Solar System

Robert L. Marcialis
Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona, U.S.A.

Abstract
The contents and composition of our solar system are inventoried and described. A concise description of some interesting features for each planet and many major satellites, minor planets, and comets is provided and updated to reflect the state of our knowledge as of 2014.

INTRODUCTION

Planetary science is the branch of knowledge benefiting most as a result of the space age. In 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" a generation ago has become "comparative planetology."

Technological developments such as adaptive optics, large-aperture 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 mostly 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 to exist two decades ago, now has well over 1000 cataloged members; it took 122 years to discover that many asteroids. By the time this entry goes to press, even distant Pluto will have been visited by a spacecraft. Thus, initial reconnaissance of the "classical" solar system is nearly complete. Our questions are evolving from the "What?" of quick flybys to the "Why?" of synoptic, in situ observation.

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 mid-2010s. However, rapid progress continues. Orbiters are now in place around every planet from Mercury to Saturn, save for Jupiter. The Juno spacecraft will arrive there in July 2016. 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. Composed 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 nitrogen (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 daughter clouds, each destined to form a separate stellar system.

As each daughter cloud 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 directly proportional to its cross-sectional area and mass, the forces exerted on individual particles vary. The result is low-velocity collisions. A nonnegligible 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

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Table 1 Inventory of planets and known satellites in the solar system

Object	Equatorial diameter (km)	Mass (kg)	Rotation period (days)	Orbital period (days or yr)	Orbital distance (10^3 km or AU)	Orbital eccentricity	Orbital inclination (°)	Escape velocity (km sec^{-1})	Known or probable surface composition
Sun	1,391,400	1.989×10^{30}	25.4 (equatorial)		0			617.75	Ionized gas
Mercury	4,879.4	3.301×10^{23}	58.6	89	0.387 AU	0.206	7.005	4.25	Basaltic dust and rock
Venus	12,103.6	4.869×10^{24}	243 R	225	0.723 AU	0.007	3.395	10.36	Basaltic dust and rock
Earth	12,756.28	5.9742×10^{24}	1	365.25	1.000 AU	0.017	0	11.18	Water, granitic soil
Moon	3,476	7.35×10^{22}	Synchronous	27.321661	384,401	0.05490049	18.28–28.58	2.38	Basaltic dust and rock
Mars	6,794	6.419×10^{23}	1.02	687	1.524 AU	0.093	1.851	5.02	Basaltic dust and rock
Phobos	26.8 × 22.4 × 18.4	1.0598×10^{16}	Synchronous	0.31891023	9.375	0.01511	1.0756	11 m/sec	Carbonaceous soil
Deimos	15.0 × 12.2 × 10.4	1.513×10^{15}	Synchronous	1.2624407	23.458	0.00024	1.7878	5.7 m/sec	Carbonaceous soil
Asteroid Belt		2.8×10^{21}							
Jupiter	142,984	1.8985×10^{27}	0.41 (equatorial)	11.9 yr	5.203 AU	0.048	1.305	59.54	N/A
J1 Io	3,658 × 3,638 × 3,632	8.9316×10^{22}	Synchronous	1.769137761	421.8	0.0041	0.036	2.56	Silicates, Sulfur, SO_2
J2 Europa	3,128 × 3,122 × 3,122	4.79982×10^{22}	Synchronous	3.551181055	671.1	0.0094	0.466	2.03	H_2O ice, dust
J3 Ganymede	5,264.6	1.48186×10^{23}	Synchronous	7.15455325	1,070.4	0.0013	0.177	2.74	H_2O ice, dust
J4 Callisto	4,806	1.07593×10^{23}	Synchronous	16.6890170	1,882.7	0.0074	0.192	2.45	H_2O ice, dust
J5 Amalthea	262 × 146 × 134	2.068×10^{18}	Synchronous	0.498179	181	0.003	0.4	0.18	Sulfur, SO_2 coated rock
J6 Himalia	150 × 120 × 120	4.20×10^{18}	0.324246	250.5662	11,461	0.1623	27.496	81 m/sec	Carbonaceous rock
J7 Elara	~80	8.7×10^{17}	~0.5 ?	259.64	11,741	0.2174	26.627	54 m/sec	Carbonaceous rock
J8 Pasiphae	~36	3.0×10^{17}	?	743.63 R	23,624	0.4090	151.431	47 m/sec	Carbonaceous rock
J9 Sinope	~28	7.50×10^{16}	0.548	758.90 R	23,939	0.2495	158.109	27 m/sec	Carbonaceous rock
J10 Lysithea	~24	6.28×10^{16}	0.533	259.20	11,717	0.1124	28.302	26 m/sec	Carbonaceous rock
J11 Carme	~30	1.32×10^{17}	0.433	734.17 R	23,404	0.2533	164.907	34 m/sec	Carbonaceous rock
J12 Ananke	~20	3.0×10^{16}	0.35	629.77 R	21,276	0.2435	148.889	20 m/sec	Carbonaceous rock
J13 Leda	~10	1.09×10^{16}	?	240.92	11,165	0.1636	27.457	17 m/sec	Carbonaceous rock
J14 Thebe	116 × 98 × 94	1.50×10^{18}	Synchronous	0.6745	221.90	0.0176	1.08	63 m/sec	Rock
J15 Adrastea	20 × 16 × 14	7.50×10^{15}	Synchronous	0.29826	129	0.0018	0.054	11 m/sec	Rock

J16 Metis	60 × 40 × 34	1.20×10^{17}	Synchronous	0.29478	128	0.0012	0.019	27 m/sec	Rock
J17 Callirrhoe	~8.6	?	?	736 R	24,596.24	0.206	143	?	?
J18 Themisto	~8.0	?	?	130	7,450	0.20	46	?	?
J19 Megaclite	~5.4	?	?	734.1 R	23,439.08	0.5277	151.7	?	?
J20 Taygete	~5.0	?	?	650.1 R	21,671.85	0.2460	163.545	?	?
J21 Chaldene	~3.8	?	?	591.7 R	20,299.46	0.1553	165.620	?	?
J22 Harpalyke	~4.4	?	?	617.3 R	20,917.72	0.2003	149.288	?	?
J23 Kalyke	~5.2	?	?	767 R	24,135.61	0.3177	165.792	?	?
J24 Iocaste	~5.2	?	?	606.3 R	20,642.86	0.2686	149.906	?	?
J25 Erinome	~3.2	?	?	661.1 R	21,867.75	0.3465	160.909	?	?
J26 Isonoe	~3.8	?	?	704.9 R	22,804.70	0.2809	165.039	?	?
J27 Praxidike	~6.8	?	?	624.6 R	21,098.10	0.1458	146.353	?	?
J28 Autonoe	~4.0	?	?	778.0 R	24,413.090	0.4586	152.056	?	?
J29 Thyone	~4.0	?	?	610.0 R	20,769.90	0.2833	148.286	?	?
J30 Hermippe	~4.0	?	?	624.6 R	21,047.99	0.24739	149.785	?	?
J31 Aitne	~3.0	?	?	679.3 R	22,274.41	0.3112	164.343	?	?
J32 Eurydome	~3.0	?	?	752.4 R	23,830.94	0.3255	150.430	?	?
J33 Euanthe	~3.0	?	?	620.9 R	20,983.14	0.1427	146.030	?	?
J34 Euporie	~2.0	?	?	555.2 R	19,509.12	0.1013	146.367	?	?
J35 Orthosie	~2.0	?	?	613.6 R	20,848.89	0.2863	140.902	?	?
J36 Sponde	~2.0	?	?	690.3 R	22,548.24	0.5189	155.220	?	?
J37 Kale	~2.0	?	?	679.4 R	22,300.64	0.3250	164.794	?	?
J38 Pasithee	~2.0	?	?	748.76 R	23,780.14	0.2795	165.568	?	?
J39 Hegemone	~3.0	?	?	715 R	23,006.33	0.2494	152.330	?	?
J40 Mneme	~2.0	?	?	599.65 R	20,500.28	0.2080	147.950	?	?
J41 Aoede	~4.0	?	?	747 R	23,743.83	0.4051	159.408	?	?
J42 Thelxinoe	~2.0	?	?	635.82 R	21,316.68	0.2383	150.965	?	?
J43 Arche	~3.0	?	?	748.7 R	23,765.12	0.2337	163.254	?	?
J44 Kallichore	~2.0	?	?	681.94 R	22,335.35	0.2234	163.867	?	?
J45 Helike	~4.0	?	?	601.40 R	20,540.27	0.1375	154.587	?	?
J46 Carpo	~3.0	?	?	455.07	17,056.04	0.2949	55.1470	?	?
J47 Eukelade	~4.0	?	?	735.27 R	23,485.28	0.2828	164.000	?	?

(*Continued*)

Table 1 Inventory of planets and known satellites in the solar system (*Continued*)

Object	Equatorial diameter (km)	Mass (kg)	Rotation period (days)	Orbital period (days or yr)	Orbital distance (10^3 km or AU)	Orbital eccentricity	Orbital inclination (°)	Escape velocity (km sec^{-1})	Known or probable surface composition
J48 Cyllene	~2.0	?	?	737.80 R	23,544.84	0.4118	141.006	?	?
J49 Kore	~2.0	?	?	807.20 R	24,974.03	0.2217	140.886	?	?
J50 Herse	~2	?	?	715.4 R	23,097	0.200	164.2	?	?
S/2003 J2	~2	?	?	982.5	28,570	0.380	151.8	?	?
S/2003 J3	~2	?	?	504.0	18,340	0.241	143.7	?	?
S/2003 J4	~2	?	?	723.2	23,258	0.204	144.9	?	?
S/2003 J5	~4	?	?	759.7	24,084	0.210	165.0	?	?
S/2003 J9	~1	?	?	683.0	22,442	0.269	164.5	?	?
S/2003 J10	~2	?	?	767.0	24,250	0.214	164.1	?	?
S/2003 J12	~1	?	?	533.3	19,002	0.376	145.8	?	?
S/2003 J15	~2	?	?	668.4	22,000	0.110	140.8	?	?
S/2003 J16	~2	?	?	595.4	21,000	0.270	148.6	?	?
S/2003 J18	~2	?	?	606.3	20,700	0.119	146.5	?	?
S/2003 J19	~2	?	?	701.3	22,800	0.334	162.9	?	?
S/2003 J23	~2	?	?	759.7	24,055	0.309	149.2	?	?
S/2010 J1	~2	?	?	723.2	23,314	0.320	163.2	?	?
S/2010 J2	~1	?	?	588.1	20,307	0.307	150.4	?	?
S/2011 J1	~1	?	?	580.7	20,155	0.296	162.8	?	?
S/2011 J2	~1	?	?	726.8	23,330	0.387	151.9	?	?
Saturn	120,536	5.6847×10^{26}	0.43 (equatorial)	29.5 yr	9.537 AU	0.056	2.484	35.48	N/A
S1 Mimas	415.6 × 393.4 × 381.2	3.752×10^{19}	Synchronous	0.942421952	185.539	0.0196	1.574	0.16	H_2O ice
S2 Enceladus	513.2 × 502.8 × 496.6	1.080×10^{20}	Synchronous	1.370218092	238.042	0.0000	0.003	0.24	H_2O ice
S3 Tethys	1,076.8 × 1,056.6 × 1,052.6	6.173×10^{20}	Synchronous	1.887802533	294.672	0.0001	1.091	0.39	H_2O ice
S4 Dione	1,126.8 × 1,122.6 × 1,052.6	1.10×10^{21}	Synchronous	2.736915569	377.415	0.0022	0.028	0.52	H_2O ice
S5 Rhea	1,530.0 × 1,526.2 × 1,524.8	2.31×10^{21}	Synchronous	4.51750273	527.068	0.0002	0.333	0.64	H_2O ice
S6 Titan	5,149.46	1.3452×10^{23}	Synchronous	15.9454484	1,221.865	0.0288	0.306	2.64	H2O, CH4 ice
S7 Hyperion	360.2 × 266.0 × 205.4	5.620×10^{18}	Chaotic	21.2766582	1,500.933	0.0232	0.750	0.57	H_2O ice
S8 Iapetus	1,491.4 × 1,491.4 × 1,424.2	1.806×10^{21}	Synchronous	79.331122	3,560.854	0.0293	8.298	0.57	H2O ice, soil

S9 Phoebe	218.8 × 217.0 × 203.6	8.28×10^{18}	0.3864	546.414 R	12,893.24	0.1756	173.73	0.10	Carbonaceous soil
S10 Janus	203.0 × 185.0 × 152.6	2.09×10^{19}	Synchronous	0.6945	151.472	0.0068	0.163	55 m/sec	H_2O ice
S11 Epimetheus	129.8 × 114 × 106.2	5.79×10^{17}	Synchronous	0.6942	151.422	0.0098	0.351	36 m/sec	H_2O ice
S12 Helene	43.4 × 38.2 × 26	2.55×10^{16}	Synchronous	2.7369	377.40	0.000	0.212	14 m/sec	H_2O ice
S13 Telesto	32.6 × 23.6 × 20.0	7.19×10^{15}	Synchronous	1.8878	294.66	0.001	1.158	8 m/sec	H2O ice, soil
S14 Calypso	30.2 × 23.0 × 14.0	3.59×10^{15}	Synchronous	1.8878	294.66	0.001	1.473	5 m/sec	H2O ice, soil
S15 Atlas	40.8 × 35.4 × 18.8	6.33×10^{15}	Synchronous	0.6019 chaotic	137.67	0.0012	0.003	24 m/sec	H_2O ice
S16 Prometheus	135.6 × 79.4 × 59.4	1.76×10^{17}	Synchronous	0.613	139.38	0.0022	0.008	22 m/sec	H_2O ice
S17 Pandora	104 × 81.0 × 64.0	1.51×10^{17}	Synchronous	0.6285	141.72	0.0042	0.050	21 m/sec	H_2O ice
S18 Pan	34.4 × 31.4 × 20.8	4.95×10^{15}	Synchronous	0.575	133.585	0.0000	0.000	7 m/sec	H_2O ice
S19 Ymir	~20	?	0.496758	1,315.13 R	23,128	0.3338	173.496	?	?
S20 Paaliaq	~26	?	0.784	686.95	15,204	0.3325	46.230	?	?
S21 Tarvos	~14	?	0.44546	926.35	18,243	0.5382	33.725	?	?
S22 Ijiraq	~12	?	0.543	451.52	11,408	0.2721	47.483	?	?
S23 Suttungr	~8	?	0.31	1,016.68 R	19,468	0.1139	175.815	?	?
S24 Kiviuq	~16	?	0.9158	449.22	11,384	0.3325	46.766	?	?
S25 Mundilfari	~6	?	0.280	952.80 R	18,654	0.2098	167.466	?	?
S26 Albiorix	~32	?	0.556	783.46	16,393	0.4797	34.059	?	?
S27 Skathi	~8	?	0.48	728.10 R	15,635	0.2718	152.633	?	?
S28 Erriapus	~10	?	1.17	871.13	17,602	0.4723	34.481	?	?
S29 Siarnaq	~42	?	0.4246	895.51	18,182	0.2801	45.809	?	?
S30 Thrymr	~8	?	1.1 or 1.7 ?	1,093.38 R	20,419	0.4661	177.665	?	?
S31 Narvi	~7	?	0.65 or 0.47 ?	1,003.92 R	19,349	0.4295	145.735	?	?
S32 Methone	~3.2	?	Synchronous	1.010	194.44	0.0001	0.0072	?	?
S33 Pallene	5.8 × 5.6 × 4.0	?	Synchronous	1.154	212.28	0.0040	0.1810	?	?
S34 Polydeuces	3.0 × 2.4 × 2.0	?	Synchronous	2.737	377.20	0.0192	0.1774	?	?
S35 Daphnis	8.6 × 8.2 × 6.4	8.40×10^{13}	Synchronous	0.594	136.50	0.000	0.000	1.7 m/sec	?
S36 Aegir	~6	?	?	1,117.83 R	20,751	0.2524	166.668	?	?
S37 Bebhionn	~6	?	0.66	834.86	17.116	0.4682	35.101	?	?
S38 Bergelmir	~6	?	?	1,005.76 R	19,336	0.1420	158.557	?	?

(Continued)

Table 1 Inventory of planets and known satellites in the solar system (*Continued*)

Object	Equatorial diameter (km)	Mass (kg)	Rotation period (days)	Orbital period (days or yr)	Orbital distance (10^3 km or AU)	Orbital eccentricity	Orbital inclination (°)	Escape velocity (km $\sec^{-1}$)	Known or probable surface composition
S39 Bestla	~7.5	?	0.610	1,088.04 R	20,145	0.5196	145.156	?	?
S40 Farbauti	~5	?	?	1,086.65 R	20,390	0.2414	156.520	?	?
S41 Fenrir	~42	?	?	1,260.35 R	22,454	0.1347	164.963	?	?
S42 Fornjot	~6	?	?	1,494.09 R	25,146	0.2077	170.372	?	?
S43 Hati	~6	?	0.227	1,040.18 R	19,868	0.3710	165.808	?	?
S44 Hyrrokkin	~6	?	0.532	931.87 R	18,440	0.3359	151.536	?	?
S45 Kari	~6	?	0.32	1,231.18 R	22,093	0.4756	156.067	?	?
S46 Loge	~6	?	?	1,311.37 R	23,059	0.1862	167.689	?	?
S47 Skoll	~6	?	0.45 or 0.35 ?	878.18 R	17,667	0.4635	161.008	?	?
S48 Surtur	~6	?	?	1,297.12 R	22,941	0.4459	169.688	?	?
S49 Anthe	~1.8	?	?	1.0365	197.7	0.001	0.1	?	?
S50 Jarnsaxa	~6	?	?	1,006.94 R	19,354	0.2178	163.649	?	?
S51 Greip	~6	?	?	937.14 R	18,457	0.3146	174.800	?	?
S52 Tarqeq	~6	?	~3.0	885.15	17,962	0.1676	46.292	?	?
S53 Aegaeon	~0.5	?	Synchronous	0.808	167.4	0.0002	0.001	?	?
S/2004 S7	~6	?	?	1,103	19,800	0.580	165.1	?	?
S/2004 S12	~5	?	?	1,048	19,650	0.401	164.0	?	?
S/2004 S13	~6	?	?	906	18,450	0.273	167.4	?	?
S/2004 S17	⊥4	?	?	986	18,601	0.259	166.6	?	?
S/2006 S1	~6	?	?	970	18,981	0.130	154.2	?	?
S/2006 S3	~6	?	?	1,142	21,132	0.471	150.8	?	?
S/2007 S2	~6	?	?	800	16,560	0.218	176.7	?	?
S/2007 S3	~5	?	?	1,100	20,518	0.130	177.2	?	?
Uranus	51,118	8.6844×10^{25}	0.72 R (equatorial)	84.0 yr	19.191 AU	0.05	0.041	21.29	N/A
U1 Ariel	1,162.2 × 1,155.8 × 1,155.4	1.353×10^{21}	Synchronous	2.520379052	190.9	0.0012	0.128	0.560	H_2O ice, soil
U2 Umbriel	1,169.4	1.172×10^{21}	Synchronous	4.14417646	266.0	0.0039	0.079	0.520	H_2O ice, soil
U3 Titania	1,577.8	3.527×10^{21}	Synchronous	8.70586693	436.3	0.0011	0.068	0.770	H_2O ice, soil
U4 Oberon	1,522.8	3.014×10^{21}	Synchronous	13.463242	583.5	0.00014	4.338	0.727	H_2O ice, soil
U5 Miranda	480.8 × 468.4 × 465.8	6.59×10^{19}	synchronous	1.413479408	129.9	0.0013	4.2	0.193	H_2O ice, soil

U6 Cordelia	40.2	4.50×10^{16}	Synchronous	0.335033842	49.77	0.00026	0.08	17 m/sec	Ice and soil
U7 Ophelia	42.8	5.39×10^{16}	Synchronous	0.376400393	53.79	0.0099	0.1	17 m/sec	Ice and soil
U8 Bianca	51.4	9.29×10^{16}	Synchronous	0.434578986	59.17	0.0009	0.19	22 m/sec	Ice and soil
U9 Cressida	79.6	3.43×10^{17}	Synchronous	0.463569601	61.78	0.0004	0.01	34 m/sec	Ice and soil
U10 Desdemona	64.0	1.78×10^{17}	Synchronous	0.473649597	62.68	0.00013	0.11	27 m/sec	Ice and soil
U11 Juliet	93.6	5.57×10^{17}	Synchronous	0.493065489	64.35	0.00066	0.07	40 m/sec	Ice and soil
U12 Portia	135.2	1.67×10^{18}	Synchronous	0.513195920	66.09	0	0.06	57 m/sec	Ice and soil
U13 Rosalind	72	2.54×10^{17}	Synchronous	0.558459529	69.94	0.0001	0.28	31 m/sec	Ice and soil
U14 Belinda	80.6	3.57×10^{17}	Synchronous	0.623527470	75.26	0.00007	0.03	34 m/sec	Ice and soil
U15 Puck	160 × 150	2.89×10^{18}	Synchronous	0.761832871	86.01	0.00012	0.32	70 m/sec	Ice and soil
U16 Caliban	~72	7.34×10^{17}	?	579.73 R	7,231	0.18	141.53	47 m/sec	Ice and soil
U17 Sycorax	~150	5.37×10^{18}	?	1,288.38 R	12,179	0.52	159.42	?	?
U18 Prospero	~50	?	?	1,978.37 R	16,277	0.44	151.83	?	?
U19 Setebos	~48	?	?	2,225.08 R	17,420	0.59	158.24	?	?
U20 Stephano	~16	?	?	677.47 R	8,007	0.22	143.82	?	?
U21 Trinculo	~18	?	?	749.40 R	8,505	0.22	166.97	?	?
U22 Francisco	~22	?	?	267.09 R	4,283	0.13	147.25	?	?
U23 Margaret	~20	?	?	1,661.00	14,147	0.68	57.37	?	?
U24 Ferdinand	~20	?	?	2,790.03 R	20,430	0.40	169.79	?	?
U25 Perdita	~26.6	?	Synchronous	0.638	76.417	0.00329	0.068	?	?
U26 Mab	~20	?	Synchronous	0.923	97.736	0.00254	0.134	?	?
U27 Cupid	~9.8	?	Synchronous	0.613	74.392	0.0013	0.099	?	?
Neptune	49,528	1.0242×10^{26}	0.67 (equatorial)	164.8 yr	30.069 AU	0.01	1.769	23.50	N/A
N1 Triton	2,705.2	2.139×10^{22}	Synchronous	5.87685407 R	354.759	0.0000	156.865	1.453	N2, CH_4 ice
N2 Nereid	340	3.08×10^{19}	0.48	360.13619	5,513.82	0.7507	32.55	0.155 m/sec	CH_4 ice
N3 Naiad	96 × 60 × 52	1.95×10^{17}	Synchronous	0.294396	48.227	0.00033	4.74	28 m/sec	Ice and soil
N4 Thalassa	104 × 100 × 52	3.744×10^{17}	Synchronous	0.311485	50.075	0.00016	0.21	35 m/sec	Ice and soil
N5 Despina	180 × 148 × 128	2.10×10^{18}	Synchronous	0.334655	52.526	0.00014	0.07	61 m/sec	Ice and soil
N6 Galatea	204 × 184 × 144	3.75×10^{18}	Synchronous	0.42875	61.953	0.00012	0.05	75 m/sec	Ice and soil
N7 Larissa	216 × 204 × 168	4.95×10^{18}	Synchronous	0.55465	73.548	0.00139	0.2	82 m/sec	Ice and soil
N8 Proteus	436 × 416 × 402	5.033×10^{19}	Synchronous	1.122315	117.646	0.0005	0.075	180 m/sec	Ice and soil

(*Continued*)

Table 1 Inventory of planets and known satellites in the solar system (*Continued*)

Object	Equatorial diameter (km)	Mass (kg)	Rotation period (days)	Orbital period (days or yr)	Orbital distance (10^3 km or AU)	Orbital eccentricity	Orbital inclination (°)	Escape velocity (km sec^{-1})	Known or probable surface composition
N9 Halimede	~62	?	?	1,881.038	15,728	0.571	134.1	?	?
N10 Psamathe	~40	?	?	9,116.640	46,695	0.4500	137.4	?	?
N11 Sao	~44	?	?	2,914.695	22,422	0.293	48.5	?	?
N12 Laomedeia	~42	?	?	3,166.718	23,571	0.424	138	?	?
N13 Neso	~60	?	?	9,737.565	48,387	0.495	132.6	?	?
S/2004 N1	~18	?	Synchronous	0.9362	105.3	~0	~0	?	?
(134340) Pluto	2,306.0	1.3034×10^{22}	6.3872273	247.74066 yr	39.482 AU	0.250248	17.142	1.23	N_2, CH_4, CO, CO_2, C_2H_6, HCN ice
P1 Charon	1,207.2	1.5199×10^{21}	Synchronous	6.38725	19.573	0.00000	0.080	~0	H_2O ice, soil
P2 Nix	93 ± 47	?	?	24.854943	48.841	0.00230	0.000	?	?
P3 Hydra	115 ± 57	?	?	38.20169	64.736	0.00658	0.304	?	?
P4 Kerberos	29 ± 15	?	?	32.1866	57.890	0.0045	0.426	?	?
P5 Styx	18 ± 10	?	?	20.16170	42.487	0.0034	0.080	?	?
Edgeworth–Kuiper Belt									

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	0.060	0.80
Neon	0.010	0.16
Magnesium	0.003	0.06
Silicon	0.004	0.09
Sulfur	0.002	0.05
Iron	0.003	0.14

inner regions of the disk are mainly refractory materials: high-temperature species such as metals, oxides, and silicate minerals. Farther out, in the cooler regions, ices dominate solid particles, as ices are hundreds to 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. Its 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 82% of the planet's radius and 55% of its volume. The Moon's core is only 2–3% of its radius; 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 65% 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. Therefore, 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 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, owing 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 65% 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.

Mercury lies very deep in the Sun's gravitational well. Mariner 10 flew past the planet in 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. 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.

For 35 years following the Mariner flybys, the data were analyzed, reanalyzed, reinterpreted, overinterpreted, and extrapolated in efforts to understand the planet without information about the unseen 55% remainder of Mercury's surface. Finally, in March 2011, the MESSENGER spacecraft entered orbit around the planet. With only passive cooling, an elliptical orbit was chosen. While still heated by the full energy of the Sun, the time away from the planet gave periodic respite from the additional thermal load of heat reradiated from the planet. Consequently, the on-board laser altimeter was effective only in the northern hemisphere, near periapse, and images of the north are much more detailed than for the south.

MESSENGER has been able to image 100% of the planet (in places at up to 10 m/pixel) and to refine many of the results derived from the Mariner data. Detailed compositional maps were made by an imaging spectrometer. Integrating over the entire planetary network of compressional scarps, it is deduced that the planet has shrunk by 0.23–0.30% (2.4–3.6 km) in radius since the surface solidified, consistent with thermomechanical models of cooling. The core is slightly larger than what Mariner deduced, and still liquid: the presence of the planetary magnetic field and measurable longitude librations ("sloshing" of the innards as the planet orbits the Sun) provide the evidence. In order to prevent core freezing, there must be substantial quantities of S, Si, and possibly Ca and Mg dissolved in it to allow freezing point depression below that of pure Fe.

Mercury's strange magnetic field is not centered on the core, either, but offset axially to the north. Simple "onion skin" planetary models do not allow for this.

Water ice has been identified in permanently shaded regions (PSRs) at the bottom of craters within 6° to 7° of the north pole, on the basis of both neutron attenuation and radar reflectivity. At this writing, actual images of surface ice in the crater Prokofiev (among others) are being released. These PSRs act as cold traps for any volatiles either outgassed from the interior or deposited on the surface by cometary impacts over the eons. (A similar mechanism operates on Earth's Moon.)

MESSENGER's extended mission ends in March 2015. After that, we will have to wait until the European Space Administration (ESA) Bepi-Colombo mission arrives in 2022 for new details about this small planet.

VENUS

Venus' radius and mass are slightly less than those of 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. 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 a 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 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.

Magellan images revealed regions of local tectonism (crustal folding and stretching), lava channels, and eolian features. 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. What role, if any, does H_2O have in this disparity, and why does water's abundance on the two planets differ so remarkably?

ESA's Venus Express has been in orbit around Venus since April 2006. Again, an elliptical orbit has been chosen to help with spacecraft cooling. This spacecraft has a CCD imager and IR spectrometer (CCD = Charge Coupled Device, sensitivity 0.9–45 μm) to study the planet's atmosphere, clouds, wind vector fields, and the local plasma environment. Lightning is seen, with events comparable in frequency to Earth. Global thermal maps of surface temperatures are being made with an IR radiometer. Perhaps one of the most significant findings is that areas of Venus have been volcanically active in the last 3 million years. This suggests the planet may be geologically active today.

Radio signals from the spacecraft, beamed through the Cytherean atmosphere to Earth, are also used to probe Venus' atmosphere. As seen from Venus, Earth subtends less than one pixel of the spacecraft's imaging spectrometer. Therefore, Earth observations from Venus Express have been used to "search for life" on our planet. The process is analogous to what terrestrial telescopes will need to do to when searching for life on planets around other stars.

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, 04.0989 sec) allows diurnal temperatures to be moderated and supplies the Coriolis force that gives weather systems their characteristic size scale. The spin axis is inclined 23½° 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 drift is also about this size, as is the time characteristic for biological evolution. Plate tectonics (a.k.a. continental drift) is constantly renewing and rearranging the surface. It is known that plant and animal biological 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.

Earth's average surface temperature currently is about 15°C. But extremes have been recorded as +70°C and −89°C. We are all familiar with past (and future) Ice Ages and periods of global warming which stretch these records far beyond present values. Less familiar is the putative Snowball Earth era, thought to have occurred sometime earlier than 650 Myr ago. Its ending presaged the proliferation of multicellular life forms known as the Cambrian explosion.

Earth's internal temperature rises to a peak value of about 7000°C at the core. The source of this heat is twofold: initial energy of assembly, and subsequent decay of radionuclides (most notably, ^{40}K, ^{238}U, ^{235}U, and ^{232}Th). The near-surface underground temperature gradient is about $25°C\,km^{-1}$.

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% Earth's radius. It is composed of dense, molten rock, and transports heat to the surface by convection. (We 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. 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.

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 mid-oceanic ridges. Trenches and island arcs occur at subduction zones (Japan, the Aleutians, and 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 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, its apparent high-temperature chemistry, low density (3.3 versus 5.53 g cm^{-3} for Earth), desiccated state, and 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-thick 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 382.3 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 as 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 Earth's—further evidence for a largely solid interior. Passive monitoring showed that 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 was detected, although the magnetometer on NASA's 1998 Lunar Prospector detected a small metallic core 1–2% of the Moon's total mass.

As with Mercury, permanently shaded regions near the poles were theorized to act as cold traps for volatiles (H_2O) as early as 1961. An 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). In 2009, a kinetic impactor hit in the crater Cabeus, near the south pole. Spectral analysis of the resulting ~1000 K plume revealed dissociation products of H_2O, as well as other volatiles such as CO, molecular H_2, Ca, and Hg. Sequestered water is one strong incentive for placing future lunar settlements near the poles, in contrast to the near-equatorial Apollo landing sites.

Corner cube reflectors at the Apollo landing sites are still used to conduct laser-ranging experiments. The Moon currently is receding from the Earth. For the period 1970–2007, the results are: $+38.247 \pm 0.004$ mm yr^{-1} increase in the mean Earth–Moon distance. From the observed change in the Moon's orbit, conservation of angular momentum yields a resultant increase in the length of Earth day: +2.3 msec/century.

Data collected from NASA's twin GRAIL orbiter spacecraft in 2012 have exquisitely mapped the Moon's gravity field to reveal details of its internal structure. This gravity model has helped to understand the MASCONs (mass concentrations) first discovered in the 1960s, as well the conditions prevalent when the lunar basins were emplaced by impacts. The Moon's average crustal thickness is 34–43 km, somewhat thinner than previously thought.

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.

Today, Mars' atmosphere is thin and dry: 6–9 mbar (600–900 Pa), comprising 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 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 (Curie temperature). 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 perhaps 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 ($3.9\ \mathrm{g\ cm^{-3}}$) and dimensionless moment of inertia (0.365). At one extreme, a 1300-km-radius metallic iron (Fe) core fits the data. At the other extreme, a 2000-km-radius iron–sulfur (FeS) core also works. Petrochemical evidence from known Martian meteorites, the SNCs, shows that the upper mantle is depleted in siderophile ("iron-loving") and chalcophile ("sulfur-loving") elements. (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. They are thought to originate from the planet Mars.) 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.

For the past two decades, NASA's Mars exploration strategy has been "follow the water." Whether the mission be orbiter (Global Surveyor, Reconnaissance Orbiter, Odyssey, Maven), lander (Pathfinder, Phoenix), or rover (Spirit, Opportunity, Curiosity), the search for water, water-involved mineralogical processes, and organics is the common denominator.

Odyssey's gamma ray spectrometer and neutron detector experiments produced global maps of subsurface ice (on average, about 6 weight-% in the top half meter). Phoenix landed north of the arctic circle on "polygonal" terrain, an area of cohesive icy soil that has undergone seasonal- or longer-term freezing. In a trench dug by the Robotic Arm, bright material was exposed at 4–5 cm depth. When reimaged four Sols later, it had disappeared, consistent with subliming H_2O ice. While a disappointing failure overall, the thermal evolved gas analyzer did observe a small endothermic peak coincident with melting ice at −2°C and evolved water coming off a sample at higher temperatures. The rovers have found a suite of sedimentary rocks, cemented rocks, clay minerals, hematite, veins, nodules, and chloride evaporate deposits—all direct results of aqueous alteration (phyllosilicate minerals). Curiosity also identified toxic, highly reactive perchlorates.

On orbit since 2006, Mars Reconnaissance Orbiter's pushbroom CCD camera has a resolution of 1 μrad/pixel, or 30 cm at the surface. A few fresh impact craters (approximately meters across) were emplaced over the course of the mission. Their debris aprons had time-variable albedos, with the bright component demonstrating a clear H_2O spectral signature. The SHARAD radar instrument has estimated the volume of water ice in the north polar cap as over 0.8 million km^{-3}, or about 30% that of Greenland's ice cap.

It is unclear whether "follow the water" is the best way to explore geology on the Red Rock, but it is popular with the public and a subset of scientists who hold that Mars was once inhabitable. Fortunately, other mineralogy is being investigated via spectral observations. At least the search for water and other resources is of value to future manned missions. As in the heyday of the Apollo lunar landings 45 years ago, manned missions to Mars are still "twenty years off."

Some aspects of Mars science have been neglected. For example, the 1976 Viking missions each had seismometers, neither of which successfully deployed. Someday, a network of seismometers may be deployed around the planet. Relatively inexpensive penetrators, using "bunker buster" technology to implant sensors below the surface, would gather seismic and internal heat flow data. Is Mars' interior solid and dead? We still do not know.

Mars has two small satellites, Phobos and Deimos. The party line is that these bodies are captured asteroids. However, 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 nineteenth 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? 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 410,000 numbered asteroids, and about an equal number yet unnumbered. The sampling of the main belt is likely complete down to ~20 km diameter. It is estimated that 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 (either due to collisions or the Yarkovsky effect) 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), About 11,500 of these objects are known. The primary source of meteorites, NEAs are continually swept up by the terrestrial planets. Apollo asteroids are those whose orbits cross 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 5000 are known; there may be more than a million larger than 1 km in size) 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, all of the planets, except Mercury and Pluto, have confirmed "Trojans." This means that, by the adopted IAU definition of a planet, not only is Pluto not a planet, but none of the planets are planets, save for Mercury!)

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. After a year's reconnaissance in orbit around 4 Vesta, the Dawn spacecraft reignited its Xe-ion engines and departed for a similar mission to 1 Ceres. It will arrive there in the first quarter of 2015.

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%). (Compare these values with Table 1.) 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.

Rapid rotation and heating from below cause Jupiter's cloud structure to be very different from Earth's. 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, winds blowing 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 reequilibrated 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 4.2 G (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. A human's body temperature would be raised by about 1 K at Io's distance from Jupiter due to radiation.

Jupiter has 66 satellites. Over half of the outer satellites are in irregular and/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 satellites Titan and Enceladus).

En route to Jupiter is the Juno spacecraft, to arrive in 2016. The one-year mission calls for a highly elliptical, polar orbit, partly to give the electronics and solar panels periodic respite from the intense radiation and particle environment. (The most sensitive electronics are shielded in a rad-hard titanium vault that reduces radiation exposure by a factor of 800.) During its 33 orbits, Juno will complement previous missions in scientific scope. Infrared and microwave instruments will characterize the deep atmosphere and map polar auroras. Magnetometers and plasma experiments will investigate particles and fields. Other instruments will measure the core size and map the gravity field (internal structure, dynamo), and determine the precise ratio of oxygen to hydrogen (a proxy for water abundance, and a constraint on formation models). The radio transmitter will allow relativistic orbital frame-dragging (Lense-Thirring precession) to be measured.

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 $0.69\ \mathrm{g\ cm^{-3}}$: 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 26½° 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 $500\ \mathrm{m\ sec^{-1}}$.

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 10–100 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 100 K. 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. Cassini's Cosmic Dust Analyzer revealed surprisingly low erosion rates by micrometeorite impacts; it is now thought that the rings have existed for most of Saturn's history.

Saturn has 61 known moons. In general, they are small bodies, with albedos in excess of 90%. Densities, where known, are $0.90\ \mathrm{g\ cm^{-3}}$, 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 1.5 times Earth's. The N_2 likely was produced by the UV photolysis of NH_3 (ammonia) over the eons. Its 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. Titan remains arguably the most profitable place in the solar system to search for life (excluding Earth). Its meteorology is dominated by a "hydrologic" cycle where CH_4 takes the place of H_2O in forming clouds and precipitation. Clouds of HCN (hydrogen cyanide) recently were discovered, too: we should not oversimplify Titanian meteorology and atmospheric chemistry.

The joint NASA/European Cassini-Huygens mission arrived at Saturn in 2004. Since then, it has been playing a gravitational billiards game with the satellite system, studying each moon at encounter time and investigating Saturn, its rings, and environment between visits. With

$>$100 close flybys in the first decade, the mission recently was extended to 2017. A very brief list of discoveries and observations includes water ice geysers erupting from Enceladus' south pole, with evidence for an internal, briny ocean layer; a strange equatorial ridge girdling Iapetus; a massive Great White Spot (storm) in Saturn's northern hemisphere; a test of general relativity [PPN parameter $\gamma = 1 + (2.1 \pm 2.3) \times 10^{-5}$]; a change in the radio rotational period of Saturn (6 min longer than Voyager measured in 1980); a host of ring phenomena (spokes, warps, braids); 6 new satellites; and particles and field measurements throughout the system.

Cassini's radar system (13.78 GHz) is used to penetrate Titan's haze and produce SAR maps of its surface, one swath at a time, at each encounter. Over 50% has been mapped to date. Surface topography is varied (mountains, dunes, craters, channels, sedimentary deposits, and blandlands). The jury is still out on cryovolcanism. While theorized seas of methane/ethane were not found, many lakes (1–100-km-sized) are seen at high northern latitudes. One, Ligeia Mare, is larger than Lake Superior. Some seasonal changes in morphology are seen between repeat encounters. Titan joins Earth as one of only two bodies in the solar system to have free-standing liquid on the surface.

The Huygens entry probe was released into Titan's atmosphere. During a 2 hr 28 min parachute descent, it obtained hundreds of images, differential spectral radiometry, mass spectrometer, aerosol pyrolyser, and Doppler wind measurements. Images of the ground were suggestive of a pediment or alluvial fan (drainage outflow). Huygens actually survived to land on Titan, and continued to operate for an additional 3 hr 14 min.

Landing site conditions were 95.6 K and 1.467 bar. The area's appearance was that of a stream bed, with eroded (rounded) "rocks" of water ice up to 15 cm in size. Penetrometer and accelerometer measurements indicate the underlying darker, softer material to be consistent with gravel, wet sand, or clay. The darkening agent likely is precipitated photochemical smog (tholins) produced in the atmosphere. A 40% step pulse in measured CH_4 was seen upon landing, consistent with evaporation from the damp soil beneath the warm spacecraft body.

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. Autumnal equinox occurred in December of 2007, and Hubble has imaged plentiful cloud structures, consistent with visual reports made at the last equinox (1965). These clouds have allowed wind speeds to be measured over a range of latitudes. There is a north/south asymmetry in wind speeds, which are retrograde (westward) at the equator, and peak at about 200 m sec^{-1} prograde at latitude $\pm 60°$. Uranus is a "zebra" that changes its stripes with season.

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 did 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 deeper due to a cooler temperature profile. The topmost cloud layer is CH_4 ice crystals. Methane has an absorption band at 725 nm, giving the mostly whitish clouds a slight 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$1 m). Thought to be mainly water ice, the blackening probably results from the UV photolysis of a methane component in the ice. (Saturn's distance from the Sun makes it too warm for methane to condense, so its rings stay bright.) The outermost (epsilon) ring is elliptical and varies in radial width. Voyager imaged two small ($<$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 collisional grinding.

Uranus has 27 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- 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 $1.66\ \mathrm{g\ cm^{-3}}$. 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 and less seasonal.

Voyager 2 observations in 1989 recorded abundant cloud features. There is significant variation in the rotation rate of the clouds with latitude, from $450\ \mathrm{m\ sec^{-1}}$ westward at the equator to $300\ \mathrm{m\ sec^{-1}}$ 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) persisted 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, Liberte, Egalite 1, Egalite 2, and Frater-nitae) are constrained from spreading is unknown.

Neptune's satellite system can be divided into three regions. The inner region comprises seven small satellites, ranging from 18 to 216 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 middle 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. The outer set is smaller, in eccentric and inclined orbits. Most likely, these are captured bodies.

Triton is a bizarre world. Its surface temperature is a mere 38 K—the coldest planetary-sized body. Its thin atmosphere (mainly N_2) is in vapor equilibrium with surface frosts of N_2, CH_4, CO, and CO_2. In 1989, Voyager measured a surface pressure of $14\ \mu\mathrm{bar}$. Since then, seasonal global warming of about 2 K (from 37.5 to 39.3 K in 1997; solstice was in 2000) has increased the surface pressure by about a factor of 3–4. Though small, this temperature increase is actually a 5–7% in absolute temperature, corresponding to about 15–20 K on Earth.

Few craters on the tan- 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. This is about to change when the New Horizons spacecraft flies through the system on July 14, 2015.

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 peak value of about 30% in 2000. 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 from the time of the planet's discovery through equinox in 1988. 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. While the albedo features are basically fixed, small secular changes in their details are apparent.

Nothing definitive was known regarding Pluto's size or composition for half a century. 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. 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 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, more likely is due to a temperature gradient in the lower troposphere. Pluto's atmospheric pressure is on the order of microbars. Subsequent stellar occultations have shown a trend of increasing surface pressure, from about 1 μbar in 1988 to 2.7 ± 0.2 μbar in 2013. This trend continues well past perihelion, demonstrating a substantial phase lag in surface/atmospheric response to insolation. Theories of a decade ago predicting total atmospheric collapse as Pluto recedes toward aphelion are unlikely; some gas will blanket the planet throughout its year.

The Hubble Space Telescope has been used to refine estimates of Charon's orbital radius a from 19,405 to 19,662 km (~1.5 Earth diameters). 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.

Hubble's impact on Pluto science continues. In the period 2005–2012, four more smaller satellites were discovered (diameters in the 10–100 km range). Between 2000 and 2002, a marked reddening occurred [from (B–V) = 0.968 to (B–V) = 0.9540]. Has a frosty surface veneer sublimed to reveal a redder substrate? Or is the change due to continued progression of the subsolar point to more northern latitudes (different terrain)?

The future is bright. New, large, Earth-based telescopes equipped with adaptive optics will allow many new and synoptic observations to be made in unprecedented detail, surpassing even Hubble's resolving power. The James Webb Space Telescope will far exceed Hubble's IR capabilities. And New Horizons Pluto–Kuiper Express will soon encounter Pluto, with closest approach on July 15, 2015.

COMETS/KUIPER BELT

Aristotle thought comets were a phenomenon of 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 twentieth 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 24%, 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.

A total of eight comets have thus far been visited by spacecraft. Each comet nucleus has its own unique appearance. The European Giotto and Soviet Vega were dispatched to Halley in 1986. Images returned from these probes (and the Deep Space 1 probe to Borrelly in September 2001) provided closeup views. NASA's Stardust encountered Wild 2 in January 2004. The probe imaged and did a real-time chemical analysis of the coma. Particles in the coma were collected by an aerogel coating on the spacecraft panels and returned to Earth for analysis.

In 2005, the Deep Impact spacecraft blasted a crater in Comet Temple 1 with a 370 kg copper "bullet" impacting at 10.2 km sec^{-1}. A crater was created, 150 m in diameter and 30 m deep. It continued to outgas for ~13 days. Besides water, also positively identified in the ejecta (via spectroscopy) were carbonates, crystalline silicates, clays, and sodium.

ESA's Rosetta mission went into orbit around Comet 67P/Churyumov-Gerasimenko in August, 2014. Its 100-kg Philae probe "landed" on the comet on November 12. (Landing is a poor term, as approach velocity was 1 m sec^{-1}, but the comet's escape velocity is half that.) Anchoring "harpoons" failed to deploy, and Philae bounced twice before settling to the surface. (First bounce was 0.38 m sec^{-1}, up to 1 km in altitude and lasted 2 hours; the second, at ~0.03 m sec^{-1} lasted 7 minutes.) Unfortunately, the final landing spot was leaning against a "rock" in a shaded region and the spacecraft's batteries were unable to recharge. Nonetheless, all experiments on board returned some useful data during the two days of surface operations.

Examining the orbits of the approximately 6000 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, an icy (and much more massive) version of the asteroid belt. It spans the region from Neptune out to about 50 AU and is disk-shaped.

The Pluto system is one of the largest members of the Kuiper Belt. After New Horizons visits the Pluto system, it will be redirected to a small KBO, making the first flyby of this class of object. After years of unsuccessful ground-based searches for potential targets, a last-ditch effort by Hubble finally discovered one or two reachable candidates. It is interesting that, for the few KBOs bright enough for spectroscopic observations, a diverse set of surface compositions is seen (much as in the Pluto system).

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 ~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 comet impacting 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.

Recent simulations support the theory that an early near-commensurability between Jupiter and Saturn caused Jupiter to get nudged slightly closer to the Sun, while all orbits of the exterior planets migrated outward by much greater amounts. As their orbits expanded, so too did the unstable regions of their orbital resonances. Among the consequences of this radial sweeping of resonances was a gravitational stirring of the solar system's leftover crumbs. Both the era of Late Heavy Bombardment and the Kuiper Belt may trace their origins to this early Jupiter–Saturn interaction.

CONCLUSION

This entry has attempted to review our current state of knowledge of the solar system—trying to hit what is, at best, a moving target. In the two short months since I began updating it, India and the United States each have placed orbiters around Mars. Exposed water ice was imaged near one of Mercury's poles. Cassini found evidence for an internal ocean in Saturn's tiny satellite Mimas. Europe's Rosetta craft went into orbit around Comet Churyumov–Gerasimenko. Hubble located a potential Kuiper Belt target for the New Horizons mission. And the Chinese have launched a robotic lunar mission, a rehearsal for a future sample return attempt. The future of solar system investigation is every bit as bright as it has been over the past 60 years.

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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.