4.2.4 Planets of the outer Solar System

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The planets of the outer Solar System are Jupiter, Saturn, Uranus and Neptune. The former two are the giant planets, the latter two are also known as sub-giants. The planets are significantly more massive (compare Table 1 of Section 4.2.2.2) than the terrestrial planets and have considerably larger radii. Their mean densities are much smaller, between roughly 690 kg/m^3 (Saturn) and 1640 kg/m^3 (Neptune). The density values indicate volatile-rich compositions dominated by hydrogen and helium (Jupiter and Saturn) and water, ammonia, and methane (Uranus and Neptune). The latter compounds are often referred to as the ice component and Uranus and Neptune are sometimes referred to as the ice giants; H and He are also termed the gas component. Together with rock/iron, the major component of the terrestrial planets, the ice and the gas components are the main ingredients of simple planetary models. A recent review of the physics of the giant and sub-giant planets can be found in [07Gui]. The planets have numerous satellites (163 known at the time of this writing, compare Table 7 in 4.2.2.4) ranging in size from hundreds of meters to the radius of Ganymede (2632 km). The planets also have ring systems, the most prominent one is that of Saturn which is easily visible from Earth with small telescopes. Some of the smaller satellites are embedded in the ring systems and may feed the rings with particles such as e.g., Enceladus feeding Saturn's E ring. Other satellites shepherd rings to sharpen their edges [06Esp] such as Prometheus and Pandora shepherd Saturn's F ring. Data on the satellites and rings are collected in Sections 4.2.2.4 and 4.2.2.5.

4.2.4.1 Rotation, radii, shapes, gravity fields

Rotational Elements: The rotational elements of a planet are the three angles right ascension α_0, declination δ_0, and W, the location of the prime meridian in the epochless International Celestial Reference Frame (ICRF, see Section 4.2.3.1.2.1.). The recommended values, accurate to one-tenth of a degree or better, are listed in Table 1. T is the interval in Julian centuries (=36525 Julian days), d is the interval in days from the standard epoch (2000 January 1.5, i.e. JD 2451545.0 TT) (see Section 4.2.2.1). W refers to the rotation of the magnetic field [07Sei].

Table 1. Rotational elements of the giant and sub-giant planets [07Sei].

Planet	α_0 [°]	δ_0 [°]	W [°]
Jupiter	268.056595	64.495303	284.95 + 870.5366420d
	−0.006499T	+0.002413T	
	+0.000117 sin Ja	+0.000050 cos Ja	
	+0.000938 sin Jb	+0.000404 cos Jb	
	+0.001432 sin Jc	+0.000617 cos Jc	
	+0.000030 sin Jd	−0.000013 cos Jd	
	+0.002150 sin Je	+0.000926 cos Je	
	(Ja = 99°.360714 + 4850°.4046T		
	Jb = 175°.895369 + 1191°.9605T		
	Jc = 300°.323162 + 262°.5475T		
	Jd = 114°.012305 + 6070°.2476T		
	Je = 49°.511251 + 64°.3000T)		
Saturn	40.589 − 0.036 T	83.537 − 0.004 T	38.90 + 810.7939024d
Uranus	257.311	−15.175	203.81 − 501.1600928d
Neptun	299.36+0.70 sin N	43.46-0.51 cos N	253.18 + 536.3128492d-0.48 sin N
	(N=357.85+52.316T)		

Radii and shapes: The shapes of the gaseous planets are described as twoaxial ellipsoids ($a = b > c$, where a and b are the radii in the equatorial plane). The radii listed in Table 2 refer to the 10^5 Pa isobaric surfaces.

Table 2. Size and shape parameters of the giant and sub-giant planets [07Sei]

Planet	Mean radius [km]	Equatorial Radius [km]	Polar radius [km]	RMS deviation from spheroid [km]
Jupiter	69911 ± 6	71492 ± 4	66854 ± 10	62.1
Saturn	58232 ± 6	60268 ± 4	54364 ± 10	102.9
Uranus	25362 ± 7	25559 ± 4	24973 ± 20	16.8
Neptune	24622 ± 19	24764 ± 15	24341 ± 30	8

Gravity Fields: The gravity fields are measured by Doppler tracking of spacecraft, e.g., [03See] and by earthbound observation of satellite and planetary orbits. Most of the data available are from the Voyager and Pioneer missions (see Section 4.2.6.2). The potential of the gravity field can be expanded into spherical harmonics as introduced in Section 4.2.3.1.3.2, Equ. 1. The gravity vector is then calculated by taking the gradient of the potential. Coefficients of the expansion of the potentials are given in Table 4 below together with the values for the product of planetary mass M and universal gravitational constant G.

Table 4. Gravity fields of the giant and sub-giant planets. (see http://ssd.jpl.nasa.gov/?gravity_fields_op)

Parameter	Jupiter [03Jac]	Saturn [06Jac]	Uranus [07Jac]	Neptune [08Jac]
GM (km^3s^{-2})	126712765±2	37940585±1	5794557±5	6836527±10
$J_2 \times 10^6$	14696.43±0.21	16290.71±0.27	3341.29±0.72	3408.49±4.60
$J_3 \times 10^6$	0.64±0.90	-		
$J_4 \times 10^6$	−587.14±1.68	−935.83±2.77	−30.44±1.02	−33.48±2.93
$J_6 \times 10^6$	34.25±5.22	86.14±9.64		
$J_6 \times 10^6$		−10.[88Nic]		
$C_{22} \times 10^6$	0.006±0.008			
$S_{22} \times 10^6$	−0.013±0.009			

4.2.4.2 Giant planet atmospheres

Giant planet atmospheres are composed mainly of primordial hydrogen and helium. In the planet's deep interior, equilibrium chemistry dominates whereas in the middle atmosphere, photochemistry converts methane into higher hydrocarbons. The latter can condense to form organic aerosol which traps radiation and contributes to the formation of the temperature inversion. Studying the giant planet atmospheres helps to understand reducing environments, to unravel the interplay between equilibrium chemistry (where air parcels have constant Gibbs free energy) and photochemistry, and to develop understanding of the recently discovered "hot Jupiter" class of exoplanets (see Section 4.2.5). The base of the atmosphere in a gas planet is obviously not easily defined. A reasonable base of the atmosphere can be taken at the 10^5 Pa level which is generally used to define the radius of the planet.

Jupiter – the atmospheric composition of important species is summarised in Table 6. Data is taken from: [95Feg] (and references therein, mostly based on Voyager data); [99Enc] based on the Infrared Space Observatory (ISO) and from [98Zah] and [04Won] measured by the Galileo probe. Note that the latter sampled a rather unusual meteorological situation so may be atypical of Jupiter [04Won].

In Table 6, all [04Won] values have been converted to volume mixing ratios assuming a value of 0.864 for molecular hydrogen (H_2). [05Mos, 96Gla] modelled the hydrocarbon photochemistry with a globally-averaged column model and noted some discrepancies in the relative amounts of e.g. C_2 compounds compared with observations. Improved knowledge of Eddy diffusion coefficients and reaction rate data are desirable to address such issues [05Mos; 99Yun]. The Cassini swingby of Jupiter

[04Kun] implied meridional variations of some hydrocarbon concentrations – suggesting interplay between atmospheric photochemistry and dynamics. The study of [06Smi] applied a photochemical model to analyse uncertainties in the chemical rate data. [99Yun] discuss the photochemical pathways of Jupiter (and other giant planets) in detail.

Table 6. Jupiter's atmospheric composition

Species	Concentration [vmr]	Ref.	Notes
H_2	(0.898±0.02)	95Feg	
	0.864	04Won	
He	(0.102±0.02)	95Feg	
	(0.1359±0.0027)	98Zah	(2…12) bar
CH_4	$(3.0\pm1) \times 10^{-3}$	95Feg	
	2.1×10^{-3}	99Enc	
	$(2.05\pm0.49) \times 10^{-3}$	04Won	Troposphere
CH_3D	$(2.0\pm0.4) \times 10^{-7}$	95Feg	
	2.5×10^{-7}	99Enc	
NH_3	$(2.6\pm0.4) \times 10^{-4}$	95Feg	
	$(5.74\pm2.19) \times 10^{-4}$	04Won	(8.9…11.7) bar
PH_3	$(7.0\pm1) \times 10^{-7}$	95Feg	
H_2O	$(4.2\pm1.4) \times 10^{-4}$	04Won	(17.6…20.9) bar
	$(3.0\pm2.0) \times 10^{-5}$	95Feg	6 bar
	$(4\pm1) \times 10^{-6}$	95Feg	(2…4) bar
	1.4×10^{-5}	99Enc	(3…5) bar
	1.5×10^{-9}	99Enc	(< 0.01bar)
CO	$(1.6\pm0.3) \times 10^{-9}$	95Feg	
	1.6×10^{-9}	99Enc	Troposphere
	1.5×10^{-9}	99Enc	Stratosphere (uncertain)
C_2H_2	$(1.1\pm0.3) \times 10^{-7}$	95Feg	
C_2H_4	$(7\pm3) \times 10^{-9}$	95Feg	
C_2H_6	$(5.8\pm1.5) \times 10^{-6}$	95Feg	
	4.0×10^{-6}	99Enc	$(0.3…50) . 10^{-3}$ bar
C_4H_2	$(3\pm2) . 10^{-10}$	95Feg	Mid-latitudes
C_6H_6	2×10^{-9}	95Feg	In northern aurora
AsH_3	$(2.2\pm1.1) \times 10^{-10}$	95Feg	
GeH_4	7×10^{-10}	95Feg	
H_2S	$< 3.3 \times 10^{-8}$	99Yun	Troposphere
	$< 2 \times 10^{-9}$	99Yun	Stratosphere
	$(7.7\pm1.8) \times 10^{-5}$	04Won	(12…15.5) bar

Temperature reaches about 170 K near 1 bar, declining to 110 K at the tropopause at around 0.04 bar [81Lin] where it starts to rise with altitude due to aerosol heating. In the thermosphere, it has been known since Pioneer 11 (e.g. [76Fje]) and subsequently confirmed by Galileo [98Sei], that Jupiter's temperature (reaching 1000 K) is about 5 times warmer than expected from radiative absorption. Several mechanisms have been proposed to address this puzzle. [77Hun] suggested heating via energy deposition from electrons accelerated in the magnetosphere. More recently [97You] proposed breaking gravity waves depositing their energy in the thermosphere, although [99Mat] suggested these waves probably do not fully account for the observed signal.

Jupiter's atmospheric dynamics features the familiar global pattern of adjacently-flowing bands coloured orange (called "belts") and white (called "zones"). Winds of around 100 ms^{-1} in adjacent bands blow in opposite directions. Cloud particles consisting mainly of frozen water, ammonium hydrosulphide and ammonia form at around 5, 2 and 0.5 bar, respectively [e.g. 99Irw]. [04Fla] derived zonal-mean height fields for temperature and wind from Cassini data, noting localised hotspot regions near 10^{-3} bar and a 4-5year oscillation in temperature above 10^{-2} bar. The “Great Red Spot” – the persistent anticyclonic storm at around 22°S, 2-3 Earth diameters in size and rotating with ~ 6 day period – has been successfully captured in 3D model simulations, e.g. [00Cho]. [05Vas] reviewed knowledge of atmospheric dynamics on Jupiter after the Galileo and Cassini missions.

X-rays on Jupiter have been observed from both auroral and non-auroral sources. The auroral emission is driven by the precipitation of highly ionized oxygen and sulfur from the outer magnetosphere into the polar regions, and their interaction with Jupiter's upper atmosphere [02Gla, 04Bra]. The non-auroral emission is mainly caused by scattering of solar X-rays [00Mau, 05Bha].

Saturn – the atmospheric composition is summarised in Table 7:

Table 7. Saturn’s atmospheric composition

Species	Concentration [vmr]	Ref.	Notes
H_2	(0.963±0.024)	95Feg	
He	(0.0325±0.024)	95Feg	
	(0.11-0.15)	00Con	
CH_4	4.5×10^{-3}	95Feg	
	4.4×10^{-3}	99Enc	
CH_3D	$(3.9±2.5) \times 10^{-7}$	95Feg	
	3.2×10^{-7}	99Enc	
HD	$(1.10±0.58) \times 10^{-4}$	95Feg	
NH_3	$(0.5…2.0) \times 10^{-4}$	95Feg	
	5.8×10^{-4}	99Atr	
PH_3	$(1.4±0.8) \times 10^{-6}$	95Feg	
	$(3±1) \times 10^{-6}$	94Wei	(0.1…1) bar
H_2O	$<2 \times 10^{-8}$	95Feg	
	2×10^{-7}	99Enc	> 3 bar
	$(2…20) \times 10^{-9}$	99Enc	$< 10^{-4}$ bar
H_2S	$(2.2±0.3) \times 10^{-4}$	89Bri	(2…25) bar
	$<2 \times 10^{-7}$	95Feg	
CO	$(1.0±0.3) \times 10^{-9}$	95Feg	
	2×10^{-9}	99Enc	Troposphere
	$\sim 2 \times 10^{-9}$	99Enc	Stratosphere
CO_2	3×10^{-10}	99Enc	$< 10^{-2}$ bar
C_2H_2	$(3.0±1.0) \times 10^{-7}$	95Feg	
	3.5×10^{-6}	99Enc	10^{-4} bar
	2.5×10^{-7}	99Enc	10^{-3} bar
C_2H_6	$(7.0±1.5) \times 10^{-6}$	95Feg	
	4×10^{-6}	99Enc	$< 10^{-2}$ bar
C_3H_8	$(2.7±0.8) \times 10^{-8}$	06Gre	5×10^{-3} bar, 20°S
	$(2.5±0.8) \times 10^{-8}$	06Gre	5×10^{-3} bar, 80°S
CH_3C_2H	6.0×10^{-10}	99Enc	$< 10^{-2}$ bar
C_4H_2	9.0×10^{-11}	99Enc	$< 10^{-2}$ bar
CH_3	$(0.2…1.0) \times 10^{-7}$	99Enc	3×10^{-7} bar
AsH_3	$(3±1) \times 10^{-9}$	95Feg	
GeH_4	$(4±4) \times. 10^{-10}$	95Feg	
HCl	$< 6.7 \times 10^{-9}$	06Tea	
SiH_4	$<4 \times 10^{-9}$	95Feg	
HCN	$<4 \times 10^{-9}$	95Feg	
HCl	1.1×10^{-9}	96Wei	Tentative

Saturn features less helium (Table 7) than Jupiter (Table 6) which may reflect more efficient removal of helium into Saturn's core [99Yun] or/and rainout of helium droplets deep into the innermost atmosphere [07Gui] although the mechanism(s) are not well-determined. [00Con] based on Galileo results, suggested that earlier Voyager measurements of helium on Saturn may be too low for reasons currently not clear. Differences in the hydrocarbon compositions of Saturn and Jupiter are also possible e.g. [99Atr] suggested around twice as much methane and acetylene on Saturn than on Jupiter. Model sensitivity studies are required to shed light on this issue which is currently not well constrained. The study by [05Mos] presented Cassini data implying hydrocarbon variations with latitude which could not be explained by photochemistry alone, suggesting an interplay between the meridional circulation and photochemistry.

Temperature on Saturn reaches about 120 K at 1 bar, declining to a minimum of 70 - 80 K at the tropopause near 0.03 bar. Cassini measurements [08Fle] reported a hexagonal vortex at northern high latitudes – clearly a long-lived feature since the Voyager mission reported a similar feature in the early 1980s. Additionally, Cassini measurements of the atmospheric tracer phosphine implied sinking of air into the vortex centre [08Fle].

X-rays have been detected from Saturn's disk, but no convincing evidence of an X-ray aurora has been observed [04Nes1, 04Nes2]. The non-auroral emission is mainly caused by scattering of solar X-rays [05Bha1]. Also the rings of Saturn were detected in X-rays; this radiation is attributed to fluorescent scattering of solar X-rays on oxygen atoms in the tenuous oxygen atmosphere and ionosphere over the rings [05Bha2]. A review of the X-ray properties of the outer planetary systems is presented in [07Bha].

Uranus – the strong obliquity of Uranus leads to 42 years of constant illumination at high latitudes so strong seasonality is expected. The atmospheric composition is summarised in Table 8:

Table 8. Uranus' atmospheric composition

Species	Concentration [vmr]	Ref.	Notes
H_2	(0.825±0.033)	95Feg	
He	(0.152±0.033)	95Feg	
CH_4	2.3×10^{-2}	95Feg	Troposphere
	2×10^{-5}	95Feg	Stratosphere
	$(3…10) \times 10^{-5}$	99Enc	Stratosphere
	$(3.3±1.1) \times 10^{-2}$	95Gau	Troposphere
C_2H_2	1×10^{-8}	95Feg	$(1…3) \times 10^{-4}$ bar
	$(2…4) \times 10^{-7}$	99Enc	
C_2H_6	$(1.0±0.1) \times 10^{-8}$	06Bur	10^{-4} bar
	$(1…20) \times 10^{-9}$	95Feg	
C_3H_4	$(2.5±0.3) \times 10^{-10}$	06Bur	10^{-4} bar
C_4H_2	$(1.6±0.2) \times 10^{-10}$	06Bur	10^{-4} bar
CO	$< 3 \times 10^{-8}$	99Enc	Stratosphere
	$< 5 \times 10^{-7}$	99Enc	Troposphere
CO	$< 3 \times 10^{-8}$	95Feg	
CO_2	$(4±0.5) \times 10^{-11}$	06Bur	10^{-4} bar
	$< 3 \times 10^{-10}$	99Enc	$< 2 \times 10^{-3}$ bar
HD	1.48×10^{-4}	95Feg	
CH_3D	8.3×10^{-6}	95Feg	
H_2S	$< 8 \times 10^{-7}$	95Feg	
	$(1±1) \times 10^{-4}$	89Bri	Troposphere
NH_3	$< 1 \times 10^{-7}$	95Feg	
HCN	$< 1.0 \times 10^{-10}$	95Feg	

The ratio (He/H) in Table 8 is close to the solar value, suggesting that helium is not removed significantly to the planet's interior. Hydrocarbon (including methane) concentrations are generally very low. Methyl radical concentrations (not yet detected) are much lower than for Saturn and Neptune [06Bur]. Clouds consisting of methane, hydrogen sulphide and water-sulphide-ammonium mixtures form at 1, 6, and 100 bar, respectively [93Lun].

Temperature reaches about 80 K at 1 bar, declining to 50 - 60 K at the tropopause near 0.1 bar where it starts rise due to aerosol and heating from methane [93Lun]. Uranus features an unusually low internal heat-source compared with the other gas giants [e.g. 07Gui]. [95Pod] suggested this is because Uranus' deep atmosphere is not homogeneously mixed, which switches off convective mixing so that heat loss proceeds by slow diffusive mixing. (D/H) ratios (~ 5×10^{-5}) are higher than the gas giants (2×10^{-5}) which is interpreted as evidence of a different formation mechanism involving icy planetesimals [93Lun]. Atmospheric composition and dynamics on Uranus (and Neptune) are reviewed by [93Lun].

Neptune – the atmospheric composition is summarised in Table 9:

Table 9. Neptune's atmospheric composition

Species	Concentration [vmr]	Ref.	Notes
H_2	(0.80±0.03)	95Feg	
He	(0.19±0.032)	95Feg	
CH_4	$(1…2) \times 10^{-2}$	95Feg	Troposphere
	$(3.3±1.1) \times 10^{-2}$	95Gau	Troposphere
	$(6.0…50.0) \times 10^{-4}$	99Enc	Stratosphere
	7×10^{-4}		$(0.05…1) \times 10^{-3}$ bar
C_2H_2	6×10^{-8}	95Feg	
	1.1×10^{-7}	99Enc	10^{-3} bar
C_2H_6	1.5×10^{-6}	95Feg	
	1.3×10^{-6}	99Enc	$(0.03…1.5) \times 10^{-3}$ bar
HD	1.92×10^{-4}	95Feg	
CH_3D	1.2×10^{-5}	95Feg	
	2.2×10^{-7}	99Enc	
H_2S	$< 3.0 \times 10^{-6}$	95Feg	
	$(7.5±3.25) \times 10^{-4}$	91Pat	Troposphere
NH_3	$< 6.0 \times 10^{-7}$	95Feg	
CO	2.2×10^{-6}	07Hes	Upper stratosphere
	1.2×10^{-6}	95Feg	
	$< 10^{-6}$	99Enc	Troposphere
CH_3	$(2…9) \times 10^{-8}$	99Enc	2×10^{-7} bar
HCN	1.0×10^{-9}	95Feg	

Table 9 implies that Neptune has relatively more helium than Uranus for reasons poorly understood [99Yun]. Methane is much more abundant than on Uranus and may even be over-saturated for reasons which need exploring [93Lun]. Upper cloud layers are comparable to Uranus. The lower mixed cloud layer on Neptune may penetrate deeper – up to 500 bar compared with 400 bar on Uranus [93Lun].

Unlike Uranus, Neptune features an internal heat source with vigorous transport from the lower to the upper atmosphere, which is thought to account for a broadly similar temperature structure on Neptune as on Uranus (see above) despite Neptune's greater distance from the Sun. The internal heat source also impacts the photochemistry via much enhanced Eddy diffusion on Neptune. Neptune's "Great Dark Spot" was discussed by [07Beau] who proposed a dynamical origin.

4.2.4.3 Interior models

Interior structure models of the giant and sub-giant planets can be calculated assuming hydrostatic equilibrium and mass and energy conservation

$$\frac{\partial P}{\partial r} = -\rho\, g \tag{1}$$

$$\frac{\partial T}{\partial r} = -\frac{\mathrm{d}T}{\mathrm{d}P}\rho\, g \tag{2}$$

$$\frac{\partial m}{\partial r} = 4\pi\, r^2 \rho \tag{3}$$

$$\frac{\partial L}{\partial r} = 4\pi\, r^2 \rho \left\{ Q - T\frac{\partial S}{\partial t} \right\} \tag{4}$$

where P is the pressure, r is the radial distance from the centre, ρ is the density, g is gravity, T is temperature, m is the mass within the sphere of radius r, L is the intrinsic luminosity, Q is the heat production rate per unit mass, S is the specific entropy, and t is time. These equations have to be supplemented by a suitable equation of state. The equation of state is a major source of uncertainty. For the giant and sub-giant planets, the polytrope

$$P(\rho)\big|_T = \Psi \rho^{1+1/n} \tag{5}$$

is often used, with Ψ the polytropic constant and n the polytropic index. The polytropic index increases from zero at low pressures to 1.5 at extremely large pressures. In this limit a model planet or star will not increase in radius when the mass is increased. In the pressure range characteristic of the deep interiors of giant planets n equals 1. The polytrope can be used to calculate mass-radius relations for model planets assuming an isochemical composition. These calculations – e.g., [89Hub] – show that Jupiter and Saturn plot close to the H-He (in cosmic concentration ratio) polytrope but Uranus and Neptune do not. Thus hydrogen and helium cannot be the dominant components of the compositions of the latter planets. Instead, these planets consist of what is called the planetary ices (mostly water, ammonia, and methane).

Another important consideration concerns the phase diagram of hydrogen and helium. Thermodynamic considerations show that hydrogen should become metallic at pressures around 0.5 TPa depending to some extent on temperature. Likewise, helium goes out of solution with hydrogen at similar pressure values. The central pressure in the giant planets can be estimated from

$$P_{centr} \approx \frac{GM^2}{R^4} \tag{6}$$

to be 1 to 10 TPa. These values are considerably larger than the molecular/metallic transition pressures for Jupiter and Saturn and therefore we expect the transition to occur in these planets.

Following the work of Zharkov and Trubitsyn, Hubbard and co-workers and Guillot and co-workers ([74Zha], [02Hub], [07Gui] for reviews) the interiors of Jupiter and Saturn are divided into a core consisting of the rock/iron and the ice components, a metallic hydrogen and helium shell, and an outer shell consisting of mostly molecular hydrogen and helium. Because the atmosphere is depleted in helium with respect to the solar ratio (compare Section 4.2.4.2) the metallic hydrogen shell is assumed to contain a corresponding abundance of helium resulting in an overall solar ratio. The transport of helium from the outer shell to the shell below is assumed to occur through helium rain. For Jupiter, the surface is at 165 K and 10^5 Pa. The transition to metallic hydrogen is located at a radius of 0.75 planetary radii and the temperature there is about 10^4 K. There may be an inhomogeneous layer above the transition where the He concentration varies with depth. The core has a relative radius of about 0.2. Estimates of the core mass are about 10 Earth masses. The central pressure is estimated to be 4.25 TPa and the temperature $2 \cdot 10^4$ K.

For Saturn, the surface is at 135 K and 10^5 Pa. The molecular to metallic hydrogen transition occurs at 0.45 planetary radii where the temperature is estimated to be 10^4 K. As for Jupiter, an inhomogeneous layer may have formed at the basis of the outer shell. Since the pressure gradient in Saturn is smaller than in Jupiter, the latter inhomogeneous sub-layer would be thicker for Saturn. Saturn’s core is estimated to have a relative radius of about 0.2 and a mass of up to 7 Earth masses. The central pressure is about 1.2 TPa and the temperature around 10^4 K.

The interiors of Uranus and Neptune are also thought of as layered although the transitions between the layers should be more gradual as the work by [89Hub] and [99Gui] suggests. In these models, the outer layer extending down to 0.8 to 0.9 planetary radii consists of mostly the gas component (molecular H and He) and some ice. The shell below is composed of ice plus little gas and there is a rock/iron plus ice core of a few Earth masses.

4.2.4.4 Luminosity and thermal evolution

Jupiter, Saturn and Neptune emit significantly more energy than they receive from the sun [e.g., 07Gui]. The intrinsic luminosities (emitted flux per unit area) are 5.44±0.43, 2.01±0.14, and 0.433±0.046 W m^{-2}, respectively. For Uranus, the difference between absorbed and emitted power is much smaller, $0.042^{+0.047}_{-0.042}$ W m^{-2}. The consequence of the intrinsic flux is that the interiors of the planets are likely to be fluid, convecting vigorously with mostly adiabatic temperature distributions (an assumption underlying Equ. 2 of 4.2.4.3). It is possible that the difference between Uranus and Neptune is simply a consequence of their orbital distances. Both planets emit about the same power of 0.693 (Uranus) and 0.701 (Neptune) W m^{-2} but Neptune being farther out receives only 35% of Uranus' insolation. However, it is also possible that a larger part of Uranus interior is not homogeneously mixed and stably (with respect to convection) stratified [95Pod]. In any case the intrinsic luminosity of Uranus can be explained by radiogenic heating in the rock core but the luminosity of Neptune is about an order of magnitude too large to be explained in this way.

The intrinsic luminosity of Jupiter has been explained to be caused by contraction upon cooling of the planet (Kelvin-Helmholtz contraction) [97Bur]. This is not possible for Saturn [99Hub, 03For] for which cooling would be too fast and the gravitational power gained by helium rain has been invoked as an additional heat source. Although He separation is also possible for Jupiter, helium rain would unreasonably retard the cooling of this planet. [04Gui] maintain that the model can be improved to solve the problem. Contraction upon cooling may also contribute to Neptune's energy balance.

4.2.4.5 Magnetic fields

Even before spacecraft visited Jupiter it was known that Jupiter possesses a magnetic field [07Con]. This was concluded from the non-thermal decametric emission from the planet and later from the synchrotron radiation emitted by electrons trapped in the Jovian van Allen belt. The first spacecraft to fly closely by Jupiter was Pioneer 10 followed later by Pioneer 11, Voyager 1 and 2 and Ulysses (see Section 4.2.6). Most recently, Galileo orbited Jupiter. The most useful magnetic field data for Jupiter are from Pioneer 11, Voyager 1, and Ulysess. Saturn was visited by Pioneer 11, the two Voyagers and is presently orbited by Cassini. Uranus and Neptune were both visited by Voyager 2.

The magnetic field strength is measured in Teslas (T). An often used unit in geophysics and planetary science is the Gauss (G) equal to 10^{-4} T. Fields measured by spacecraft close to the planets depend on the orbital distance but typically range from tens of nT (Mercury, Mars) to a few G for Jupiter [07Con]. The measurement of the internal field is perturbed however, by the ambient (external) magnetic field, mostly due to the solar wind but also due to the field of the planet (e.g., Jupiter) if the field of a satellite (e.g., Ganymede) is to be measured. The Earth's surface magnetic field is about 30,000 nT.

The simplest means of characterizing a planetary magnetic field is by fitting a dipole field to the data measured by spacecraft. The dipole can be tilted with respect to the planetary rotation axis and offset from the centre. The model is known as the offset tilted dipole or OTD. The magnetic induction vector $\boldsymbol{B}$ of a dipole is related to the dipole moment $\boldsymbol{m}$ measured in Tm^3 or Gm^3 and the radial distance from the centre $\boldsymbol{r}$ by

$$\boldsymbol{B}(\boldsymbol{r}) = -\frac{\boldsymbol{m}}{r^3} + \frac{3(\boldsymbol{m}\cdot\boldsymbol{r})\boldsymbol{r}}{r^5} \tag{8}$$

In the absence of local currents ($\nabla \times \boldsymbol{B} = \boldsymbol{0}$) the magnetic induction vector $\boldsymbol{B}$ can be expressed as the gradient of a scalar potential that will satisfy the Laplace equation. The potential can be expanded in spherical harmonics and the components of the field are given by

$$V = R\sum_{1}^{\infty}\left\{\left(\frac{r}{R}\right)^{n} T_n^l + \left(\frac{R}{r}\right)^{n+1} T_n^i\right\} \tag{9}$$

where R is the planetary radius and r is the radial distance from the centre of the planet. The first term in the series represents the potential of the field due to sources external to the planet with

$$T_n^l = \sum_{m}^{n}\left\{P_n^m(\cos\theta)\left[G_n^m \cos(m\Phi) + H_n^m \sin(m\Phi)\right]\right\} \tag{10}$$

where θ is the co-latitude (measured from the axis of rotation), and Φ the longitude increasing in the direction of rotation. P_n^m are the Schmidt quasi-normalized Legendre functions (e.g., [07Con]) and G_n^m and H_n^m are the external Schmidt coefficients.

The second series in Equ. (2) represents the potential of the internal field with

$$T_n^i = \sum_{m}^{n}\left\{P_n^m(\cos\theta)\left[g_n^m \cos(m\Phi) + h_n^m \sin(m\Phi)\right]\right\} \tag{11}$$

where g_n^m and h_n^m are the internal Schmidt coefficients. The values of the coefficients are determined by least-square fitting to the spacecraft data. The difficulty in modelling the data recorded by spacecraft stems to a large part from the difficulty of separating fields with external and internal origin.

The components of the planetary field vector $\boldsymbol{B}$ are calculated by taking the gradient of the potential due to internal sources. The dipole moment m (compare Equ. (8)) can be calculated from

$$m = R^2\left\{\left(g_1^0\right)^2 + \left(g_1^1\right)^2 + \left(h_1^1\right)^2\right\}^{1/2} \tag{12}$$

Table 13 gives recent spherical harmonic expansion models for the giant planets Jupiter and Saturn and the sub-giants Uranus and Neptune while Table 14 gives the parameters of the OTDs. The Jupiter model is based on Voyager 1 magnetometer data and observations of the location of the foot print on Jupiter of the Io Flux Tube IFT. The IFT (a tube of highly concentrated magnetic field energy generated by the interaction of the Jovian moon Io with Jupiter's magnetic field and responsible for Jupiter's decametric radiation) traces a magnetic field line that passes through Io at its orbital distance of approximately 5.9 Jupiter radii. The IFT footprints in the northern and southern hemispheres can be clearly observed in the infrared with Earth-based telescopes. The footprints move along the surface of Jupiter as Io orbits the planet. The model for Saturn is derived from Cassini data while the Uranus and Neptune magnetic field models are based on Voyager data.

It is clearly seen that the dipole term g_0^1 dominates for Jupiter and Saturn (as it does for the Earth). This is not observed for Uranus and Neptune. A dominating dipole is usually interpreted as indicating a deep source of the magnetic field such as the iron core of the Earth. A relatively flat spectrum indicates magnetic field generation relatively close to the surface.

Table 13. Selected magnetic field models of the Jovian planets. Coefficients are given in nT. The Jupiter model is VIT 4 from [82Con1], Saturn model is SOI, epoch 2004.5 of [82Con2], the Uranus model is Q_3 from [87Con] and the Neptune model is O_8 from [91Con]. The radii assumed for the planets are: 71,323 km for Jupiter, 60,268 km for Saturn, 25,600 km for Uranus and 24,765 km for Neptune.

Coefficient	Jupiter	Saturn	Uranus	Neptune
g_1^0	428077.	21084.	11893.	9732.
g_1^1	−75306.		11579.	3220.
h_1^1	24616.		−15684.	−9889.
g_2^0	−4283.	1544.	−6030.	7448.
g_2^1	−59426.		−12587.	664.
g_2^2	44386.		196.	4499.
h_2^1	−50154.		6116.	11230.
h_2^2	38452.		4759.	−70.
g_3^0	8906.	2150.		−6592.
g_3^1	−21447.			4098.
g_3^2	21130.			−3581.
g_3^3	−1190.			484.
h_3^1	−17187.			−3669.
h_3^2	40667.			1791.
h_3^3	−35263.			−770.
g_4^0	−22925.			
g_4^1	18940.			
g_4^2	−3851.			
g_4^3	9926.			
g_4^4	1271.			
h_4^1	16088.			
h_4^2	11807.			
h_4^3	6195.			
h_4^4	12641.			

Table 14. Offset Tilted Dipole (OTD) models of the magnetic fields of the giant and sub-giant planets.

	Jupiter	Saturn	Uranus	Neptune
Moment [G R^3]	4.3535	0.2108	0.2284	0.1424
Displacement [planetary radii]	0.11	0.004	0.33	0.55
Tilt [°]	9.5	1	60	47

While significant progress has been made for models of the dynamo in the Earth and the terrestrial planets (compare Section 4.2.3.8.1) models of the Jovian dynamo are scarce [07Bus]. It is agreed, however, that the region of dynamo action in Jupiter and Saturn is the region below the transition from molecular to metallic hydrogen, see also Section 4.2.4.3. The preferred source region is consistent with the dipolar characteristic of the field. The latter transition will not occur in the sub-giants Uranus and Neptune. The dynamo probably operates in regions of ionic conductivity in these planets closer to the surface.

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4.2.4.6 References for 4.2.4

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