Planetary Atmospheres (Nick Achilleos, Atmospheric Physics Laboratory, UCL) (*for Prof. A. Aylward)*

- What is an atmosphere ? - structure, length scales
- What determines the temperature of a planet ?
- Terrestrial planets (Earth, Venus, Mars)
- Other planets: Jupiter and Saturn
- Atmosphere - magnetosphere interaction
- Website for lecture notes

http://www.homepages.ucl.ac.uk/~ucapnac/

Important Points

UCL

• The structure of a planet's atmosphere arises from a 'balancing act' between the random, thermal motions of molecules (**pressure**) and the force of **gravity** due to the planet itself.

• The temperature is determined by an 'energy budget', usually heating due to **absorption** of solar radiation versus the heat **reflected** by the planet back into space.

• The notion of human-induced global warming on our planet at the **very least should be taken seriously**.

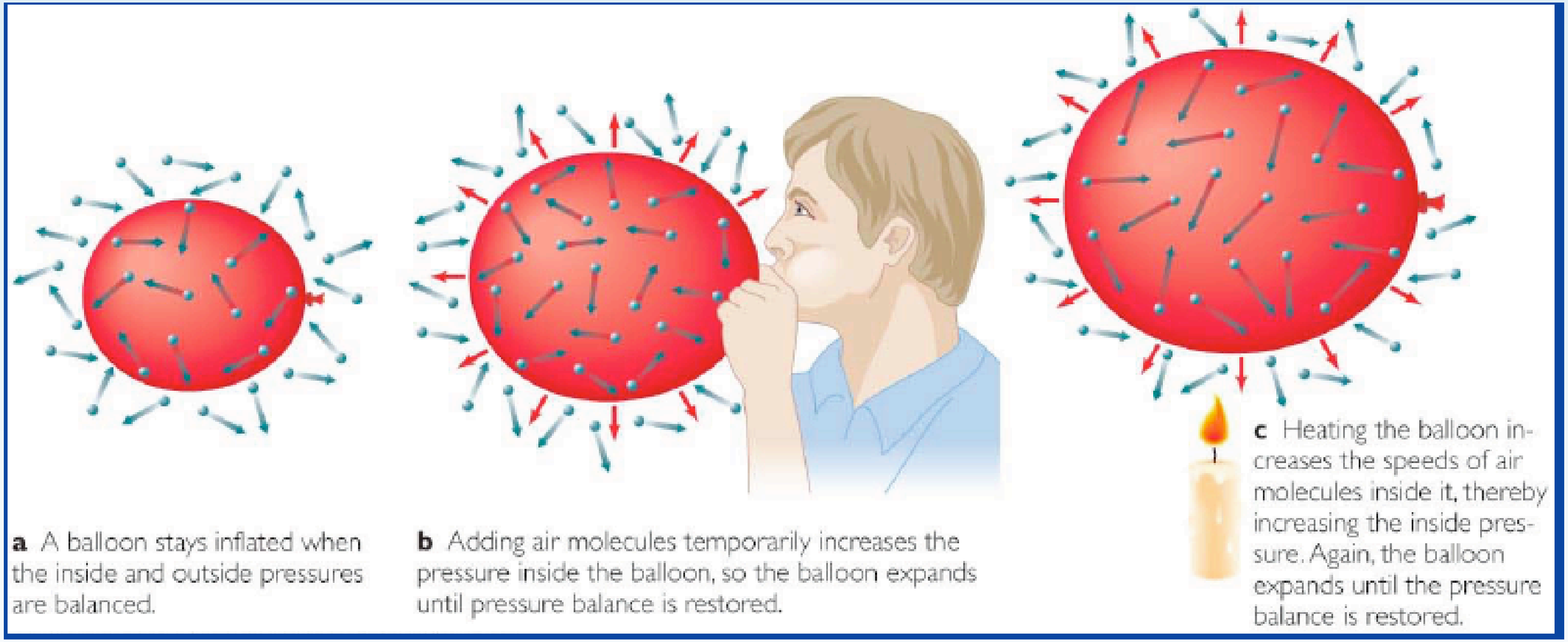
Earth: A thin atmosphere

• Earth diameter ~ 13000 km. Thickness of troposphere ~ 10 km, or about 0.1 % of the diameter

• Atmospheric species are mainly:

-Nitrogen	N_2	(78 %)
-Oxygen	O_2	(21 %)
-Carbon Dioxide	CO_2	(0.04 %)

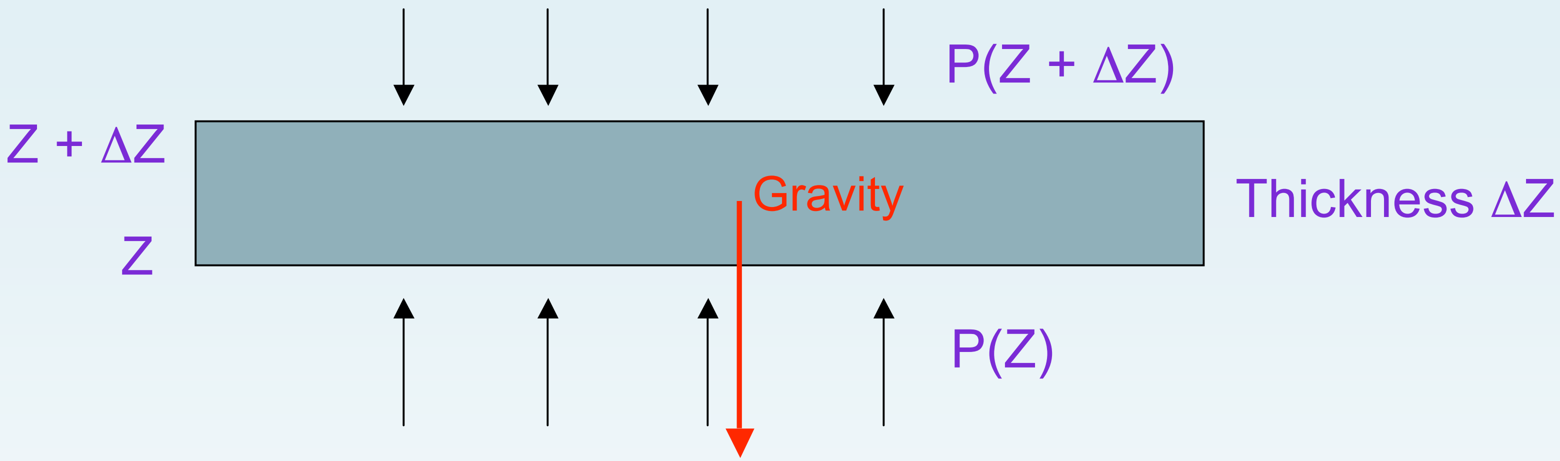
The concept of pressure



Mathematically: $\mathbf{P = N\, k_B\, T}$ (N=number density, T = temperature)

So pressure can have dimensions of *force per unit area*, or equivalently *energy per unit volume*. It is supported by *random* or *thermal* motions of molecules.

The concept of hydrostatic equilibrium



For the 'slab' of atmosphere here, pressure upward balances gravity downward when:

$P(Z) - P(Z + \Delta Z) = \rho\, g\, \Delta Z$ ρ = mass density, g = grav acceln

Equivalently: $\mathbf{dP/dZ = -\rho\, g}$ **pressure decreases with height**

The concept of hydrostatic equilibrium

Start with: **$dP/dZ = - \rho g$** **pressure decreases with height**

Note that: $\rho = Nm$ = number density x mean molec mass
$= (P/kT)m$

Using this: **$dP/dZ = - P / H$**

Where the **scale height $H = kT / mg$**

For a simple isothermal atmosphere (const T) this is easily solved:

$P = P_O \exp(-Z / H)$

- Pressure falls off exponentially with altitude.

- H summarises the competition between thermal energy (higher T means thicker atmosphere) and gravity (higher g means thinner atmosphere)

Examples of scale heights

Planet	Surface T	g	H
Earth	*~300 K*	$g=10\ ms^{-2}$	*8 km*
Venus	*~700 K*	*0.9 g*	*15 km*
Mars	*~230 K*	*0.4 g*	*16 km*

The effects of atmospheres

- *Pressure* in an atmosphere determines whether liquid (water) can exist at surface.

- *Absorption and scattering* of solar radiation.

- They underpin global *wind, weather and climate.*

- May interact with the *solar wind* to contribute to formation of a magnetosphere.

- The *greenhouse effect* may make planetary surface warmer - it requires an atmosphere to operate.

The concept of equilibrum temperature

Assume to begin with that the atmosphere is *not important* for heating the planet:

$\boldsymbol{T_{eq}}$ is then the temperature at which the energy received by the planet from the Sun (solar radiation) per unit time balances the rate at which it radiates energy back into space (assuming it behaves as a *black body* radiator).

A highly *reflective* surface, with a high ***albedo*** *A*, will keep a planet cool, while a planet with small **orbital radius *d*** will tend to heat up (Earth receives 1.4 kW m^{-2})

$$T_{eq} = 280\text{ K} \times [(1-A) / d_{AU}^2]^{1/4}$$

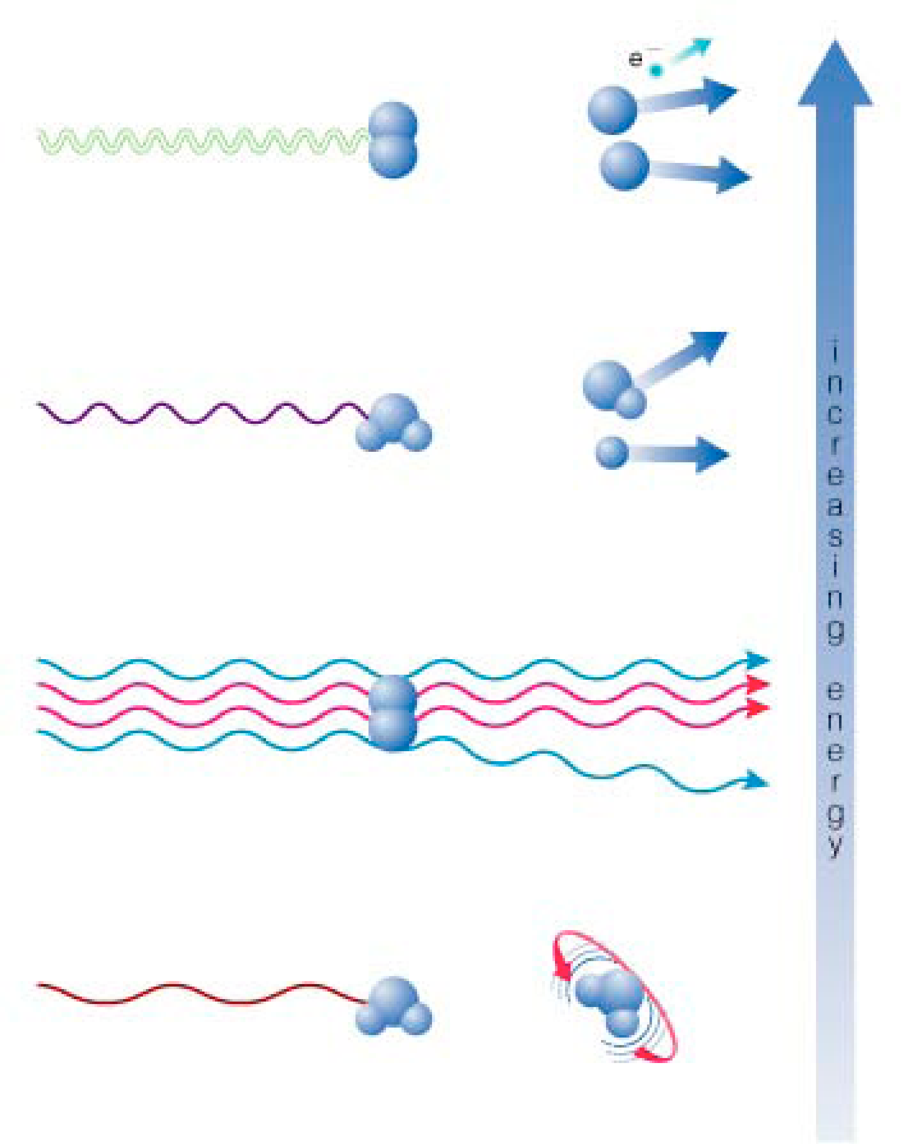
How close is this formula to reality ?

- For a planet like Mars, pretty good, but let's consider the Earth and Venus:

Planet	**A**	**d_{AU}**	**T_{eq}**	**Actual T**	**Difference**
Earth	*0.29*	*1*	*-16 C*	*15 C*	*+31*
Venus	*0.75*	*0.7*	*-40 C*	*470 C*	*+510*

- *Both* planets, especially Venus, are warmer than the 'naïve picture' predicts. We suspect the atmosphere must play a role, otherwise Earth would be a 'fridge' at the present time !

How does light interact with an atmosphere ?



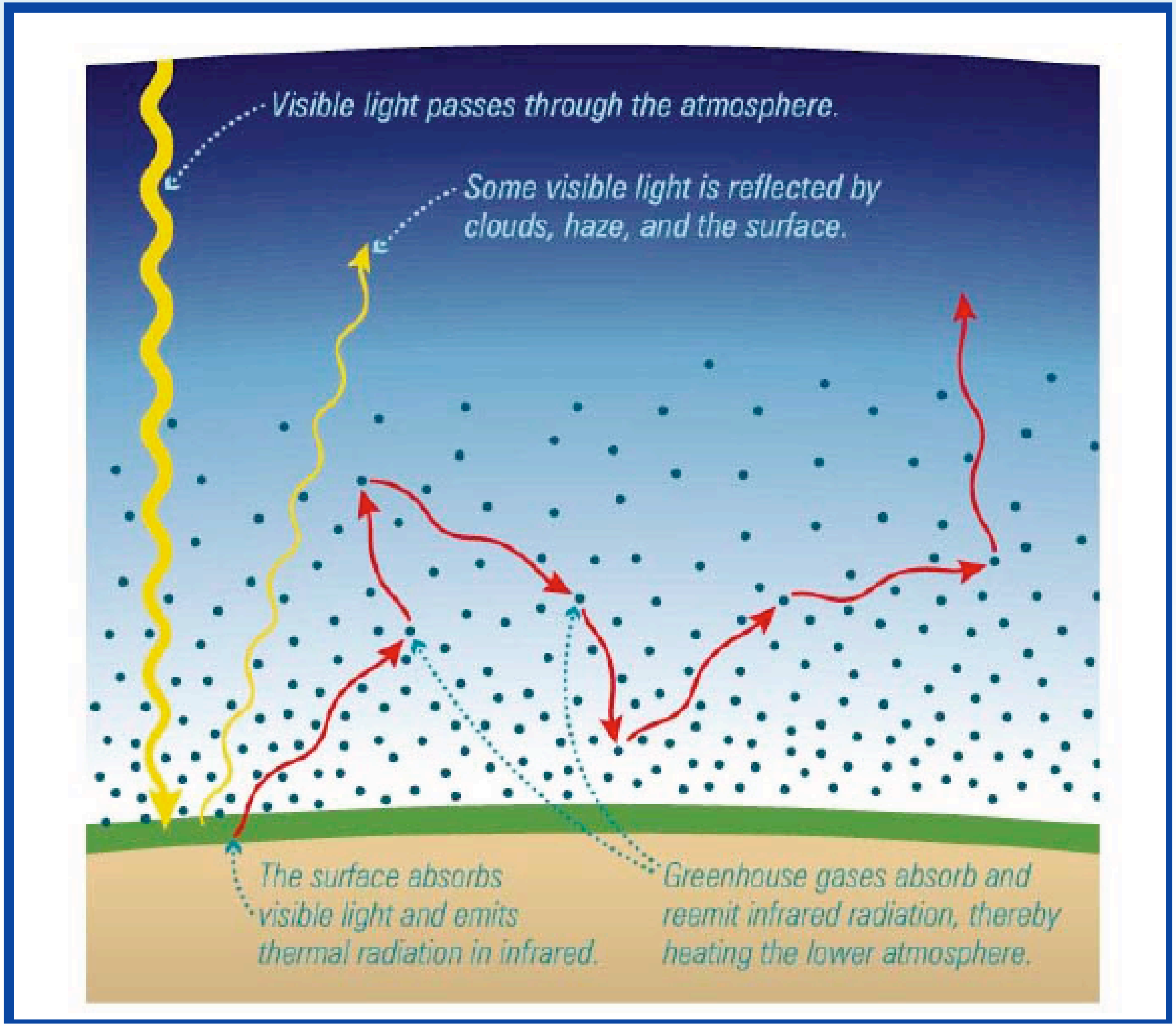
Ionisation - photon energy liberates electrons from parent nuclei (X-ray)

Dissociation - photon energy disrupts molecular bond (UV)

Scattering - photon changes direction (visible)

Absorption - molecule promoted to 'higher state' (infrared or IR)

How does the Greenhouse Effect warm an atmosphere?



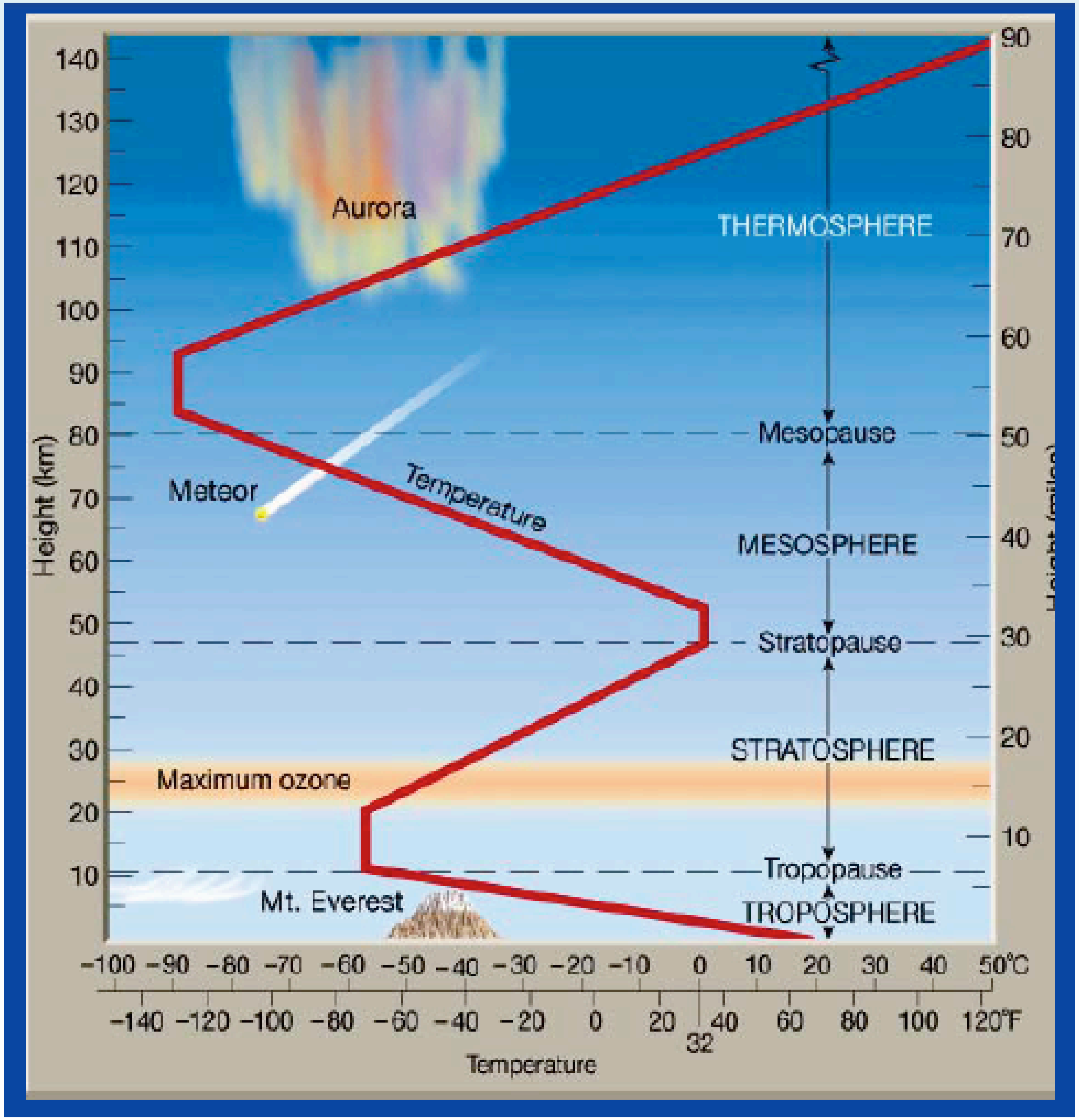
The main Greenhouse gases

There are three ‘big ones’:

Carbon dioxide (CO_2), water vapour (H_2O), methane (CH_4)

Natural processes usually ensure that a certain level of these gases is maintained in the atmosphere. However problems may arise when the concentration of a greenhouse gas *increases so rapidly* that these processes cannot ‘moderate’ the resulting increase in atmospheric temperature.

Temperature structure for Earth



X-rays, UV heat and ionise gas, balanced by thermal conduction

UV deposits a lot of energy here

Greenhouse gas traps IR, convection.

Reflect on this question …

What would happen to the Earth's atmospheric temperature if its surface were *less reflective* ?

(a) It would increase

(b) It would decrease

(c) It would stay the same

What would happen to the Earth's atmospheric temperature if its surface were *less reflective ?*

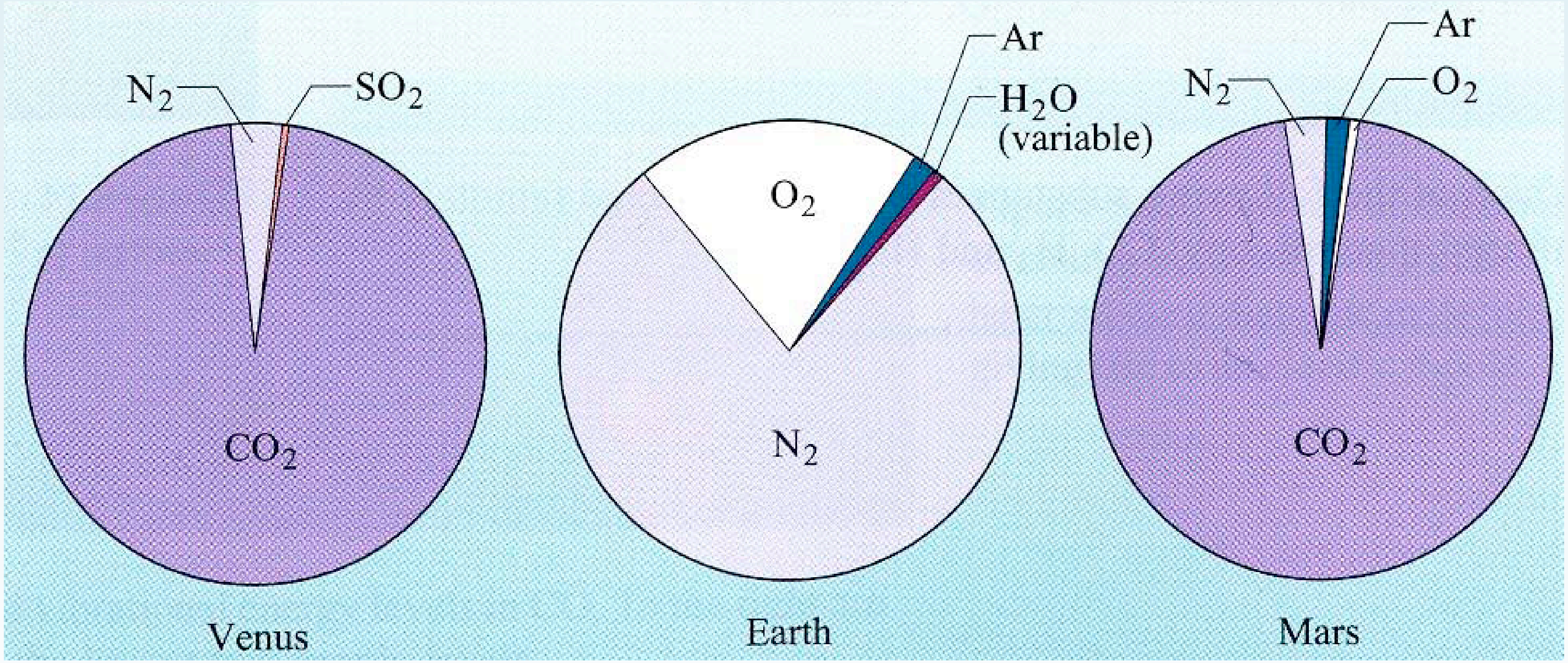
(a) It would increase

This is what happens when artic ice melts (e.g. in the summer) - arctic water absorbs more light, temperature rises

Evolution of an atmosphere

- Atmospheres are not static phenomena, they are *dynamic*.
- Over the very largest time scales (4.6 billion years) planetary atmospheres have also gradually changed
- Early atmospheres may have been very different from their present-day appearance - the planets in our own Solar System apparently evolved in quite different ways.

Comparing atmospheric compositions

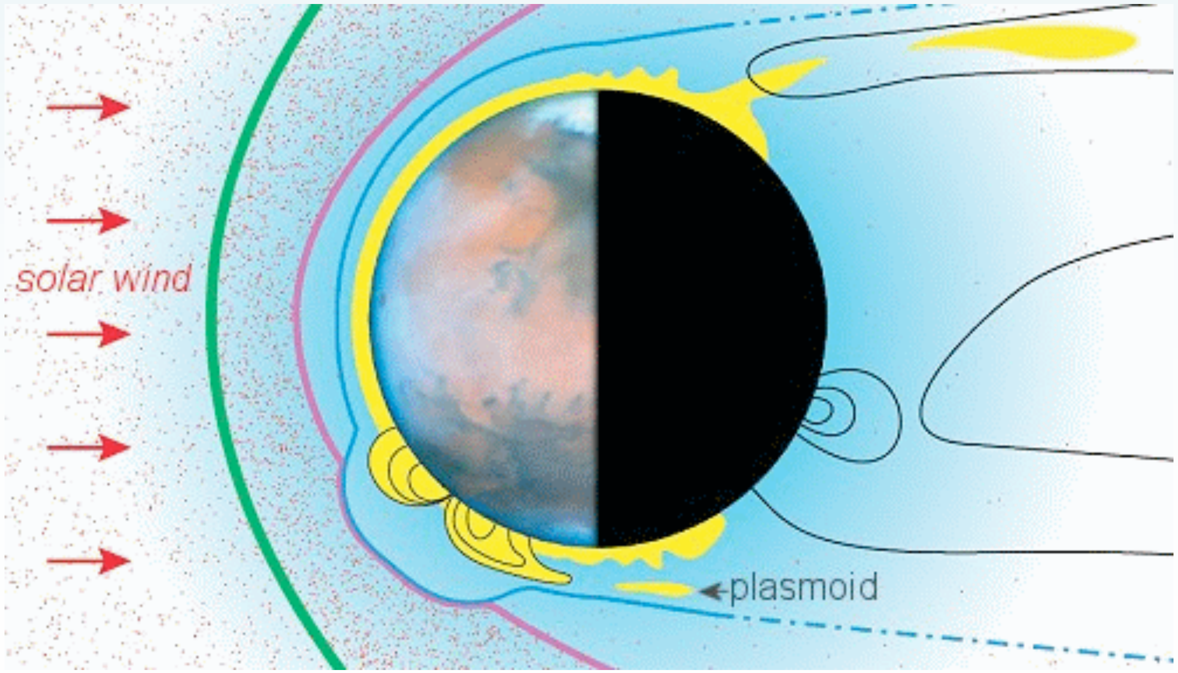


Have these planets always been so different ? How did they end up like this ?

The primordial atmosphere

- Consisted of the most abundant elements at the time of Solar System formation: H_2, He

- Where did they go ? One popular theory is that the primordial Earth did not have a strong magnetic field, thus the planet was directly exposed to the the *solar wind*, which ‘erodes’ or ‘strips’ the atmosphere.



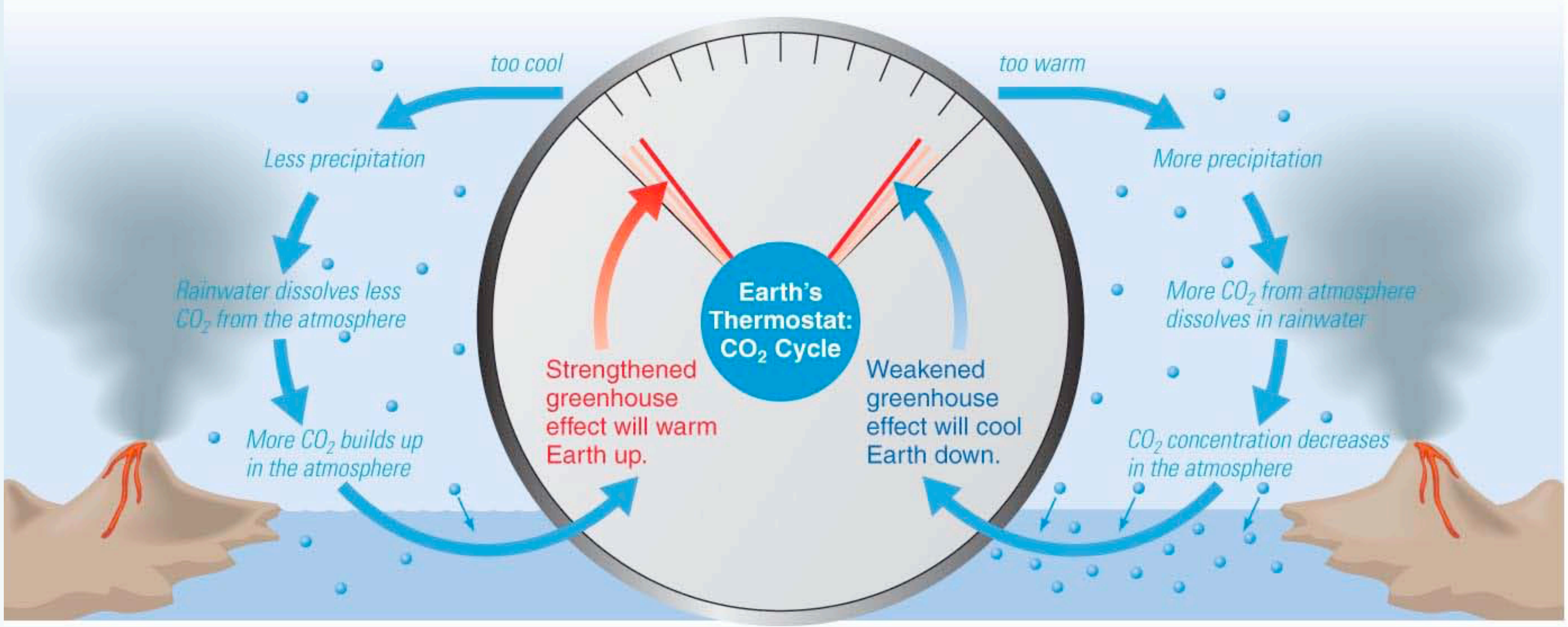
The 'volcanic' atmosphere

- Volcanoes on the Earth released gases such as H_2O, CO_2, SO_2 , CH_4
- No free O_2 but water can form oceans as Earth cools.
- Once oceans have formed, CO_2 can dissolve or become 'locked' in marine sediments.

The atmosphere as we know it

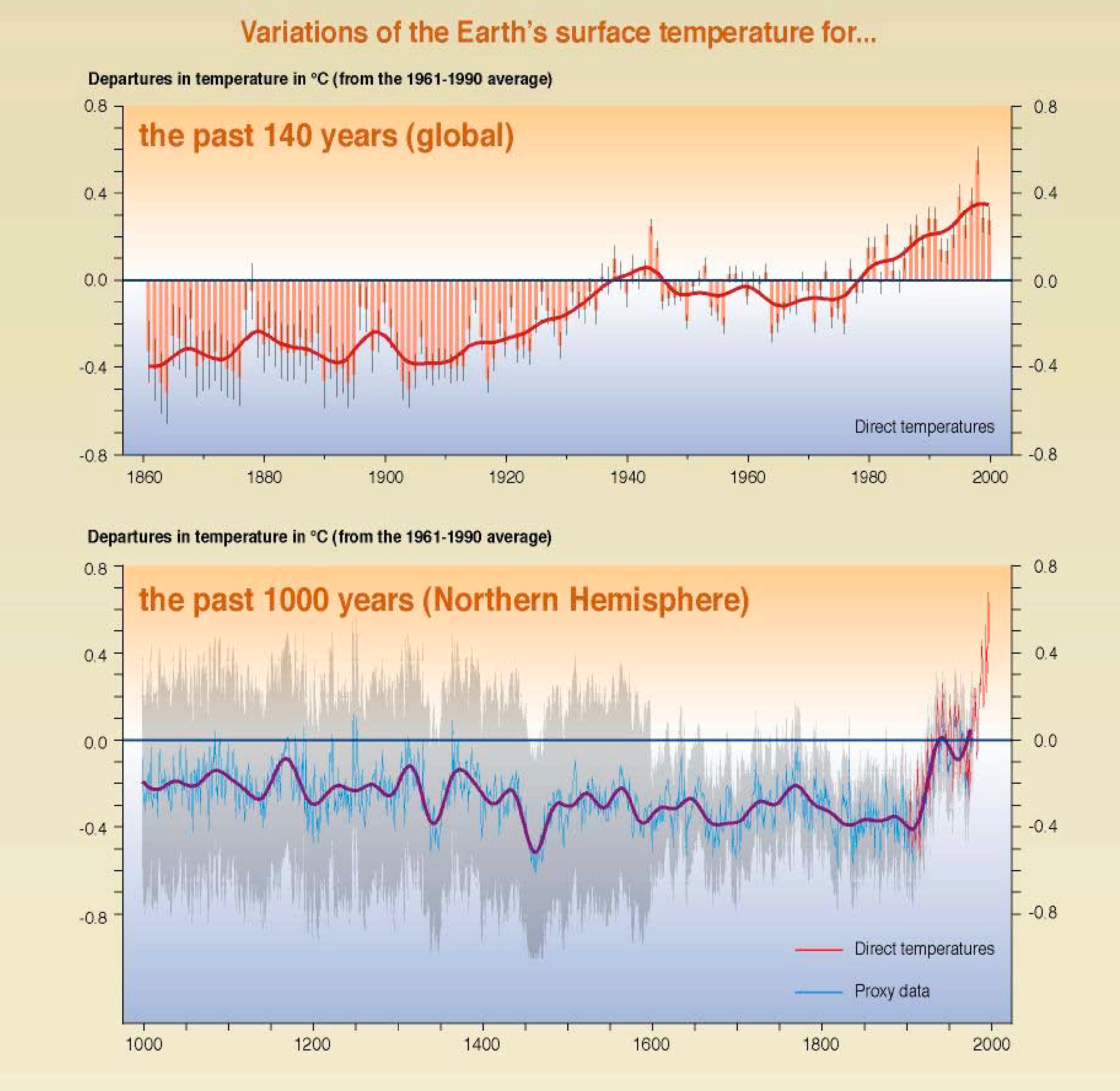
- Characterised by a ~20% abundance of O_2, and relatively little CO_2
- O_2 production: A little was produced when UV light dissociated water molecules. Once this happens, ozone O_3 is formed and can protect the planet from high-energy UV photons through
  $O_3 + h\nu\ (\lambda<900\ \text{Å}) \rightarrow O_2 + O$
- On a protected Earth, life emerges: *cyanobacteria* and eventually other plants supply further oxygen through *photosynthesis*

The carbon ‘thermostat’



- *Cooling* allows CO_2 to increase.
- *Warming* causes it to decrease through increased preciptation.
- This feedback can cope with changing CO_2, but only to a certain point. Human production of CO_2 relatively rapid.
- More on climate change: www.ipcc.ch

Variability of Earth's surface temperature



From www.ipcc.ch (2007 IPCC report)

Explaining the Venusian climate

- A question: What would happen to the Earth if we moved it towards the Sun, to a location at Venus' orbit ?

Clue: Consider also that warmer atmosphere is capable of holding more water vapour …

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Answer (it's not pretty!):

1. *The more intense solar radiation would raise atmospheric temperatures.*
2. *Higher temperature increases evaporation of water into atmosphere,* ***but*** *a warmer atmosphere holds more water vapour, which is a greenhouse gas and thus increases the temperature further …*
3. *This 'runaway effect' results in a Venus-like climate: Oceans evaporate, any water released in volcanoes cannot remain on surface, carbon dioxide remains in the atmosphere and cannot be removed or recycled.*

Explaining the Martian climate

- We have geological evidence that liquid water was probably abundant on Mars in the distant past (>3 billion years ago).

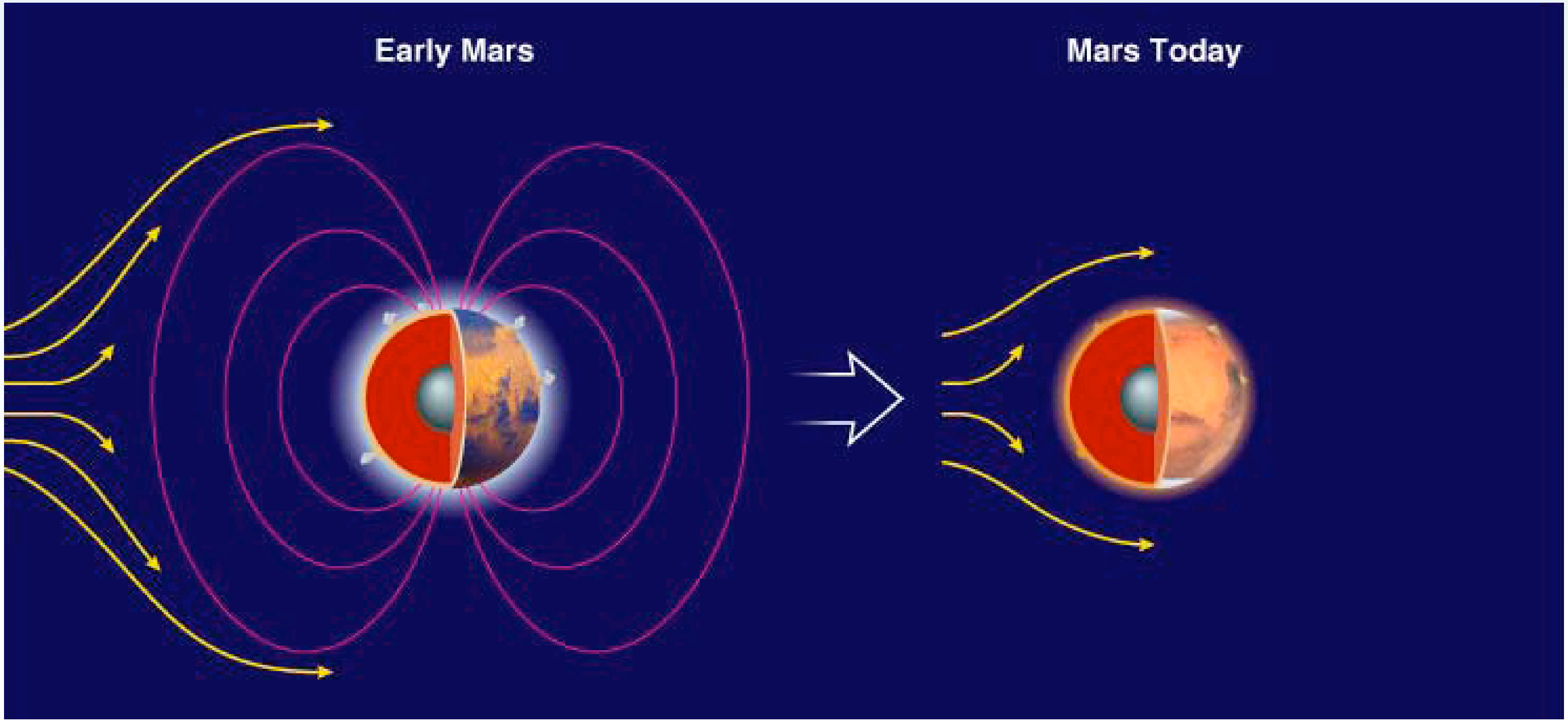
- At present, there is some evidence for ice mixed in with the surface soil, and a very thin atmosphere which would not be effective in Greenhouse warming.

- So how did Mars lose its atmosphere ?

Explaining the Martian climate

- So how did Mars lose its atmosphere ?

One scenario is that a change (cooling?) in the planet's core ceased production of the magnetic field, and the solar wind 'stripped away' atmospheric layers (spacecraft have seen this happening in the present era!) A thinner atmosphere leads to drop in temperature, surface water freezes.



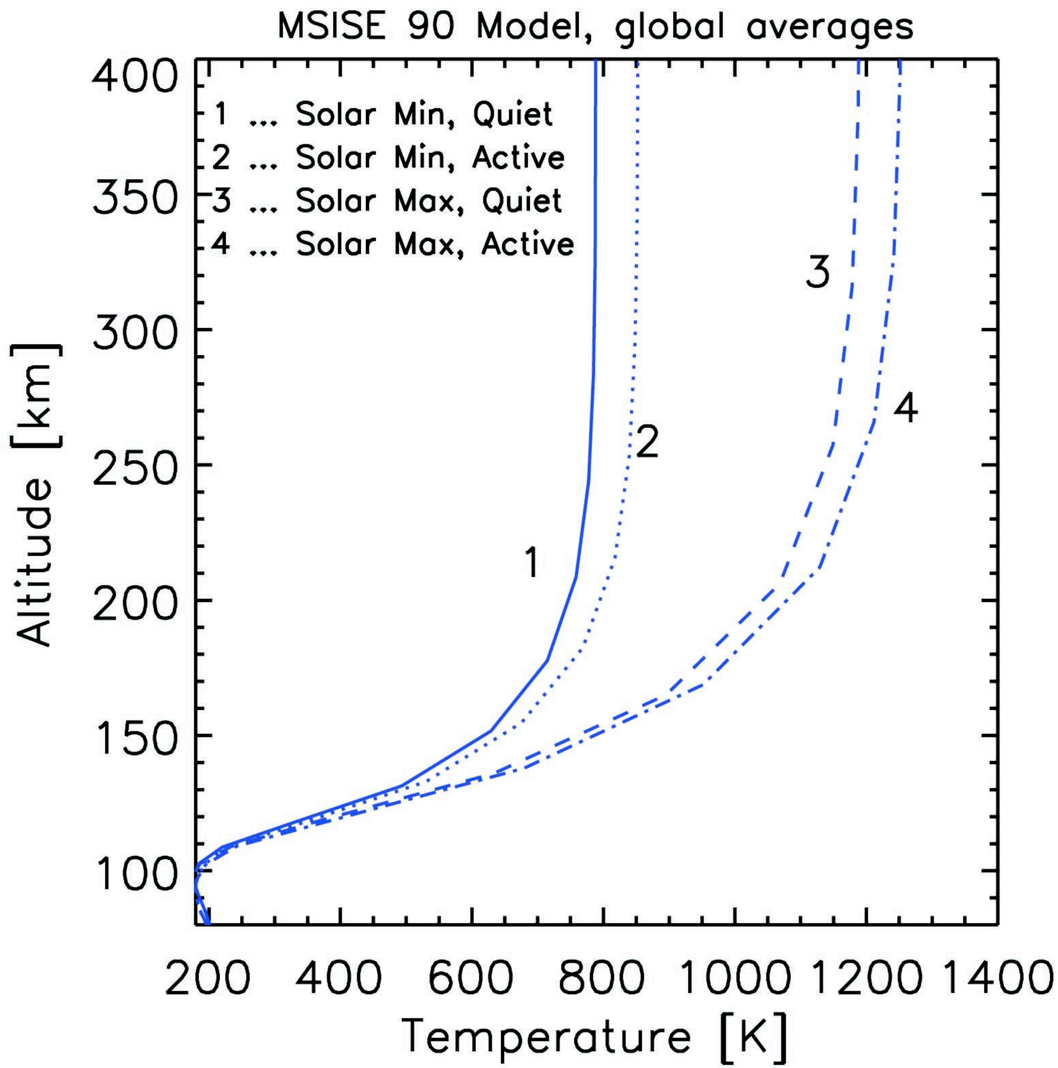
Special role of the Thermosphere

The thermosphere can be thought of as the 'interface' between a planet's atmosphere and its space environment

Thermosphere:

- Energy sources:
  - absorption of EUV (200-1000Å; photoionizing O, O_2, N_2) and UV (1200-2000 Å), photodissociating O_2), leading to chemical reactions and particle collisions, liberating energy
  - dissipation of upward propagating waves (tides, planetary waves, gravity waves)
  - joule heating by auroral electrical currents
  - particle precipitation from the magnetosphere
- Energy sinks:
  - thermal conduction into the mesosphere, where energy is radiated by CO_2, O_3 and H_2O
  - IR cooling by NO and CO_2

Thermal Structure

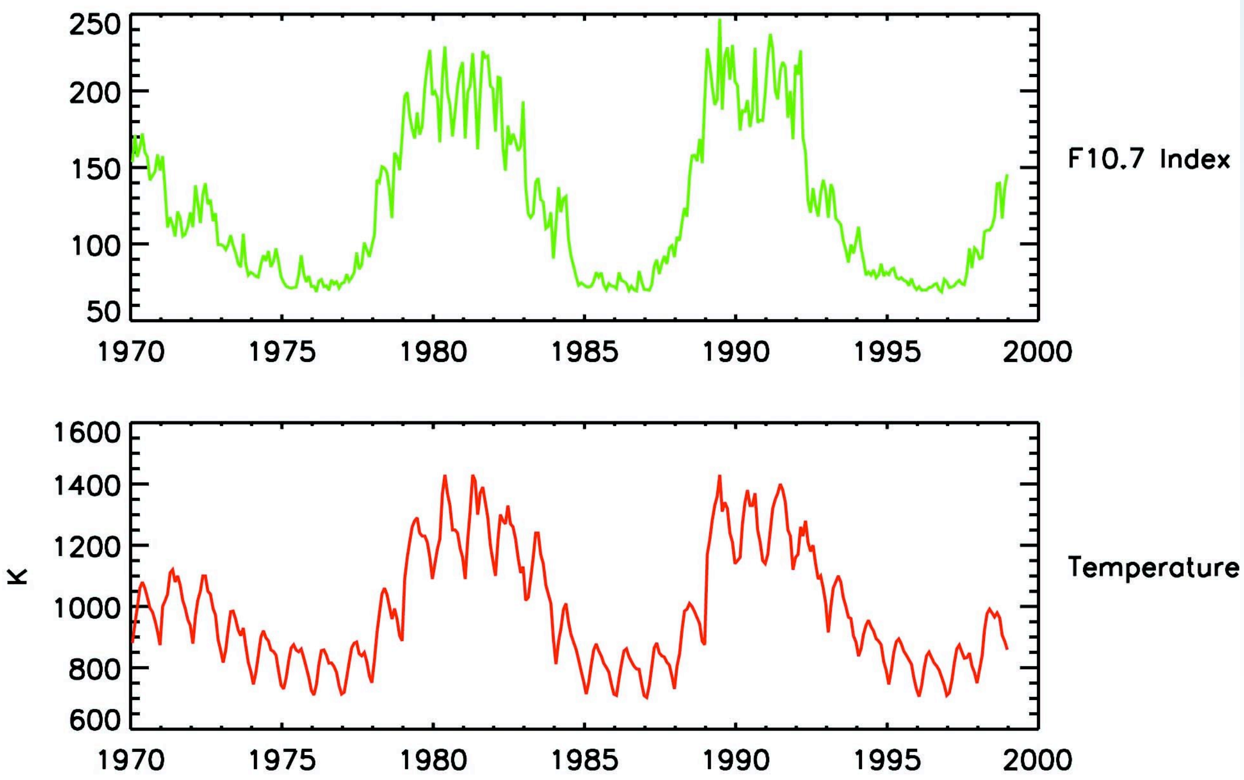


Thermal Variability with Solar Cycle

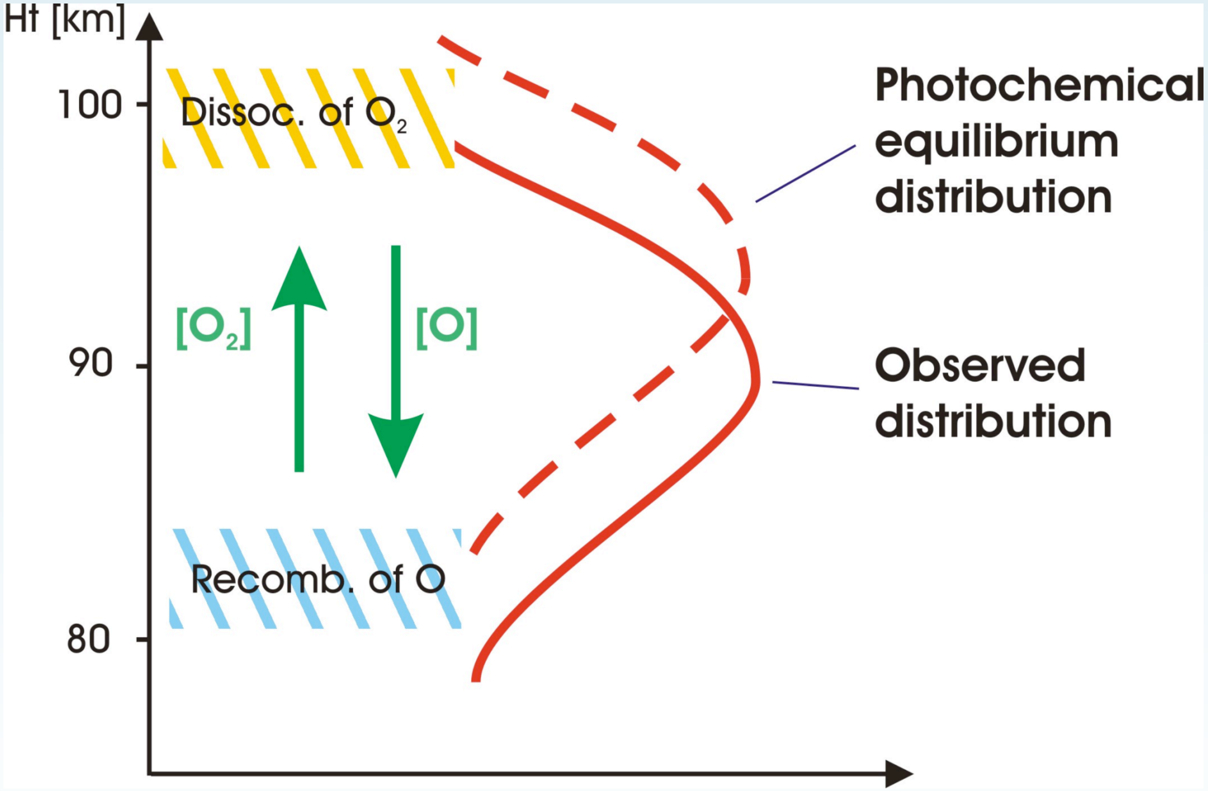
Solar flux intensity is characterized by the F10.7 index, which gives the flux of solar radiation at 10.7 cm wavelength. Although this wavelength is of no importance to the upper atmosphere, its flux correlates well with UV and EUV fluxes.

The solar flux intensity varies with an 11 year cycle.

Exospheric temperatures vary strongly with solar activity as well as season.



The impact of winds on the vertical distribution of [O]



At 80-100 km $\tau_K << \tau_{recombination}$ $\Rightarrow$ eddy mixing important

Mixing transports O down to lower heights, where recombination is more rapid

Modelling Thermosphere Dynamics

Momentum equation for neutral gas (Navier-Stokes)

$$\frac{\partial}{\partial t}\vec{U} + \left(\vec{U}\cdot\vec{\nabla}\right)\vec{U} = -\frac{1}{\rho}\vec{\nabla}p - 2\vec{\Omega}\times\vec{U} + \frac{1}{\rho}\vec{\nabla}(\mu\vec{\nabla}\vec{U}) - \nu_{ni}(\vec{V}-\vec{U})$$

Advection

Pressure gradient

Coriolis

Viscosity

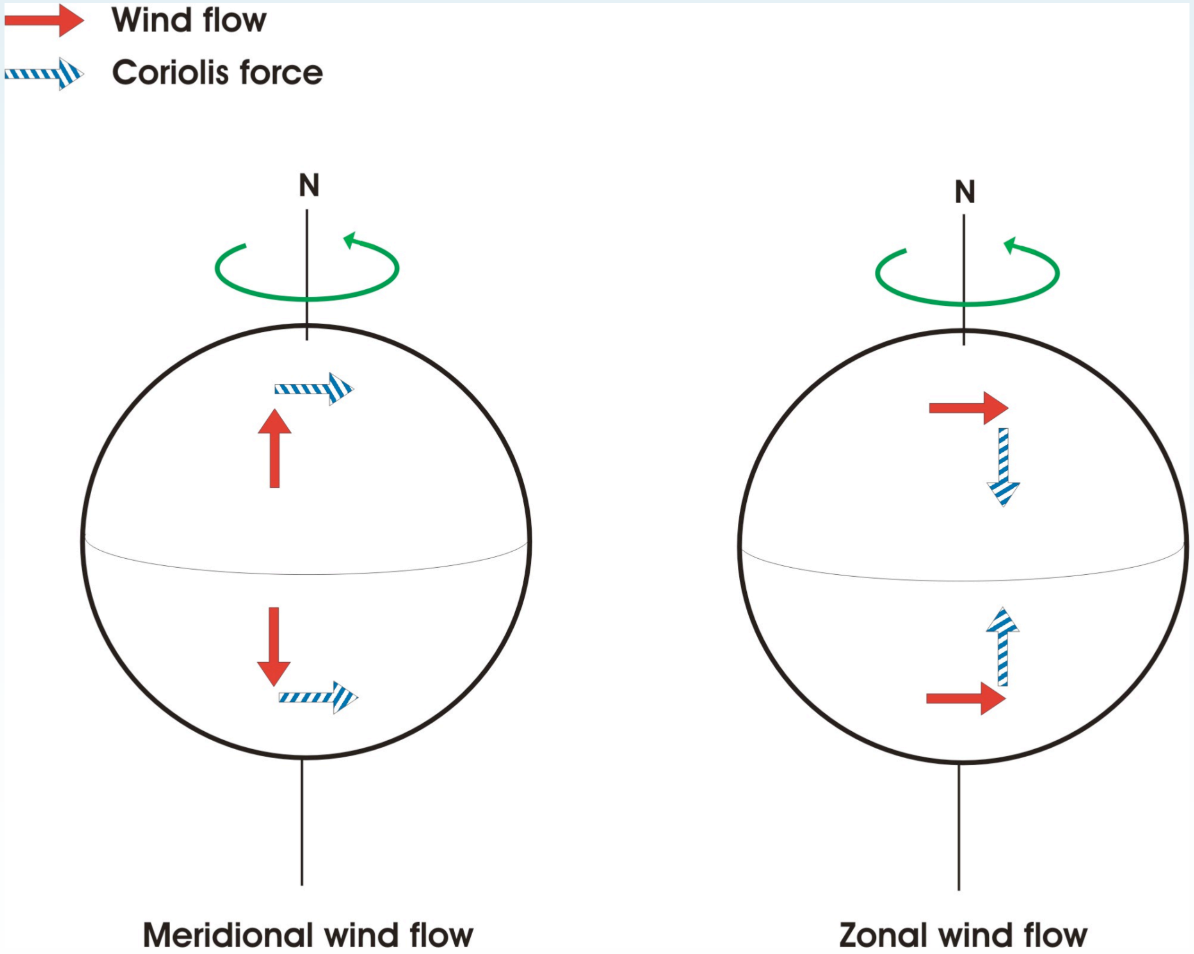
Ion drag

Pressure gradients are driven by temperature differences
Advection is transport of momentum by winds
Coriolis force is caused by the Earth's rotation
Viscosity is due to gas particle collisions
Ion drag is transfer of momentum from ions to neutrals

Ion drag is an **external force**, the rest are **internal**

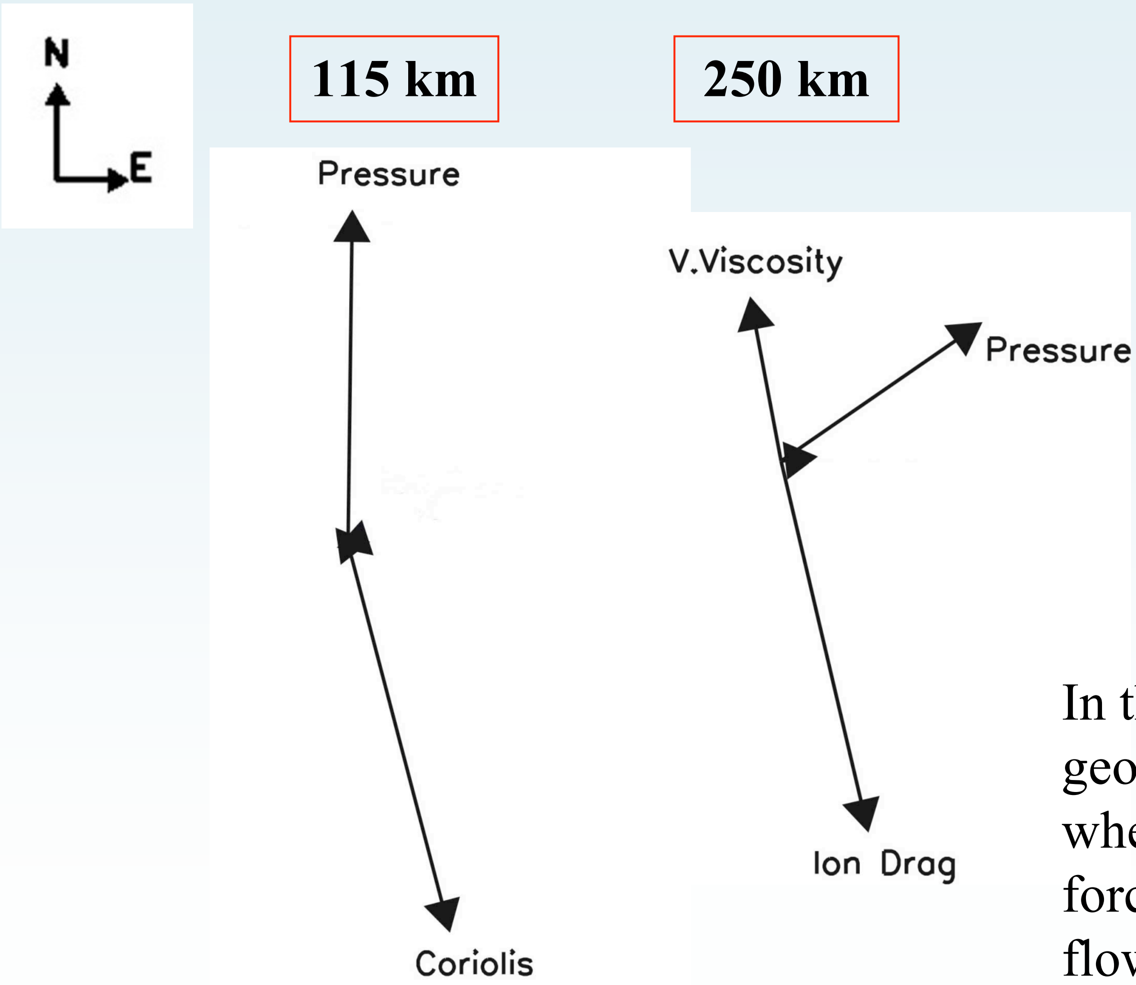
Influence of Coriolis force in a corotating frame

Coriolis force acts **perpendicular** to the **wind vector**. It deflects poleward winds towards the east and eastward winds equatorward. So, winds are driven clockwise (anticlockwise) in the northern (southern) hemisphere around pressure minima.



Momentum balance

March, 30N, 54E, 15:40 LT

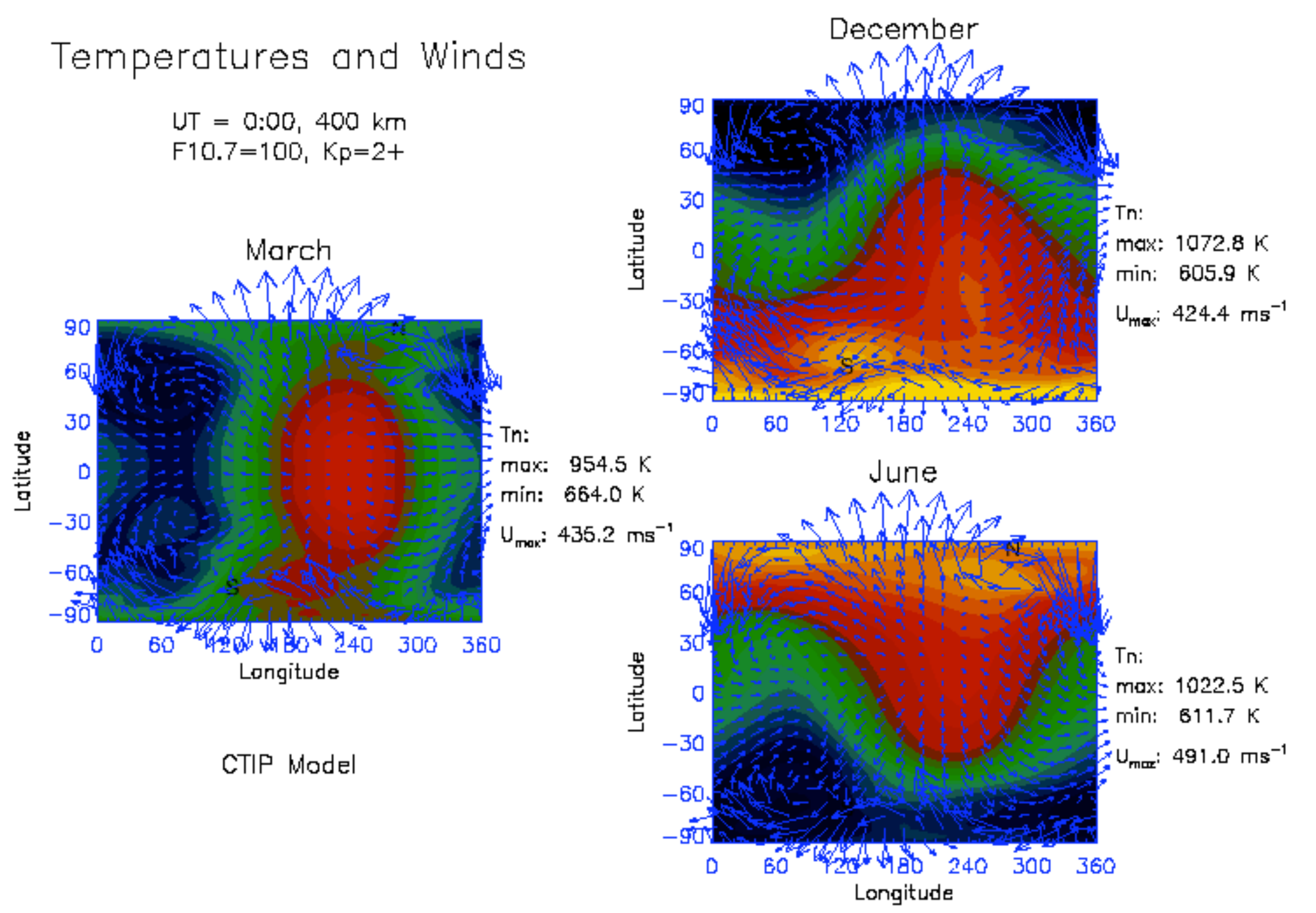


Note the differences in momentum balance at different altitudes!

In the lower thermosphere, geostrophic balance is found, where Pressure and Coriolis forces almost balance. Winds flow roughly perpendicular to isobars.

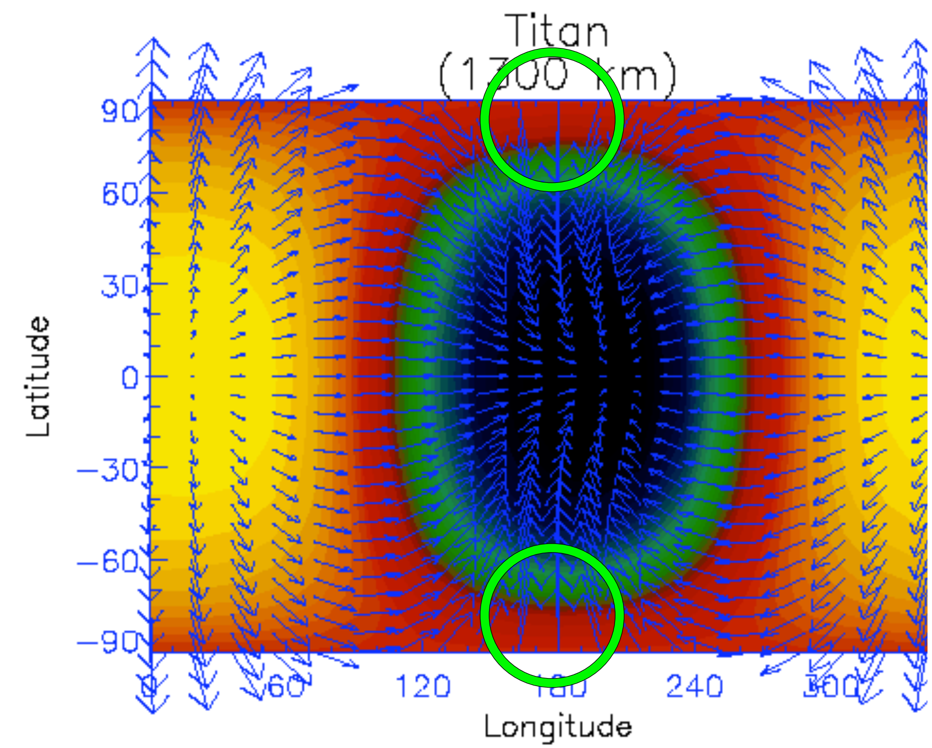
Activities at UCL

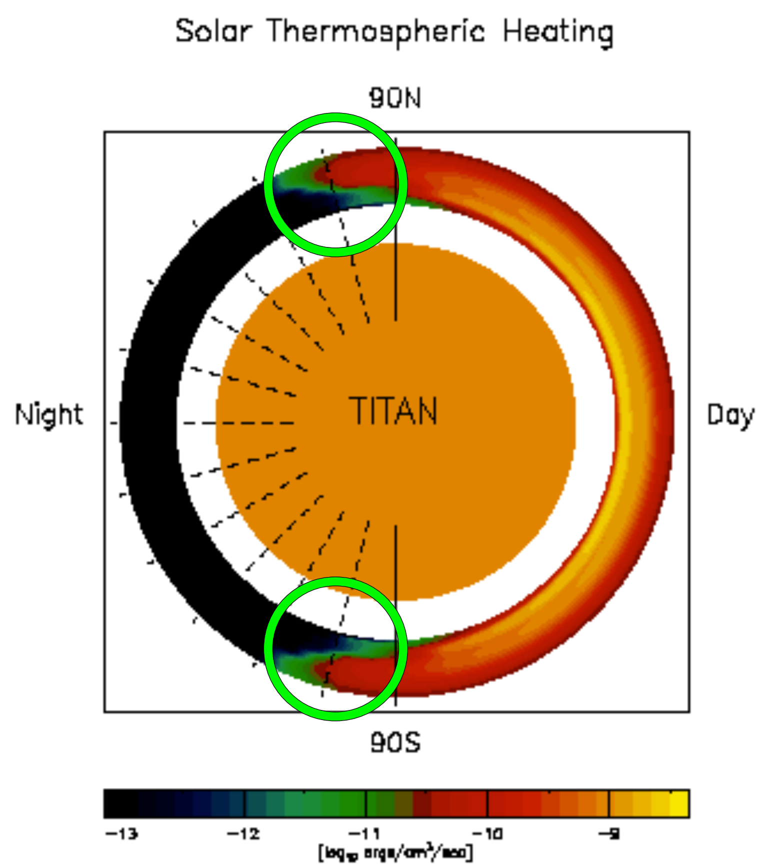
• The Atmospheric Physics Laboratory (APL) is a group whose origins lie in studies of the Earth's ionosphere, aurora and thermosphere -both theoretical and observational. Models such as CTIP and CMAT provide simulations of the Earth's global thermosphere and ionosphere.



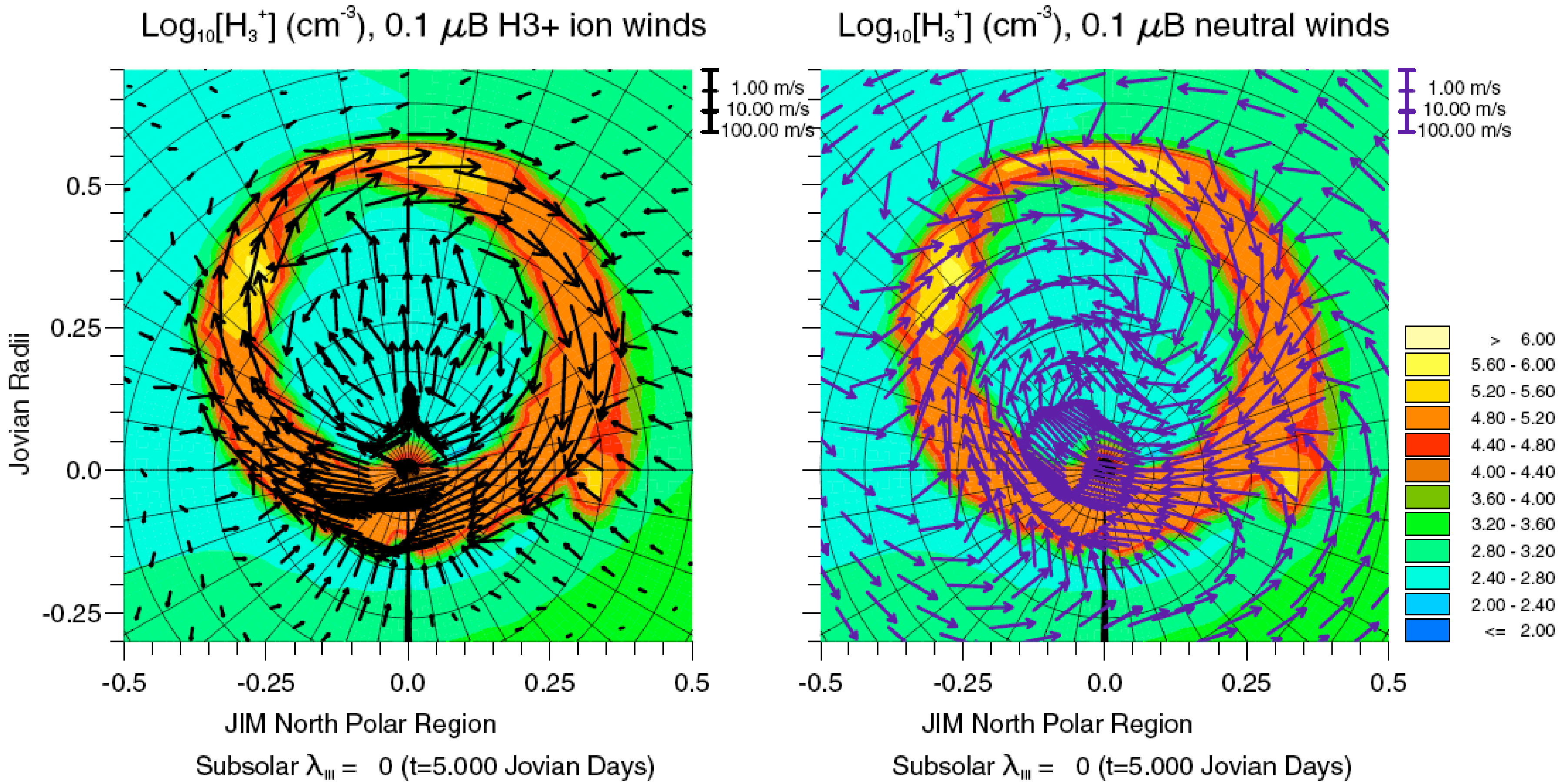
Nightside heating on Titan

The basic hydrodynamic framework can be adapted to treat other planetary bodies. Some examples follow …



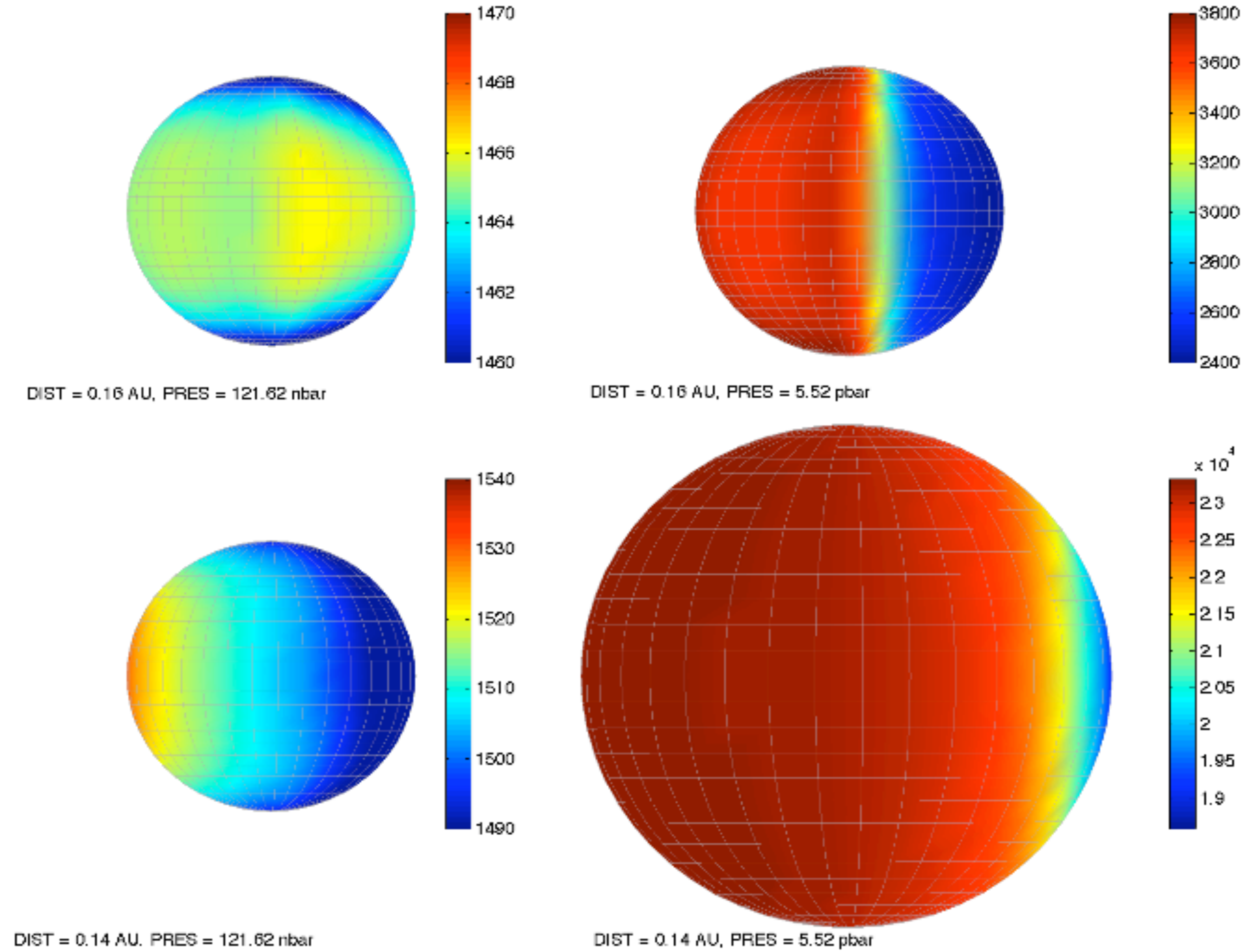


Polar flow at Jupiter



From *Achilleos et al (2001, NJP)*, first attempt to check how the *magnetosphere* 'forces' the thermosphere. Important to note that ion motions predicted by model have been observed, and that the model can link these with neutral motions (not so easy to observe). **The H3+ ion is a very important coolant of the Jovian thermosphere.**

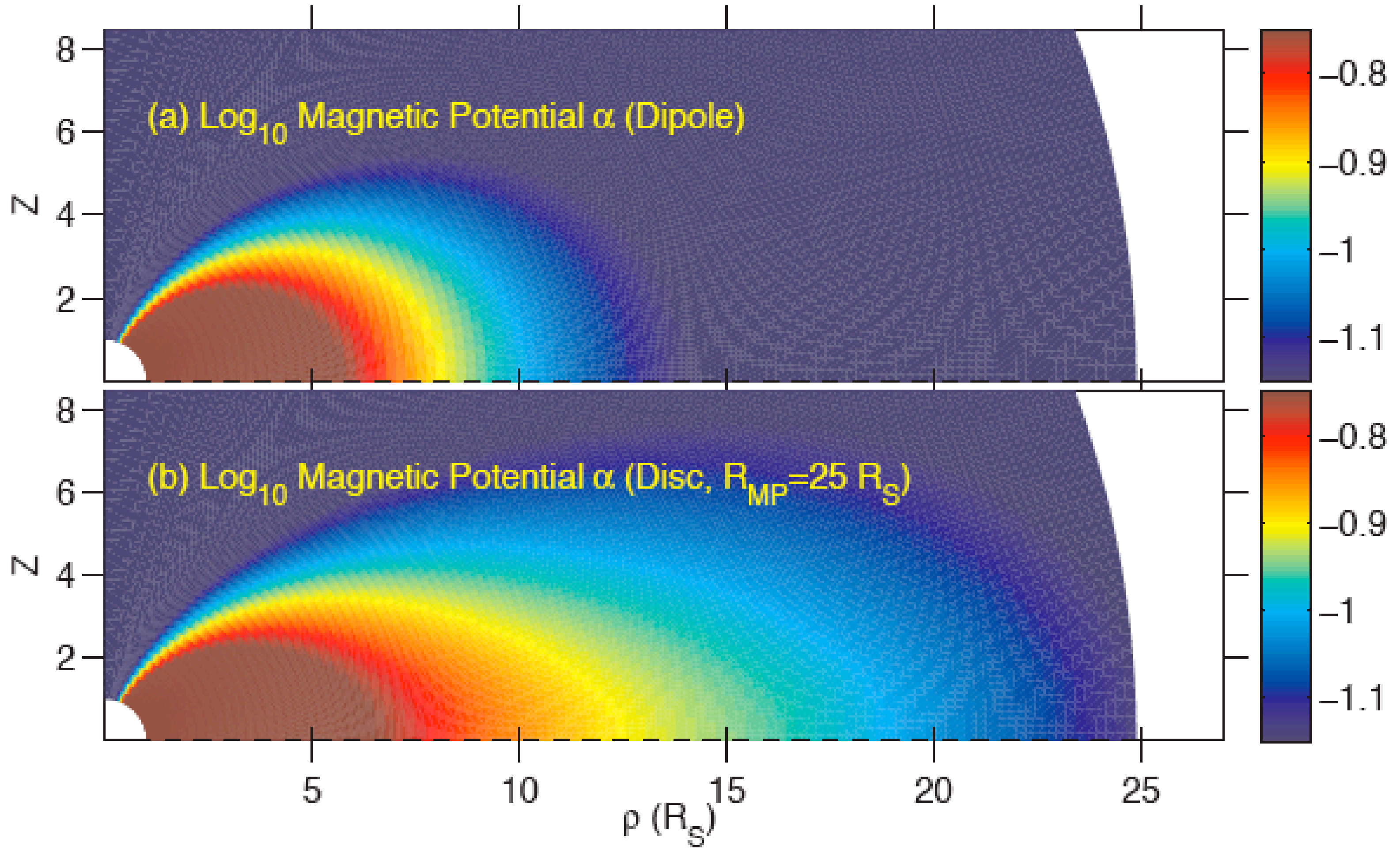
H3+ is good at cooling exoplanets !



From *Koskinen et al (2007, Nature)*, a 'numerical experiment' to see how close to a Sun-like star one could place a Jupiter-like planet.

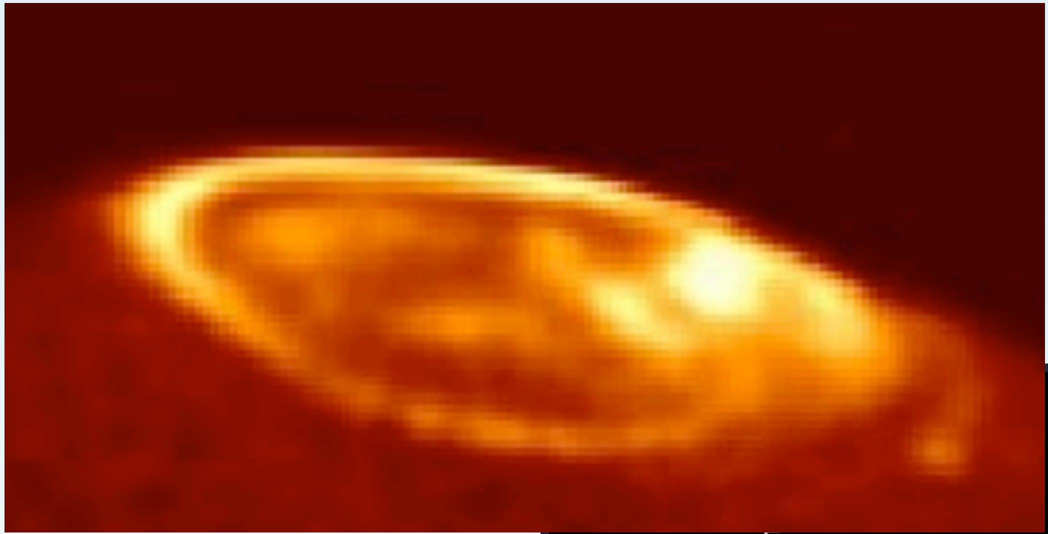
The link to other regions…

Atmospheres are very interesting places, but an important lesson is that they are ***not isolated systems***. Through our collaborations with Cassini scientists, we have also branched out into magnetospheric science at Saturn, modelling magnetic field and plasma (ionised gas) …

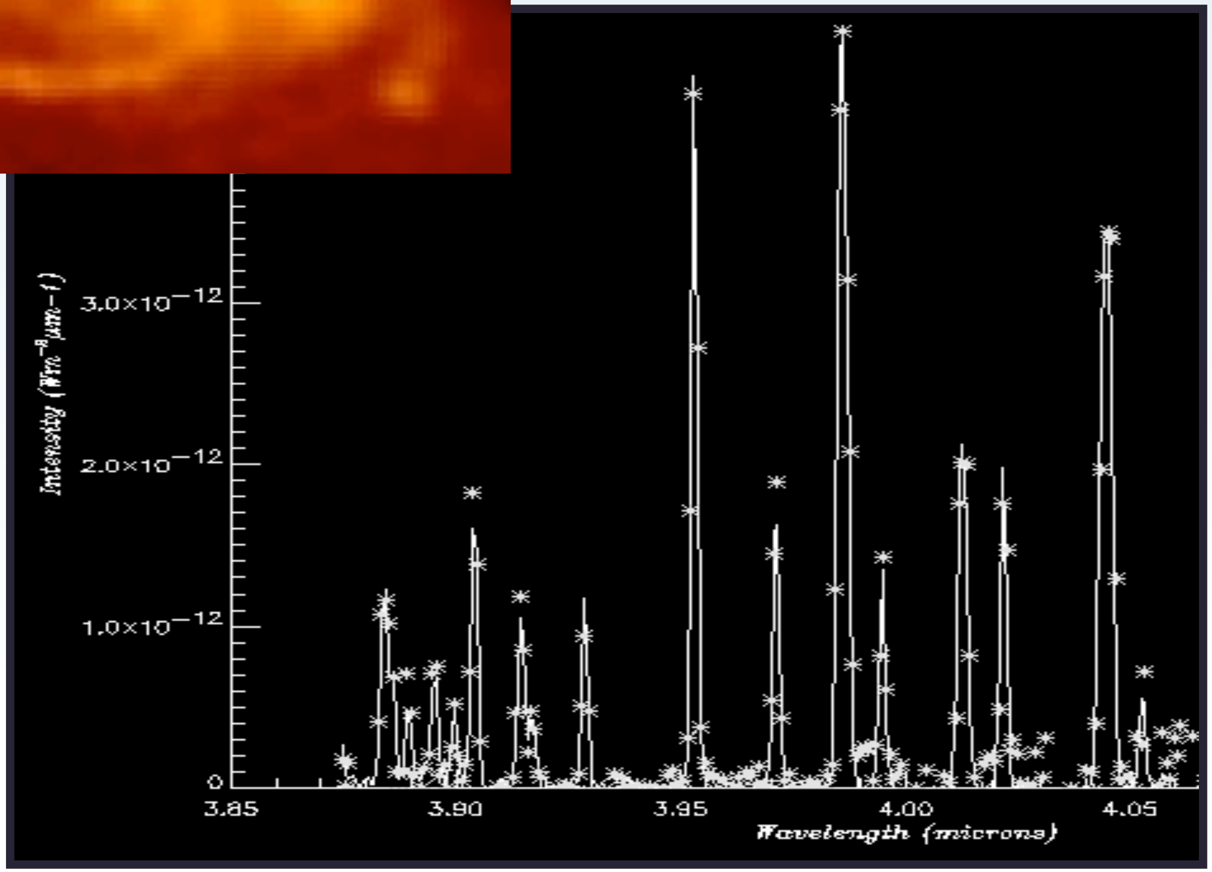


… from *Achilleos, Guio and Arridge (MNRAS, in press, 2009)*

Don't forget observations ! …



Infrared image and spectrum of Jupiter auroral region (H3+ emission). UCL calculations of H3+ spectra helped make the first detection of this ion at Jupiter.



Concluding remarks …

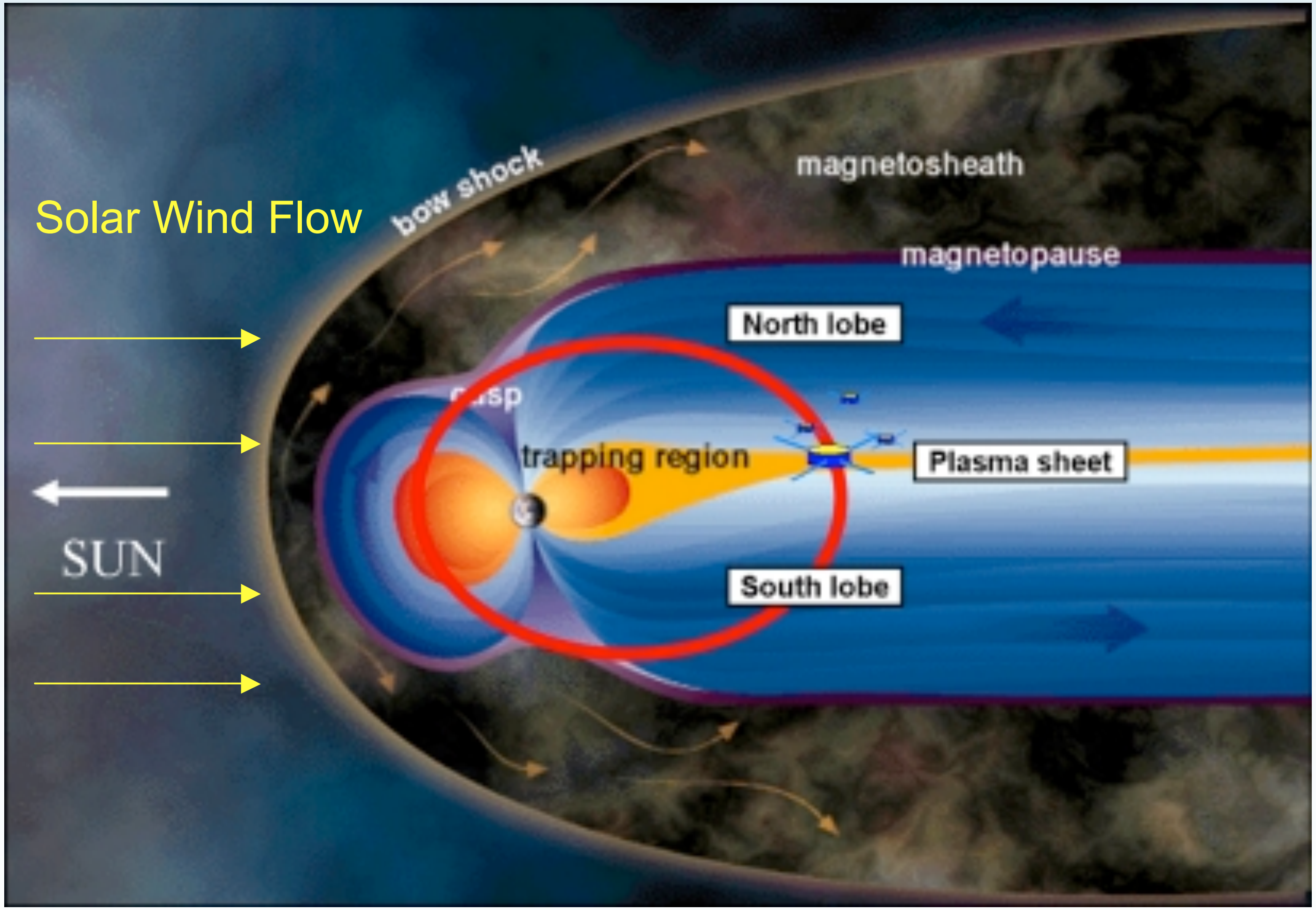
- The structure of a planet's atmosphere arises from a 'balancing act' between **pressure** and **gravity.**

- The temperature is determined by an 'energy budget', e.g. **absorption / reflection** of solar radiation, auroral heating.

- The notion of human-induced global warming on our planet at the **very least should be taken seriously**.

- Atmospheres are **not isolated systems** - coupling to ionospheres, aurora, magnetospheres.

The Earth's Magnetosphere: An overview



- To make progress, we need to understand something about the physics of *plasma* (a fully ionized gas)
- The **magnetic field** plays a central role, as we shall see
- The 'trapping region' forms a *plasmasphere* and *ring current*