



SPACE ENVIRONMENT

THERMAL CHARACTERISTICS OF THE SPACE ENVIRONMENT	1
Where about in space	2
The Earth atmosphere (ascent and reentry).....	3
Low Earth orbit (LEO).....	5
Outer space.....	6
Background radiations	6
Microwave background radiation	7
Cosmic radiation	7
Radiation from the Sun	7
The Sun structure	8
Space weather	9
Solar wind	10
Solar power and spectrum.....	11
Solar radiation absorptance, transmittance, and reflectance	14
Radiation near other celestial bodies	15
Albedo.....	23
Planet emission	28
Thermal characteristics of planetary missions	29
Mercury.....	31
Venus	31
The Moon.....	33
Mars	36
Jupiter.....	37
Saturn	38
Uranus	40
Neptune	41
Comets	41
A few data to keep in mind for spacecraft thermal control.....	42
References.....	42

THERMAL CHARACTERISTICS OF THE SPACE ENVIRONMENT

This is a review of the environmental characteristics of space that may be relevant to [spacecraft thermal control design](#). The space environment is of interest to spacecraft design in many respects:

- The [vacuum](#) environment (effects on pressure, heat transfer, and outgassing).
- The [radiation environment](#) (electromagnetic, and particulate: atoms, ions, and electrons).
- The [gravitation environment](#) (including [microgravity](#)).

- The [micrometeoroids](#) and [space debris](#).
- The residual atmosphere environment (residual [gas drag](#), aerodynamic heating, and chemical [reactions](#)).
- The [electrical](#) and [magnetic](#) environment, etc.

Where about in space

It seems that the term ‘space’ was first used to mean the region beyond Earth's sky in John Milton's Paradise Lost in 1667. Several regions in space are of interest to spacecraft thermal control (STC), beginning with the Earth atmosphere, passing by outer space (the void that exists between celestial bodies), and reaching other planetary atmospheres and surfaces.

Gases retained by gravitational attraction around planets and moons (and stars) have no clearly delineated boundary; gas density exponentially decreases with distance from the object until it becomes indistinguishable from the surrounding environment. It is then a matter of consensus to define where the space begins. For the purpose of spacecraft flight, this bound, adopted by the International Astronautical Federation ([IAF](#)) as a rough separation from aeronautics (possibility of aerodynamic flight) and astronautics (possibility of non-powered orbital flight) is 100 km, known as the Kármán line (Theodore von Kármán deduced in the 1950s that a vehicle would have to fly faster than orbital velocity to have sufficient aerodynamic lift from the air to stay aloft at that altitude). The Kármán line in Venus is around 250 km high, and in Mars about 80 km.

At 100 km altitude, the mean free path of gas molecules is $\lambda=0.14$ m, rendering the continuum hypothesis (requiring $L \gg \lambda$) untenable for ordinary systems (of size L), and kinetic theory of free molecular flow must be applied. The Knudsen number, $Kn \equiv \lambda/L$, is used to separate the continuous-media fluid model ($Kn \ll 1$) from the free molecular flow ($Kn \gg 1$); the kinetic theory of gases shows that $\lambda = k_B T / (\sqrt{2} \pi d^2 p)$, where k_B is Boltzmann's constant, T gas temperature, d gas particle diameter, and p gas pressure.

As for the upper limit of terrestrial space ([geospace](#)), one may take the influence of the Earth magnetic field on solar wind ([magnetosphere](#)), which delimits a kind of paraboloid with the nose at about ten Earth radii, $10 \cdot R_E$, in facing the Sun, extending in the opposite direction to the limits of the heliosphere, about $1000 \cdot R_E$). The Moon passes through the geo-magnetosphere tail during roughly four days each month, during which time the surface is shielded from the solar wind. Another limit might be the region where Earth's gravity dominates, what depends on the presence of other celestial bodies; e.g. accounting just for the Sun, Earth's gravity dominates up to $1.5 \cdot 10^6$ km ($235 \cdot R_E$) the distance to the Sun-Earth Lagrangian points; a body within this geospace (e.g. the Moon is at about $60 \cdot R_E$) is attracted mainly by the Earth (if not within the Earth-Moon Lagrangian points).

The two bodies controlling the space environment for most spacecraft are the Earth and the Sun, with other planets and moons only important to specific spacecraft missions in their surroundings.

The Earth atmosphere (ascent and reentry)

Before take-off, the spacecraft environment is controlled by the ground air-conditioning service to the launcher cargo bay (payloads may be subjected to 10 °C to 30 °C for many hours at the launch pad).

After launch, the ascent phase lasts only a quarter of an hour to half an hour, so that thermal inertia prevents major thermal changes. During the initial phase of ascent, the spacecraft is thermally protected from the aerodynamic heating by the rocket fairing (or the shuttle-bay doors), reaching in less than 5 minutes from lift-off some 100 km altitude and some 3 km/s speed. At that altitude, the fairing is jettisoned to save accelerating mass, since air-drag has decreased a lot from the peak at about 5..10 km altitude (about 1 minute after lift-off), and aerodynamic heating has fallen below solar heating values. After fairing jettisoning and until orbit injection (what takes some 10 min more), free molecular heating impose a heat flux in the range $\dot{q} = c_K \frac{1}{2} \rho v^3 = 100..1000 \text{ W/m}^2$ (where v is vehicle speed, ρ density of rarefied gas, and the coefficient $c_K=0.5..0.9$). In most cases, spacecraft and carrier are slowly spun for stabilization. After some orbit and attitude manoeuvres, a stable low Earth orbit (for parking or final destination) is finally reached (about half an hour after take-off), or direct injection to other orbits continue.

Reentry differs from the ascent phase basically in the range of speeds involved, because the crossing at 3 km/s of the 100 km altitude (Kármán line) during ascent, transform into 8 km/s during descent from low orbits or up to 11 km/s when coming from higher orbits (and kinetic energy is proportional to the square of the speed). Fortunately, gas dissociation at high temperatures greatly increase thermal capacity and hence, temperatures attained by dynamic deceleration (e.g. the temperature in the shock layer before a blunt reentry body) grows proportionally to speed (around 100 K per km/s) instead of proportionally to $v^2/(2c_p)$ (e.g. on Apollo return from the Moon at 11 km/s, the gases in front of the ablative shield attained 11 000 K, instead of some $(11 \cdot 10^3)^2 / (2 \cdot 1000) = 60\,000 \text{ K}$ if the ideal gas model for air was applied).

The temperature profile in the Earth's atmosphere is sketched in Fig. 1, and Table 1 presents further data for the rarefied atmosphere at great altitudes. Notice that the tropopause, separating the layer of temperature decrease (troposphere) from the layer of near constant temperature in the lower stratosphere (assumed to take place at 11 km altitude in the International Standard Atmosphere, [ISA](#)), may reach up to 18 km in the tropics, and 8 km at the Poles.

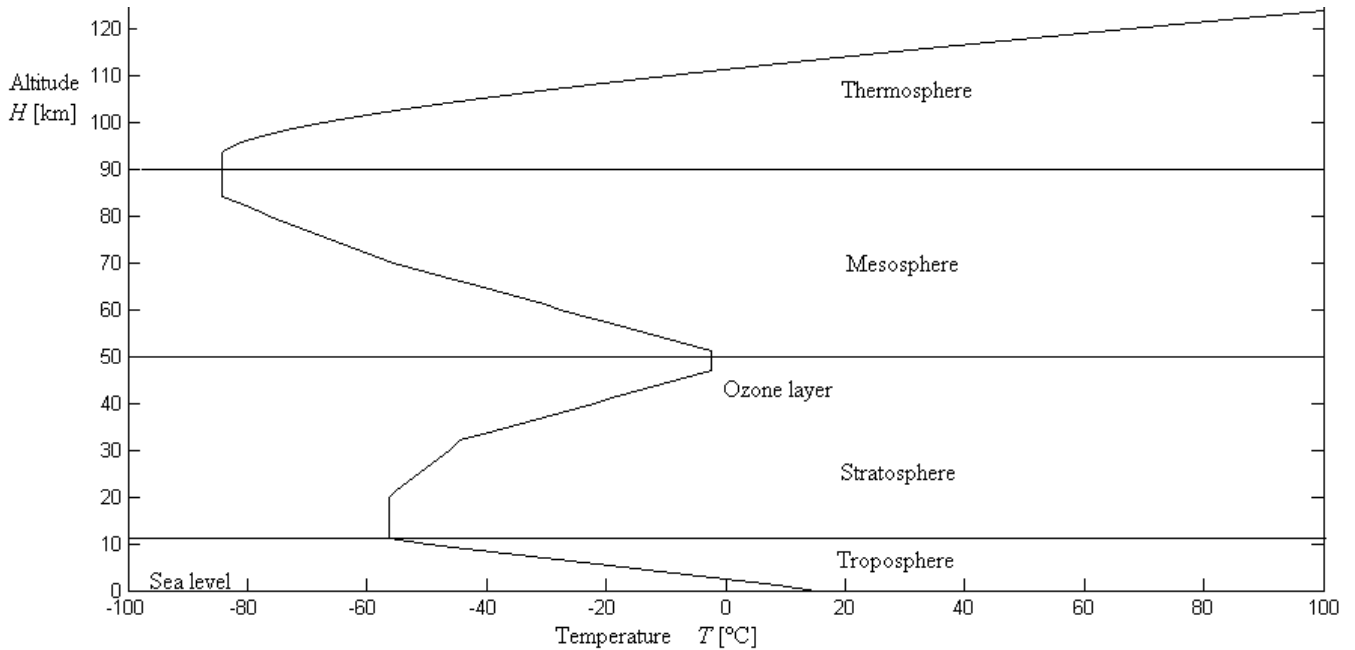


Fig. 1. Vertical thermal structure of Earth's atmosphere (extended ISA).

Table 1. Some data for the rarefied Earth atmosphere at great altitudes.

Altitude	Satellite lifetime ^{a)}	Density ^{b)}	Composition and particle density	Temperature and pressure ^{c)}	Mean free-path ^{c)}
50 km	NA	$1 \cdot 10^{-3} \text{ kg/m}^3$	N ₂ 78 %, O ₂ 21 %, Ar 1 %	271 K, 76 Pa	$\lambda=10^{-4} \text{ m}$
100 km	NA	$0.6 \cdot 10^{-6} \text{ kg/m}^3$	N ₂ 77 %, O ₂ 18 %, O 4 %	195 K, 0.03 Pa	$\lambda=0.1 \text{ m}$
120 km	1 orbit	$2 \cdot 10^{-8} \text{ kg/m}^3$		360 K, 0.003 Pa	$\lambda=3 \text{ m}$
200 km	1 day..2 wk	$10^{-10} \dots 10^{-9} \text{ kg/m}^3$	O>50 %, N _O = 10^{15} 1/m^3 .	500..1100 K, 10^{-4} Pa	$\lambda=200 \text{ m}$
300 km	2 wk..2 mt	$10^{-11} \dots 10^{-10} \text{ kg/m}^3$	O 83 %, N ₂ 15 %, He 1 %	600..1500 K, 10^{-5} Pa	$\lambda=2.5 \text{ km}$
400 km	0.2 yr..5 yr	$10^{-12} \dots 10^{-11} \text{ kg/m}^3$	O 91 %, He 5 %, N ₂ 4 %	600..1800 K, 10^{-6} Pa	$\lambda=20 \text{ km}$
500 km	1 yr..50 yr	$10^{-13} \dots 10^{-11} \text{ kg/m}^3$		600..1800 K, 10^{-7} Pa	$\lambda=100 \text{ km}$
600 km	>50 yr	$10^{-14} \dots 10^{-12} \text{ kg/m}^3$	N _O = $10^{11} \dots 10^{14} \text{ 1/m}^3$.	600..1800 K, 10^{-8} Pa	$\lambda=300 \text{ km}$
1000 km		$10^{-15} \dots 10^{-14} \text{ kg/m}^3$	He 84 %, H 14 %, O 2 %	600..1800 K, 10^{-8} Pa	$\lambda=400 \text{ km}$
GEO 36·10 ⁶ m	Do not fall (but drift)		H, N _H = $3 \cdot 10^6 \text{ 1/m}^3$.		

a) Satellite lifetime is based on a ballistic coefficient $c_B \equiv m/(c_D A) \sim 1 \text{ kg/m}^2$ for typical satellites (e.g. the [Phobos-Grunt](#) probe, launched in 8-Nov-2011 and failed to be injected to Mars, fell back from 280 km mean altitude in an uncontrolled reentry on 15-Jan-2012). It is proposed that all satellites must provide means to guaranty a maximum life-span of 25 years after use, to avoid space debris.

b) Maximum density corresponds to solar maximum.

c) Gas kinetic theory shows that pressure and temperature are related to kinetic energy in the form $p=(N/V)mv_{\text{rms}}^2/3$, and $(3/2)kT=(1/2)mv_{\text{rms}}^2$, and mean free path to particle density N and effective particle diameter d by $\lambda = 1/(\sqrt{2}\pi d^2 N) = kT/(\sqrt{2}\pi d^2 p)$. High vacuum corresponds to a mean-free

path of the order of the object (e.g. for $\lambda=L=1$ m, $z>110$ km and $p<10^{-3}$ Pa, whereas in ultra-high vacuum (UHV), $p<10^{-7}$ Pa, $z>500$ km, each of the atoms in a surface only get the collision of one atom per orbit, in the average.

Notice that altitudes from those of sounding balloons (40 km) to LEO minimum (250 km) cannot be attained with a vehicle in sustained flight (neither aerostatic, nor aerodynamic or astrodynamic, although levitation by strong microwave beams has been proposed). This passing-by region is studied with sounding rockets, and consists of a plasma with some $10^{12}..10^{20}$ charged particles per m^3 at an equivalent temperature that may reach to 1000 K in daytime, and get below 500 K by night. Table 1 summarises some characteristics of the rarefied Earth atmosphere at great altitudes. [Details of the atmosphere as a radiation filter can be found aside](#). Pressurisation is required for life support on any aerospace vehicle above 5 km altitude.

Exercise 1. Find the standard air pressure and density at 20 km altitude, assuming the temperature profile in Fig. 1, i.e. 15 °C at the Earth surface, a constant slope $T'=-6.5$ °C/km up to 11 km (tropopause), and constant temperature from 11 km to 20 km.

Sol.: The hydrostatic equation, $dp=-\rho g dz$, with the ideal gas law, $pV=mRT$, and the given temperature law, $T(z)=T_0+T'z$, give the differential equation that solves the problem, $dp=-\rho g dz/(R(T_0+T'z))$. Integrating in the two zones, with continuity at the tropopause (11 km) finally yields $p_{20}=5.5$ kPa, and $\rho=p/(RT)=5500/(287 \cdot 216.5)=0.089$ kg/ m^3 .

Low Earth orbit (LEO)

Low Earth orbits (300..800 km altitude) are used as a first stop for other destinations (i.e. as a parking orbit), or as a final destination. In the latter case, after LEO is reached, there may be a period (from a few hours to a couple of weeks) when the spacecraft is not fully deployed (solar cells, antennas, attitude attainment...), and the TCS must still perform well. Lower orbits are not used (because of the aerodynamic drag), and higher orbits neither (to avoid a stronger radiation environment). At these altitudes, molecular oxygen is dissociated into atomic oxygen, which is the main constituent of the rarefied gas. Above 800 km, helium becomes the most abundant component, with hydrogen atoms taking over when the exosphere meets the interplanetary gas.

LEO environment characteristics:

- Earth rarefied atmosphere, with extremely low density and pressure, but very high temperature (though of no interest to STC because radiation heat transfer is dominant). At low spacecraft altitudes (say $H=300..1000$ km for useful LEO), the gravity-trapped gas layer (generally named atmosphere but more precisely named thermosphere because of its high temperature, some 1000 K), gets heated by UV absorption of solar radiation. Atmospheric pressure at a 350 km LEO is of a few micropascals (in the range $(3..5) \cdot 10^{-6}$ Pa). The lowest LEO working altitude is the 255 km used by [GOCE spacecraft](#) (Gravity field and steady state Ocean Circulation Explorer), already demanding a small continuous propulsion to balance air drag (some 10 mN for a 1000 kg, $1.1 \cdot 5.3$ m³ spacecraft). Spacecraft become negatively charged at LEO by O^+ ions impact, mainly on frontal areas because their thermal velocity is lower than orbital velocity, whereas e^-

impact equally everywhere. For instance, a surface in front of the ISS (i.e. in the forward direction) gets some $20 \cdot 10^{24}$ oxygen-atoms per square metre per day, and a tenth of that if the surface is facing aft.

- Earth magnetic field (due to relative internal motion of Earth's iron nucleus). A [magnetometer](#) measure the field strength and, when used in a three-axis triad, magnetic field direction, what can be used to know the spacecraft attitude (if its position is known). By using magnetic coils to interact with the geomagnetic field ([magnetic torquers](#)), it is possible to control attitude in small satellites.
- Solar radiation. Mainly electromagnetic radiation (EMR) in the amount of 1360 W/m^2 (with a minimum of 1320 W/m^2 in July and a maximum of 1420 W/m^2 in January), but also solar wind (charged particle radiation, basically a proton plasma with number-density of $N_{\text{H}^+} = 9 \cdot 10^6 \text{ 1/m}^3$, typical velocities of $V_{\text{H}^+} \sim 450 \text{ km/s}$, and kinetic temperatures of $T_{\text{H}^+} = 10^5 \text{ K}$).

Outer space

Further than LEO, usually limited to $<1000 \text{ km}$ altitude, there are other terrestrial orbits of interest, the further being the geostationary orbit (GEO) at about $36\,000 \text{ km}$ ($6.6 \cdot R_E$), the [cislunar](#) space (up to Moon's orbit), and deep space beyond.

Spacecraft thermal control in this void region depends on the celestial bodies at sight, with the Sun dominating in most cases.

Outer space is the closest known approximation to a perfect vacuum. The mean free path of a photon in intergalactic space is about $100 \times 10^{24} \text{ m}$, or 10×10^9 light-years. Outside the protective atmosphere and magnetic field of celestial bodies, there are no obstacles to the propagation of radiation (electromagnetic, and particulate).

Background radiations

To begin with, recall that radiation is the transfer of energy as material particles, electromagnetic waves (immaterial particles), sound (within a material medium), or any other kind of energy. Radiation effects in space not only affect the thermal control, but to communications (radio, IR, visual...) and survivability (UV and ionizing radiation dose). Nomenclature refresh: *radiative* comes from radiation in general (EM, particles), whereas *radioactive* refers to the spontaneous emission of radiation from unstable atomic nuclei (α, β , and γ particles).

Natural and artificial radiations are crucial to humankind welfare, but can be damaging too (from dielectric overheating caused by intense radiowaves, microwaves, or infrared sources, to ionising nuclear radiation, passing by sunlight blindness, erythema, and skin cancer). It is estimated that astronauts in the ISS get some 0.24 Sv/yr (Benton and Benton, Radiation Measurements 33, 255–263, 2001), whereas outside Earth's magnetosphere (16 Earth radii in the sunward direction, several times this in the anti-sunward direction), the dose is of the order of the safe limit for astronauts, 0.5 Sv/yr , and much more in

the event of solar flares. For a few-day's journey to the Moon there is little risk, but for a Mars trip this is a problem.

Several types of background radiations in space can be distinguished, either grouped by their source, or by its matter content. In the latter case, atomic and subatomic particles are usually included when studying the radiation environment, but larger particles are treated apart; the latter can be classified according to size as (relative speed is always in the range 10..20 km/s):

- Cosmic dust, with sizes in the range $d=1..100$ nm, mostly inorganic particles with a variety of atomic composition, similar to comet dust and planets-and-moons regolith.
- Small micrometeoroids, and dust from debris (of anthropogenic origin), with sizes in the range $d=0.1..10$ μm . Typical spacecraft envelopes, and even space suits, with >0.5 mm thick protective layer, protect from particles of $d<1$ μm without damaging the shield, and from particles of $d<10$ μm with minor external damage.
- Large micrometeoroids and small debris, with sizes in the range $d=10..1000$ μm .
- Meteoroids, if $d>1$ mm. Those with size $d>100$ mm (some 20 000 in LEO) are currently tracked from ground to avoid major accidents.

Microwave background radiation

Cosmic background radiation is electromagnetic radiation in the microwave band filling the observable universe almost uniformly. This deep-space nearly-isotropic radiation (also known as cosmic microwave background, [CMB](#)) is a relic from the Big Bang, predicted by Gamov in 1948 and discovered in 1964 by A. Penzias and R. Wilson. It has a nearly black-body behaviour with $T_{\text{bb}}=(2.73\pm 0.05)$ K, $\lambda_{\text{max}}=1.9$ mm (160 GHz).

Cosmic radiation

This is an isotropic particle radiation generated outside the solar system during supernova explosions, and composed of very high and sparse energetic particles (basically 1 particles/($\text{m}^2\cdot\text{s}$) with 10^9 eV; 90 % protons, 9 % alpha particles and some heavier nuclei, and 1 % beta particles), besides some EM γ -rays. Most cosmic particles are deflected by the solar magnetic field and the geomagnetic field (recall that protons and electrons are deflected by both magnetic and electric fields, but photons are not). When cosmic rays enter the Earth's atmosphere they collide with nitrogen and oxygen molecules, producing neutrons and mesons (unstable sub-particles with negative, neutral, or positive charge).

Cosmic radiation contributes to about half the total effective dose received by astronauts in LEO, and generate radionuclides in the atmosphere; two of these cosmogenic radionuclides are used for dating of past events: C-14 (formed by ${}^1_0\text{n} + {}^{14}_7\text{N} = {}^{14}_6\text{C} + {}^1_1\text{p}$, incorporated to the carbon cycle, and decaying by ${}^{14}_6\text{C} = {}^{14}_7\text{N} + {}^0_{-1}\text{e} + \bar{\nu}_e$), and Be-10 (created by ${}^1_0\text{n} + {}^{14}_7\text{N} = {}^{10}_4\text{Be} + {}^4_2\text{He} + {}^1_1\text{p}$, incorporated to aerosols, and decaying by ${}^{10}_4\text{Be} = {}^{10}_5\text{B} + {}^0_{-1}\text{e} + \bar{\nu}_e$).

Radiation from the Sun

The [Sun](#) is a middle-size star, a spherical ball of hot plasma with no solid surface, and their visible outline (photosphere) is used to describe their size (from outside the Earth's atmosphere, the Sun is seen white,

not yellow). At present, this is the only star amenable to structure studies. It provides light and warmth to us on Earth surface, and to all orbiting spacecraft, most of each are solar powered too. Earth's orbit has a small eccentricity, $e=1.67\%$ (closer to the Sun in January), and Earth's axis is tilted 23.45° (North Pole towards the Sun in July); this is also the inclination of Earth's Equator plane to the ecliptic plane (Earth's orbit plane).

However, not all radiations from the Sun are helpful; solar flares (and other solar storms) can have serious effects on the Earth, and especially to spacecraft. We therefore may consider separately the mean [solar radiation](#) as a resource, and its unwanted fluctuations as [space weather](#) effects.

In spite of its huge gravitational attraction (the Sun comprises about 99.86 % of the mass of the Solar System), it is very difficult for a spacecraft to approach the Sun because of the 30 km/s tangential Earth's entrainment (several [gravity-assisted](#) pulls are needed to slow down this circular motion and let it approach the Sun).

The Sun structure

In terms of its equatorial radius, $R_S=696\cdot 10^6$ m ($R_S=109\times R_E$), the following layers may be distinguished:

- [Core](#), $r/R_S<0.3$. This is where nuclear-fusing reactions take place. Assumed central values: $T=16$ MK, $p=25\cdot 10^{15}$ Pa, $\rho=150\cdot 10^3$ kg/m³. It rotates faster than outer layers.
- Radiation zone, $0.3<r/R_S<0.7$ (with no convection). Thermal radiation is the primary means of energy transfer.
- Convection zone, $0.7<r/R_S<1$ (with important motions, which create the magnetic field). At around 0.7 is the [tachocline](#), a very large shear layer where the rotation rate changes very rapidly from uniform (inside) to zonal (outside).
- Surface, or [Photosphere](#), about 500 km thick ($<0.001R_S$). Mean values are: $T=5780$ K, $p=5$ kPa, $\rho=0.2\cdot 10^{-3}$ kg/m³ (at bottom 6500 K, 12 kPa, $0.4\cdot 10^{-3}$ kg/m³; at top 4800 K, 0.1 kPa, $3\cdot 10^{-6}$ kg/m³) The photosphere is a stable layer with deep convective currents overshooting, creating a rough turbulent surface with large sporadic flares. Because the upper part of the photosphere is cooler than the lower part, an image of the Sun appears brighter in the centre than on the edge or limb of the solar disk, in a phenomenon known as limb darkening. The visible light is produced as electrons reacting with hydrogen atoms to produce H^- ions.
- Atmosphere. Matter above the photosphere (only visible by hiding the solar disc, since it is almost transparent in the visible), with the following layers:
 - [Chromosphere](#), about 2000 km thick ($\approx 0.003R_S$). The chromosphere is visible as a coloured flash at the beginning and end of total solar eclipses, what gave its name. At its bottom stands the temperature-minimum zone, a very thin layer with $T_{S,\text{mim}}=4400$ K. At its top, temperature reaches 20 000 K. There is a 200 km thin transition zone between the chromosphere and the corona, with a very large temperature increases from 0.02 MK to 1 MK.
 - [Corona](#), extending a few million km outwards ($\approx 1..4R_S$) depending on the wavelength observed. Temperature reaches 10..20 MK (i.e. $T_{S,\text{max}}$), may be due to strong magnetic

effects over the very-low-density plasma ($\rho \approx 10^{-13}$ kg/m³). Corona light, easily seen on total eclipses, is due to a combination of photospheric dispersion, and own emission of highly-ionised atoms. The corona is not a spherical shell but a spiked shape changing a lot along the solar cycle; it is most prominent in areas with sunspot activity, and, during calm periods, it is mainly equatorial (no polar corona), and it has holes, i.e. regions where the magnetic field lines of the Sun are open, allowing coronal gas to flow outward into space and producing the solar wind.

- [Heliosphere](#), extending some 100 ua (almost coincident with Sun magnetosphere). This is the region where solar wind can be distinguished from interstellar medium. It contains all solar planets (Earth is at $215R_S=1$ ua, Pluto aphelion 49 ua; Voyager 1 was at 131 ua in 2015).

Space weather

[Space weather](#) refers to the variability of physical conditions in outer space, mainly due to the Sun, and focused on the Earth surroundings, i.e. in the magnetosphere, thermosphere, and ionosphere (extending the field of terrestrial weather, which focuses on the troposphere and stratosphere).

Space weather is important to spacecraft design because radiation has an impact on living beings, telecommunications (space-to-space, air-to-ground, and ground-to-ground), positioning and tracking (including GPS), thermo-optical degradation and electrostatic charging of external surfaces, and several direct modes of electronics malfunction. The direct heating effect of solar wind, $\dot{q} \approx \frac{1}{2} \rho_{\infty} v_{\infty}^3$, may account to a few degrees in the worst case, what is negligible except at low temperature, as for cryogenic radiators. As more business on Earth are dependent on satellite services (telecommunications, positioning, navigation, remote surveillance), the importance of space weather to the general public might follow that on meteorological weather.

Main components of space weather are:

- [Solar wind](#), a directional flux of particles (e^- , p^+ , ^4He) with $E < 100$ keV at about 400 km/s. It is almost steady, and easy to shield.
- [Solar flares](#), sudden strong emission of particles (p^+) with $E > 100$ keV. Require thick shields for protection.
- [Cosmic rays](#), radiation from outside the Solar System (from exploding stars), γ -ray with E up to 1 TeV; it has low intensity, but cannot be shielded.
- [Van Allen belts](#), trapped particles (p^+ with $E < 300$ MeV and e^- with $E < 3$ MeV). The inner belt is at $R/R_E = 1.2..3$, and the outer belt at $R/R_E = 3..10$, being strongest at $R/R_E = 4..5$. Require thick shields to protect, but can be avoided by going around.
- [Upper atmosphere](#), mainly molecular oxygen (O), and UV radiation. Around spacecraft, outgassing and thruster exhausts must be accounted. There are not too dangerous, and are easy to shield. Main effects on spacecraft are orbit and attitude perturbations (including orbit decay), and radiation damage.

[Radiation damage](#) on a spacecraft may account to:

- Biological damage, which can be mild or strong, acute or chronic (even mutagenic). Astronaut are required to wear a dosimeter during missions to keep track of the radiation to which they have been exposed.
- Single event upsets ([SEU](#)), may cause an erroneous signal or a one-bit change in electronic memory.
- Single event latchup ([SEL](#)), when radiation destroys a section of the electronics.
- Spacecraft electrical charging (SEC), is the accumulation of electrostatic charges on a non-conducting material by low energy particles. Spark (discharge) occurs if enough charge is built-up. Charging is the predominant space weather effect in GEO.
- Surface degradation (SD), particularly of mirrors, low-absorptance coatings, radiators, and MLI, have an impact on thermal control.

Mitigation measures against adverse space weather (such as shielding) are expensive, since additional weight increases launch costs.

Solar wind

The solar wind is the fluctuating stream of plasma released from the Sun corona (mainly from equatorial regions), through regions of concentrated magnetic field, and composed of high energy particles (1.5..10 keV, about 10^6 part/m³: protons, electrons, and some alpha particles), moving at about 400 km/s, and causing comet tails, auroras, geomagnetic tails and storms (also on Mercury and Venus, but not on the Moon).

The solar magnetic field is embedded in the plasma and flows outward with the solar wind, basically as a broad sprawling surface ($\sim 10^4$ km thick) jutting outward from the Sun's equator, named [current sheet](#), because the Sun's slowly-rotating magnetic field induces an electrical current of 10^{-7} A/m² on it. As the Earth orbits the Sun, we cross the current sheet during Sun's magnetic-field reversals, what can stir up stormy space weather around our planet. The current sheet acts as a barrier to cosmic rays too.

The worst space radiation hazard is a solar magnetic storm, which may last for hours or days, seen as a [solar flare](#) (a bright spot on the Sun), ejecting a large stream of electrons and ions that reach the Earth a day or two after the event (solar wind takes about four days to reach the Earth). Satellites like [DSCOVR](#), placed near the L₁ Lagrange point in between Sun and Earth (at $1.5 \cdot 10^9$ m from Earth, not exactly at L₁ because communications are difficult along the Sun-Earth line) can give an early warning of incoming solar ejections about an hour before reaching the Earth (incidentally, the L₁ position is ideal to [watch solar eclipses](#) from above).

A periodic change in solar activity, the 11 year solar cycle, was discovered in 1843 by S. Schwabe from the number of visible [sunspots](#) (dark areas on the surface, usually in pairs, first seen by Galileo and others, when the telescope was invented in 1609), nowadays explained from the variations of the Sun

magnetic fields, which fluctuates a lot locally, and changes polarity every 11 years, ultimately creating the [solar wind](#), the main component of space weather.

Side effects of solar wind are Van Allen [Radiation Belts](#), which are toroidal regions around the Earth, where charged energetic particles (protons and electrons) are held in place by Earth's magnetic field. The inner belt is the most energetic, with 10..100 MeV protons, located from 1000 km to 5000 km altitude at the magnetic Equator (with a dipping down to 250 km altitude at [South Atlantic](#)), whereas the outer one has 1 MeV ions, and sites at 3 to 4 Earth radii (Fig. 2).

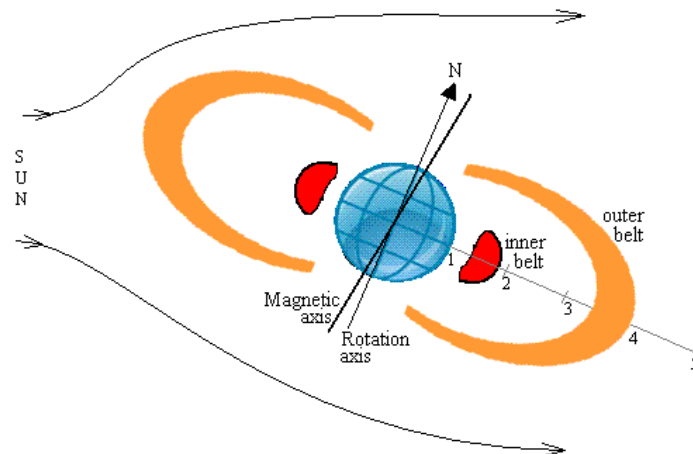


Fig. 2. Van Allen's radiation belts.

Solar power and spectrum

Solar radiation energy is what keeps us alive, maintaining a favourable thermal environment, supplying the free energy (relative to the background of deep space) that drives all living and non-living processes, besides providing illumination.

The Sun has a concentric shell structure. At the core (some 80 % the Sun diameter) the thermonuclear reaction of hydrogen to helium releases a large amount of energy that is transported convectively outwards in a mantle to the photosphere, the thin layer from which visible light is emitted and on which the Sun diameter is based (it is really around 500 km thick, made of a proton plasma that becomes dense and visually opaque with depth). Outer to the photosphere are the chromo-sphere and the corona (extending to a few solar radii) which are rarefied plasma shells nearly transparent in the visible, but emitting a major part of the ionising radiation (UV and X-ray) that are the cause of planet ionospheres. The Sun disc appears a little darker at its edge (limb darkening).

The main characteristics of solar radiation are: power and spectral distribution. Properties of matter relative to solar radiation are absorptance, transmittance and reflectance.

Total solar irradiance (TSI) at 1 astronomical unit (1 ua, formerly 1 AU, redefined in 2012 as a constant, 1 ua = 149 597 870 700 m and no longer experimentally), i.e. the mean extraterrestrial solar flux, E_0 (improperly called '[solar constant](#)', C_s) has an average value of $C_s=E_0=1361.5 \text{ W/m}^2$ (see Fig. 3), corresponding to a baseline minimum total solar irradiance of $1360.8\pm 0.5 \text{ W/m}^2$ (updated in 2011 from

the previous value of $1365.4 \pm 1.3 \text{ W/m}^2$, due to [calibration mismatch](#)), growing to a maximum of about 1363 W/m^2 in correlation to the number of sunspots in the 11 year solar cycle (Fig. 3). Notice that there are larger TSI changes in short periods over those monthly-averaged values, e.g. it is not uncommon to have variations of up to 5 W/m^2 on time scales of days to weeks.

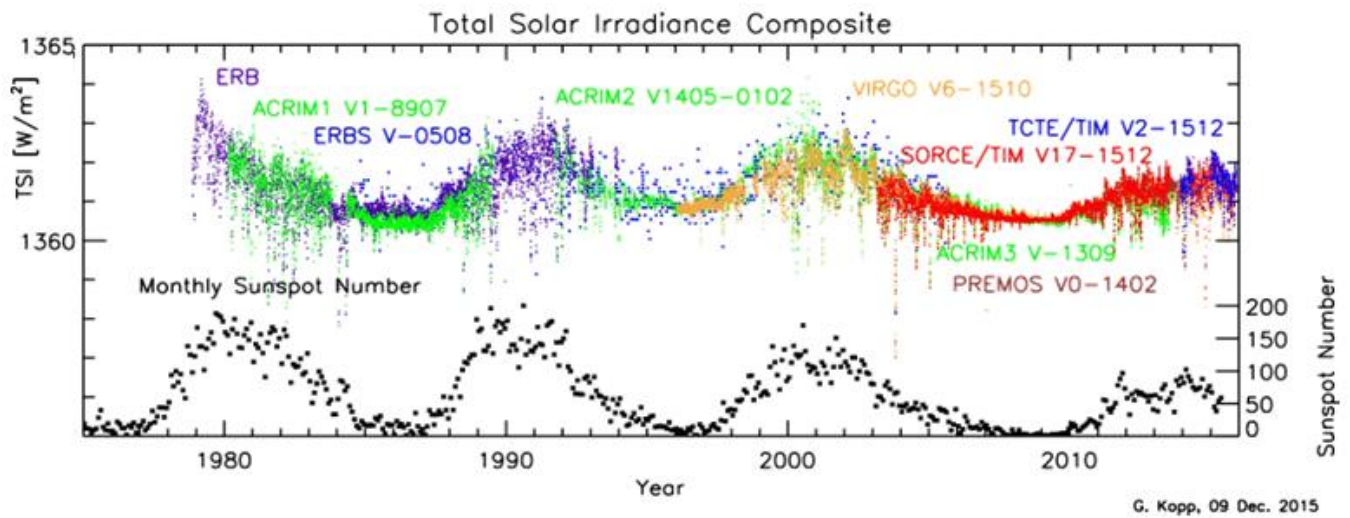


Fig. 3. Evolution of total solar irradiance at 1 ua (TSI), and its correlation with monthly sunspot number.

Since Earth-Sun distance variation is $\pm 1.7 \%$ along the year (eccentricity $e=0.017$), corresponding solar irradiance variation is $\pm 3.4 \%$ ($\pm 1.7 \cdot 2$) i.e. from 1410 W/m^2 in early January to 1315 W/m^2 in early July. From this irradiance value one can estimate the Sun apparent temperature, T_s , which happens to be around 5800 K (first found by J. Stefan in 1879). Pyranometers are routinely used in meteorology to measure hemispherical total solar irradiance, but the most accurate instruments are absolute cavity radiometers.

Most spacecraft are powered by solar radiation captured by photovoltaic cells, from the smallest satellite to the ISS; the exception are short-duration missions like the Shuttle, and deep probes, since, beyond Mars orbit, solar panels are not practical (Juno-2011 mission to Jupiter will be the first to use solar panels instead of the traditional radioisotope thermoelectric generators, RTG).

Directionality. Solar radiation can be considered collimated (i.e. as a parallel beam coming from a point), because at 1 ua, the sun subtends an angle of 0.0093 rad (0.53°), or a solid angle of $68 \cdot 10^{-6} \text{ sr}$. Even for Mercury flybys this approximation is acceptable, although for the closest approach of Solar Orbiter (launch in 2012), at 0.22 ua (48 solar radii), the Sun diameter subtends 0.04 rad (2.4°) and one must account for penumbra (a mission reaching 0.05 ua , i.e. $< 10R_s$, has been proposed for 2015: Solar Probe+).

Before rockets and spacecraft, estimates of the solar constant had to be made from ground based measurements of solar radiation after it had been transmitted through the atmosphere and thus in part absorbed and scattered by components of the atmosphere. Some extrapolations from the terrestrial measurements were based on attenuation versus zenith angle (assuming a uniformly layered atmosphere),

or on values made from high mountains (based on estimates of atmospheric transmission in various portions of the solar spectrum).

Radiation pressure. Related to solar irradiance is radiation pressure, $p=E/c$ if the surface absorbs all radiation, $p=2E/c$ if it reflects all radiation; in the latter case, at 1 ua, it is $p=E_0/c=2 \cdot 1360/(3 \cdot 10^8)=9 \cdot 10^{-6}$ Pa. It has been suggested as a possible future means of space sailing.

Exercise 2. Find the solar constant, E_0 , based on the following measurements of direct solar irradiation on a horizontal surface at sea level: 940 W/m² at 20° zenith angle, 860 W/m² at 40° zenith angle, and 670 W/m² at 60° zenith angle.

Sol.: Assuming Beer's law of light absorption, $E(x)=E_0 \exp(-x/x_0)$, and near planar atmosphere, $x=x_1/\cos(\beta)$, where β is the zenith angle of the Sun ($\beta=0$ if on the vertical direction) and x_1 is the atmosphere thickness, the measured irradiation must verify $E(\beta)=E_0 \exp[-x_1/(x_0 \cos(\beta))]$, or $\ln E = \ln E_0 - x_{10}/\cos(\beta)$, with $x_{10}=x_1/x_0$; and we have to fit the data: $\ln(940)=\ln E_0 - x_{10}/\cos(20^\circ)$, $\ln(860)=\ln E_0 - x_{10}/\cos(40^\circ)$, $\ln(670)=\ln E_0 - x_{10}/\cos(60^\circ)$; three equations for two unknowns E_0 and x_{10} . The best fitting gives $E_0=1380$ W/m², not far from the real value $E_0=1360$ W/m².

Exercise 3. Find the Sun radius, from the following data: mean Sun-Earth distance (1 ua), E_0 , T_s .

Sol.: The energy balance is $4\pi R_s^2 \sigma T_s^4 = E_s 4\pi R_{sp}^2$, from which $R_s = R_{sp} (E_s / (\sigma T_s^4))^{1/2} = 150 \cdot 10^9 (1360 / (5.67 \cdot 10^{-8} \cdot 5800^4))^{1/2} = 695 \cdot 10^6$ m (109 Earth radii); the Sun diameter subtends an angle from the Earth of $2 \cdot 695 \cdot 10^6 / 150 \cdot 10^9 = 0.01$ (0.53°).

Solar irradiance has a wavelength distribution (Fig. 4) that can be approximated by a black-body at 5780 K (approx. 5800 K), i.e. with the maximum at 0.50 μm (0.45 μm for the real spectrum) and 95 % of incoming energy is in the range 0.3..3 μm (10 % UV, 40 % visible and 50 % IR (in comparison, Earth's emission peaks at 10 μm, and contains 80 % of emitted energy in the range 5..25 μm). The term "black-body" was introduced by Gustav Kirchhoff in 1860.

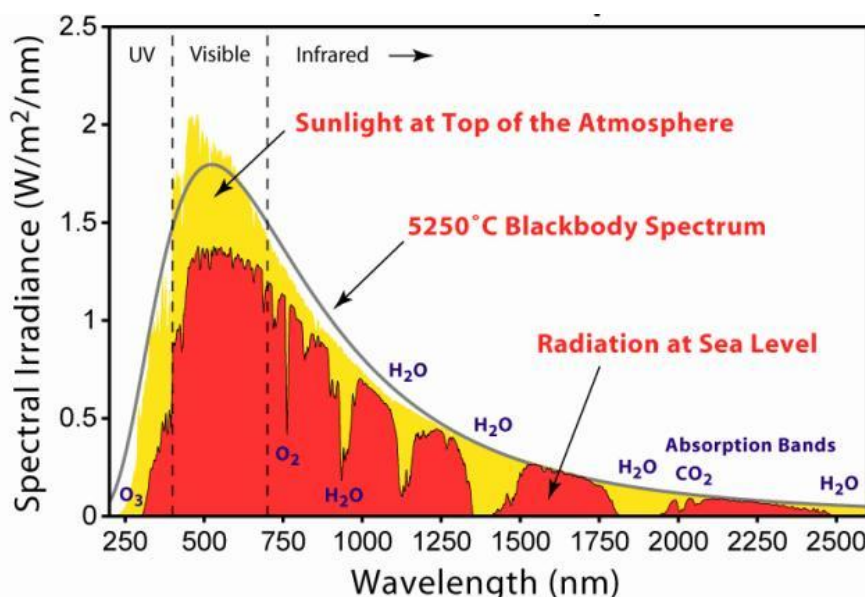


Fig. 4. Solar spectrum outside Earth atmosphere and at sea level. (<http://en.wikipedia.org/>)

Exercise 4. Find the Sun temperature, assuming it emits as a black-body and that the maximum spectral irradiance measured on Earth surface, $0.5 \mu\text{m}$, is the same as in outer space.

Sol.: According to Wien's displacement law, the wavelength of maximum emission is related to the temperature of the emitting black-body by $\lambda_{Mmax}=C/T$, with $C=2.8978 \cdot 10^{-3} \text{ m} \cdot \text{K}$; thus, for $\lambda_{Mmax}=0.5 \mu\text{m}$, $T=0.0029/(0.5 \cdot 10^{-6})=5800 \text{ K}$.

Solar radiation absorptance, transmittance, and reflectance

When solar radiation interacts with matter, a part is absorbed (which can be thought of as taking place at the surface of highly absorbing, i.e. opaque, media), a part is reflected, and the rest is transmitted through the medium (with some absorption and dispersion).

Absorptance, α , is the fraction of the incoming radiant energy which is absorbed by a body of specified thickness (if not opaque) and surface conditions and at a given temperature (increasing its internal energy, and generating electricity in photovoltaic cells), not only depends on material properties but on the direction and wavelengths of incoming radiation. Ultraviolet solar radiation in the $120..200 \text{ nm}$ range is absorbed in the mesosphere (from 50 km to 100 km altitude), whereas UV-radiation in the $200..320 \text{ nm}$ is absorbed in the stratosphere around 35 km altitude. At the Earth surface, solar absorption is not uniform because of incident inclination, which causes large latitudinal differences (Fig. 5), but also due to differences in surface absorptance. Notice in Fig. 5 that absorption over the oceans is greater than over land, and that at Sahara is particularly low, in spite of its clear sky and subtropical condition.

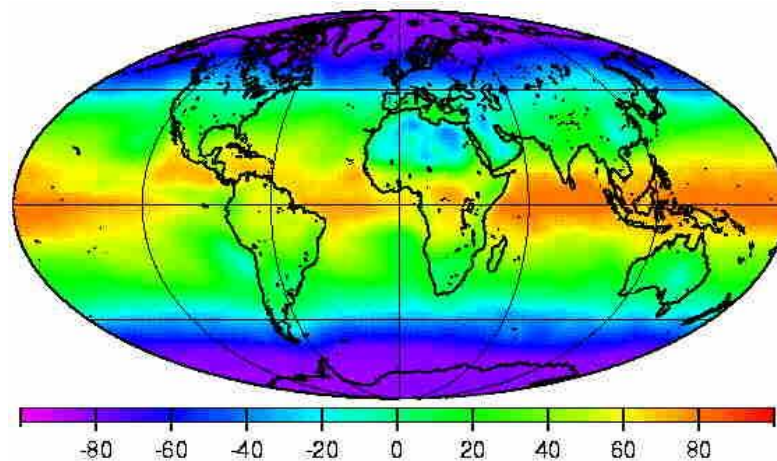


Fig. 5. Annual average solar energy absorption (pseudo-colour relative to the 240 W/m^2 terrestrial surface mean). (<http://www.atmosphere.mpg.de/enid/to.html>)

Transmittance, τ , of solar radiation by matter, not only depends on matter but on the direction and wavelengths of incoming radiation, and the refraction direction considered. Most gases and liquids are transparent for short path-lengths, with a $1/\lambda^4$ -Rayleigh scattering due to molecules (of size 10^{-10} m), although a fine dispersion (e.g. cloud, milk, with particles of size 10^{-6} m) makes the fluid opaque. Most solids are opaque, except glasses, and some pure crystalline oxides (SiO_2 , CaCO_3 ...).

Reflectance, ρ , of solar radiation by matter, not only depends on matter but on the direction and wavelengths of incoming radiation, and output direction considered. Dense matter (even transparent solids and liquids) reflect part of the incoming radiation at interfaces. Directional reflectance characteristics may vary from near-specular behaviour, to near-cathadioptric behaviour (i.e. retro-reflection), with most cases lying in between around the ideal diffuser. The ideal diffuser, also called perfect diffuser, Lambertian surface, or cosine-law surface, is an opaque surface that scatters any incoming radiation back in all outgoing directions, in such a way that, for a fix unitary area, dA , the amount reflected is proportional to the cosine of the zenith angle, β , although a finite surface is seen uniformly shining when looking from any directions because the area viewed is also proportional to $\cos\beta$ (i.e. if an ideal diffuser dA of reflectance ρ receives an irradiance E , it reflects $\rho E dA \cos\beta$, but per unit normal area, $dA \cos\beta$, the reflected power, ρE , is isotropic). Notice, thence, that, looking from the incident direction, a Lambertian sphere and a Lambertian disc (or any other surface with a frontal circular shape, like a tilted ellipse) look uniformly bright (although of different intensity in each case); however, it suffices to look laterally to see the three-dimensional effect; real surfaces show a combination of diffuse and specular behaviour and thus, when looking at a lit sphere along the illumination direction, it appears brighter at its centre.

Most diffuse surfaces only reflect around half of the incoming energy (e.g. green grass some 20 %, dry sand some 40 %, soil some 60 %, white paper and snow some 80 %) the rest being absorbed, but, even in the limit $\rho=1$, diffuse reflection should not to confused with specular reflection).

Planet reflectance from sunlight was named albedo (whiteness) since first defined by G. Bond, who in 1861 published a comparison of the brightness of the Sun, the Moon, and Jupiter. Albedo is an important parameter in the thermal control of low-orbit spacecraft, and the most variable contribution to their thermal loads. Albedo is also a basic data source for celestial analysis (investigators frequently rely on albedo measurements to determine the surface compositions of satellites and asteroids), and the inner structure of stars.

Radiation near other celestial bodies

We present here an overview of radiation coming from celestial bodies, from the farthest stars to the nearest planets and moons, basically in the visual range, before details on albedo and infrared emission are covered further below. Radiation from stars, other than the Sun, can always be neglected in spacecraft thermal control (until we send probes to stars), although it is important for star sensors in spacecraft, and for astrophysics (the only information we have about a star is the light it emits).

Hipparchus of Nicaea (190-120 BC), the first known astronomer to have developed mathematical models for the motion of the Sun and the Moon, proposed, while working at Rhodes around 150 BC, a star classification system based on their apparent bright to the naked eye, starting from the brightest (i.e. stars of first magnitude, $m=1$, e.g. Sirius, Canopus, α -Centauri, Vega), then what he took as half-as-luminous that the first class ($m=2$), until the last discernible class (he reached at the 6th magnitude, $m=6$, for the faintest visible stars). He included around 850 stars in his catalogue (magnitudes and positions; he did not

include the Sun as a star), which was slowly being enlarged (some 300 years later, there were around 1000 stars in Ptolemy's Almagest), until the telescope development in 1609 and the Hubble space telescope in 1990 (one may see up to $m=10$ with good binoculars, up to $m=25$ with the best telescope on Earth, and up to $m=30$ with Hubble space telescope; to be followed by Gaia (launch in 2011, position and motion of 10^9 stars), and by the much larger James Webb's space telescope, with a 6 m diameter mirror and $m=32$). Notice the exponential increase in number of stars with decreasing magnitude: in Ptolemy's Almagest there were about 10 stars amongst the 1st and 2nd magnitude, about 10^2 stars amongst the 3rd and 4th magnitude, and nearly 10^3 amongst the 5th and 6th magnitude. Planets (Gr. planet, wandering star) were visible but not included in the catalogue (the first celestial bodies discovered in modern times were Jupiter's four larger moons in 1610 with magnitudes around $m=5$, Uranus in 1690 with $m=6$, and Neptune in 1846 with $m=8$).

Hipparchus' magnitude system is just a relative dimensionless scale of luminous point intensity in the sky, based on human eye perception at night (scotopic vision, not the normal photopic sight). Recall that our eyes have two types of photoreceptors; rods for grey-levels, and cones for colours; rods are more abundant (120 million) and sensitive than cones and have a higher proportion around the edges of the retina; cones are less abundant (7 million, adding up all: red, blue and green), less sensitive, and more clustered near the centre of the retina; that is why we can hardly discern colours by night. By daytime, the Sun light scattered by the atmosphere prevents us from seen any other celestial body (the Moon, Venus, and some other bright objects may be seen at dawn and dusk). Astronomy observation is thence a night work (besides, celestial bodies are closer to the Earth by night). Scotopic vision (night vision), once adapted (it takes the eye some time to adapt to darkness) is centred around $\lambda=495$ nm, with a maximum luminous efficacy of 1700 lm/W at around 507 nm, whereas photopic vision is centred at $\lambda=555$ nm, with a maximum luminous efficacy of 683 lm/W at 555 nm (the V-filter in astrophysics has a 505..595 nm window).

Luminous intensity, I , refers to the brightness of point-like sources, measured in candelas (cd) in the SI when the human vision filter is accounted for, or in watts per steradians (W/sr) when the whole spectrum of the radiation is accounted for. Stars are seen as point light sources because their angular dimension (diameter divided by distance) is below the angular resolution, θ , of the eye and most telescopes, which is limited by diffraction effects to $\theta=1.22\lambda/D$ (Rayleigh criterion), with λ being the wavelength of light, and D the aperture of the optical system (lens diameter, or primary-mirror diameter). Point-like sources separated by an angle smaller than the angular resolution cannot be resolved. Some luminous intensity values are: the Sun, $I=2.5 \cdot 10^{27}$ cd; a 100 W lamp, around $I=100$ cd; a candle flame, around $I=1$ cd; notice that all three examples are really extended objects and thus these point-source values only apply to distances larger than the source size (e.g., $I=2.5 \cdot 10^{27}$ cd for the Sun, means that it shines with $2.5 \cdot 10^{27}$ lm/sr on far objects from its centre, i.e. that the Sun emits $\Phi=4\pi I=4\pi \cdot 2.5 \cdot 10^{27}=31 \cdot 10^{27}$ lm. Recall that, the candela is defined (CGPM-1979) as the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540 \cdot 10^{12}$ Hz and that has a radiant intensity in that direction of $1/683$ W/sr. The luminous efficiency or efficacy of the Sun, $\Phi_{\text{vis}}/\Phi_{\text{total}}=(31 \cdot 10^{27} \text{ lm})/(385 \cdot 10^{24} \text{ W})=80$

lm/W, is just 12 % of the reference standard maximum (683 lm/W for monochromatic radiation of $\lambda=555$ nm); we see that the Sun is a poor lighting device (it is a much better heater).

For extended objects (i.e. when their angular size can be resolved, e.g. for the Sun seen from the Earth, the angular diameter is 0.0093 rad, and its solid angle $68 \cdot 10^{-6}$ sr; see below), luminance can be used (i.e. brightness of a patch in a wide light source), instead of luminous intensity (brightness of a point light). Luminance, L , is the photometric measure of the luminous power per unit normal cross-section area in a given solid-angle direction (the SI unit being cd/m²). When all wavelengths in radiation are considered, the radiometric quantity is called radiance, i.e. radiant power per unit normal area and given solid-angle direction (the SI unit being W/(m²·sr)). A few luminance values are: $L=1.6 \cdot 10^9$ cd/m² for the Sun at the zenith in a clear day, some 10^7 cd/m² for a lamp filament, some 10^4 cd/m² for daylight, a fluorescent tube, and a candle flame, some 4000 cd/m² for full moon at the zenith (falling to 2 cd/m² at moonrise and set, where 40 equivalent atmospheres are interposed), etc. Luminance values do not depend on either the size of the object (it is a unit-area value) nor on the distance to the observer (it is a unit-solid-angle value).

Hipparchus' magnitude system gives a comparative measure of luminous intensities of celestial bodies as if all were at the same distance to the viewer (a celestial sphere of unknown, but unique, radius). These means that, if a constant luminance were assume for all celestial bodies, the magnitude would measure the solid angle subtended (in a logarithmic scale, as explained below), i.e. the size of the stars (magnitude).

In the 19th century, objective measurement of luminous intensity was developed (first by Herschell, regulating telescope aperture, and later by photographic exposure), and these photometric star magnitudes were calibrated against the subjective Hipparchus scale, assuming a logarithmic eye response, i.e. 'brightness proportional to logarithm of intensity', following the general Weber-Fechner law of human response to a physical stimulus (other models may yield a better fit, as the Stevens' power law). The scale is extrapolated to brighter and fainter objects, and real numbers instead of integer values are assigned; notice that negative, counter-intuitive, magnitude values occur because the magnitude number increases with decreasing brightness, and objects brighter than Hipparchus's brightest are now included. It was found (Pogson 1856) that old magnitude levels really correspond to a ratio of around 2.5 times in luminosity, instead of the half-as-bright subjective Hipparchus' scale; the most precise matching found was that a jump of 5 apparent magnitudes (from the 1st to the 6th) corresponded to a luminosity ratio of 100, and this equivalent factor was adopted, $100^{1/5}=10^{2/5}=2.512$ instead of the original 2 or the rough 2.5; that is why the factor 2/5 appears in all astronomical magnitude calculations where logarithms to the base 10 are used, as in the luminous intensity ratio, I_1/I_2 , for two bodies of apparent magnitude m_1 and m_2 :

$$\frac{I_1}{I_2} = 100^{\frac{-(m_1-m_2)}{5}} = 10^{\frac{-2(m_1-m_2)}{5}} = e^{-4.6(m_1-m_2)} = 2.512^{-(m_1-m_2)}$$

The technology used to measure apparent magnitudes has evolved from the naked-eye astronomy of antiquity, to photography in the nineteenth and twentieth centuries and the incredible efficiency and

power of modern photoelectric techniques (CCD matrix). The apparent magnitude of a celestial body is then a measure of its visual brightness as seen by an observer on the Earth surface (with appropriate instruments, if not visible to the naked eye), normalized to the value it would have in the absence of the Earth's atmosphere and using the visual waveband (V-filter; CCDs are most sensitive around 700 nm), taking the brightness of the star Vega as reference ($m=0$), although, lately, a fixed radiant flux was adopted and a value of $m=0.03$ was ascribed to Vega. This magnitude system was extended to be applied not only to stars but to any celestial body (Table 2), including extended objects like the Sun (with $m=-26.7$) and the Moon (with $m=-12.7$ at full moon, but $m=-10.7$ at half moon; see details below). The ISS has a maximum apparent magnitude of $m=-4.5$ (at perigee and opposition), nearly the same as Venus, the brightest planet (also known as the morning star, or the evening star), shining nearly 150 times brighter than a first magnitude star ($I_V/I_1=2.512^{-(4.4-1)}=145$); Venus' magnitude varies in brightness from -4.4 to -3.7 . Sputnik-I was a faint object in the sky ($m=6$), but its second-stage rocket, made highly reflecting on purpose, was visible from the ground at night as a first magnitude object following the Sputnik-1 (ahead of the satellite flew the payload fairing, also of $m=6$). Note that a comet of magnitude 5 will not be as easy to see as a star of magnitude 5, because that same amount of brightness that is concentrated in a point for the star is spread out over a region of the sky for a diffuse comet with a relatively-large coma. Besides the apparent visual magnitude just described, Table 2 presents the distance to the celestial body (from the Earth), and its absolute magnitude, temperature, and radiant power, to be discussed below.

Table 2. Astronomical magnitude for celestial body brightness (in distance order). The parsec is the distance subtending a second-of-arc parallax from 1 ua distance (1 pc = 206265 ua = 3.26 light-years = $30.86 \cdot 10^{15}$ m)

	Distance to Earth d [m]	App. magn. m	Abs. magn. M	Temp. T [K]	Radiant power Φ [W]
Moon ^{a)}	$385 \cdot 10^6$	(max) -12.7	0.25	274	$11.5 \cdot 10^{15}$ W
Venus ^{b)}	(min) $38 \cdot 10^9$	(max) -4.4	30	750	$96 \cdot 10^{15}$ W
Mars ^{c)}	(min) $56 \cdot 10^9$	(max) -2.9		220	$6.8 \cdot 10^{15}$ W
Sun	$150 \cdot 10^9$ ($4.85 \cdot 10^{-6}$ pc)	-26.74	4.83	5800	$385 \cdot 10^{24}$ W ($\equiv 1$ Sun)
Jupiter ^{d)}	(min) $590 \cdot 10^9$	(max) -2.9	27	165	$1200 \cdot 10^{15}$ W
α -Centauri AB ^{e)}	$42 \cdot 10^{15}$ (1.34 pc)	-0.27	4.4	5800	1.5 Sun
Sirius	$82 \cdot 10^{15}$ (2.64 pc)	-1.44	1.45	9900	22.5 Sun
Vega (α -Lyra)	$240 \cdot 10^{15}$ (7.76 pc)	0.03	0.58	9600	50.1 Sun
Arcturus	$350 \cdot 10^{15}$ (11.25 pc)	-0.05	-0.31	4300	114 Sun
Canopus	$3100 \cdot 10^{15}$ (100 pc)	-0.72	-5.53	7350	13 600 Sun
Polaris	$4030 \cdot 10^{15}$ (130 pc)	1.97	-3.64	7200	2 400 Sun
β -Centauri	$5000 \cdot 10^{15}$ (161 pc)	0.60	-5.4		12 000 Sun

^{a)}Moon-to-Earth distance varies from $363 \cdot 10^6$ m to $406 \cdot 10^6$ m; quoted magnitudes are for full moon (apparent magnitude falls to $m=-10.7$ at half moon, and $m=-1$ at totally eclipsed moon; surface temperature varies from 60 K at the Poles to 390 K behind the sub-solar point at the equator.

^{b)}Venus-to-Earth distance varies from $38 \cdot 10^9$ m to $260 \cdot 10^9$ m; apparent magnitude varies from $m=-4.6$ when crescent (the closest to the Earth) to $m=-3.8$ when gibbous or full (it is further); surface temperature varies very little.

- ^{c)}Mars-to-Earth distance varies from $56 \cdot 10^9$ m to $401 \cdot 10^9$ m; apparent magnitude varies from $m=-2.9$ at perihelic opposition to $m=+1.8$ at conjunction; surface temperature varies from 190 K at the Poles to 270 K behind the sub-solar point at the equator.
- ^{d)}Jupiter-to-Earth distance varies from $590 \cdot 10^9$ m to $960 \cdot 10^9$ m; apparent magnitude varies from $m=-2.9$ at perihelic opposition to $m=-1.6$ at conjunction; surface temperature is around 165 K when pressure is 100 kPa (it is a dense-gas planet). Jupiter emits about 50 % more radiant power than what it absorbs from the Sun, due to internal nuclear reactions.
- ^{e)}Alpha-centauri is a triple star system with the brighter two, α -Centauri-AB, forming a close orbiting binary, the nearest visible star, 'only' 4.4 light-years away (it was first measured by T. Henderson in 1832; but he did not published the result because he thought it was too large); the third star, Proxima (or α -Centauri-C) is closer, 4.2 light-years, but too faint to the naked eye, $m=11$, $M=15.5$, $\Phi=57 \cdot 10^{-6}$ Sun).

Radiant power is a characteristic of the body and does not depend on the observer (e.g. the Sun power is $\Phi=A\sigma T^4=385 \cdot 10^{24}$ W, with $A=6.1 \cdot 10^{18}$ m²), and the same for radiant power density emitted (e.g. the Sun emittance is $M=\sigma T^4=63 \cdot 10^6$ W/m²). On the other hand, the radiant power density received by an observer from a body depends on the observer's distance to the source (e.g. the Sun irradiance is $E=1360$ W/m² at the mean Sun-Earth distance of $150 \cdot 10^9$ m, 1 ua), and for three-dimensional emissions it decreases with the square of the distance. Radiance, like luminance, do not depend on either the size of the object nor on the distance to the observer (e.g. the Sun radiance is $L=M/(\pi)=20 \cdot 10^6$ W/(m²·sr); its luminous efficiency or efficacy, $\Phi_{vis}/\Phi_{total}=L_{vis}/L_{total}=(1.6 \cdot 10^9 \text{ cd/m}^2)/(20 \cdot 10^6 \text{ W/(m}^2 \cdot \text{sr)})=80 \text{ lm/W}$, i.e. 12 % of the reference standard: 683 lm/W for monochromatic radiation of $\lambda=555$ nm; we see that the Sun is a poor lighting device (it is a much better heater). The temperature of a star can be determined from its radiance assuming it emits like a black-body, $\pi L=\sigma T^4$ (e.g., for the Sun, $L=20 \cdot 10^6$ W/(m²·sr), and $T=(\pi \cdot 20 \cdot 10^6/(5.67 \cdot 10^{-8}))^{1/4}=5800$ K).

Angular diameter

To compute astronomical distances by triangulation, precise angular measurements are first required. The angular diameter, θ , of a spherical object of radius R_O , as seen from a given position (e.g. the Earth), is roughly its diameter divided by the distance to the observer, R_{OE} , i.e. $\theta=2R_O/R_{OE}$. The human eye can resolve, in the average, 1 arc-minute ($1'=291 \cdot 10^{-6}$ rad, i.e. 0.3 mm separation at 1 m distance). The angular resolution is limited by diffraction effects to $\theta=1.22\lambda/D$ (Rayleigh criterion), i.e. to $\theta=1.22 \cdot 0.5 \cdot 10^{-6}/1=0.6 \cdot 10^{-6}$ rad (around 0.1 arc-second, or 0.1"; $1''=4.85 \cdot 10^{-6}$ rad); however, the atmospheric filter makes ground-based telescopes to smear the image of a star to an angular diameter of about 0.5 arc-second in good conditions (and up to 1" or 2" in bad atmospheric conditions). Space telescopes are not affected by the Earth's atmosphere, but are still diffraction limited; for example the Hubble space telescope can reach an angular size of stars down to about 0.1".

The largest astronomical angular sizes (really a range, because of distance variation), as seen from the Earth, are: the Sun $\theta=31.6'..32.7'$, the Moon $29.3'..34.1'$, Venus $10''..66''$, Jupiter $30''..50''$, Saturn $15''..20''$, Mars $4''..25''$, Mercury $5''..13''$, Uranus $3''..4''$, Neptune is circa $2''$, Alpha Centauri A ca. $0.007''$, Sirius ca. $0.007''$, etc. Subtended solid angles, Ω , can be obtained from angular diameters by means of the relation $\Omega=\pi R_O^2/R_{OE}^2=(\pi/4)\theta^2$.

Astronomical distance

Distances to unreachable objects can be found by trigonometric triangulation, or, since the invention of radar in mid 20th century, by active sampling. But distances to stars cannot be found by triangulation from two land points, because the angular resolution needed is beyond the optical resolution of our eyes and common optical instruments.

Eratosthenes of Cyrene, the second chief librarian of the Great Library of Alexandria, around 250 BC, is credited with many relevant astronomical developments (besides the prime number sieve): he devised a system of latitude and longitude (and made a map of the known world), computed the Earth radius (by the angle of elevation of the Sun at noon on the summer solstice in Alexandria and in the Elephantine Island near Aswan), the tilt of the earth's axis, a most precise length of the year (suggesting the leap year), invented the armillary sphere (a model of the celestial sphere), and the distance to the Sun (according to a quoting by Eusebius of Caesarea, without any further indication; it was not incorporated to the scientific heritage).

Copernicus was able to determine approximate distances between the planets through trigonometry, relative to the distance between the Earth and the Sun, the astronomical unit (1 ua) first estimated by Jean Richer and Giovanni Domenico Cassini in 1672 by measuring the parallax of Mars from two locations on the Earth.

With the invention of radar, the distance to Venus could be determined very precisely (but the radar method is not applicable to the Sun because of the very poor reflection). As the planets orbit the Sun, their distance from us change, being the smallest at opposition' (when they are in the direct opposite direction from the Sun in our sky; the best times to study a planet in detail). The planet Mars reaches opposition every 780 days; because of their elliptical orbits around the Sun, some oppositions are more favourable than others; every 15 to 17 years, Mars approaches within $55 \cdot 10^9$ m to the Earth (at that time its angular size across its equator is 25.5 arc-seconds).

Absolute magnitude

Once astronomical distances are amenable to measure, the actual size of stars can be computed based on their apparent visual magnitude, although the apparent magnitude also depends on star temperature (most stars are colder than the Sun), and the presence of the atmospheric filter (when observing from ground), and interstellar dust. Nowadays, stars are classified with two parameters, absolute magnitude, and spectral type (colour, or temperature), but we only pursue here with absolute magnitude.

The absolute magnitude of a celestial body is a correction of the apparent magnitude to account for the actual distance to the observer, d , since the illuminance (in lux, $1 \text{ lx} = 1 \text{ lm/m}^2$) or the irradiance (in W/m^2 , if all the spectrum is considered) of a point source will be proportional to $1/d^2$ (the luminous intensity is preserved because it is by unit solid angle).

The absolute magnitude of a star, M (not to be confused with emittance, M), or of any celestial body outside of the solar system, is defined as the apparent magnitude it would have if it were 10 pc away (only a few stars are closer: α -Centauri at 1.3 pc, Sirius at 2.6 pc, Vega is at 7.8 pc...), i.e.:

$$M \equiv m - \frac{5}{2} \log_{10} \left(\frac{d}{d_0} \right)^2, \quad \text{with } d_0 = 10 \text{ pc} = 0.31 \cdot 10^{18} \text{ m}$$

where the 5/2 coefficient comes from the accepted calibration of 5 apparent magnitudes equal to 10^2 times measured irradiance, as explained above.

To better grasp the difference, consider two stars of comparable visual (apparent) magnitude, α -Centauri and β -Centauri ($m_\alpha = -0.3$ and $m_\beta = 0.6$), which happens to be at very different distances from Earth ($d_\alpha = 1.34$ pc and $d_\beta = 161$ pc). The latter has to be much more powerful than the former, to shine roughly the same being so farther away; thence, if we could move both stars to a common distance of $d_0 = 10$ pc, α -Centauri would be seen too much dimmer than β -Centauri (we can find the values $M_\alpha = 4.4$ and $M_\beta = -5.4$ from their apparent magnitudes and distances in Table 2); i.e. instead of α -Centauri being 2.2 times brighter (their luminous intensity ratio $I_\alpha/I_\beta = 2.512^{-(0.3-0.6)} = 2.2$), once the two stars are brought to 10 pc, β -Centauri would be 8300 times brighter ($2.512^{-(4.4+5.4)} = 0.00012$), their radiant power being 1.5 times and 12 000 times that of the Sun, respectively.

Exercise 5. Find the absolute magnitude for the Sun, and its relative brightness relative to full moon.

Sol.: The Sun is a star, thence:

$$M_S \equiv m_S - \log_{10} \left(\frac{d_s}{d_0} \right)^5 = -26.74 - \log_{10} \left(\frac{150 \cdot 10^9}{0.3 \cdot 10^{18}} \right)^5 = 4.83$$

The absolute magnitude of the Sun is $M = 4.83$ in the V band (i.e. the central visual band, around $\lambda = 555$ nm, yellow); it is $M = 5.50$ in the B band (blue band, 435 nm), $M = 5.60$ in the U band (UV band, 360 nm, and $M = 3.30$ in the K band (mid IR band of 2180 nm).

The relative brightness (relative luminous intensities) of the Sun to full moon is $I_S/I_M = 2.512^{-12.7 - (-26.7)} = 400\,000$ times brighter. Their apparent sizes being quite the same, the above relation applies also to luminance values, $L_S/L_M = (1.6 \cdot 10^9 \text{ cd/m}^2) / (4000 \text{ cd/m}^2) = 4 \cdot 10^5$.

Even for an observer in Neptune, 30 ua away, the Sun would be the brightest star at sight $15 \cdot 10^6$ times brighter than the next (Sirius), although extending only 60 arc-seconds in the sky instead of 30 arc-minutes (about the same angular diameter than Jupiter from the Earth).

However, for solar planets (or any other solar-system body), the absolute magnitude, M (the symbol H is also used), is the apparent magnitude it would have if it were 1 astronomical unit away from both the Sun and Earth (i.e. at a phase angle of zero degrees, what is a physical impossibility, as it requires the

observing telescope to be at the centre of the Sun, but it is convenient for purposes of calculation). Absolute magnitude for planets is thus defined by:

$$M \equiv m(\phi) - \frac{5}{2} \log_{10} \left(\frac{d_{bs}^2 d_{bo}^2}{p(\phi) d_0^4} \right), \quad \text{with } d_0 = 1 \text{ AU} = 150 \cdot 10^9 \text{ m, and } p(\phi) \equiv 2 \int_0^\pi \frac{L(\phi)}{L(0)} \sin \phi d\phi$$

with d_{bs} being the distance body-to-Sun, d_{bo} being the distance body-to-observer, d_0 a reference distance (1 ua), and $p(\phi)$ the phase integral, defined in terms of measured radiances to correct for the actual phase of the body corresponding to the apparent magnitude measurement, m , which depends on the phase angle, ϕ . From the cosine law of triangles:

$$\phi = \arccos \frac{d_{bs}^2 + d_{bo}^2 - d_{os}^2}{2d_{bs}d_{bo}}$$

The phase integral, $p(\phi)$, can be analytically deduced for the ideal case of a perfect spherical diffuser at large distances, yielding:

$$p(\phi) = \frac{2}{3} \left[\left(1 - \frac{\phi}{\pi} \right) \cos \phi + \frac{1}{\pi} \sin \phi \right]$$

which yields $p(0) = 2/3$ at opposition (i.e. for zero phase angle), and $p(\pi/2) = 2/(3\pi)$ at quadrature (i.e. at 90 degrees to the observer-Sun line of sight). Notice that a full-phase diffuse sphere reflects 2/3 as much light as a diffuse disc of the same diameter in the illumination direction, although the integral along all directions is the same: for the planar disc $\int_0^{\pi/2} \cos \phi 2\pi \sin \phi d\phi = \pi$, and for the sphere $\int_0^\pi p(\phi) 2\pi \sin \phi d\phi = \pi$.

To convert a stellar or galactic absolute magnitude into a planetary one, you have to subtract 31.57, which is the factor corresponding to the difference between the Sun's visual magnitude of -26.74 and its (stellar) absolute magnitude of $+4.83$.

Finally notice that there has been found a simple empirical relation between the total radiant energy emitted by a star (only applicable to stars in the main sequence) and its absolute magnitude, $\Phi_1/\Phi_2 = (M_1/M_2)^{3.9}$, but there is no relation between visual magnitudes and emission in planets and moons.

Exercise 6. Find the absolute magnitude for the Moon, at full moon and at half moon, using the perfect diffuser model for the phase integral, knowing the corresponding apparent magnitudes $m_{M\text{full}} = -12.7$ and $m_{M\text{half}} = -10.7$.

Sol.: For planets and moons in the solar system:

$$M_M \equiv m_M - \frac{5}{2} \log_{10} \left(\frac{d_{Ms}^2 d_{Mo}^2}{p(\phi) d_0^4} \right) = -12.7 - \frac{5}{2} \log_{10} \left(\frac{(150 \cdot 10^9)^2 (385 \cdot 10^6)^2}{\frac{2}{3} (150 \cdot 10^9)^4} \right) = -0.19$$

where the value for full moon, $p(0)=2/3$, has been substituted. The actual value for the absolute magnitude of the Moon is $M_M=+0.25$; the deviation is due to the non-Lambertian behaviour of the Moon surface.

At half moon, $p(\pi/2)=2/(3\pi)$, and with $m_{M\text{half}}=-10.7$, we have:

$$M_M \equiv -10.7 - \frac{5}{2} \log_{10} \left(\frac{(150 \cdot 10^9)^2 (385 \cdot 10^6)^2}{\frac{2}{3\pi} (150 \cdot 10^9)^4} \right) = 0.57$$

which should be the same (the absolute magnitude was defined to be independent of the phase angle). The drawbacks in this comparison have been pointed above.

Albedo

Albedo is the reflected fraction of the solar radiation shining on a celestial body (i.e. coming from the Sun, and reflected or scattered by the planet surface and its atmosphere, if any). By extension, the reflectance of any object to solar radiation is termed albedo (the object must reflect diffusively; mirrors are not included).

What is usually measured is normal albedo (i.e. reflectance in the incident direction), usually assumed to be independent of direction and wavelength, but, as more precise measures become available, different albedo definitions are introduced. First, one may distinguish between global albedo (when the whole body is considered, e.g. the Moon), and local albedo (when only part of the body surface is considered, e.g. a lunar crater). Besides, one may consider all angular directions (e.g. hemispherical solar reflection at the Moon) or just a particular direction (e.g. the reflection we see at half moon). Finally, one may consider the whole solar spectrum at a time, or analyse the solar reflection as a function of wavelength. The most common terms are thence:

- Bolometric albedo of a body (also called Bond albedo in the case of planets and moons) is the quotient between reflected energy (in all directions and wavelengths) and incident solar energy (i.e. total hemispherical reflectance of the object). Bond albedo directly enters into the energy balance for the Earth and celestial bodies other than stars, because, for the steady state of a non-dissipative body (i.e. without important nuclear reactions in its interior), the energy balance is: ‘energy in’ (absorbed) equals ‘energy out’ (emitted): $(1-\rho)E\pi R^2=4\pi R^2\varepsilon\sigma T^4$, if it is assumed isothermal. Unfortunately, Bond albedo is difficult to measure, because we only see celestial bodies at night (at low phase angles) from the Earth (we can only see from the rear Mercury, Venus and the Moon; Mars, the closest exterior body, shows phases that always let at least 87 % of its cross-section illuminated). The Bond albedo of the Moon is $\rho=0.12$, meaning that 88 % of sunshine is absorbed and 12 % reflected (scattered). There are other celestial bodies with very low albedo, like Mercury (12 %), and others with very large albedo (Enceladus, an icy moon of Saturn, has the largest albedo in the solar system, with $\rho=0.99$). Venus is fully cloud covered, and has a large albedo, around $\rho=0.68$. Details of Earth and Moon albedo are treated below. Mars albedo is also low, $\rho=0.15$, and peaks around 700 nm; that is why it is named the ‘red planet’.

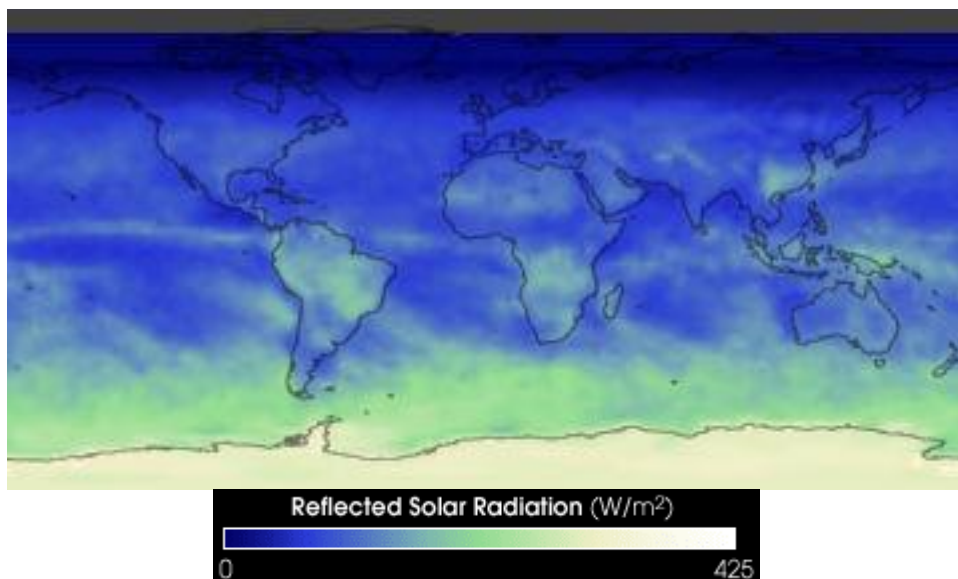
Exterior planets have larger albedo values. In comparison, charcoal and water reflect less than 5 %, whereas white paper and metals may reflect 95 % or so.

- Spectral albedo is the relative reflectance of a narrow-band part of solar energy. In thermal control studies, albedo is usually assumed to be independent on solar-radiation wavelength, in spite of the fact that reflectance usually drops with increasing wavelength; e.g. the Earth reflects solar radiation non-uniformly along the spectral wavelength: some 50 % in the UV, 40 % in the visible, and 20 % in the near IR, with a maximum around 470 nm. In this respect it must be pointed out that the word albedo is sometimes used as a synonym of reflectance for incident radiations other than Sun shine (e.g. microwave albedo).
- Normal albedo is the bidirectional reflectance when a surface is frontally illuminated (with Sun light) and observed along the same direction (i.e. measured with a photometer normal to the surface). When the observer is on the Earth surface, the exact normal albedo of a celestial body cannot be measured because it would be under eclipse (e.g. full moon is at least 1.5° off the Sun-Earth axis). Normal albedo distribution on the Moon cannot be measured from Earth because we always see the same face of the Moon (we can only measure normal albedo at its centre), although albedo distribution on full moon is sometimes said normal albedo. However, retro-reflecting properties of regolith in bare celestial bodies has an important effect on directional albedo; e.g. we measure from the Earth an average quasi-normal Moon albedo of $\rho=0.09$ (it varies point to point from 0.07 to 0.30), whereas the real average normal albedo (measured from satellites) is $\rho=0.12$.
- Lateral albedo is the bidirectional reflectance of a given surface (a whole body or a patch) when illuminated in one direction by sunlight, and viewed from another direction (the angle in between is called phase angle, ϕ); e.g. half-moon brightness ($\phi=\pi/2$) is globally 10 times smaller than full-moon brightness, and local brightness is maximum at the lit limb, decreases to zero at the terminator, and remains null on the dark side (neglecting earthshine). Notice that when a constant uniform light beam (like sunshine at 1 ua), shines on a diffuse planar surface, the light reflected back along the shining direction should fall as $\cos\beta$ with the angle this common direction forms with the surface normal, if the surface is Lambertian; thence, a frontally illuminated sphere would show brighter at the centre and dark at the limb, but real rough surfaces show important retro-reflection effect that make them appear more uniformly brilliant. As said above, the global Bond albedo of the Moon is $\rho=0.12$ (which happens to coincide with its normal albedo), and we see a nearly uniform bright distribution with $\rho=0.09$ at full moon (1.5° off-axis), and an average of $\rho=0.009$ at half moon (10 times less luminance, due to the strong retro-reflection at full moon, because for a perfect diffuse sphere this ratio would be just π).
- Geometric albedo is an astronomical term used to measure normal brightness relative to a perfect diffuser, i.e. the quotient between normal albedo measured, and that corresponding to a perfect diffuser frontal planar disc of the same cross-section, or, in terms of Bond albedo ρ_B and the phase integral, $p(\phi)$, defined above, geometric albedo, $\rho_g \equiv \rho_B/p(\phi)$. Bond albedo may be greater or smaller than the geometric albedo, depending on surface and atmospheric properties of the body in question, but be warned that the geometric albedo may be larger than unity, as for Enceladus, which has $\rho_B=0.99$ and $\rho_g=1.4$, what simply means that it reflects in the incoming direction 40 % more than an ideal spherical diffuser.

Terrestrial albedo

Leonardo da Vinci was the first to explain, around the year 1500, that the dark whiteness of the moon (that allows viewing the whole moon contour and not just the Sun-shine area, even with new moon) was due to the reflection of Earth albedo on the Moon (i.e. secondary albedo, called earthshine).

The Earth's albedo has a mean value of $\rho=0.30$ (i.e. 30 % of solar irradiance is reflected back in all directions, and the remaining 70 % is absorbed), varying a lot (Fig. 6) with location (around $\rho=0.23$ at the Equator, and $\rho=0.7$ at the Poles, that is why an average of $\rho=0.25$ is sometimes used for low-inclination orbits, and an average of $\rho=0.40$ for polar orbits), season, weather, wavelength and viewing direction; it would be around 0.09 without clouds (ocean $\rho=0.05$, land $\rho=0.2$), but clouds and ice may reflect up to $\rho=0.8$. The Earth's albedo spectrum is nearly all in the visible range, since reflectance in the IR is much lower (only important in metallised surfaces). Tilted reflection introduces some polarisation, but it is of no interest in thermal problems. Directional effects may affect albedo intensity too, as for the Moon albedo, analysed below. Cloud cover has a controlling influence in Earth's albedo; white thin high-clouds like cirrus tend to cool the Earth because they have little greenhouse effect, in spite of their relatively low albedo ($\rho=0.2..0.4$), whereas dark thick low-stratocumulus tend to heat up the Earth by an increased greenhouse effect, in spite of their higher albedo ($\rho=0.4..0.8$); this effect is more prominent in cumulonimbus, the great vertical extent clouds with white highly-reflecting tops ($\rho=0.9$) and very dark bottoms, associated to thunderstorms.



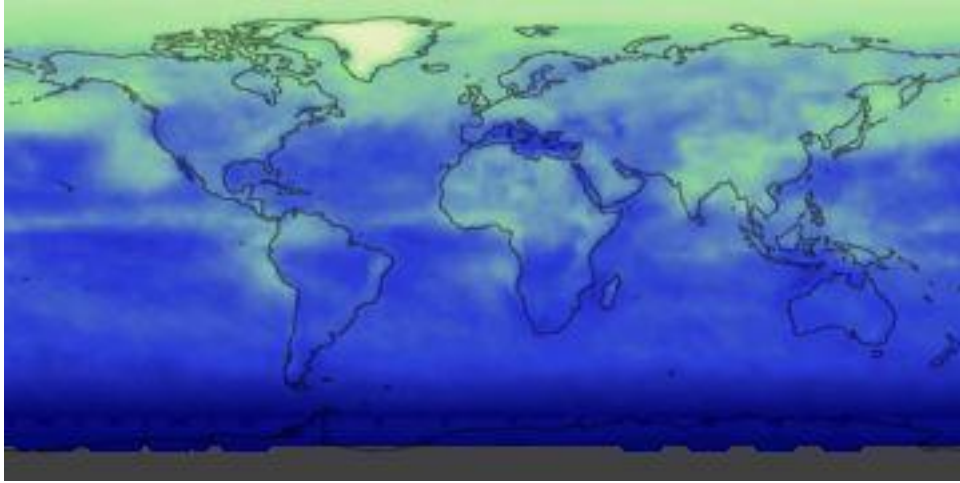


Fig. 6. Solar power reflected per unit of projected area in Jan-2005 (maximum reflection from Antarctic summer) and Jul-2005 (maximum reflection from Greenland summer). Albedo values can be obtained by dividing solar irradiance, E ($E=1410 \text{ W/m}^2$ in the former case, and by $E=1320 \text{ W/m}^2$ in the latter).

The Earth has a larger albedo than the Moon ($\rho_E/\rho_M=0.30:0.12=2.5$), and larger size ($(R_E/R_M)^2=(6370/1740)^2=13.4$). An observer on the Moon will see ‘full Earth’ (at new moon) 4 times wider than the Sun disc, and 100 times brighter than we see full moon, corresponding to an apparent magnitude (if the observer reference point is exchanged in the definition of apparent magnitude) of $m=-17.7$ (as can be checked from the full moon magnitude, $m=-12.7$, and the ‘brightness’ ratio, $I_E/I_M=2.512^{-(m_E-m_M)}=2.512^5=100$); notice that the illuminance it creates on the lunar surface is around 20 lx, a good value for ‘ambient light’ in a living room, and for outdoor night lighting (Apollo 8 astronauts described relief features flying over the dark side of the Moon); full moon shine yields around 0.25 lx on the Earth surface (although it may reach 1 lx at great altitudes near the equator); good reading light is about 200 lx (up to 2000 lx for precision work, matching natural diffuse light; maximum Sunlit yields nearly 100 000 lx). Notice also that the brightness ratio (100:1) does not coincide with the product of Bond albedo ratio ($0.30:0.12=2.5$) times area ratio (13.4), which is $2.5 \cdot 13.4=34$, because of atmospheric absorption and directional effects.

The importance of Earth’s albedo in STC decreases with orbit altitude due to the decreasing view factor, as shown in Fig. 7, and the same happens for planetary IR emission (outgoing longwave radiation, OLR); notice that their effects are negligible at GEO distances (maximum albedo load on a facing plate at GEO is 7.2 W/m^2 , and Earth emission 5.5 W/m^2 , against the 1360 W/m^2 solar flux), and in general for altitudes greater than the planet radius. Fortunately, even in the case of LEO, there is no need to know the details of the sub-satellite scene (cloud coverage, water, land, ice, vegetation...), because the high speed ($>7 \text{ km/s}$ at LEO) and the thermal inertia of the spacecraft smooths all the details. However, when low-thermal-inertia critical items in LEO have to be analysed (minimum relaxation time considered is 100 s), a coldest case value of $\rho=0.06$ and a hottest case value of $\rho=0.50$ should be considered, since it this been found to happen statistically every 10 days or so.

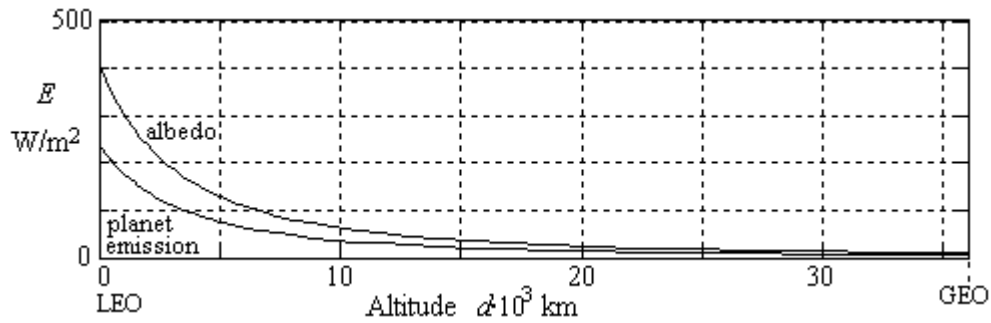


Fig. 7. Spacecraft heat loads from Earth albedo and planet emission vs. altitude.

Lunar albedo

What we see from planets, moons, comets, asteroids, and artificial satellites, is their albedo. The lunar albedo, of course, is the one we got used to, too often without paying attention to its features. Already Anaxagoras in 428 BC recognised that what we see from the Moon is the reflected light from the Sun (he described both celestial bodies as giant spherical rocks). If the Moon were a perfect diffuser (it is not), and if we looked at it with the Sun behind us (it is impossible to do it from the Earth surface because this would occlude sunshine; the Moon must be at least 1.5° out axis, to be lit), we would see a lit disc brighter at the centre, because if a patch dA is not perpendicular to the Sun-viewer-lunar axis but tilted an angle β ; it would get a solar power $EdA\cos\beta$; and the reflected power would be directly proportional, i.e. proportional to $\cos\beta$, which would have a component $\cos^2\beta$ along the viewing direction, but, as we see a real surface $dA/\cos\beta$ behind a frontal area dA , the final dependence is as $\cos\beta$. However, the real Moon, when observed under that condition from a spacecraft (the shadow on the Moon is then negligible) or from the Earth close to a lunar eclipse, it appears nearly uniformly bright, even more brilliant towards the edges (its limb) due to a marked retro-reflecting effect of the regolith, and darker at land depressions (the maria).

When the Moon is observed not in full moon but in a partially lit phase, say at a quarter (i.e. when we see half the disc illuminated), we do not see a uniform brightness in the lit side but a brighter rim at the lit limb and a darker terminator (recall that the lunar features, maria and highlands, do not change with lunar phases, since the Moon rotates synchronously with its translation around the Earth, with a synodic period of 29.5 days).

The global albedo of the Moon (Bond albedo) is around 12 %, but it is strongly directional and non-Lambertian, displaying also a strong retro-reflector effect caused by the very porous first few millimetres of the lunar soil (that is why full moon is much more brighter than half moon); the mean lunar albedo, as seen from the Earth is rather low, 7 %, as the result of the porous upper layers, which cast shadows over a substantial percentage of the visible surface. A Cartesian trihedral made of mirrors is a nearly perfect retro-reflector, as can be explained by a drawing, following a few light-ray reflections.

Celestial bodies without clouds or icy covers like the Moon, have small albedo values, because their surface is made of loose heterogeneous soil material (regolith) covering the rock substrate. In the Moon, the first few centimetres of regolith is made of soft dusty sand with 12 % albedo (only 7 % along the

normal). Moon spectral albedo varies from $\rho=0.1$ at $\lambda=0.4 \mu\text{m}$ to $\rho=0.2$ at $\lambda=1 \mu\text{m}$. The retro-reflector effect is caused by the very porous first few millimetres of the lunar soil, made of tiny glassy spheres formed when the molten splashing from meteorite impact cools and solidify.

Planet emission

All bodies, celestial or not, emit thermal radiation according to their temperature. All planets and moons in the solar system emit in the non-visible infrared region of the spectrum because they are not too hot; the hottest body is Venus with 735 K at its surface, well below the visible threshold of around 1000 K (besides, because of a huge greenhouse effect by Venus thick atmosphere of CO_2 , Venus emission is low).

The emitted power per unit surface, M , from celestial bodies is measured with infrared detectors from spacecraft, or with microwave detectors from the Earth surface (to avoid the atmospheric filter effect), taking care in all cases to avoid albedo contributions in M . Celestial body temperatures can be estimated by assuming black-body properties and using Stefan-Boltzmann's law $M=\sigma T^4$, or by assuming grey body (emissivity independent of wavelength) and using Wien's displacement law, $\lambda_{Mmax}=C/T$, with $C=2.8978 \cdot 10^{-3} \text{ m}\cdot\text{K}$. If the surface temperature of the celestial body is not determined by Stefan-Boltzmann's law (e.g. if it is computed by Rayleigh-Jeans approximation in the radio range, $M=2k_B T/\lambda^2$ [$\text{W}/(\text{m}^2 \cdot \text{Hz})$]), an emissivity can be defined by $M=\varepsilon\sigma T^4$. For instance, average Earth emissions is $240 \text{ W}/\text{m}^2$, corresponding to a black-body at 255 K, or to a real body at 288 K with an emissivity $\varepsilon=0.61$. For most critical items (with relaxation time above 100 s in any case), planet emissions in the range of $110 \text{ W}/\text{m}^2$ to $330 \text{ W}/\text{m}^2$ should be considered, for low Earth orbits.

Planet emission is the radiation emitted by the planet as a direct consequence of its temperature, although in practice it is measured as the exitance in the infrared range of the spectrum, thus including the tiny contribution of the planet reflectance to solar radiation in this range, which is some 7 % of the emission for the Earth.

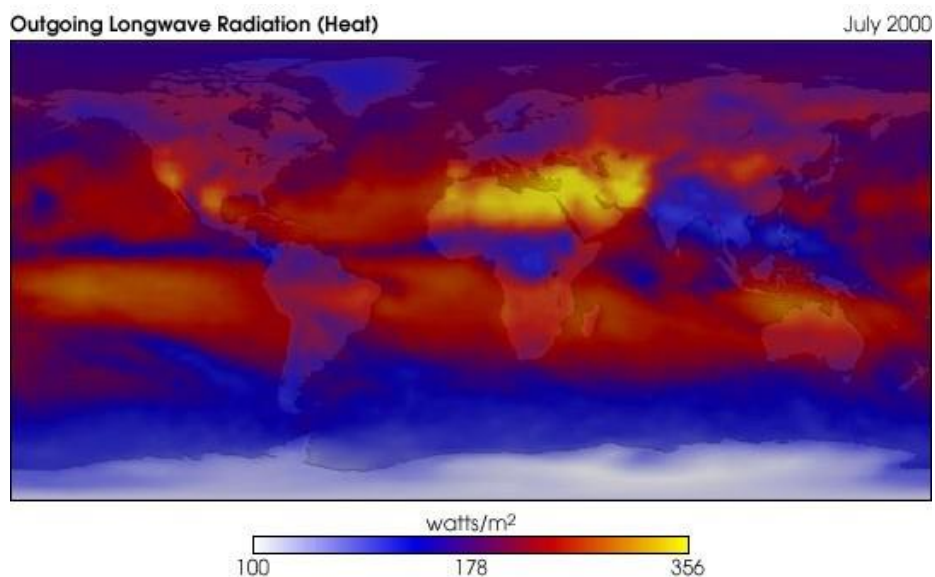


Fig. 8. Earth infrared exitance measured from satellites, corresponding to atmospheric emission plus surface emission transmitted through the atmosphere, i.e. $M_{total}=\varepsilon_{atm}IR\sigma T_a^4 + \tau_{atm}IR\varepsilon_{surface}\sigma T_s^4$. Notice maximum emission from North Africa and Middle East. (NASA source).

Exercise 7. Find the variation with orbit altitude, H , of the heat load on a perpendicular plate, due to Earth's IR emission, knowing that the view factor of a sphere from a small frontal plate is $F=1/(1+(H/R)^2)$.

Sol.: Knowing that for small altitudes, $H \ll R$, Earth emission corresponds to a grey body with an emissivity $\varepsilon=0.6$ at a mean temperature of $T_p=288$ K, infrared irradiance from the close-up planet is $E_p=\varepsilon\sigma T_s^4=0.6 \cdot 5.67 \cdot 10^{-8} \cdot 288^4=234$ W/m² (roughly the average 240 W/m² measured), decreasing with altitude with the given law, $E_p=F\varepsilon\sigma T_s^4$, plotted in Fig. 7 above.

Thermal characteristics of planetary missions

Knowledge of planetary environments is required to predict thermal loads in planetary orbits and flybys, both for unmanned spacecraft, and for human exploration.

Until the [Space Age](#) in the second half of the 20th century, our knowledge was by remote observation; initially with the unaided eye and then with the telescope; the highest explored altitude before WWII was 22 km in a crewed balloon flight in 1935, but in 1959 a robotic spacecraft (Luna 1) already scaped from Earth to perform a fly-by of the Moon.

Spacecraft have landed on the Moon (USA Apollo in 1968, with crew on 1969), Venus (URSS Venera 7 in 1970), Mars (USSR Mars 2 in 1971), Jupiter (USA Galileo probe 'landed' on the thick atmosphere in 1995), Titan (Cassini-Huygens probe in 2005), Eros asteroid (shoemaker-NEAR probe in 2001), Churyumov-Gerasimenko comet (Rosetta's Philae probe in 2014)...Voyager 1 is the furthest of any human-made objects from the Sun (in August 2013, at 125 ua, it was the first man-made object to leave the solar system, and it is still sending and receiving data). Human exploration in the EU is coordinated at ESA under the AURORA programme, with Mars as its main objective and the Moon a very likely intermediate step.

When a spacecraft is in the neighbourhood of a celestial body other than the Earth, the same rules apply as when near the Earth, changing only the values of Sun-to-Planet distance, Planet diameter, and Planet thermal properties, namely planet albedo and sun-distance (for absorption), and planet reference temperature and emissivity (for emission). In the case of planetary atmospheres: Mars, Venus, the giant planets, and some of their satellites (Titan, a moon of Saturn, and Triton, a moon of Neptune, have noticeable nitrogen atmospheres), the aerodynamic heating on air-braking, descent, and to a lower extent on ascent, poses special problems to thermal control systems.

How to measure from Earth the temperature of a planet? Ans.: By using Planck's law, of course, but in which waveband, at λ_{Mmax} ? No; at radio waves, in spite of the low intensity at this tail of the spectrum, because the Earth (and planet) atmospheric filter in the IR would jeopardize the measurement otherwise.

Planet characterization for thermal radiation is usually based on the following assumptions:

1. Spherical geometry. Planets and large moons are quasi-spherical because they deform under their own large gravity forces. Relative size for planets and moons in the solar system is shown in Figs. 8 and 9.
2. Uniform diffuse reflector for solar radiation (i.e. uniform brightness).
3. Uniform temperature, or uniform day and night temperature, or uniform zonal temperature. Diurnal variations may be large on slow-rotating bodies: from 270 K to 300 K on Earth, from 90 K to 400 K on the Moon, from 140 K to 290 K on Mars, 80..700 K on Mercury.
4. Uniform black-body emitter for IR radiation, or grey-body (i.e. uniform brightness; metals look brighter at the periphery, and non-metals brighter at the centre), or semitransparent thin atmosphere layer plus opaque surface, or semitransparent thick atmosphere. In spite of lack of water, most planet atmospheres are cloudy.
5. Vertical temperature profiles are presented for main planetary atmospheres.

A summary of [planet and moon properties is compiled aside](#), including mass, geometry, orbit and thermal data; a visual size comparison is here presented for planets (Fig. 9), and for moons, (Fig. 10).

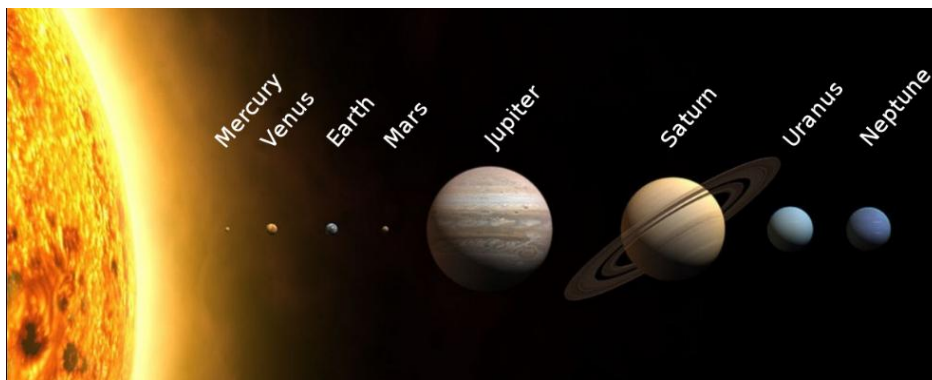


Fig. 9. Relative size of planets in the solar system (distances not to scale). [Wiki](#).



Fig. 10. Relative size of moons in the solar system. [Wiki](#).

Mercury

Environment. Translation period is 88 Earth-days and rotation is 58 Earth-days, what means that at a given place there is 176 Earth-days of sunshine and 176 Earth-days of shadow, with the consequence that surface temperatures are extreme (and corresponding planet IR too). Mercury orbit has the largest inclination to the ecliptic (7.0° , followed by Venus 3.4°), and the largest eccentricity $e=0.2$ ($R_{sp}=0.31$ ua at perihelion and $R_{ap}=0.47$ ua at aphelion) followed by Mars $e=0.1$. Mercury is the only interior planet that has a magnetic field like the Earth, but weaker.

Probes: Mercury Orbiter spacecraft, Messenger, launched in 2004, first Mercury flyby in 2008, and orbit insertion by 2011. Mariner 10 flyby in 1975. Messenger has to operate at 0.38 ua from the Sun; it has a ceramic cloth sunshade around the body, with solar panels made 70 % with optical solar reflectors (OSR) and 30 % with solar cells. The OSR is made of quartz mirror tiles to reflect sunlight and radiate in the infrared. They were used extensively on Magellan, operating at Venus's distance from the Sun (0.72 ua). The ceramic sunshade, together with the 'refrigerated' solar panels, will keep the spacecraft at room temperature despite sunlight being eleven times more intense at Mercury distance to Sun than at the Earth distance to Sun. BepiColombo mission in 2013.

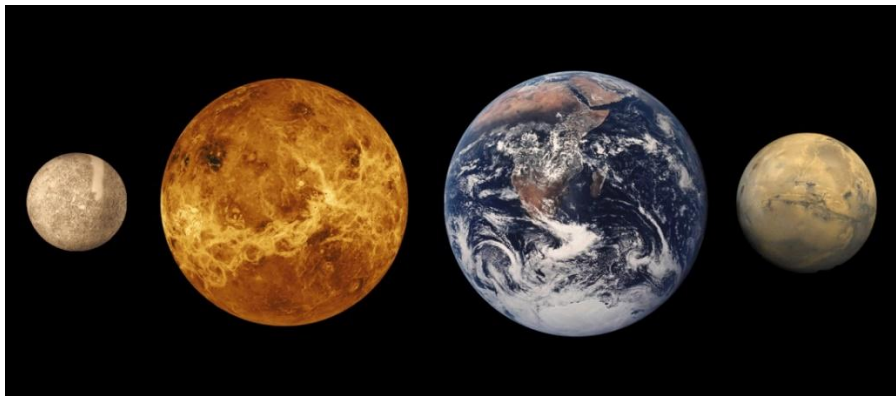


Fig. 11. Relative size of Mercury, Venus, Earth, and Mars (from left to right). [Wiki](#).

Venus

Environment. Venus orbit is nearly circular (0.72 ua at perihelion and 0.73 ua at aphelion) with 3.4° inclination over the ecliptic. Venus has a slow "retrograde" rotation, i.e. if viewed from above the ecliptic North Pole, the Sun and all of the planets are orbiting in a counter-clockwise direction; but while most planets also rotate counter-clockwise, Venus rotates clockwise around its axis. The standard answer to this question and things like Neptune's tilt is that there was a large collision early in the planetary formation process (solar system formation would keep the angular momentums of the planets and their orbits in the same direction as the initial angular momentum of the gas cloud). Venus orbit period is 225 Earth-days, rotation period 243 Earth days (i.e. a local day lasts longer than a local year). Venus is nearly the same size and mass than the Earth (its gravitational constant is 8.9 m/s^2 instead of 9.8 m/s^2). Being an interior planet, Venus is seen always close to the Sun from Earth (its maximum elongation is below 48°). A small isothermal spherical blackbody in an equatorial orbit would reach a steady temperature of 121°C in light and -105°C in shadow. Venus albedo is more than twice the albedo of the Earth.

Venus atmosphere is two or three times thicker than the Earth's one (the Kármán line is around 250 km altitude instead of 100 km). Conditions at 100 km altitude in Venus are: $T=160$ K, $p=3$ Pa, $\rho=10^{-4}$ kg/m³; total mass is 93 times than Earth's atmosphere. It basically consists of carbon dioxide gas (by volume, 96 % CO₂, 3.5 % N₂, 150 ppm SO₂, 30 ppm H₂O), with large (20 km-thick) highly-reflecting clouds of H₂SO₄(liq) at around 50 km altitude (from 30 km to 60 km), which can precipitate but the acid rain evaporates before reaching the ground (like in Earth deserts); i.e. Venus' atmosphere is clear below 30 km altitude. This permanent cloud cover prevents the visual observation of Venus surface from the outside, and direct sunshine shining on its surface, although the bottom 40 km are nearly transparent (CO₂ gas, without aerosols). Conditions at the surface are very uniform: $T=735$ K, $p=9.3$ MPa, and $\rho=6.7$ kg/m³. A sketch of the vertical temperature profile in Venus atmosphere is presented in Fig. 12. Venus has no intrinsic magnetic field, but a weak magnetic field is induced by an interaction between the ionosphere and the solar wind. Venus rotates so slowly that there is only a single Hadley cell per hemisphere (because of the weak Coriolis force) instead of three cells as in Earth. Venus atmosphere is transparent to microwaves and radiowaves (i.e. for $\lambda > 1$ mm), but being opaque to solar radiation implies that landers need radioisotope power beyond the few hours of batteries capability.

Probes: ESA-Venus Express-2006, USA-Magellan-1990, USSR-Venera (lander)-1982. The Venera 3 probe crash-landed on Venus on March 1, 1966. It was the first man-made object to enter the atmosphere and strike the surface of another planet. In 1985 the Soviet Venus probes Vega 1 and Vega 2 each dropped a balloon radiosonde into the atmosphere of Venus; one of them was tracked for two days, travelling 13 000 km at around 55 km height.

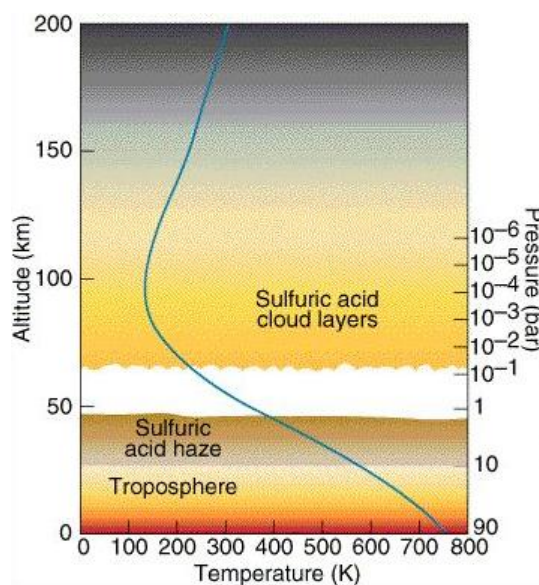


Fig. 12. Venus atmosphere (Pearson Addison-Wesley).

Exercise 8. The following thermal model is to be analysed for the thermal control of a spacecraft orbiting Venus at 500 km altitude in the ecliptic plane. The probe, spin stabilised, can be approximated by a cylindrical body 70 cm in diameter and 70 cm in height. Inside it, the platforms holding the instruments (zone A in Fig. 1) is approximated as a flat cylinder of 30 cm in height, 50 kg of mass, and 1000 J/(kg·K) of thermal capacity, with 100 W of continuous electrical dissipation. The outer cylindrical wall (zone B in Fig. 1), is 1 cm thick, has 5 kg of mass with

the same specific thermal capacity, an effective thermal conductivity of $5 \text{ W/m}\cdot\text{K}$), and is fully covered with solar cells. Two identical base plates (C in Fig. 1) close the cylinder at both ends; the properties of these panels are to be selected to solve the thermal requirement of the instrument zone being within the operational range of $0 \text{ }^\circ\text{C}$ to $50 \text{ }^\circ\text{C}$. To start with the analysis, panels C can be modelled as honeycomb structures 5 mm thick, made of aluminium ribbon 0.1 mm thick, in hexagonal cells with 5 mm from side to side, covered by thin sheets painted black. All internal faces can be modelled as black-bodies, and the assemble A+B can be considered isothermal. To do:

- Find the external heat loads (solar, albedo and infrared) as a function of orbit position.
- Find the thermal conductance between each plate C and the assembly A+B.
- Find the view factors between all surfaces involved, and the radiative couplings between nodes.
- Establish the nodal equations.
- Find the steady temperatures at the sub-solar point.
- Same as above but on the opposite point in the orbit.
- Find the eclipse duration and compare it with the spacecraft relaxation time.
- Find the temperature evolution along the orbit, in the periodic state.
- Redesign the C panels if necessary.

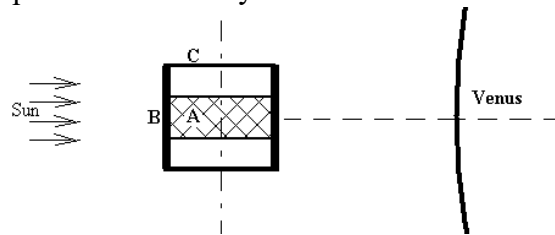


Fig. E8. Sketch of the Venusian satellite at sub-solar point in a plane perpendicular to the orbital one.

Sol.: ([.pdf](#)). NOTE. This is a rather complicated exercise. [View factor](#) computation and detailed [thermal analysis](#) are explained aside.

The Moon

(The Earth atmosphere has been treated above.)

Environment. Our Moon, the closest to the Sun and the fifth largest in the solar system (the first in proportion to its host planet), has an orbit around the Earth tilted 5.1° to the ecliptic (from 18.5° to 28.5° to Earth's equator, with a 18.6 year period). The Moon rotates around the Earth with synodic period of 29.5 days (i.e. from new moon to new moon; 27.3 days relative to fix stars). The Moon differs from most satellites of other planets in that its orbit is close to the plane of the ecliptic, and not to the planet's equatorial plane. The lunar orbit plane is inclined to the ecliptic by 5.1° , whereas the Moon's spin axis is inclined by only 1.5° to the ecliptic (6.7° to its orbit plane).

The Moon has no noticeable atmosphere. Its total atmospheric mass is less than 10^4 kg (made of noble gasses and metallic ions; $p=10^{-8} \text{ Pa}$ in daytime and 10^{-10} Pa by night). The Sun is about 400 times as wide as the Moon, but it is also 400 times further away from Earth, so that the two look the same size in the sky (a unique situation among our solar system's eight planets and almost 200 moons). The Moon appears

larger when close to the horizon due to the vanishing-line illusion (we unconsciously amplify objects at the horizon because we think they are the farthest), but in fact, when the Moon is near the horizon it is actually about 1.5 % smaller than when it is high in the sky (because it is farther away by up to one Earth radius); the colour change from orange to white is also an illusion (our eyes change the colour balance according to the background; actual colour is around 600 nm, dull brownish dust). For people living in the North hemisphere, the terminator (the line dividing the illuminated and dark part of the moon or planet) moves from right to left (from new moon, late at night at the west, to full moon, early at night at the East), whereas it progresses from left to right when seeing from the South hemisphere).

Regolith thickness is around 10 m (from 2 m to 20 m). The first 5..15 mm thin layer is made of soft dusty sand (recall the footprints left by the Apollo astronauts, and that the lander did not sink, as feared by some previous predictions), with average properties of $\rho=1000 \text{ kg/m}^3$, $c=800 \text{ J/(kg}\cdot\text{K)}$, very low thermal conductivity $k=0.002 \text{ W/(m}\cdot\text{K)}$, $\varepsilon=0.94$ and 12 % albedo (7 % along the normal); the retro-reflector effect on the surface of the Moon is caused by the very porous first few millimetres of dusty soil, made of tiny glassy spheres formed when the molten splashing from meteorite impact cools and solidify.. Underneath this powder (1 mm and smaller particle size) there is a 0.1..0.2 m thick layer of gravel with particle size about 1 cm and $\rho=1500 \text{ kg/m}^3$, $c=800 \text{ J/(kg}\cdot\text{K)}$, and $k=0.01 \text{ W/(m}\cdot\text{K)}$, which sets over igneous rock with $\rho=2000..3000 \text{ kg/m}^3$, $c=1000 \text{ J/(kg}\cdot\text{K)}$, and $k=0.1 \text{ W/(m}\cdot\text{K)}$.

A small isothermal spherical blackbody in an equatorial Moon orbit would reach a steady temperature of 65 °C in daylight (67 °C in Moon's perihelion and 61 °C in aphelion) and -199 °C in shadow; for a normal polar orbit, 22 °C in perihelion and 17 °C in aphelion. The overall albedo of the Moon is around 12 %, but it is strongly directional and non-Lambertian (we get at full moon 10 times more light than at half moon). Minimum surface temperature is 26 K at a North-Pole crater (the coldest surface ever measured in the solar system), measured in 2010 by the Lunar Reconnaissance Orbiter (from a 30..70 km altitude polar orbit). The steady-state temperature approximation is good enough in view of the low rotation rate. Maximum surface temperature is at subsolar point, with a typical value $T_{\max}=390 \text{ K}$, decreasing with latitude ϕ and longitude ψ in the way $T=T_{\max}(\cos\phi\cos\psi)^{1/4}$. There is some 100 K in the dark side (very uniform in the whole dark hemisphere, since temperature falls from 280 K to 120 K in about 20..30 hours after sunsets; i.e. 6..8 °C/h). Lunar albedo has been extensively covered before, under Albedo.

Exercise 9. Find the average emissivity for the Moon, from the energy balance and the bolometric albedo.

Sol.: The energy balance is $(1-\rho)E\pi R^2=4\pi R^2\varepsilon\sigma T^4$, so that $\varepsilon=(1-\rho)E/(4\sigma T^4)=(1-0.12)\cdot 1360/(4\cdot 5.67\cdot 10^{-8}\cdot 274^4)=0.94$.

Probes. The first artificial object to escape Earth's gravity and pass near the Moon was the USSR Luna 1, the first artificial object to impact the lunar surface was Luna 2, and the first photographs of the normally occluded far side of the Moon were made by Luna 3, all in 1959. The first spacecraft to perform a successful lunar soft landing was Luna 9, and the first unmanned vehicle to orbit the Moon was Luna 10,

both in 1966. The USA Apollo program achieved the only manned missions to date, resulting in six landings between 1969 and 1972 (Fig. 13). European, Chinese and Indian probes have visited our moon.



Fig. 13. Earth's shine seen from the Moon (Apollo 8, 1968). [Wiki](#).

Exercise 10. The following simplified thermal model is to be analysed for the thermal control of a small spacecraft orbiting the Moon in a circular orbit at 300 km altitude in the Moon's orbital plane. The satellite is 3-axes stabilised, with a cubic main body of 0.5 m side, with four protruding flaps protecting from sunlit the face pointing to the Moon (Fig. 1). All walls are made of aluminium 1 mm thick, and the three faces exposed to sunlit are covered with thin solar cells with an effective area of 90% and an electrical efficiency of 20%. Inside the box, there is a 2 mm thick aluminium plate at mid height, with an electronics box of $40 \cdot 40 \cdot 20 \text{ cm}^3$ and 10 kg at each side, centred, with an averaged thermal capacity of $1000 \text{ J}/(\text{kg} \cdot \text{K})$, holding batteries and a control system to deliver a constant electrical power all the time. For the thermal model, the following nodes are to be considered: one at each of the six faces of the main box (1,2,3,4,5,6), one at each flap (7,8,9,10), and another one for the internal assembly of e-boxes and instrument support plate (11). Thermo-optical properties of surfaces should be adequately selected. To do:

- j) Find the relative eclipse duration, and the minimum extent of the flaps to guarantee that the Sun rays never fall on the face pointing to the Moon.
- k) Find the external heat loads (solar, albedo and infrared) as a function of orbit position.
- l) Find the thermal conductance and radiative couplings between nodes.
- m) Establish the node equations.
- n) Find the steady temperatures at the sub-solar and at the opposition points.
- o) Find the orbital mean temperatures at the nodes.
- p) Find the temperature evolution along the orbit, in the periodic state.

Sol.: (.pdf). NOTE. This is a rather complicated exercise. [View factor](#) computation and detailed [thermal analysis](#) are explained aside.

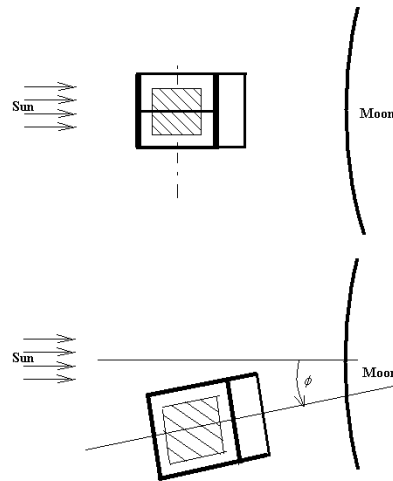


Fig. E10. Lunar satellite geometry.

Mars

Environment. Mars has an eccentric orbit (1.4 ua at perihelion and 1.7 ua at aphelion) what means that the average irradiation, $E_{\text{mean}}=590 \text{ W/m}^2$, becomes 717 W/m^2 at perihelion and 493 W/m^2 at aphelion, what governs the climate seasons. Its rotation rate, 24.6 h, is quite similar to Earth's 24 h. A small isothermal spherical blackbody in an equatorial orbit at Mars perihelion would reach a steady temperature of $11 \text{ }^\circ\text{C}$ in light and $-162 \text{ }^\circ\text{C}$ in shadow ($-16 \text{ }^\circ\text{C}$ and $-163 \text{ }^\circ\text{C}$ at Mars aphelion). Mars has a 25° tilted spin (23.5° the Earth), and polar ice caps (but of dry-ice). Mars atmosphere is about $1/100^{\text{th}}$ thinner than Earth's, 0.6 kPa in the average (instead of our 101 kPa), spanning from 0.03 kPa on Olympus Mons's peak to 1.2 kPa in the depths of Hellas Planitia, and it is made of CO_2 ($>95 \%$ in volume), with some 3% N_2 and 2% Ar . It is the only transparent atmosphere in the solar system, besides ours, although periodic dust-storm episodes make it opaque. Its vertical temperature profile is sketched in Fig. 14. Surface temperatures range from $-113 \text{ }^\circ\text{C}$ at the winter pole to $0 \text{ }^\circ\text{C}$ on the dayside during summer, and may change $80 \text{ }^\circ\text{C}$ from day to night. The ice cap in the South Pole region is bias to one side due to climate effects. Orbit speed in low Mars orbit (e.g. 300 km altitude) is 3.4 km/s (period is 1.9 h), and entry into Mars atmosphere requires heat shields; descent is slowed down with a parachute, and landing has been achieved with retro-rockets, with airbags, and with cable suspension from an ancillary descent craft.

Probes. NASA Mars Science Laboratory with rover Curiosity-2012, NASA Phoenix Mars Lander-2008, NASA Mars Reconnaissance Orbiter-2006, NASA Mars Exploration Rover mission with two rovers, Spirit and Opportunity-2004, ESA Mars Express with Beagle lander-2004, NASA Mars Odyssey-2001, NASA Mars Global Surveyor-1997, NASA Mars Pathfinder with rover Sojourner-1997, NASA Viking-1975, URSS Mars probes-1969, NASA Mariner-1964.

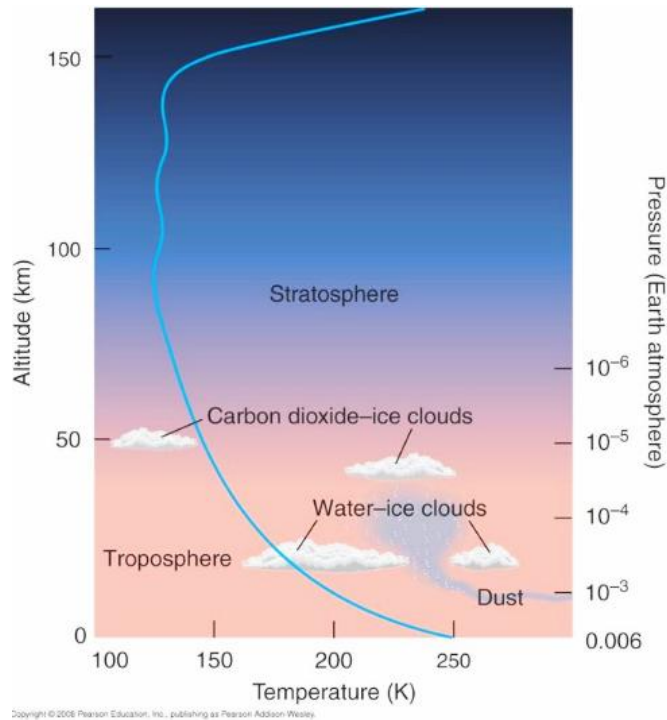


Fig. 14. Mars atmosphere. (Pearson Addison-Wesley).

- Exercise 11.** Consider a panel of $1 \cdot 0.5 \cdot 0.01 \text{ m}^3$ deployed from a spacecraft orbiting Mars (at 1.5 AU from the Sun) at the subsolar position and 300 km altitude, with its face-normal tilted 30° to sun rays. Neglect the effects of other parts of the spacecraft, and assume the panel is painted black on the face looking down the planet and white on the other face; take for the bulk properties of the panel $\rho=50 \text{ kg/m}^3$, $c=1000 \text{ J/(kg}\cdot\text{K)}$, and $k=0.01 \text{ W/(m}\cdot\text{K)}$. Find:
- The solar irradiance and the power absorbed from the Sun.
 - The heat loads from the planet.
 - The power emitted by the plate, assuming the whole plate is at temperature T_0 , and in the case of different temperatures at each face, T_1 and T_2 .
 - The steady value of T_0 , T_1 and T_2 under the above conditions.
 - The temperature evolution after entering into eclipse (assuming the above T_0 as initial state).

Sol.: (.pdf). [View factor](#) computation and detailed [thermal analysis](#) are explained aside.

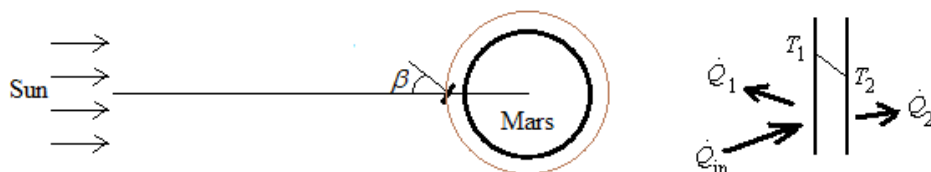


Fig. E11. A tilted plate in a Martian orbit (the plate normal is $\beta=30^\circ$ off the Sun direction), and thermal sketch.

Jupiter

Environment. Jupiter has a rocky core surrounded by dense metallic hydrogen (the supercritical state yields a big magnetic field, and densities larger than the normal solid state), which extends outward to about 78 % of the radius of the planet, merging with the gaseous [atmosphere](#) of 72 %wt $\text{H}_2(\text{g})$, 24 %He, with NH_3 -icy-clouds that show different colours due to ammonia photo-chemical reactions. Jupiter has the strongest magnetic field of the solar planets (some 10 times stronger than the Earth's). It is believed that the temperature at surface is around 10 000 K and the pressure around 200 GPa. Gas composition

Space environment

varies a lot with altitude due to gravitational stratification, because $M_{\text{He}}/M_{\text{H}_2}=2$ and $g/g_0=2.4$. The temperature over the clouds is $T=150$ K. There are winds up to 200 m/s; the red spot is actually a large cyclone. Since the lower boundary of Jupiter atmosphere is ill-defined, the pressure level of 100 kPa (Earth's surface pressure) is often taken as reference. The temperature profile with height is sketched in Fig. 15 (but taking the reference level at 10 kPa). Jupiter probes: Cassini-2000 (passed by), Galileo-1995 (orbiter and descent), Ulysses (swing-by-1992), Voyager-1979, Pioneer-10-1973.

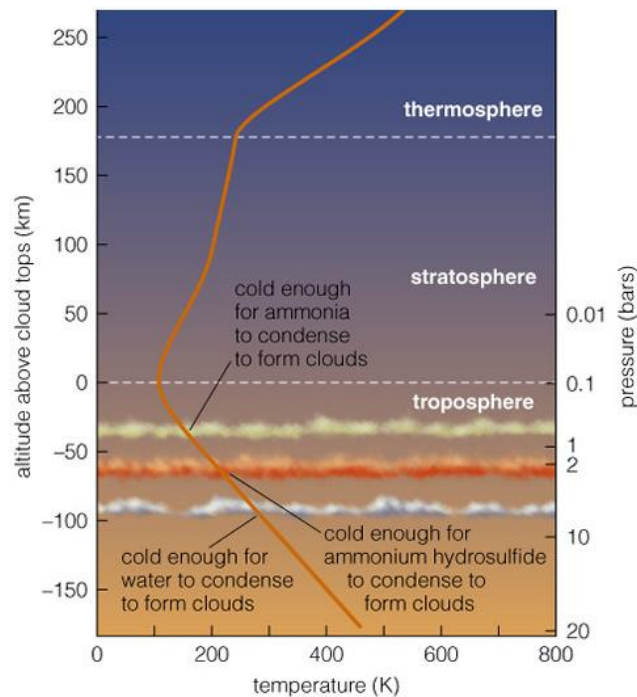


Fig. 15. Jupiter atmosphere (altitude origin at 10 kPa). [Newtonsapple](#).

Jupiter more important moons are:

- Io, with lava streams at 1500 K by tidal heating from Jupiter.
- Europa, an Earth's like body with an icy crust over a brine ocean kept liquid by tidal heating (surface tides of some 10 m). Without atmosphere. Some magnetic field.
- Ganymede, the largest solar-system moon, has also an ocean beneath the crust, and a sizeable magnetic field.

Saturn

Environment. Big gas blue planet, with little or no surface features, is the most oblate (10 %) and light (690 kg/m^3) planet in the solar system (the only one with a density below that of water). It has a thin (60 km) hydrogen atmosphere (93 %wt H_2 , 7 %He, with some ammonia and water ice), and the interior consists of a small core of rock and ice, surrounded by a thick layer of metallic hydrogen (and the thin gaseous outer layer). The atmosphere is generally bland in appearance due to a thick multi-layer cloud cover, about twice as thick as Jupiter's, with a thin water-ice layer at the bottom, and a thick ammonia layer at the top. Wind speeds on Saturn can reach 1,800 km/h, significantly faster than those on Jupiter. Saturn has a planetary magnetic field intermediate in strength between that of Earth and the more powerful field around Jupiter. Saturn's main [rings](#) are very thin, about 10 m thick, though they measure about 300 000 km across.

Space environment

- Titan, the largest Saturn moon and the only one in the Solar System with an important atmosphere, has an icy crust (made of water, ammonia, and methane) over solid cores. Titan has a nitrogen atmosphere similar to ours (150 kPa instead of 100 kPa, 98 % N₂ instead of 78 %), with some methane and ethane gas (and clouds, which make it opaque); there must be a liquid ocean (possibly of methane because of its critical temperature) some 100 km below the icy crust, because Cassini measured surface drifts of up to 30 km at some points. Cassini's probe Huygens landed on Titan in 2005, and detected some methane rain. Other moons like Triton (Neptune moon) have icy crusts too, and Pluto too.
- Enceladus, the sixth-largest moon of Saturn, has only 500 km in diameter, but shows amazing features: it reflects almost 100 % of the sunlight (i.e. negligible solar absorption), but radiates as a blackbody at 75 K (and tidal dissipation is too short to explain it); besides, its atmosphere is >90 % water vapour, and there are kind of geysers in the south polar region ejecting water vapour with some ice crystals at high speeds, so that caverns with liquid water must exist underground.

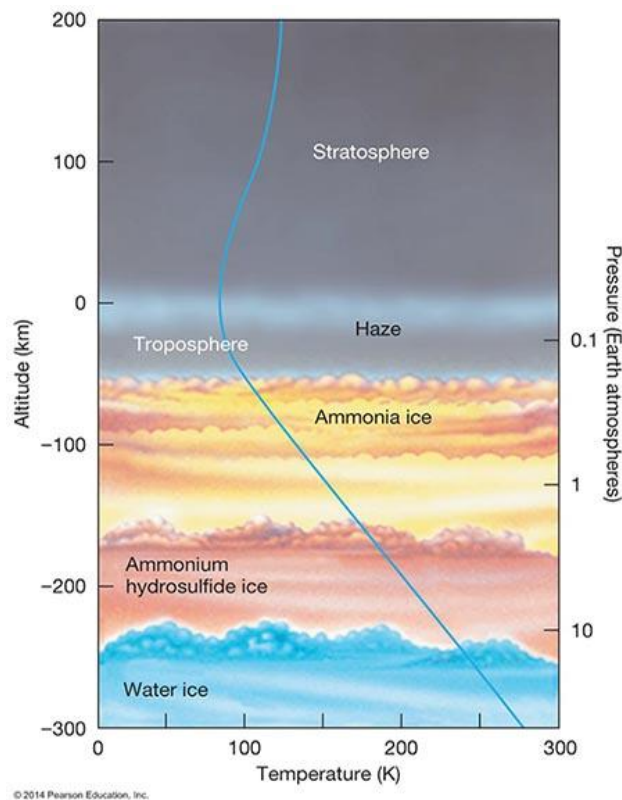


Fig. 16. Saturn atmosphere (altitude origin at cloud's top).

Saturn probes: Cassini (2004), Voyager (1980), Pioneer (1979). The Cassini-Huygens project was started in 1982, launched in 1997, entered into orbit in 2004, landed on Titan in 2005 (worked for 90 min after landing; the first landing in the outer Solar System, and the only one to now), and the orbiter is still in operation (2013). It takes 160 min for signals to travel forth and back the 10 ua to Saturn. Cassini orbiter is powered by three radioisotope thermoelectric generators (RTGs), which use heat from the natural decay of plutonium (in the form of 33 kg plutonium dioxide) to generate 800 W of power, and has also 82 small radioisotope heater units (RHU) of 1 W heat each; the associated Huygens probe contains 35 additional RHU. The RTGs have the same design as those on the Galileo and Ulysses spacecraft, but unlike the Galileo spacecraft, which was plunged into Jupiter to disintegrate in a fiery atmospheric entry, a similar

approach for Cassini may impact a large object within the rings and make it uncontrollable (a high orbit, some 20 000 km above the cloud cover, was selected, instead); an impact on a small moon with RTG contamination may not be a problem, but scientists do not want to contaminate Enceladus or Titan with radioactive waste since those satellites may have organic materials. As for Cassini-Huygens thermal control, the hottest case occurs at Sun-nearest position (at 0.6 ua, 3800 W/m²), and at Venus flyby (0.72 ua, but 78 % albedo); the high-gain antenna is used as a sunshade umbrella. The coldest case is in Saturn orbit (heaters are not electrical but small 1 W radioisotope units). For the probe, the coldest is after separation from the orbiter (15 W/m² solar, and negligible internal power), but during descent, it is exposed to 1 MW/m² of aero-heating, and the 90 K methane atmosphere.

Uranus

Uranus is named after the god of the heavens in Greek mythology, Uranus, the father of Kronos (Saturn) and grandfather of Zeus (Jupiter). The planet Uranus was the first planet to be discovered in modern times (i.e. with the telescope, since it is too small for the naked eye); the British astronomer Sir William Herschel found it in 1781 (Herschel also discovered the two largest moons of Uranus, Oberon and Titania; Uranus has more than 27 moons: Miranda, Ariel...).

Environment. A sketch of Uranus atmosphere is shown in Fig. 17. Uranus and Neptune both have a blue colour because their cloud cover consists of frozen methane crystals with high absorption bands in the red (Jupiter and Saturn have ammonia clouds). Uranus has unique weather, caused by its axial tilt of 98°. Seen from the Earth, Uranus rings (made of particulate matter up to ten meters in diameter) can appear in frontal view, circling the planet clockwise like the other moons, though in 2007 and 2008 the rings appear edge-on.

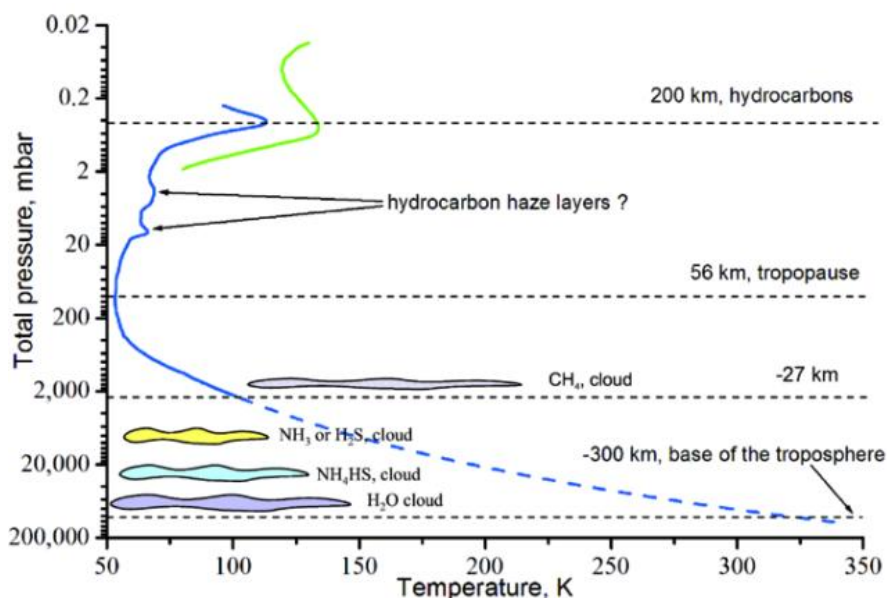


Fig. 17. Uranus atmosphere. [Wiki](#).

Probes. Voyager-2 in 1986 passed by; this was the extended Voyager 2 mission. The encounter took place on January 24, 1986. Nearly everything we know about Uranus was learned at this time.

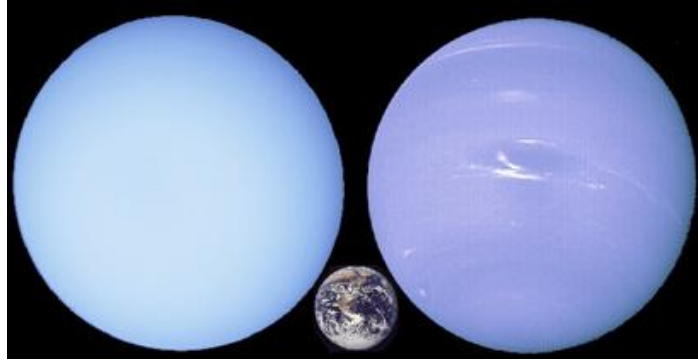


Fig. 18. Uranus (left), Neptune (right), and Earth to the same scale. (<http://www.astronomynotes.com>.)

Neptune

Environment. Neptune atmosphere is similar to Uranus, made up of hydrogen and helium together with other more complex molecules like methane whose absorption of the red wavelengths is responsible again for its bluish colour. The methane cycle is the same as in Uranus: methane is destroyed high in the atmosphere by the Sun, sinks, and it is converted into gases again at lower warmer regions to rise again. The planet is circled by very thin white cloud bands. One of the unresolved mysteries about Neptune is its internal heat source, since, like Jupiter, it gives off more heat than it receives (3 times as much).

Probes. Voyager measured similar temperatures than Uranus at the cloud deck levels, even though Neptune is much farther out.

Comets

Environment. Comets are small Solar-System bodies that orbit the Sun in high eccentric orbits and, when close enough to the Sun, exhibit a visible coma (or atmosphere) and/or a tail, both primarily from the effects of solar radiation upon the comet's nucleus. Comets nuclei are themselves loose collections of ice, dust and small rocky particles, measuring a few kilometres or tens of kilometres across.

Probes. In 1950, Fred Lawrence Whipple proposed that rather than being rocky objects containing some ice, comets were icy objects containing some dust and rock. This "dirty snowball" model was confirmed when an armada of spacecraft (including the European Space Agency's Giotto probe and the Soviet Union's Vega 1 and Vega 2) flew through the coma of Halley's comet in 1986 to photograph the nucleus and observed the jets of evaporating material. The American probe Deep Space 1 flew past the nucleus of Comet Borrelly on September 21, 2001 and confirmed that the characteristics of Comet Halley are common to other comets as well. The Stardust spacecraft, launched in February 1999, collected particles from the coma of Comet Wild 2 in January 2004, and returned the samples to Earth in a capsule in January 2006. In July 2005, the Deep Impact probe blasted a crater on comet Tempel 1 to study its interior. And in 2014, the European Rosetta probe will orbit comet Churyumov-Gerasimenko and place a small lander on its surface. Rosetta observed the Deep Impact event, and with its set of very sensitive instruments for cometary investigations, it used its capabilities to observe Tempel 1 before, during and after the impact. At a distance of about 80 million kilometres from the comet, Rosetta was the only spacecraft other than Deep Impact itself to view the comet.

A few data to keep in mind for spacecraft thermal control

Although we live nowadays with all world-wide data at our finger-tips on the Internet, it is convenient to memorise a few bold numbers (not the whole list that follows), while working on spacecraft thermal control problems, either to make back-of-the-envelope estimations, or to check more precise calculations.

Basically:

- Altitudes over the geoid (approx. mean Earth radius, $R_p=6370$ km): sounding balloons at 40 km, LEO at 400 km, GEO at 40 000 km, Moon at $400 \cdot 10^3$ km, Mars at $400 \cdot 10^6$ km as most.
- Temperatures: Sun surface temperature (quasi black-body) at 5800 K. Earth surface average is $T_s=288$ K. Deep space background temperature (quasi black-body) at 2.7 K. Blackbody emission is $M_{bb}=\sigma T^4$, with $\sigma=5.67 \cdot 10^{-8}$ W/(m²·K⁴).
- Heat rates (normal radiation flux):
 - Solar constant is $E_0=1360$ W/m² (at 1 ua= $150 \cdot 10^9$ m). The maximum in the spectrum is at $\lambda_{E_{max}}=0.5$ μm. Daily average is $1360/4=340$ W/m². (Sub-solar sea level values with clear sky: beam 930 W/m² at the oceans, 950 W/m² at deserts; plus some 80 W/m² diffuse in both cases (free of UV and IR).
 - Earth albedo is around 30 %, so that $\rho_E E_0=0.3 \cdot 1360=410$ W/m² is reflected (with the maximum still at $\lambda_{E_{max}}=0.5$ μm, free of UV and IR). For Polar orbits, an average albedo of 35 % is more realistic.
 - Earth emission (IR) is 240 W/m² with $\lambda_{E_{max}}=10$ μm, corresponding to an emissivity around 60 % ($0.61 \cdot 5.67 \cdot 10^{-8} \cdot 288^4=238$ W/m²), balancing the $340 \cdot 0.7=238$ W/m² solar absorption.

References

<http://www.solarviews.com/eng/data.htm>

<http://see.msfc.nasa.gov/>

http://www.esa.int/TEC/Space_Environment/

http://en.wikipedia.org/wiki/Space_environment

[Back to Spacecraft Thermal Control](#)