4.2.3.7 Atmospheres of the planets and satellites

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4.2.3.6.1 Exospheres of small planets and satellites

Mercury – the extremely tenuous atmosphere features a collisionless exosphere down to the surface. Studying such atmospheres improves understanding of atmospheric escape processes hence atmospheric evolution in general. First evidence of an atmosphere on Mercury was provided in 1974 by Mariner 10 [76Bro]. That study suggested a total number density of < 10^6 molecules cm^{-3} and subsolar concentrations of helium (= 4500 cm^{-3}), atomic hydrogen (= 8 cm^{-3}) (thermal component) and atomic oxygen (=7000cm^{-3}) [76Bro]. More recently [87Pot] Earth-based measurements suggested that sodium is an important atmospheric constituent. The daytime column abundance of Mercury's atmosphere is summarised in Table 1:

Table 1. Daytime atmospheric column composition on Mercury

Species	Column [atoms cm^{-2}]	Ref.
He	~3×10^{11}	81Gol
Na	$(1…2) \times 10^{11}$	87Pot
K	10^9	95Smy
Ca	1.3×10^{11}	00Bid, 05Kil
Ar	$(0.5…1.2) \times 10^9$*	02Kil

*) estimate based on an assumed diffusion coefficient, D=10^{-15} cm^2 s^{-1} through the crust.

Mercury’s atmosphere is continuously replaced by the solar wind [88Hun], vaporisation [93Kil], ion sputtering and degassing from the regolith [95Smy]. Erosion occurs via e.g. photoionisation and Jeans escape [97Mor]. Atmospheric constituents can vary strongly e.g. over a diurnal cycle, maybe due to magnetic storms or changes in degassing which are not well understood [95Smy]. The atmosphere flows from day to night, driven mainly by solar radiation pressure [95Smy].

Moon – the Apollo missions first established a tenuous lunar atmosphere in the early 1970s. Like on Mercury, the Moon features a collisionless exosphere down to the surface. Major atmospheric constituents are helium (from the solar wind) and argon [99Ste]. Apollo 17 data suggested diurnal cycles for argon (peaking in the day) and helium (peaking at night) [75Hod, 99Ste]. The presence of ice was suggested by radiowave measurements [97Sta] although atmospheric detections of water and its products are unconfirmed [99Ste]. As on Mercury, sodium and potassium are present but are about 100 times lower, possibly due to weaker surface sources [02Kil]. Column sodium values increase from pole to equator by a factor of about 7. A layer of suspended dust particles was observed to form 10 to 30 cm above the lunar surface which persisted several hours after sunset [74Ren]. These particles may be electrostatically levitated, since the surface is highly resistive [76Ber]. Unconfirmed mass spectrum data from Apollo provided fascinating hints for molecular species such as O_2, CH_4, CO, NO and N_2O although only upper limits of about $10^3$$cm^{-3}$ could be established.

4.2.3.6.2 Venus

Understanding Venus’ extreme atmosphere helps to improve climate models of the Earth. Also, investigating atmospheric chlorine chemistry [87Pri] on Venus helped to shed light on the Earth’s ozone hole phenomenon. Venus’ surface pressure and temperature are 93 bar [83Sei] and 735 K [83Sei], respectively and the planet is shrouded in thick clouds of sulphuric acid [e.g. 98Lod]. The atmospheric composition is summarised in Table 2:

Table 2. Atmospheric composition of Venus

Species	Concentration volume mixing ratio	Altitude [km]	Ref.
CO_2	(0.965 ± 0.008)	Isoprofile	83Zah
N_2	(0.035 ± 0.008)	Isoprofile	83Zah
H_2O	2×10^{-5}	0	83Zah
	$> 2 \times 10^{-6}$	0	07Sve
	$(6…15) \times 10^{-5}$	(22…42)	83Zah
	$(4 \pm 0.5) \times 10^{-5}$	35	07Sve
HDO	1×10^{-7}	Cloud top (~ 65 km)	07Sve
CO	$(1.7 \pm 0.1) \times 10^{-6}$	0	83Zah
	4.2×10^{-5}	36	90Bez
	$(2.3 \pm 0.5) \times 10^{-5}$	36	93Pol
	$(3 \pm 1.8) \times 10^{-5}$	42	83Zah
	$(4.5 \pm 1) \times 10^{-5}$	Cloud top	83Zah
O_2	$< 3 \times 10^{-7}$	Cloud top	83Tra
	3×10^{-6}	Cloud top	90Mil
HCl	$>6.0 \times 10^{-8}$	(20…30)	07Sve
	6×10^{-7}	Cloud top	67Con
	$(1.5…2) \times 10^{-8}$	Cloud top	07Sve
HF	5×10^{-9}	Cloud top	67Con
	2.5×10^{-9}	80	07Sve
COS	2.5×10^{-7}	< 50	90Bez
	4×10^{-7}	35	07Sve
SO	$(2 \pm 1) \times 10^{-8}$	Cloud top	90Na
SO_2	$(2.5 \pm 0.5) \times 10^{-5}$	10	96Ber
SO_2	2×10^{-4}	35	07Sve
SO_2	$(5…100) \times 10^{-9}$	Above cloud	93Zas
Xe	1.9×10^{-9}		83Zah
He	1.2×10^{-5}		83Zah
Kr	2.5×10^{-8}		83Zah

Incoming UV is absorbed strongly in the atmosphere but the identity of the absorber (from 200 to 320 nm) is still debated. Suggested candidates include S_2O [97Na] and polysulphur [99Yun]. Above the clouds at about 65 km the main constituent (CO_2) in the stratosphere is controlled by minor species such as chlorine-, hydrogen-, and sulphur-oxides which affect CO_2 via catalytic cycles [99Yun]. The cycles play an important role converting the products of CO_2 photolysis (i.e. CO+O) back into CO_2. [07Mil] review Venusian catalytic cycle chemistry, pointing out that many photochemical models under-estimate the catalytic oxidation of CO+O back into CO_2 and therefore over-estimate observed O_2 (formed from O).

Below the clouds observations are much more challenging. Spectral "windows" have however been discovered [84All]. High pressure and temperatures in the troposphere favour chemical equilibrium conditions. A cycle in sulphur occurs in which reduced sulphur compounds emitted at the surface are transported upwards where they are oxidised in the upper troposphere into e.g. sulphuric acid, which is a major cloud constituent. Some estimation of OCS, HCl, HF below clouds have been derived from remote sensing [90Bez]. At the surface, mineral chemistry involving pyrite and carbonate [99Yun] lead to the decomposition of sulphuric acid and the conversion of CO into COS. Modelling studies [07Kra] successfully reproduced e.g. observed CO and COS from Pioneer and Venera 12 data although kinetic data to constrain the models are rather lacking.

Large-scale atmospheric dynamics on Venus features cyclostrophic flow which exhibits so-called superrotation. Here, equatorial zonal winds can exceed 100 ms^{-1} - about sixty times faster than the rotation of the planet. 3D models often underestimate superrotation since they fail to transfer sufficient angular momentum from the surface up to the cloud deck. This shortcoming may be associated with excessive vertical mixing in the models [93Gen]. Clearer identification of the mechanism(s) which bring about the momentum transfer is desirable. Superrotation on Venus is reviewed by [97Gie].

Thick clouds enshroud the atmosphere. Cloud droplets are about 2 to 4 microns in radius and are composed mainly of sulphuric acid and water mixtures [81Kra]. Cloud optical depth on Venus can reach values of up to 100, about ten times thicker than on Earth. The thick cloud blanket may play a central role in regulating Venus' climate [01Bul].

X-rays from Venus have been detected with the Chandra satellite [02Den]. They are mainly caused by solar X-rays, which are scattered in the upper Venus atmosphere at heights around 120 to 140 km [01Cra, 02Den]. Moreover, evidence was found of an additional source of X-rays, resulting from charge exchange interactions between highly charged solar wind ions and atoms in the Venus exosphere [07Gun, 08Den].

The Venus Express Mission has studied e.g. escape of ions through the plasma wake [07Bar], has investigated the dipole vortex structure at high latitudes [07Sve] and has delivered the first reported detection of the atmospheric radical, hydroxyl (OH) [08Pic], important for constraining the catalytic cycles in the stratosphere. The existence of lightning [07Rus] has been confirmed with global flash rates of about half that on Earth.

4.2.3.6.3 Mars

Concentrations of important Martian species are summarised in Table 3:

Table 3. Atmospheric composition of Mars

Species	Concentration Volume mixing ratio	Ref.
CO_2	0.9532	77Owe
N_2	0.027	77Owe
^{40}Ar	0.016	77Owe
O_2	$1.3 \cdot \times 10^{-3}$	77Owe
CO	7×10^{-4}	77Owe
H_2O	3×10^{-4} (variable)	79Far
H_2	1.7×10^{-5}	01Kra
HD	1.2×10^{-8}	06Kra
O_3	3×10^{-8}	74Bar
H_2O_2	$(1.80 \pm 0.4) \times 10^{-8}$	04Cla
	3.2×10^{-8}	04Enc
CH_4	1×10^{-8}	04For
Ne	2.5×10^{-6}	77Owe
Kr	$3.0 \cdot \times 10^{-7}$	77Owe
Xe	8.0×10^{-8}	77Owe
He	1×10^{-5}	94Kra

Like on Venus, Mars' atmosphere is dominated by CO_2 and features catalytic cycles which maintain CO_2 by reforming it from its photolysis products. The main cycles involve hydrogen-oxides and nitrogen-oxides [99Yun]. Photochemical model studies noted that the effect of the cycles may be over-estimated because the models over-estimate hydrogen oxides [94Nai, 06Kra]. Hydrogen peroxide (H_2O_2) [04Enc] is a potentially important oxidiser of the surface, which tends to remove organic molecules and may regulate the HO_x cycles by storing HO_x at night. Ozone is rapidly destroyed by HO_x hence constitutes an important tracer of HO_x chemistry. [06Fas] discussed global ozone measurements; [04Lef] modelled 3D ozone responses. The recent methane detection [04For] has generated much discussion regarding its possible source (e.g. volcanic, exogenous, hydrogeochemical, biological) discussed e.g. in [07Atr].

Atmospheric dynamics features a global Hadley cell whose structure may depend on orography [02Ric]. Martian GCMs [e.g. 99For] with improved surface physics and atmospheric waves can more accurately simulate this Hadley cell. A strong vortex develops in high latitudes in winter as discussed e.g. in [01Leo]. Clouds composed of water-ice and/or mixed water-CO_2 can form e.g. via heterogeneous nucleation on dust and influence the water cycle and climate.

X-rays from Mars have been detected with the satellites Chandra [02Den] and XMM-Newton [06Den1]. They are the result of two processes: scattering of solar X-rays in the upper Mars atmosphere at heights of around 100 to 140 km [01Cra, 02Den] and charge exchange interactions between highly charged solar wind ions and atoms in the Mars exosphere [00Kra, 01Hol, 02Den, 05Gun, 06Den1]. Due to the low gravity of Mars, its exosphere has a considerable size and provides a large interaction region, extending outwards to several planetary radii. With XMM-Newton it was possible to trace the exospheric X-ray emission out to ~ 8 Mars radii, proceeding into exospheric regions far beyond those that have been observationally explored to-date. The X-ray emission appeared particularly pronounced at a few Mars radii above both poles, implying that the solar wind and/or exospheric density was enhanced there [06Den1]. X-ray observations open up a novel possibility to apply remote global imaging of planetary exospheres and to record spatial and temporal variability. A review of the X-ray properties of Mars is provided by [06Den2].

4.2.3.6.4 Galilean satellites

Io – Voyager measurements [79Pea] confirmed a weak, variable atmosphere on Io consisting mainly of SO_2 formed by volcanic activity. Surface temperatures vary from 300 K near volcanoes where SO_2 is more plentiful and pressure reaches 10^{-7} bar, to below 90 K on the night side or in polar regions, where SO_2 is frozen out and pressure drops to below 10^{-12} bar [99Yun]. Hubble Space Telescope (HST) measurements [04Fea] suggested atomic chlorine with an abundance of about an order of magnitude less than sulphur.

Europa – a weak surface pressure of ~ 10^{-11} bar, and temperature of 50 - 110 K was first confirmed when [95Hal] spectroscopically detected atomic oxygen (O) using the HST. The O is likely produced from dissociation of water vapour formed when water ice is released from the surface by dust particles or/and interaction with Jupiter's strong magnetic field. [96Bro] subsequently detected sodium in Europa's atmosphere, present with a total mass of about 300 times less than atmospheric oxygen, with a tail extending to about twenty-five times Europa's radius.

Ganymede – the atmosphere is very thin with a surface pressure of $< 2 \times 10^{-11}$ bar [81Bro] at the surface. HST measurements [98Hal] suggested an O_2 column of $(1…10) \times 10^{14}$ cm^{-2}. [96Nol] reported the spectroscopic detection of ozone.

Callisto – the first confirmation of a tenuous CO_2 atmosphere with a surface pressure of $7.5 \cdot\times 10^{-12}$ bar and surface temperature of about 150 K was first confirmed by the Galileo flyby [99Car].

X-Rays on Galilean satellites – these have been detected on Io, Europa, possibly Ganymede, and from the Io Plasma Torus (IPT). X-rays from the Galilean satellites are attributed to bombardment by energetic ions arising in the region of the IPT and thereabouts, whereas bremsstrahlung from nonthermal electrons may account for a substantial fraction of the observed X-ray flux from the IPT itself [02Els, 05Els].

4.2.3.6.5 Titan

Titan's thick atmosphere (surface pressure = 1.5 bar) is believed to resemble that of the prebiotic Earth hence may provide clues about the origin of life. The two major atmospheric constituents, nitrogen and methane react in the presence of ultraviolet radiation and cosmic rays to form a complex mixture of higher chain hydrocarbons and nitriles some of which can condense to form a thick aerosol blanket which enshrouds the moon. The composition of Titan's atmosphere was first unravelled by Voyager in the 1980s and then more recently since 2004 by the Cassini/Huygens mission. Aerosol and clouds on Titan have been studied recently by Cassini [e.g. Kok07]. Table 4 summarises the main atmospheric constituents (up to and including C_2):

Table 4 Atmospheric composition (up to C2) of Titan

Species	Concentration volume mixing ratio	Ref.
N_2	0.98 (surface)	05Nie
CH_4	4.9×10^{-2}	05Nie
	(1.6×10^{-2} ±0.5) (stratosphere)	05Fla
H_2	$(9.6 \pm 2.4) \times 10^{-4}$ (troposphere)	07Cou1
CO	3.2×10^{-5} (troposphere)	05Lop
	6×10^{-5} (stratosphere)	05Lop
	$(4.5 \pm 1.5) \times 10^{-5}$ (stratosphere)	05Fla
CO_2	$(1.5 \pm 0.4) \times 10^{-8}$ (stratosphere)	07Cou2
^{40}Ar	4.3×10^{-5} (lower atmosphere)	05Nie
C_2H_6	$(8.8 \pm 2.2) \times 10^{-6}$ (stratosphere)	02Liv
	$(1.3 \pm 0.3) \times 10^{-5}$ (lower latitudes, stratosphere)	07Cou2
HCN	4×10^{-7} (stratosphere)	93Cou
	$(5.7 \pm 1.2) \times 10^{-8}$ (equator, stratosphere)	07Cou2
	$(5.7 \pm 1.2) \times 10^{-7}$ (70°N, stratosphere)	07Cou2
C_2H_2	$(3.7 \pm 0.8) \times 10^{-6}$	07Cou2
C_2H_4	1.2×10^{-7} (disk average)	03Cou
	$(1.65 \pm 0.6) \times 10^{-7}$ (equator, stratosphere)	07Cou2
	$(1.2 \pm 0.7) \times 10^{-7}$ (70°N, stratosphere)	07Cou2

The lack of noble gases measured by Cassini [05Nie] suggests that Titan's thick nitrogen atmosphere did not form mainly from planetesimals but was delivered mainly in other forms such as ammonia. Carbon isotope ratios are consistent with geological, abiotic sources. The changing face of Titan's disk albedo (Titan's "smile") may imply a seasonal variation in the atmospheric aerosol [92Cal]. [07Cou2] noted meridional enhancements (based on Cassini data) for some species (e.g. HCN) in the northern hemisphere, which were mostly absent (i.e. little variation with latitude) in the southern hemisphere.

Titan's dynamics feature a slow, meridional circulation [02Sam] from equator to pole with a poorly-understood equatorial superrotation. Cassini temperature measurements [05Fla] implied a surface temperature of around 94 K (similar to that observed by Voyager) and a 70 K tropopause at 50 km. Zonal winds peak in mid-latitudes at about 160 ms^{-1} which may inhibit chemical mixing.

Chandra observed Titan in X-rays when the moon was silhouetted against the diffuse X-ray emission of the Crab nebula [04Mor].

4.2.3.6.6 Pluto, Charon and Triton

Pluto-Charon – the Pluto-Charon system may have formed from a giant impact event which has parallels with the Earth-Moon formation theory [05Can]. Knowledge of Pluto's atmosphere has increased drastically since 1985 due to lightcurve data from successive eclipses of Pluto with Charon [90Tho] as well as stellar occultation events [89Ell, 03Sic, 07Per]. Pluto features a tenuous nitrogen-dominated atmosphere with surface pressure in the range 0.1 to 1.0 μbar [99Yun, 07Stro], surface temperatures of 40 - 60 K and an isothermal upper atmosphere of 95 - 100 K [03Sic]. Atmospheric composition is summarised in Table 5:

Table 5. Pluto's atmospheric composition [93Owe]*

Species	Concentration [vmr]
N_2	0.98
CH_4	1.5×10^{-2}
CO	5×10^{-3}
CO_2	$< 7 \times 10^{-4}$

*) atmospheric composition inferred from spectral measurements of surface ices

Atmospheric pressure appears to have doubled from 1988 to 2002 [05Pas] possibly due to sublimation of nitrogen ice after the southern polar cap entered into sunlight [03Sic]. Modelling studies [97Lar, 99Kra] have suggested photochemical sources of non-methane hydrocarbons in the atmosphere. [92Ell] suggested atmospheric haze particles in the atmosphere based on changes in lightcurve slope, although [90Hub] suggested this could arise from a steep thermal gradient near the surface. Pluto's may be the only atmosphere in the Solar System which is currently undergoing hydrodynamic escape [07Stro].

Triton – The Voyager spacecraft investigated the atmosphere of Neptune's largest moon, Triton during its 1989 flyby, suggesting a cold, nitrogen dominated atmosphere which exists at vapour pressure equilibrium with the surface. The atmosphere features a surface temperature of 38 K [89Con] and a mean surface pressure of 19 μbar [00Ell] although the latter may vary strongly with season and location [95Yel]. [00Ell] suggested a possible unidentified cooling mechanism to account for the cold surface. Parallels are suspected to exist between the photochemistry of Triton and that of Titan [99Yun] except the colder temperatures on Triton imply that organic aerosols would condense more readily. Triton's ionosphere features an unusually high electron density ($> 10^4$ cm^{-3}) [99Yun].

4.2.3.6.7 References for 4.2.3.7

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