Today in Astronomy 111:
Jupiter, its atmosphere and its magnetic field

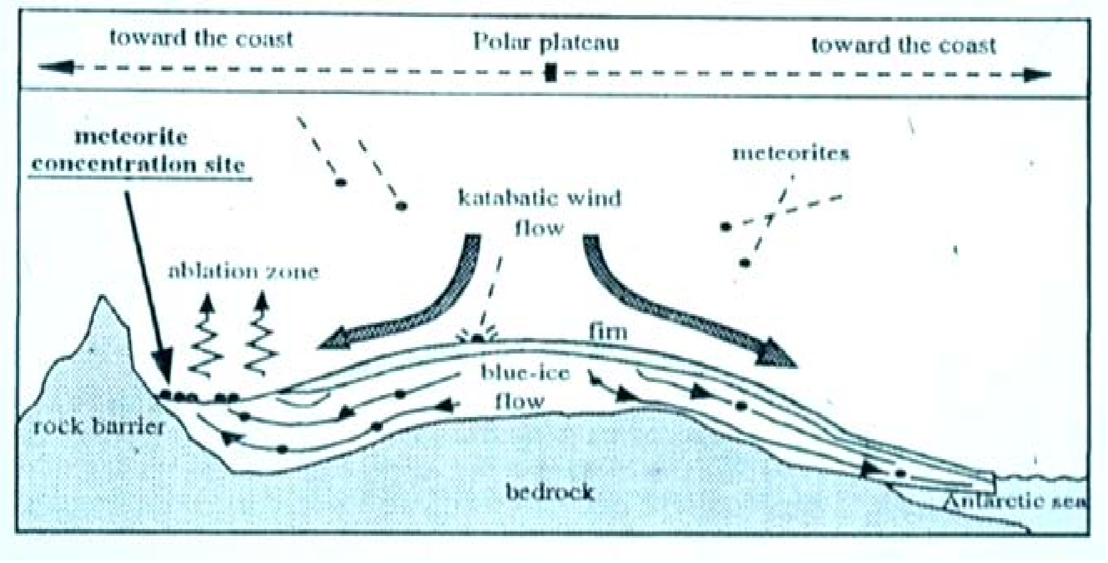
- ❑ Asteroid leftovers
- ❑ Albedo and emissivity
- ❑ The ice line and the icy domain of the giant planets
- ❑ Introduction to Jupiter
- ❑ Clouds, storms and magnetism on Jupiter
- ❑ Jupiter's interior

Jupiter and Io, from Cassini as it flew by (JPL/NASA).

Meteorite recovery

Lots of meteorites are found, well preserved and concentrated, in Antarctica. Some deserts provide good samples too.

- Suppose you were walking around in the plains of Antarctica, and came upon a rock laying on the surface. What were its options for getting there?
- Same holds for desert plains, like deep in the Sahara. If running water couldn't have brought the rock there, it might be a meteorite.



Source regions: large bodies

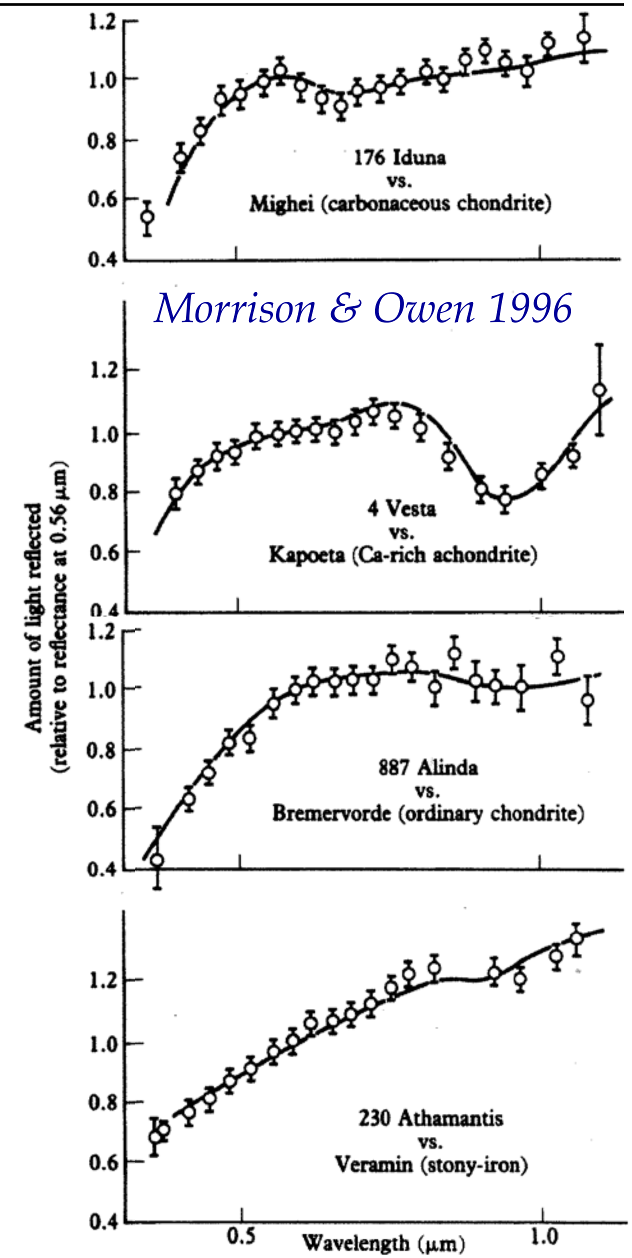
Whence come the meteorites?

- Some meteorites are exactly the same as lunar rocks (anorthosite breccias); they must be from the Moon.
- The SNC class comes from Mars:
  - The most convincing evidence is the noble gas abundances, which are distinctive and the same as those measured by the *Viking* landers.
  - One, ALH84001, became infamous: a 4.5 billion year old Martian achondrite meteorite recovered from Antarctica, with magnetite which has been interpreted as evidence for life on Mars.
- Impacts on rocky Solar-system bodies can eject rocks which can travel to Earth, particularly from Mars and the Moon because of their lower surface gravity.

Source regions: smaller bodies

But 99.4% of meteorites are from bodies smaller than the terrestrial planets.

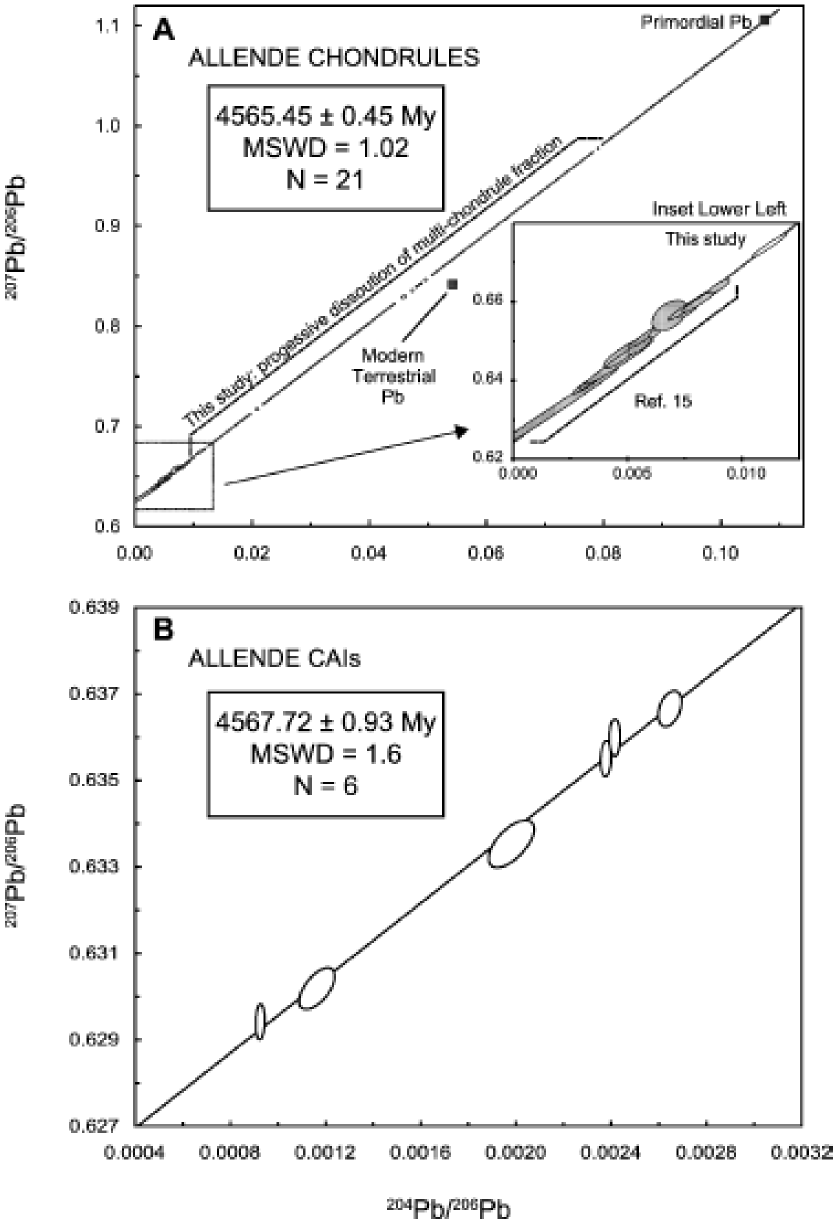
- ❑ Reflectance spectra of classes of meteorites match reflectance spectra of classes of asteroids well, as at right. →
- ❑ Comets and asteroids are the two major classes of parent body populations for chondrites.
  - Of these the C-group asteroids dominate by a wide margin, but the dividing line is somewhat indistinct.
- ❑ Achondrites and irons clearly come from the asteroid belt (Ss and Xs).
  - 63% of achondrites – the "H-E-D" classes – are from 4 Vesta alone (!).



Ages of meteorites

Because they commonly contain silicate minerals, meteorites can be radioactively dated, just like rocks.

- ❑ Result: they all turn out to be very old – even older than moon rocks – and similar to each other in age.
- ❑ Example: the CAIs in the Allende meteorite (a CV3) are **$4.5677 \pm 0.0004 \times 10^9$ years** old (Connelly et al. 2008).
  - The chondrules of carbonaceous chondrites are always younger than their CAIs, by about 2×10^6 years. (!!)
- ❑ This pretty much determines the **age of the solar system**.
  - CAIs are oldest solids we know; the pre-solar nebula itself probably formed only 10^4-10^5 years earlier.
- ❑ Moon rocks are younger (3-4.45×10^9), so have melted since then. Terrestrial rocks are all less than 4×10^9 years old.



Ages of meteorites (continued)

Ages of chondrules and CAIs in Allende, derived from U-Pb radioisotope dating (Connelly et al. 2008). U-Pb is the isotope system currently favored for use on the oldest meteorites, as Rb-Sr is for the oldest terrestrial and lunar rocks.

Note the significant difference in the ages of chondrules and CAIs, 2.3±1.0 Myr (95% confidence).

Albedo and emissivity: refinement on blackbody emission

At the low pressures of interplanetary space, water ice sublimates rapidly at temperatures above about T = 150 K; pure carbon dioxide, likewise at about 80 K.

- Bodies colder than this can retain lots of ices, so these temperatures should represent a boundary between fundamentally different kinds of solar system bodies.
- Where is that boundary, in our solar system? Not in one fixed location, because of the **wavelength dependence of emissivity**.

Sublimation temperature (K)

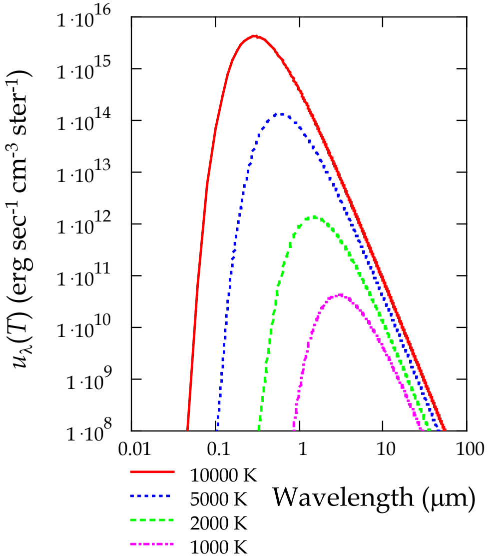
Species	Gone in minutes	Gone in 10^5 yrs
N_2	22	13
O_2	22	13
CO	25	16
CH_4	30	18
CO_2	83	50
NH_3	95	55
CH_3OH	140	80
H_2O	150	90

Tielens 2005

Albedo and emissivity (continued)

Recall that a blackbody – a perfectly absorbing body in thermal equilibrium – radiates according to

$$u_\lambda = \frac{2hc^2}{\lambda^5}\frac{1}{\exp\left(\frac{hc}{\lambda kT}\right)-1} \quad \text{, where}$$



$$h = 6.626\times10^{-27} \text{ erg sec}$$

$$k = 1.381\times10^{-16} \text{ erg K}^{-1} \quad \text{, and}$$

$$f = \sigma T^4 \quad \text{, where}$$

$$\sigma = 5.67051\times10^{-5} \text{ erg sec}^{-1}\text{ cm}^{-2}\text{ K}^{-4}$$

(see lecture notes for 6 September 2011).

Albedo and emissivity (continued)

But, as you might expect, bodies that absorb perfectly at any wavelength are rare, and bodies that absorb the same way at all wavelengths are practically nonexistent. Usually their intensity and total flux have to be written as

$$I_\lambda = \varepsilon(\lambda) u_\lambda = \varepsilon(\lambda) \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda kT}\right) - 1} \quad \text{and}$$

$$f = \bar{\varepsilon} \sigma T^4 \quad ,$$

where $\varepsilon(\lambda)$ (≤ 1) is called the **emissivity**, and $\bar{\varepsilon}$ is a complicated average of the emissivity over all wavelengths.

- If $\varepsilon(\lambda)$ is the same at all wavelengths, then $\bar{\varepsilon} = \varepsilon(\lambda)$, and the resulting object is called a **graybody**.

Albedo and emissivity (continued)

- Apart from sharp spectral features due to the quantized energy levels of atoms, molecules and solids, it is a good approximation to consider a given object to be gray over certain wide wavelength ranges…
- …and to be a different "gray" in other wavelength ranges. For instance, lots of solar-system objects are characterized well by
  - one (constant) emissivity value for visible and ultraviolet wavelengths, at which the Sun emits most of its energy,
  - and another emissivity value for infrared wavelengths, at which planets and asteroids emit most of their energy. We'll call this one ε.

Albedo and emissivity (continued)

- Conventionally, the visible and ultraviolet emissivity is characterized instead by the **albedo**, $A = 1 - \varepsilon_{V-UV}$. The albedo is something like the *reflectivity* of the object at these wavelengths.

Example 1 (compare to lecture on 20 September 2011)

What is the temperature of a spherical body with mass M and radius R, lying a distance r from the Sun, that has albedo A and infrared emissivity ε, is heated by sunlight and radioactivity, and is cooled by its own thermal emission?

- Power absorbed and generated: $$P_{\text{in}} = (1 - A)\frac{L_\odot}{4\pi r^2}\pi R^2 + M\Lambda_{\text{rad}}$$
- Power emitted: $$P_{\text{out}} = \varepsilon\sigma T^4 4\pi R^2$$

Albedo and emissivity (continued)

- $P_{\text{in}} = P_{\text{out}}: \quad (1-A)\dfrac{L_\odot}{4\pi r^2}\pi R^2 + M\Lambda_{\text{rad}} = \varepsilon\sigma T_s^4 4\pi R^2$

$$T_s = \left(\frac{1-A}{\varepsilon} \frac{L_\odot}{16\pi\sigma r^2} + \frac{M\Lambda_{\text{rad}}}{4\pi\varepsilon\sigma R^2} \right)^{1/4}$$

If radioactive heating is small enough to be neglected,

$$T_s = \left(\frac{1-A}{\varepsilon} \frac{L_\odot}{16\pi\sigma r^2} \right)^{1/4} = \left(\frac{1-A}{\varepsilon} \right)^{1/4} T_{\text{blackbody}},$$

as you showed in the last Workshop.

Albedo and emissivity (continued)

Representative cases, neglecting radioactive heating to good approximation:

$$\text{Venus} \quad A = 0.7, \varepsilon \approx 1 \quad \left(\frac{1-A}{\varepsilon}\right)^{1/4} = 0.74$$

$$\text{Earth} \quad A = 0.37, \varepsilon \approx 1 \quad \left(\frac{1-A}{\varepsilon}\right)^{1/4} = 0.89$$

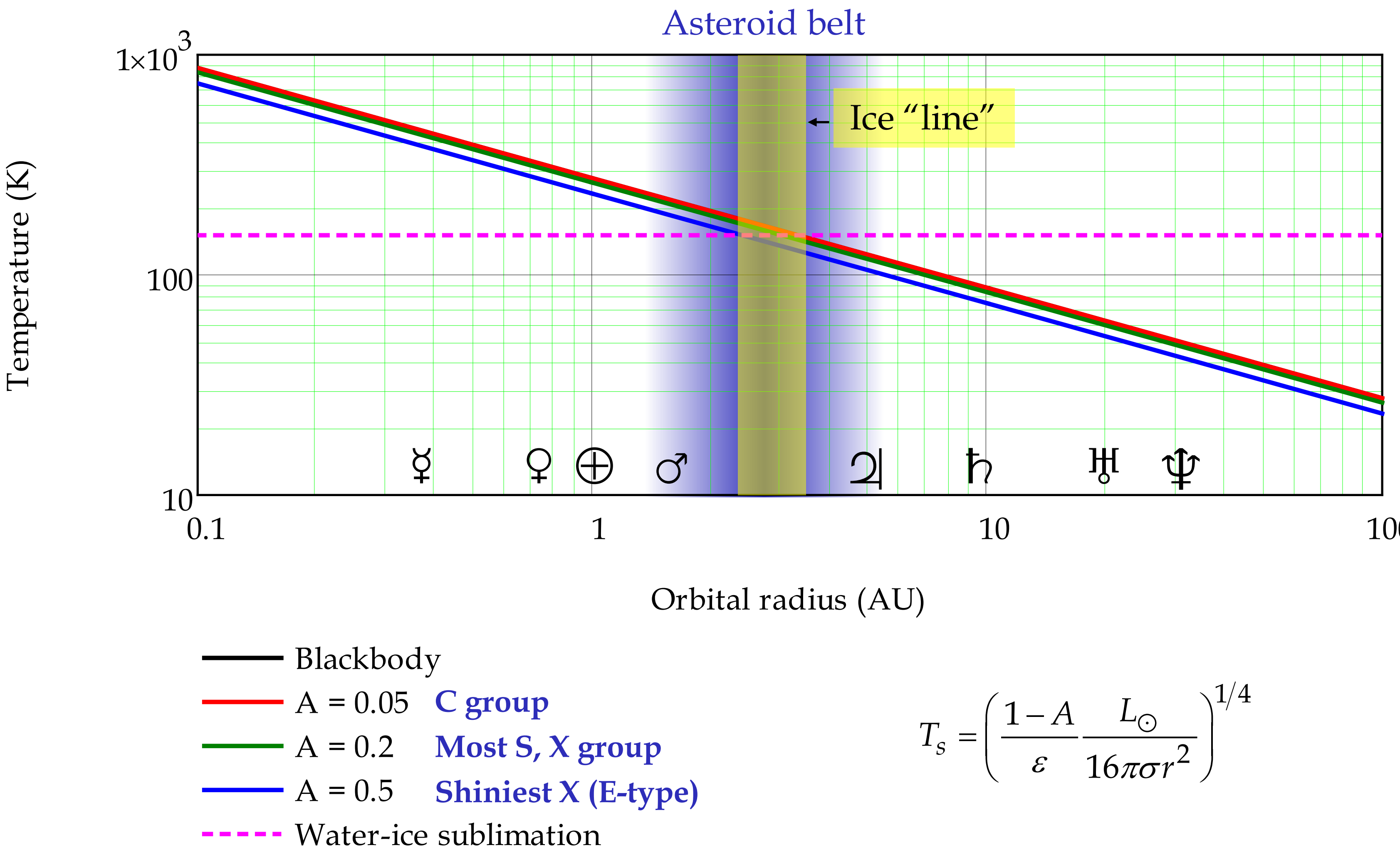
$$\text{Mars} \quad A = 0.15, \varepsilon \approx 1 \quad \left(\frac{1-A}{\varepsilon}\right)^{1/4} = 0.96$$

$\left\{ T = 248\ \text{K}, \text{ instead of } T = 278\ \text{K}. \right.$

Example 2

To return to our original question: where does the surface temperature equal the freezing/sublimation point of water, as a function of albedo?

The ice "line"



$$T_s = \left(\frac{1 - A}{\varepsilon} \frac{L_\odot}{16\pi\sigma r^2} \right)^{1/4}$$

The ice "line" (continued)

So the asteroid belt marks the transition between solar system bodies that can't have a lot of ice, and those that can.

- The ice content of the outermost asteroids – most of the C class – should be larger than the innermost.
- Everything solid that's further out than the asteroids can be expected to have a lot of ice.
- If bodies have lots of ice mixed in with the usual rocks and metals, their bulk densities are less than the 3-6 gm cm^{-3} of the terrestrial planets: the density of uncompressed water ice is just under 1 gm cm^{-3}.
- For example, C-class 1 Ceres: bulk density 2.1 gm cm^{-3}, bulk porosity 0.01.

Jupiter's vital statistics

Mass	1.8986×10^{30} gm ($318M_\oplus$)
Equatorial radius	7.1492×10^{9} cm ($11.2R_\oplus$)
Average density	1.326 gm cm^{-3}
Moment of inertia	$0.254MR^2$
Albedo	0.52
Orbital semimajor axis	7.7857×10^{13} cm (5.2043 AU)
Orbital eccentricity	0.04839
Sidereal revolution period	11.862 years
Sidereal rotation period	9.9250 hours
Moons	63
Rings	2

Jupiter, from Cassini (JPL/NASA)

Visits to Jupiter

We have learned an awful lot about Jupiter during the past 38 years, from visits by six NASA planetary probes:

- Pioneer 10 and 11 (1973 – 1974)
- Voyager 1 and 2 (1979)
- Galileo (1995 – 2003)
- Cassini (2001)

The approach of Voyager 1 to Jupiter (JPL/NASA)

Jupiter: structure and composition

Obviously, Jupiter is best thought of as a gaseous object.

- Rotates differentially, has low average density and low moment of inertia for its mass.
  - Equator rotates with P = 9h50.5m, but near the poles, the rotation period is 9h55.7m.
- Might not even have a core: best determination of range of core mass is 0-11 $M_\oplus$.
- Enhanced in elements heavier than H (except O) by factors of 2-4, relative to the Sun. Molecular constituents: 89.5% H_2, 10.2% He, 0.3% CH_4, 0.026% NH_3, 0.0028% HD, 0.00058% C_2H_6, 0.0004% H_2O.
- T = 112 K at P = 1 Earth atmosphere. (Compare to 101.5 K expected from heating by sunlight.)

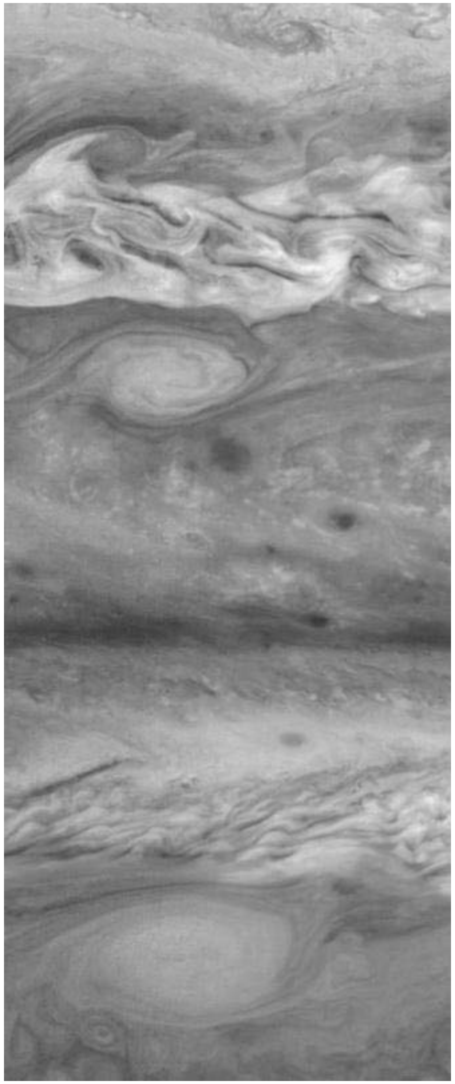
Jupiter: structure and composition (continued)

- The visible "surface" turns out to be a deck of clouds in the upper atmosphere.
- The clouds are arranged in alternating dark and light bands parallel to Jupiter's equator, of color brown/orange (called **belts**) and blue/white (**zones**), that change their structure with time.
- The colors result from various chemical compounds in atmosphere at various heights.
- Infrared observations show that the zones are cooler than the belts.

True-color image from *Galileo* (JPL/NASA)

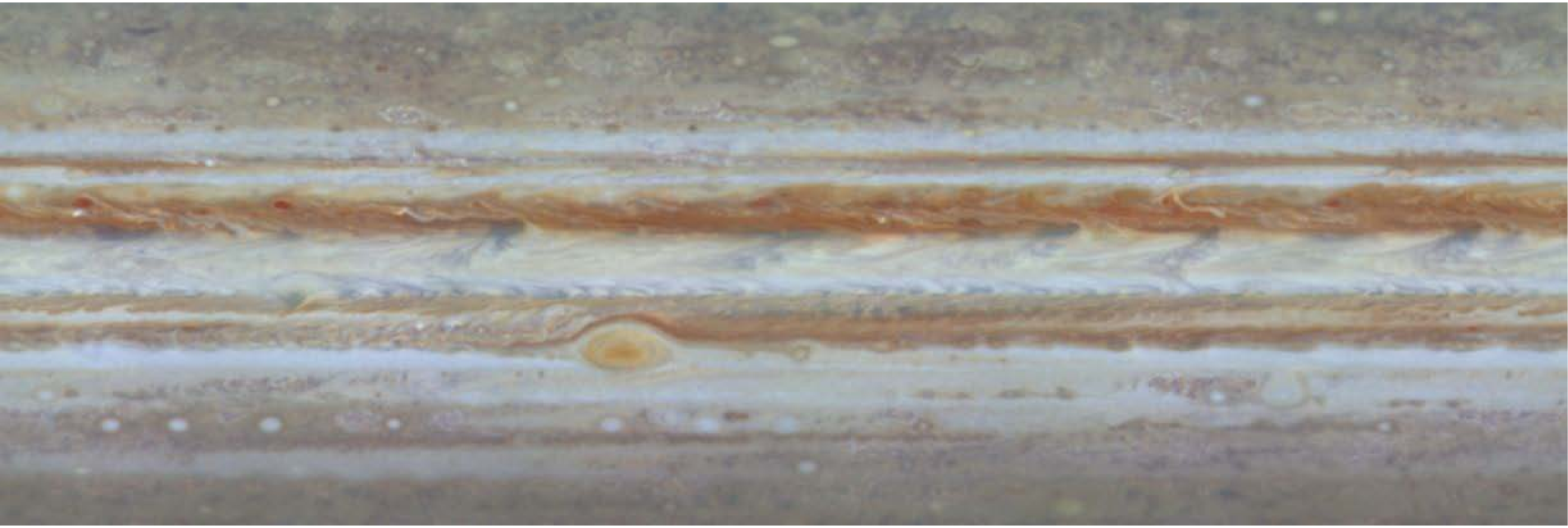
Jupiter: structure and composition (continued)

- Zones thus mark the tops of rising regions (higher altitude) of high pressure, and belts mark falling regions of low pressure.
- The tops of zones contain NH_3 ice (which sublimates at about 150 K at these pressures), then NH_4SH. Down below are NH_3 vapor, H_2O ice clouds.



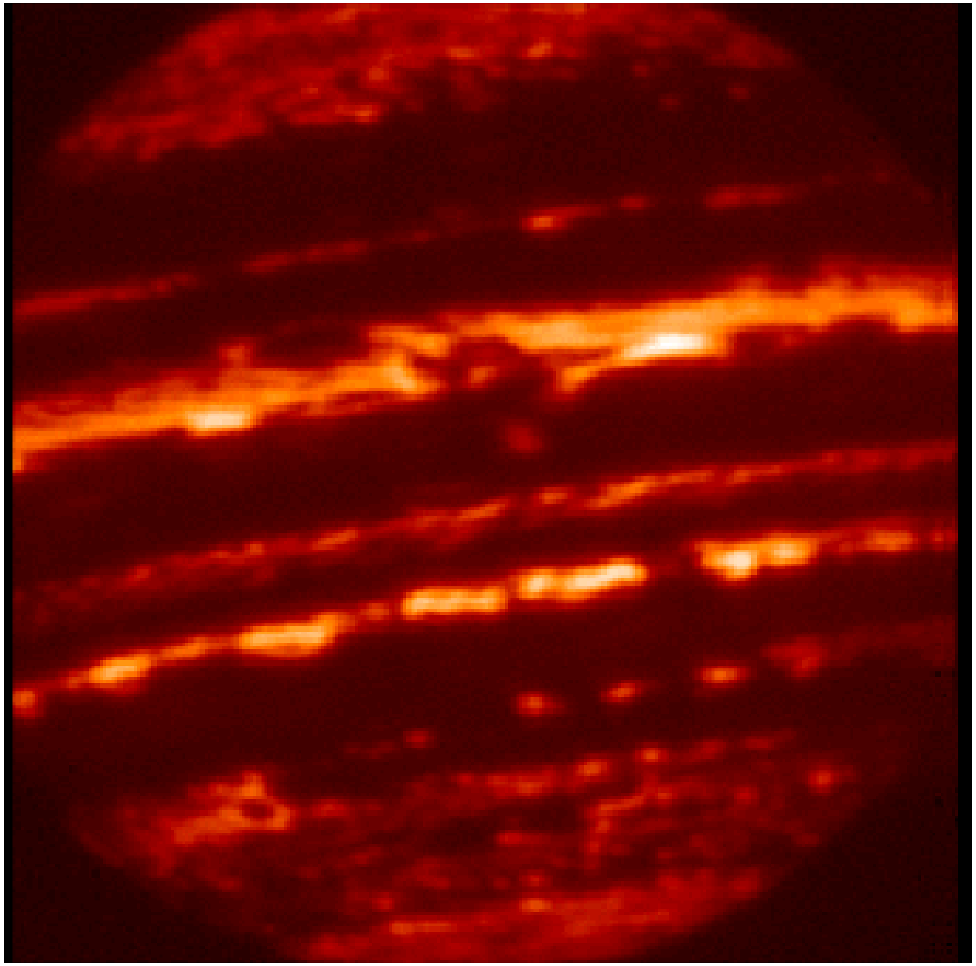
Same view as before, in near-infrared light (*Galileo*/JPL/NASA)

Jupiter: structure and composition (continued)



Jupiter's whole disk, "unpeeled," from Cassini (JPL/NASA).

Jupiter: structure and composition (continued)



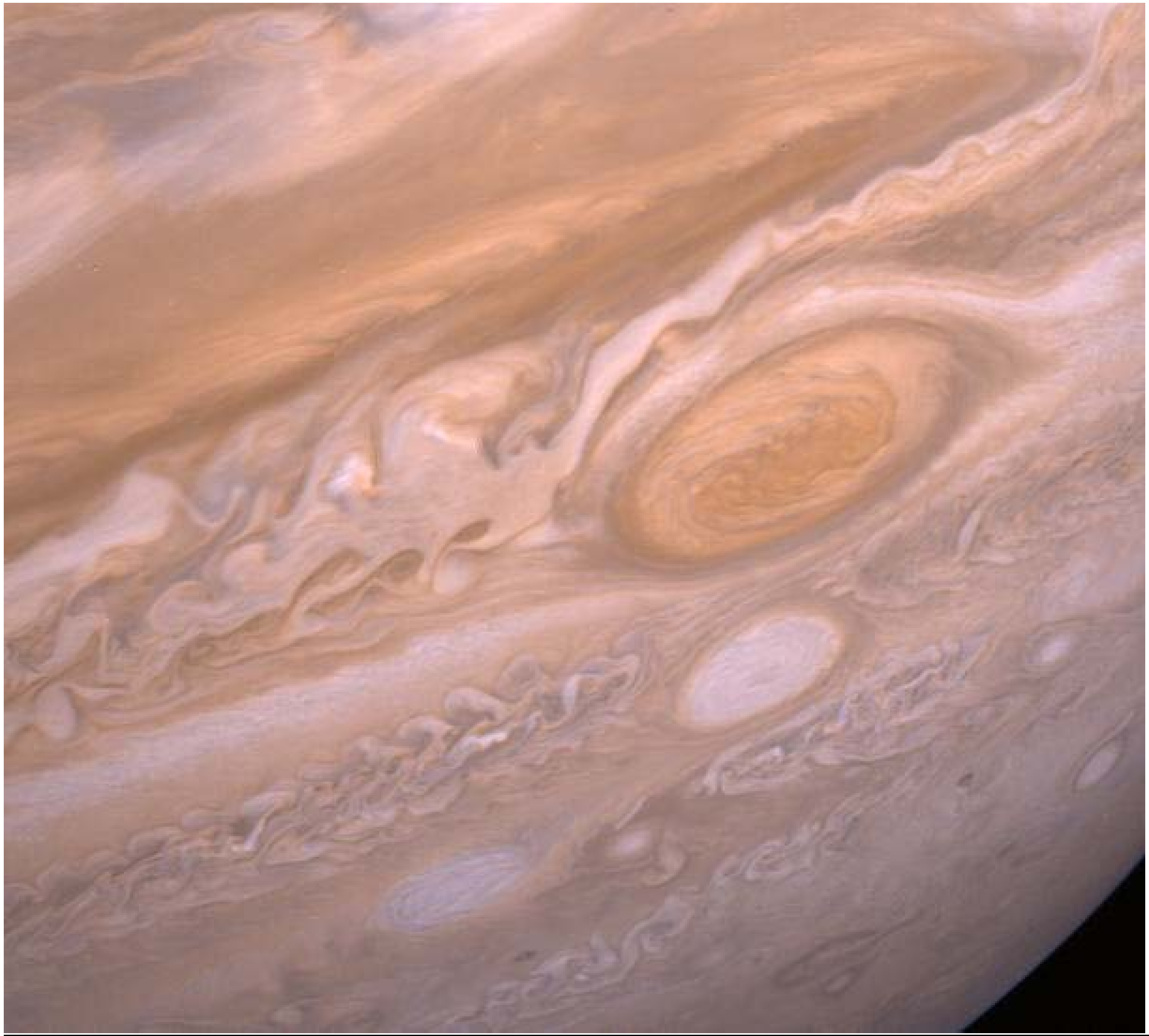
Infrared image of Jupiter (wavelength 2.2 microns), from the NASA Infrared Telescope Facility on Mauna Kea, showing the hottest parts of the visible atmosphere, i.e. the places we see deepest into the atmosphere.

Cyclones and anticyclones on Jupiter

On Earth, a **cyclone** is local CCW circulation of air in the northern hemisphere, CW in the southern hemisphere .

- They are results of the right-ward Coriolis-force deflection of air flowing toward the center of a low pressure region.
- Thus **anticyclones**, too, as air flows away from high pressure centers, spinning the opposite of cyclones.
- Jupiter's atmospheric storms appear in images as ovals. White ovals have relatively lower temperature, and thus lie above the main cloud deck.
- Brown ovals in the northern hemisphere are bright at infrared wavelengths, and therefore are holes in clouds (see deep, higher T).

Cyclones and anticyclones on Jupiter (continued)



Voyager 2 picture of the Great Red Spot region on Jupiter, showing also several white and brown oval storms (JPL/NASA).

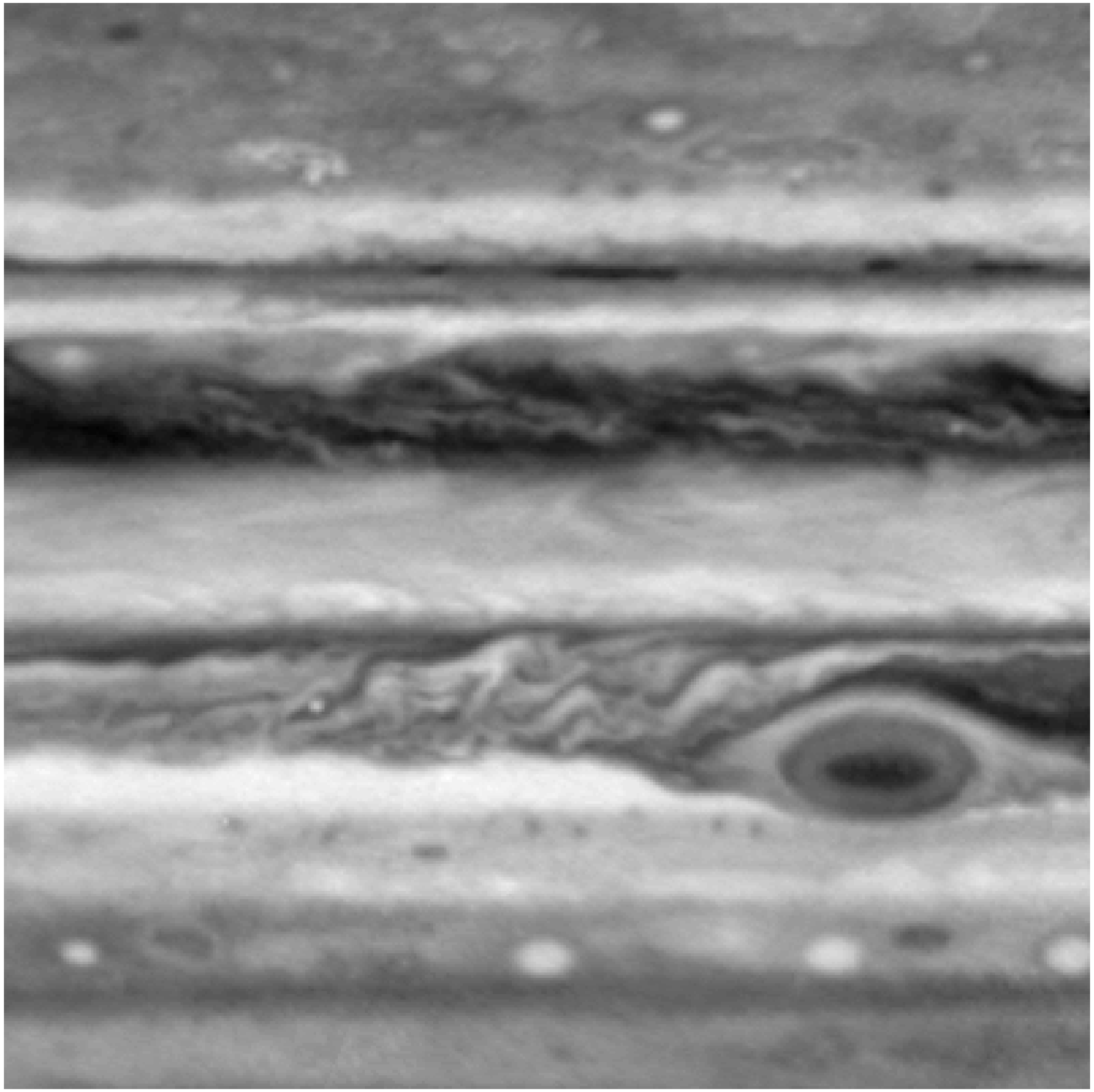
Cyclones and anticyclones on Jupiter (continued)

Special case: the Great Red Spot

- Size: 40,000 ×14,000 km (!); six-day rotation period, anticyclonic.
- It's been around for at least 300 years.
- Most of the Great Red Spot is high altitude clouds
- Most of spot is about 10 K cooler (8km above) the white clouds that surround it.

The Great Red Spot (Galileo/JPL/NASA)

Cyclones and anticyclones on Jupiter (continued)



Movie from Cassini of cloud-deck flows and rotation, including that of the Great Red Spot at lower right (JPL/NASA).

The descent of Galileo's parachute probe

Galileo dropped a probe that parachuted in with a heat shield to prevent burn-up.

- Transmission stopped at a pressure of P = 24 Earth atmospheres.
- The probe determined that the wind speeds are higher below the cloud deck than at high altitudes.
- This implies that the energy source for winds is Jupiter's internal heat, and certain atmospheric chemical processes. (Not sunlight, like on Earth.)
- It found no hint of low-lying clouds of H_2O; the H/He abundance ratio was still the same as that in the Sun, when it shut off.

Jupiter's interior

$I = 0.254MR^2$: Jupiter's density decreases faster than linearly with radius. ($I = 0.267MR^2$ for linear decrease.)

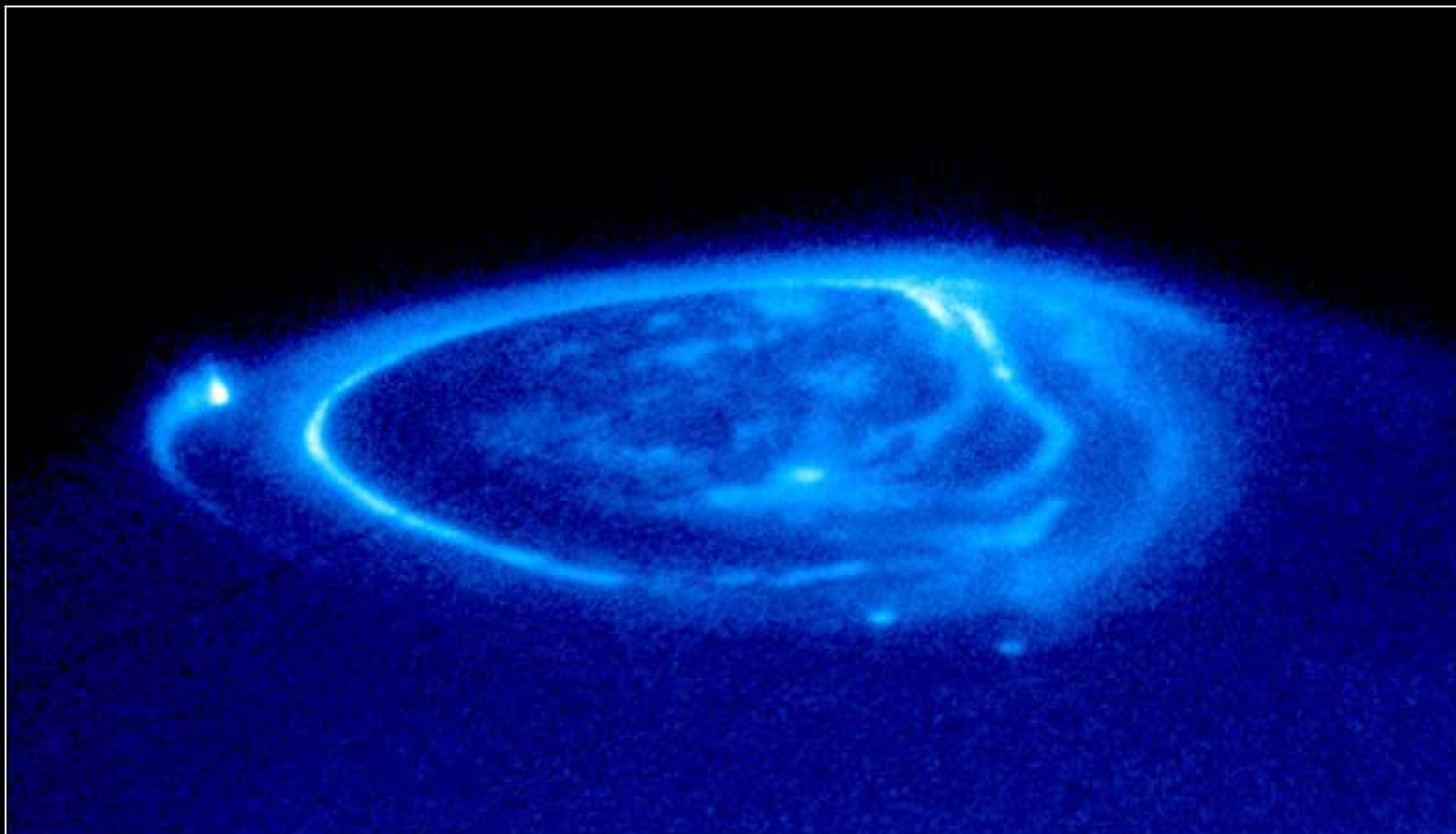
- The maximum mass of the core is about 4% that of the planet, but it's compressed $\left(\leq 11M_\oplus \text{ but only } \leq 1R_\oplus\right)$.
- Very large pressure at center due to overlying layers: $P = 8\times 10^7$ Earth atmospheres, $\rho = 20$ gm cm^{-3}, T = 25000 K.
- The high pressure has an unusual effect on H also: the compression changes hydrogen to a liquid metallic state. This liquid metal either surrounds, or comprises, the core.
- Jupiter emits about twice as much power as it receives from the Sun. This is probably an effect of a continuing, slow, internal rearrangement of mass (collapse), and is a characteristic of the other giant planets as well.

Jupiter's magnetic field

The differentially-rotating liquid metallic hydrogen in the center comprises a dynamo that is responsible for strong magnetic fields.

- That Jupiter has a such a magnetic field has long been known; Jupiter is a strong radio synchrotron emitter, which requires a strong magnetic field (***B***) to accelerate charged particles that produce the radiation.
- The Jovian magnetosphere (bounded by the solar wind) extends some 10 million km.
- Magnetic storms and **aurorae** are also observed, the latter from high-energy charged particles following the converging lines of ***B*** toward the Jovian poles.

Jupiter's magnetic field (continued)



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