactive vents have associated dark deposits. The surface shows fractures, a thin polar cap, and enigmatic areas called ''cantaloupe terrain.'' Once considered Pluto's twin, there is little doubt that Triton and Pluto are distinct, unique worlds.

PLUTO

Pluto is the only planet in our solar system that has not yet been visited by a spacecraft. Its status as the only ''telescopic'' planet in our Sun's family is unique—and daunting—to planetary scientists trying to uncover its secrets.

Clyde Tombaugh discovered Pluto in 1930. Despite a flurry of efforts during the next few years, Pluto's faintness and subarcsecond diameter thwarted most investigations. For the next quarter century, about all that could be done was to refine the determination of its strange orbit. With a period of 248.8 yr about the Sun, Pluto's orbit is more eccentric ($e = 0.25$) and more inclined ($i = 17.2°$) than that of any other planet. At perihelion, which occurred in 1996, it was only 60% as far from the Sun as at aphelion—coming closer to the Sun than does Neptune. Yet, the planets cannot collide for two reasons. First, the relative inclinations mean that their orbital paths do not intersect. Second, Pluto is in a 2:3 orbit–orbit resonance with Neptune. When Pluto is at perihelion, Neptune is on the other side of the Sun.

In 1955, photoelectric measurements of Pluto revealed a periodicity of 6.38 days—the length of Pluto's day. Subsequent photometry has revealed two trends to the light curve. First, its amplitude has increased from about 10% to a current value of 30%. Second, the average brightness has faded, even after accounting for the inverse square law. These lines of evidence tell us that Pluto's poles are brighter than the equatorial region, and that the planet must have a large obliquity. Further, the subsolar point has been moving equatorward for most of the time since the planet's discovery. Decades of photometry have been interpreted to derive albedo maps of Pluto's surface. These are comparable in detail with what the Hubble Space Telescope has been able to reveal.

Little was known regarding Pluto's size or composition until recently. In 1976, the spectral signature of methane was discovered. This implied a bright albedo, and therefore a small radius. In 1978, James Christy discovered Pluto's satellite Charon. Orbiting Pluto with the same 6.38-day period as Pluto's spin, Charon was the key to unlocking Pluto's secrets. The application of Kepler's third law and the estimated separation between the two yielded a mass determination for the system, only about 0.002 $M_{\oplus}$. Charon orbits retrograde, and Pluto is the third planet of our solar system that spins backward.

More importantly, Charon's orbital plane above Pluto's equator was seen edge-on in 1988. This produced a series of occultations and eclipses of and by the satellite, each half-orbit, from 1985 to 1992. Timing these ''mutual events'' gave the radii of both bodies—approximately 1153 km for Pluto and 640 km for Charon—the sum is about the radius of our Moon. With Charon hidden behind the planet, Pluto's spectrum could be observed uncontaminated by its moon. This spectrum, when subtracted from a combined spectrum of the pair, yielded the spectrum of Charon. Pluto's spectrum showed methane frost; Charon's revealed nothing but water ice. Independent measurements have shown that methane abundance on Pluto varies with longitude, the brighter regions being more enriched than the darker. Charon shows little water variation with longitude. When Charon passed between Pluto and Earth, it (and its shadow) selectively covered different portions of its primary. While the data set is

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complicated, interpretation has allowed refined albedo maps for one hemisphere of Pluto to be extracted.

The surface temperature of Pluto is currently being debated. Two results have been published: ~40 and ~55 K. The first value is Triton-like; the latter is more consistent with Pluto's lower albedo (0.44–0.61). In either case, it is pretty cold. There are misconceptions about how dark it would be for an observer on Pluto. Despite the planet's remote distance, the Sun would appear to have the brightness of ~70 full moons on Earth. This, combined with the high albedo, implies that it would be easy to navigate on the surface.

On June 9, 1985, Pluto occulted a star. Rather than blinking out as in a knife-edge experiment, the light gradually dimmed due to refraction by an atmosphere. Too dense to be methane alone, N_2 and CO were suspected. Both have since been identified on Pluto's surface, with nitrogen comprising about 97% of the ground material. A ''kink'' or ''knee'' in the light curve, initially interpreted as a haze layer, is now thought to be due to a temperature gradient in the lower troposphere. Pluto's atmospheric pressure is only a few microbars, and it may vary by orders of magnitude depending on distance from the Sun.

The Hubble Space Telescope has been used to refine estimates of Charon's orbital radius a from 19,405 to 19,662 km ($\sim 1.5\ D_{\oplus}$). Because all distances derived from the mutual events are cast in terms of a, this is an important result. The mass ratio of satellite/planet has been constrained as 0.122±0.005 by watching both bodies orbit around their mutual barycenter. The densities thereby derived, 1.8–2.0 g cm^{-3} for Pluto and 1.6–1.8 g cm^{-3} for Charon, tell us about internal composition: roughly a 50:50 mix of rock and ice. For the first time, realistic interior models can be made.

The future is both bright and dim. New, large, Earth-based telescopes equipped with adaptive optics will allow many new observations to be made in unprecedented detail, surpassing even Hubble's capabilities. On the other hand, recently, a ''stop work'' order was issued on the Pluto–Kuiper Express spacecraft. Unless this mission is launched by 2006, it will lose its Jupiter gravity assist, and the trip to Pluto will take years longer. We will have to wait the better part of Jupiter's year for the geometry to repeat itself. Until the task is taken seriously, Pluto will remain the only planet unvisited by a spacecraft.

COMETS

Aristotle thought comets were a phenomenon of the Earth's atmosphere. The word comet means ''hairy.'' It has taken the better part of two millennia to understand the true nature of these objects, and most of that progress has come in the 20th century. Note that comets are named after the discoverer(s).

The head (coma) is a roughly spherical region surrounding the tiny nucleus. It can be up to several Earth diameters across; it is a very tenuous cloud of gas with entrained dust particles. The tail originates in the coma, and typically extends for 10–100 million km (up to 1 AU). Comets have two distinct tails: one of dust, and one of partially ionized gas. The dust tail points more or less away from the Sun, as it is swept back by radiation pressure. The dynamics of the ion tail is dominated by the direction of the instantaneous interplanetary magnetic field.

A typical comet nucleus is an irregularly shaped chunk of dirty snow, between 1 and 20 km in diameter. It orbits the Sun in a very elliptical orbit and is active only for a short amount of time near perihelion. Primarily made of frozen water, it contains small amounts of other ices such as carbon dioxide, ammonia, methane, and perhaps nitrogen. If comet ice were only water, then activity would cease beyond 5 AU. Therefore other more volatile ices must be present. Although icy, comets are very dark (albedo 2–4%, about that of charcoal). A few percent carbon-bearing material and silicate minerals effectively reduce multiple scattering. The surface is mantled by this residuum of dark material, which is left behind when the volatile ices sublime due to solar heating. Only about 10% of an active comet's surface vents material at a given time.

The European Giotto and Soviet Vega spacecraft were dispatched to Comet Halley in 1986. Images returned from these probes (and the Deep Space 1 probe of Comet Borrelly in September 2001) are our only closeup views of a comet to date. NASA's Stardust mission currently is en route to Comet Wild 2. The encounter is in January 2004, when the probe will image and do a real-time chemical analysis of the coma. Particles in the coma will be collected by an aerogel coating on the spacecraft panels and returned to Earth for analysis in 2006.

Examining the orbits of the approximately 1000 known comets reveals much about their source regions. Short-period comets are those with orbital periods of about a century. Their orbits are overwhelmingly prograde, and they generally lie within about ±30° of the ecliptic plane. Their origins are in the Kuiper Belt, a recently discovered icy version of the asteroid belt. It spans the region from Neptune out to about 50 AU and is disk-shaped.

Long-period comets, those with orbital periods more than about two centuries, have distinctly different orbital characteristics. These much larger orbits are 50–50 prograde and retrograde, and their orientations are random in inclination. They suggest a spherical source region between 20,000 and 100,000 AU. This region is named the Oort Cloud, after the Dutch astronomer who first suggested it. Estimates put its population at about 2 trillion objects. Passing stars and galactic tides occasionally will alter the orbits of a few of these bodies by just a few centimeters per second, and the long fall sunward begins.

Both source regions must continually supply fresh comets to the inner solar system, as a comet's lifetime close to the fire is limited. A typical comet sublimes about 1 m of material per orbit. Eventually comets (or their spent husks) crash into the Sun, a planet, or are ejected from the solar system entirely by Jupiter. In 1994, Comet Shoemaker–Levy 9 smashed into Jupiter. This spectacular event was the first time a cometary impact into a planet has been seen.

Interestingly, comets did not form in either the Kuiper Belt or the Oort Cloud—the dynamical timescale for accretion in situ is too long that far from the Sun. We believe the Kuiper Belt originated as leftover ''crumbs'' in the Uranus–Neptune region of the forming solar system. Planetesimals not accreted by these nascent planets were scattered into the Kuiper Belt. The Oort Cloud formed in a similar manner. However, the much more massive young Jupiter was able to hurl leftovers from its formation region with much more authority, despite orbiting closer to the Sun than its more diminutive brothers.

The classic picture is that Kuiper Belt and Oort Cloud are distinct regions. However, recent work shows that the diffusion of objects may have resulted in a smooth, continuous transition from one region to the other. The study of dynamics and interactions between these regions is very much a state-of-the-art topic.

CONCLUSION

This article has attempted to review our current state of knowledge of the solar system—trying to hit what is, at best, a moving target. Much has happened in the year since article was written. The number of asteroids with permanent designations has grown from just over 10,000 to 52,000. The Mars Odyssey spacecraft has identified subsurface ice on the Red Planet, and from orbit has watched the seasonal evolution of the Martian polar caps over nearly half a Mars year. Both the Senate and House have approved funding for the New Horizons mission to Pluto and the Kuiper Belt, in opposition to the wishes of the President. (A study by the American Astronomical Society's Division for Planetary Sciences concluded a Pluto mission was the most important ''new start'' for NASA in the next decade.) Cloud features on Uranus are becoming very prominent as that planet approaches equinox. Over 50 Jovian-type planets have been discovered orbiting other stars. Hubble's infrared vision has been restored by the installation of a cryocooler during the last servicing mission. Astronomers eagerly anticipate the launch of the Space Telescope Infrared Telescope Facility (SIRTF) and the James Webb Next Generation Space Telescope (NGST). And both the Atlas V and Delta IV launch vehicles have had successful maiden launches, increasing our accessibility to space. The future of solar system investigation is every bit as bright as it has been over the past quarter century.

WORLDWIDE WEB LINKS

An excellent site for images is the NASA/Goddard Space Flight Center's ''Photo Gallery'' at http://nssdc.gsfc.nasa.gov/photo_gallery.

FURTHER READING

The University of Arizona Space Science Series is a most thorough compilation of information about the solar system. These volumes, and the references cited in them, represent the state of our knowledge as of their publication dates. Progress since the publication of these volumes is well documented in the journal *Icarus*, and the popular magazines *Sky & Telescope*, *Astronomy*, and *Scientific American*.

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