COMPARATIVE PLANETOLOGY

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Summary

The chemical compositions, interior structures, surfaces, evolutions, and magnetic fields of the planets and the major moons are compared in this article. The planets are largely of solar composition but differ in their depletion in volatile elements. The degree of depletion increases with decreasing mass and with decreasing distance from the sun with Jupiter being closest in composition to the Sun and with the terrestrial planets being most depleted in volatile elements.

The planets are mostly internally differentiated with the heavy elements tending to be found near the center and the most volatile elements near the surface. The gaseous planets present the observer with their top layers of their envelopes while most of the smaller planets present their solid surfaces.

These surfaces are characterized to varying degrees by relics of very early impacts, volcanic and tectonic activity, and by erosion. The volcanic activity and the magnetic fields of those planets that have self-generated fields are due to convection currents in their interiors driven by cooling and by heat generated by radioactive decay or by the dissipation of tidal energy. The source regions of the magnetic fields are metallic or, in the cases of Uranus and Neptune, ionic fluids. Life has had a chance to develop on Earth but possibly also on Mars and Europa. Finding evidence for this life is a challenge for the future. The bio-geo system of Earth may be a self-regulating system that sets this planet apart from its sister planets.

1. Introduction

The solar system contains a myriad of bodies ranging in size from the Sun to miniscule dust particles. The nine planets Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto are shown in Figure 1. The Sun, a middle-aged main sequence star, contains 98.8% of the mass of the solar system but only 0.5% of its angular momentum. The next smaller body, Jupiter, still 300 times more massive than Earth (compare Table 1), contains more than 60% of the mass of the rest. Jupiter is the biggest of the *giant planets*, a group of gaseous planets that constitute a major subgroup of the solar system. Among the giant planets are, in addition to Jupiter, Saturn, Uranus, and Neptune. The latter two are sometimes called the *subgiants* because they are notably smaller than Saturn and Jupiter. Earth, the biggest member of the other major subgroup of family members, the *terrestrial planets*, is the only planet on which we know to date that life had a chance to develop. Among the members of this group are Mercury, the innermost planet, Venus, Earth's twin with respect to size and mass, and Mars. The latter planet has the best chance of having developed some primitive forms of life, which makes it the prime target of space missions in the first decade of the twenty-first century. The terrestrial planets together have about 0.005% of the mass of the solar system. Table 1 collects some data of general interest on the planets and some major moons.
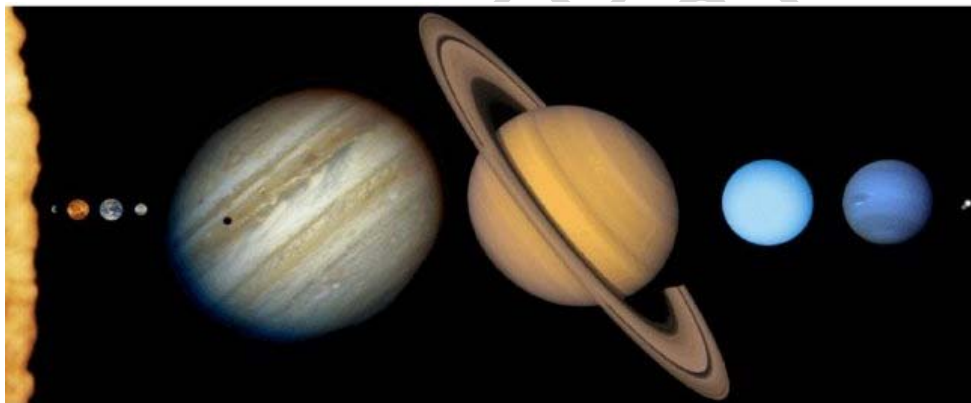

Figure 1.The nine planets Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto are shown in this compilation of NASA images with their correct relative sizes and ordered according to their distance from the Sun
Mercury is barely visible at left close to the arc of the surface of the Sun and Pluto is barely visible at the outer right. The dark spot on Jupiter is the shadow of Io, one of its major satellites. © C.J. Hamilton, available online <http://planetscapes.com>

	Terrestrial, Earth-like planets				Giant planets				
	Mercury	**Venus**	**Earth**	**Mars**	**Jupiter**	**Saturn**	**Uranus**	**Neptune**	**Pluto**
Radius (km)	2438.	6052.	6371.	3390.	71492.	60268.	24973.	24764.	1152.
Mass ($\times 10^{24}$ g)	0.3302	4.869	5.974	0.6419	1899.	568.46	86.63	102.4	0.0131
Density (10^3 kg m^{-3})	5.430	5.243	5.515	3.934	1.326	0. 6873	1.318	1.638	2.050

Uncompressed density (kg m^{-3})	5.3	4.0	4.1	3.8	0.1	0.1	0.3	0.3	2.0
Rotational period (d[a])	58.65	243.0[b]	0.9973	1.026	0.4135	0.4440	0.7183[b]	0.6713	6.387[b]
Inclination of rotation axis (°)	0.5	177.4	23.45	25.19	3.12	26.73	97.86	29.56	122.5
Orbital distance (AU[c])	0.3871	0.7233	1.000	1.524	5.203	9.572	19.19	30.07	39.54
Orbital period (a[d])	0.2410	0.6156	1.001	1.882	11.87	29.39	84.16	165.0	248.8
Magnetic moment (10^{-4}T × radius^3)	3×10^{-3}	$<3 \times 10^{-4}$	0.61	$<6 \times 10^{-4}$	4.3	0.21	0.23	0.133	?
Surface (effective) temperature (K)	445	325	277	225	123	90	63	50	44
Specific heat flow or luminosity (pW kg^{-1})	?	?	7	?	176	152	4	67	?
Known satellites	0	0	1	2	16	18	17	8	1

Planet	Earth	Jupiter				Saturn	Neptune
	Moon	**Io**	**Europa**	**Ganymede**	**Callisto**	**Titan**	**Triton**
Radius (km)	1737.	1821.	1560.	2634.	2400.	2575.	1353.
Mass (10^{20} kg)	734.9	891.8	479.1	1482.	1077.	1346.	214.7
Density (10^3 kg m^{-3})	3.344	3.53	3.02	1.94	1.85	1.881	2.054
Specific heat flow (pW kg^{-1})	8	890	300 (?)	?	?	?	?
Orbital period	27.32	1.769	3.551	7.155	16.69	15.95	5.877[b]

[a] One day (d) is equivalent to 24 h.
[b] The motion (rotation, revolution) is retrograde.
[c] One AU (astronomical unit) equals 149.6 million km.
[d] A year (a) is equivalent to 365 d.

The uncompressed density, the density at a pressure of 10^5 Pa and a temperature of 298 K, is model dependent and cannot be given with more then two significant digits.

The rotational periods of the major satellites are equal to their orbital periods. This is known to be the case for all satellites listed except for Titan, for which the rotational period is not (at the time of this writing (2003)) known. For the sake of space, we give four significant digits even for numbers that are known more accurately.

Source: The data have been taken from Lodders K. and Fegley B. Jr. (1998). The Planetary Scientists Companion, New York: Oxford University Press. and from Spohn. (2001). Planetologie, pp. 427–526 in Bergmann-Schäfer, *Lehrbuch der Experimentalphysik*, vol. 7, (ed. W. Raith), Berlin: W. De Gruyter.

Table 1.A. Properties of the planets
B. Properties of major satellites

Comparative planetology is the science of studying the planets by comparing and finding general properties and common lines of evolution as well as features that are specific. It uses the methods of the natural sciences and is strongly interdisciplinary. Comparative planetology is not restricted to the planets sensu stricto but also considers the major moons of the planets such as Earth's Moon, the major satellites of Jupiter (Io, Europa, Ganymede, and Callisto) (Figure 2), the major Saturnian satellite Titan and, finally Triton, Neptune's major satellite. Other bodies of interest include the yet largely unexplored members of the asteroid belt, the asteroids (see *Planetary Satellites, Asteroids, Comets, and Meteors*). The asteroid belt is found between Mars and Jupiter and its members are speculated to be the parent bodies of most meteorites (stones from space found on Earth's surface). These contain rich information about the formation of the solar system, its evolution, and even the evolution of matter before the formation of the solar system.

Figure 2.The four Galilean satellites of Jupiter Io, Europa, Ganymede, and Callisto, shown from left to right
© NASA/JPL, available online <http://photojournal.jpl.nasa.gov>.

Comparative planetology and planetology as such are made possible at their present levels only through the exploration of the solar system with space missions. All planets and major satellites except Pluto have been visited at least by a flyby of a robot spacecraft. Others, such as Venus, the Moon, Mars, and Jupiter have been explored by orbiters and/or by landers. The Moon has even been visited by astronauts. There is no room in this article to adequately acknowledge the role of space exploration but it has

turned dim discs in the sky observable with telescopes into worlds of their own rights waiting for exploration.

2. Planet and Satellite Orbits and Rotation States

There are some interesting commonalities between the orbits and rotation states of the planets and their major satellites. The orbits lie mostly in a plane that is defined by Earth's orbital plane, termed the ecliptic, and which is close to the equatorial plane of the Sun. The normals to the actual orbital planes have inclinations relative to the ecliptic normal that are small, only a few degrees. Pluto is the only major exception with an orbital inclination of ~17°. This, together with its orbital eccentricity, small size, and density has led some to believe that Pluto may actually be the biggest known member of the Kuiper belt. The latter is a group of icy bodies mostly between the orbital distances of Neptune and about 40 AU and is the source of the short period comets. The rotation axes of most planets and major satellites are within a few tens of degrees to the vertical to their orbital planes. Notable exemptions are Uranus, whose rotation axis lies almost in its orbital plane, Venus, whose retrograde rotation can be expressed as an inclination of almost 180°, and Pluto, whose inclination is between those of the former two. The reasons for these anomalies are unknown but are sometimes speculated to be attributable to impacts of planet-size bodies on the young planets during the late stage of *accretion*.

The rotation and revolution of most planets and moons are mostly prograde. Exceptions are Venus, Uranus, and Pluto whose retrograde rotations can also be described as inclinations of more than 90° of their rotation axes to their orbital plane normals. Another exemption is Triton, whose retrograde orbital motion about Neptune is unusual. Triton, like Pluto, is speculated to have originated in the Kuiper belt and to have been captured into its retrograde orbit by Neptune. There are many more satellites with retrograde orbits. However, these are much smaller than Triton, objects in a size range of only a few hundred km. The rotation periods of the major satellites and of most satellites in general are equal to their orbital periods. This is termed a 1:1 spin–orbit coupling and is believed to be a result of tidal evolution. The planets raise tides on their satellites just as the Moon raises tides on Earth. The gravitational force of the planet then pulls on the tidal bulge of the satellite. This torque will reduce the rotation rate of the satellite should it be greater than its average orbital angular speed and the interaction will end with the observed 1:1 coupling. As a result the satellites present their primaries with mostly the same face at all times.

The planet Mercury is particularly interesting with respect to spin–orbit coupling since it is the only planet that is in such a resonance state. However, its coupling is not 1:1, as one may expect, but 3:2 (compare Table 1). The reason for this somewhat odd ratio (odd because the ratio is not a natural number) is believed to lie with the unusually large eccentricity of Mercury's orbit, which has a value of 0.2. Values of less than 0.1 are more typical. Only Pluto's orbital eccentricity of 0.25 is larger than Mercury's. The large eccentricity causes significant differences to arise between the constant rotational angular velocity and the orbital angular velocity that varies along the orbit. The two angular velocities could only be exactly equal at all times if the orbit were perfectly circular with zero eccentricity. The orbital velocity on an eccentric orbit increases

towards the *perihelion* (the point of the orbit closest to the Sun) and decreases towards the *aphelion* (the point farthest from the Sun). Mercury's 3:2 resonance now causes the orbital angular velocity to be equal to the rotational angular velocity at perihelion. This minimizes the tidal torque on Mercury and stabilizes the resonance.

The orbital distances of the planets from the Sun roughly follow a law with the distance of one planet to the sun being roughly twice the distance to its inner neighbor. This rule is called the *Titius-Bode law* and works with Jupiter and Mars only if the asteroid belt is counted as a planet. The origin of the law is little understood and it is a condition to be used as a test for accretion models. Regular relations between orbital distances or periods (the latter two are coupled through Kepler's third law of orbital motion) are not unusual in the solar system, however. The most prominent example is the Laplace resonance between the innermost three major satellites of Jupiter: Io, Europa, and Ganymede. A comparison of the orbital periods in Table 1 shows that these are in ratios of 1:2:4. The origin of the Laplace resonance and its stability is attributed to tidal interactions between Jupiter and its three resonant moons. The orbits expand in the resonance as rotational energy is transferred through tidal interaction from Jupiter to Io and passed on in part to Europa and Ganymede. The tidal interaction and, in particular, the dissipation of tidal energy are believed to be the cause of volcanic activity on Io and of a subsurface ocean on Europa. This ocean is covered by a kilometer to a few tens of kilometers thick ice lid and may even harbor, or may have harbored, primitive forms of life.

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Bibliography

Beatty J. K. and Chaikin A. (1999). *The New Solar System*, fourth edition, 421 pp. Cambridge: Cambridge University Press. [A textbook for the nonspecialist and the general reader that introduces the objects of the solar system in stand-alone articles by leading experts in the field.]

Gehrels T., general editor. (1974 and following). *Space Science Series*. Tucson, Arizona: University of Arizona Press. [A series of voluminous textbooks aimed at graduate students and researchers. One volume usually covers a planet or a family of smaller objects such as comets.]

Lodders K. and Fegley B. Jr. (1998). *The Planetary Scientist's Companion*, 371 pp. New York: Oxford University Press. [A rich source of data on solar system objects and planetary materials including relevant fundamental physical constants and chemical data with short introductory articles on planets, major satellite groups, and asteroids.]

Rothery D. A. (1999). *Satellites of the Outer Planets: World In Their Own Right*, second edition, 242 pp. New York: Oxford University Press. [A book for the nonspecialist and the general reader on the many satellites of the giant planets and the subgiants, richly illustrated with Voyager and Galileo images.]

Shirley J.H. and Fairbridge R.W., eds. (1997). *Encyclopedia of Planetary Sciences*, 990 pp. London: Chapman and Hall. [A book with short but concise articles on many if not most aspects of planetary sciences by leading experts in the field. A must for any planetological library.]

Weissman P. R., McFadden L., and Johnson T. V., eds. (1999). *Encyclopedia of the Solar System*, 992 pp. New York: Academic Press. [A voluminous book with articles on the planets, some major moons, asteroids, comets, and various processes in the solar system by leading experts in the field.]

Biographical Sketches

Prof. **Tilman Spohn,** is a professor of planetology and planetary physics at the Westfälische Wilhelms Universität in Münster, Germany. He got his PhD in Geophysics from J. W. Goethe Universität Frankfurt (Germany) in 1978. He was a Deutsche Forschungsgemeinschaft research fellow and a research associate at the J. W. Goethe Universität Frankfurt and at the University of California Los Angeles (UCLA) from 1978 to 1984 and joined the faculty at the Westfälische Wilhelms Universität in 1984. In 19891990 and 2000/2001 he spent sabbatical semesters at UCLA and 1995 was at the Institute de Physique du Globe in Paris. His main research area is the thermodynamics of planetary interiors. He employs numerical methods to model the interior structure and evolution of planets and satellites and convective flow in planetary interiors. He also supervises the construction of space experiments to be flown to comet Wirtanen, Mars, and Mercury and contributes to the construction of landers for Mars.

Dr. Doris Breuer, is an assistant professor at the Institute of Planetolgy of the Westfälische Wilhelms Universität (WWU) in Münster, Germany. In 1994 she got her PhD in Geophysics from the WWU in Münster. She was a Deutsche Forschungsgemeinschaft postdoctoral research fellow at the Department of Geology and Geophysics, University of Minnesota, and at the Minnesota Supercomputer Institute from 1995 to 1997. As a visiting scholar she was at the Institute Physique du Globe, Paris in 1995. Her present research activities include theoretical modeling of the interior structure of terrestrial bodies and icy satellites, their thermal and chemical evolution, the evolution of the magnetic field, and the gravity field. She is scientific co-investigator of various space experiments to terrestrial bodies.

Prof. Philippe Lognonné, works on the planetary seismology. He got his PhD from the Institut de Physique du Globe de Paris, on the theory of free oscillations of Earth. He then started research in planetary seismology: he was responsible for a seismometer onboard the lost Mars 96 and is now responsible for a better instrument onboard the future Netlander mission, to be launched toward Mars in 2007. He also leads the Science Team of this mission and has participated in several Earth observation missions. He is the director of the Space Department of Institut de Physique du Globe Paris, Professor at the University of Paris VII, and junior member of the Institut Universitaire de France, and was Distinguished Visiting Scientist at the Jet Propulsion Laboratory. He was a member of the European Space Agency's Marsnet, InterMarsnet, Venus Sample Return, Mercury Sample Return Definition Group, and he is a member of the Centre Nationale d'Etudes Spatiale (CNES) Solar System Working Group.