ASTR 620: Planetary Processes

Professor Eric Nielsen

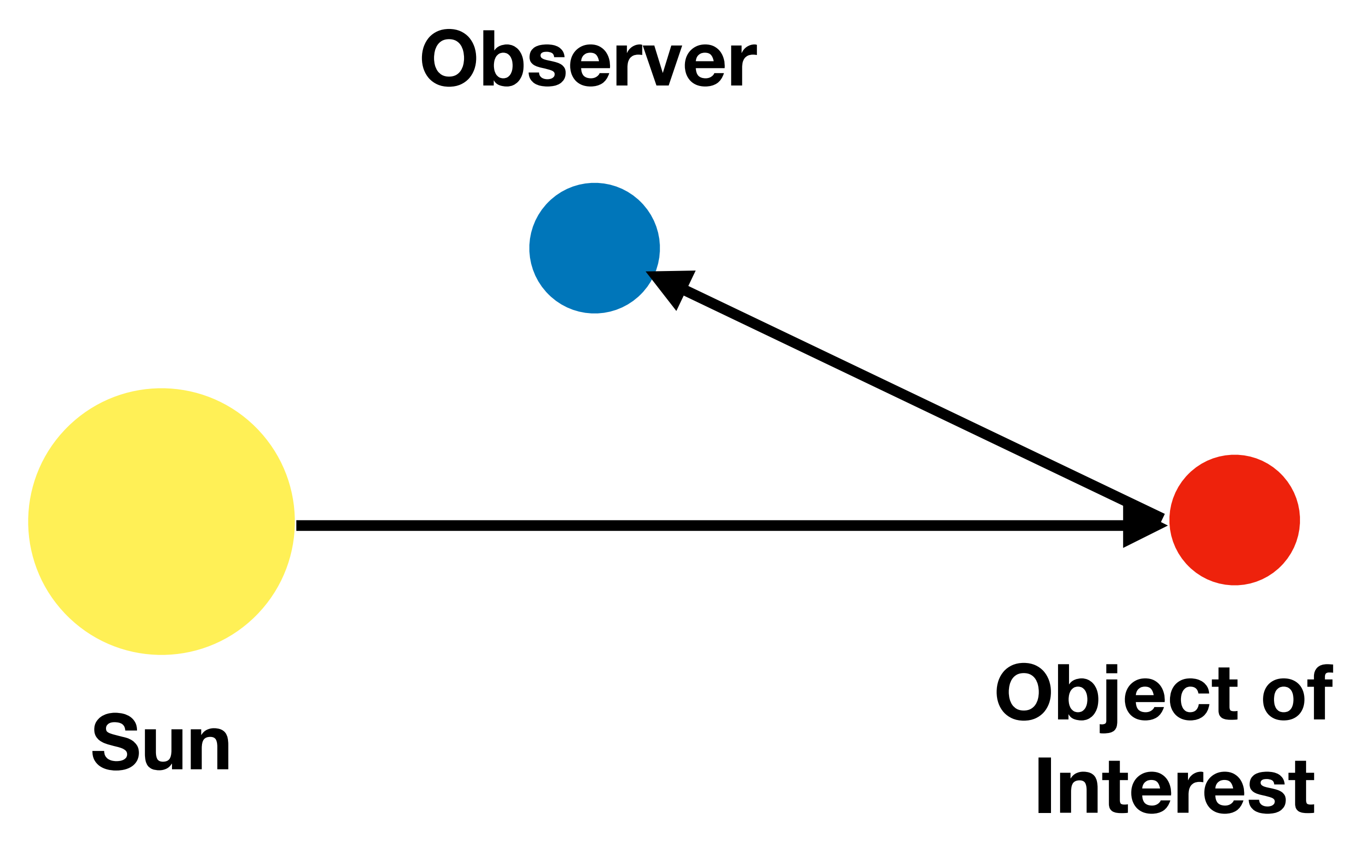
Lecture 16: Atmospheres

Logistics

- Masks are encouraged
- No laptops, phones, or other electronic devices during class (I'll let you know in advance if we'll need laptops for an activity) **You may use a tablet to take notes if prefer, but please only use it for note-taking.**
- Remember to bring you response card to class
- Homework 4 due on Wednesday, October 19 at 11:59pm

Review of the last class

- What is the scattering angle and phase angle in this image?
  - (A) — Scattering angle = 30 degrees, Phase angle = 70 degrees
  - (B) — Scattering angle = 30 degrees, Phase angle = 150 degrees
  - (C) — Scattering angle = 150 degrees, Phase angle = 30 degrees
  - (D) — Scattering angle = Phase angle = 30 degrees
  - (E) — Scattering angle = Phase angle = 150 degrees



Review of the last class

- The albedo of a certain planet is 0.4 at 5000 Angstroms. What is the emissivity of that planet at 5000 Angstroms?
  - (A) — 0.0
  - (B) — 0.4
  - (C) — 0.6
  - (D) — 1.0
  - (E) — No way to tell

Review of the last class

- The albedo of a certain planet is 0.4 at 5000 Angstroms. What is the emissivity of that planet at 20000 Angstroms?
  - (A) — 0.0
  - (B) — 0.4
  - (C) — 0.6
  - (D) — 1.0
  - (E) — No way to tell

Review of the last class

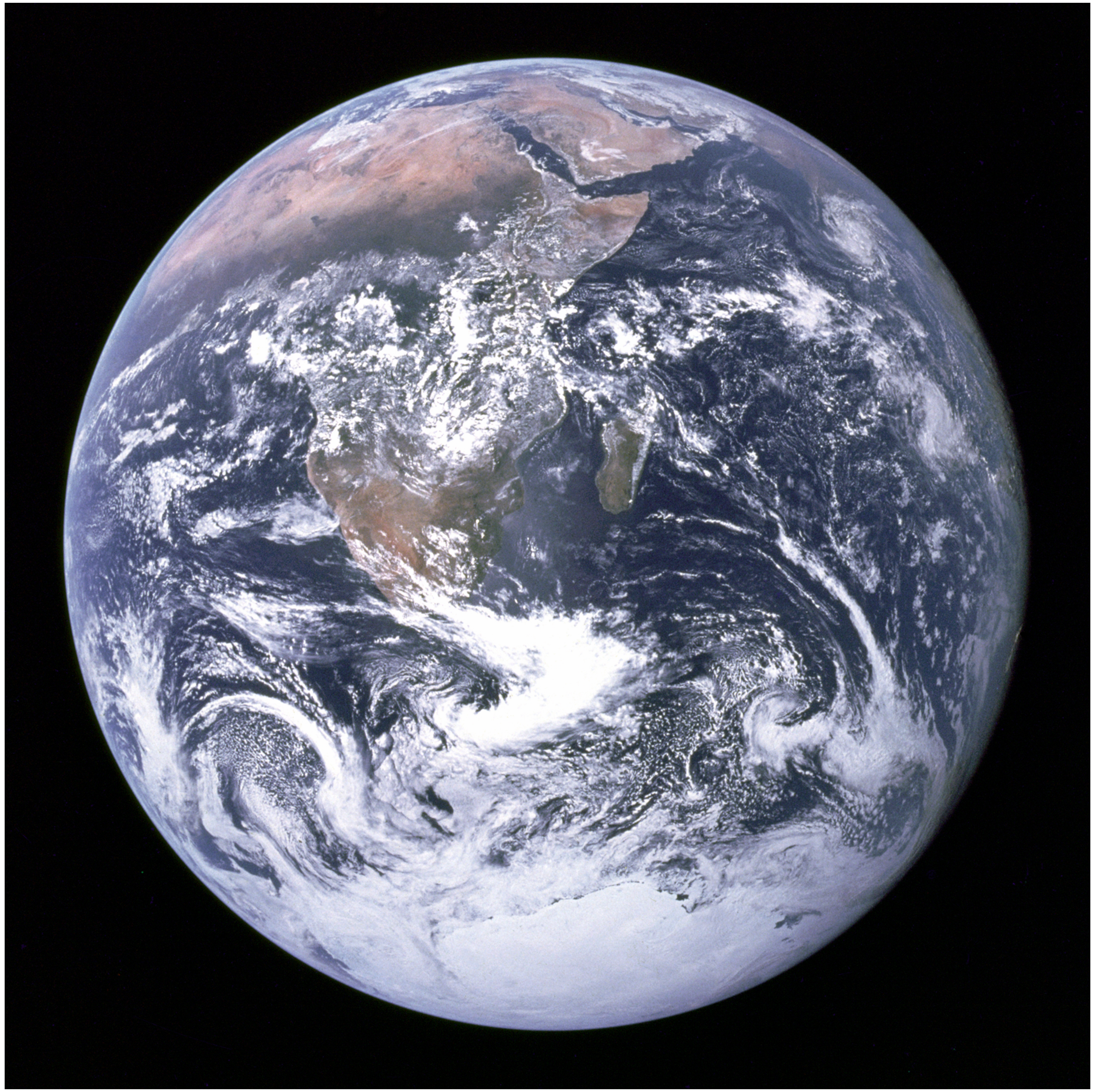
- Typical surface temperature on Earth is about 300K. What's Earth's equilibrium temperature?
  - (A) — 400 K
  - (B) — 350 K
  - (C) — 300 K
  - (D) — 250 K
  - (E) — 200 K

Review of the last class

- An atmosphere with significant greenhouse gasses, like Earth's, is:
  - (A) — mostly transparent in the visible, mostly opaque in the mid infrared
  - (B) — mostly opaque in the visible, mostly transparent in the mid infrared
  - (C) — mostly opaque in both the visible and mid infrared
  - (D) — mostly transparent in both the visible and mid infrared
  - (E) — Completely opaque in both the visible and mid infrared

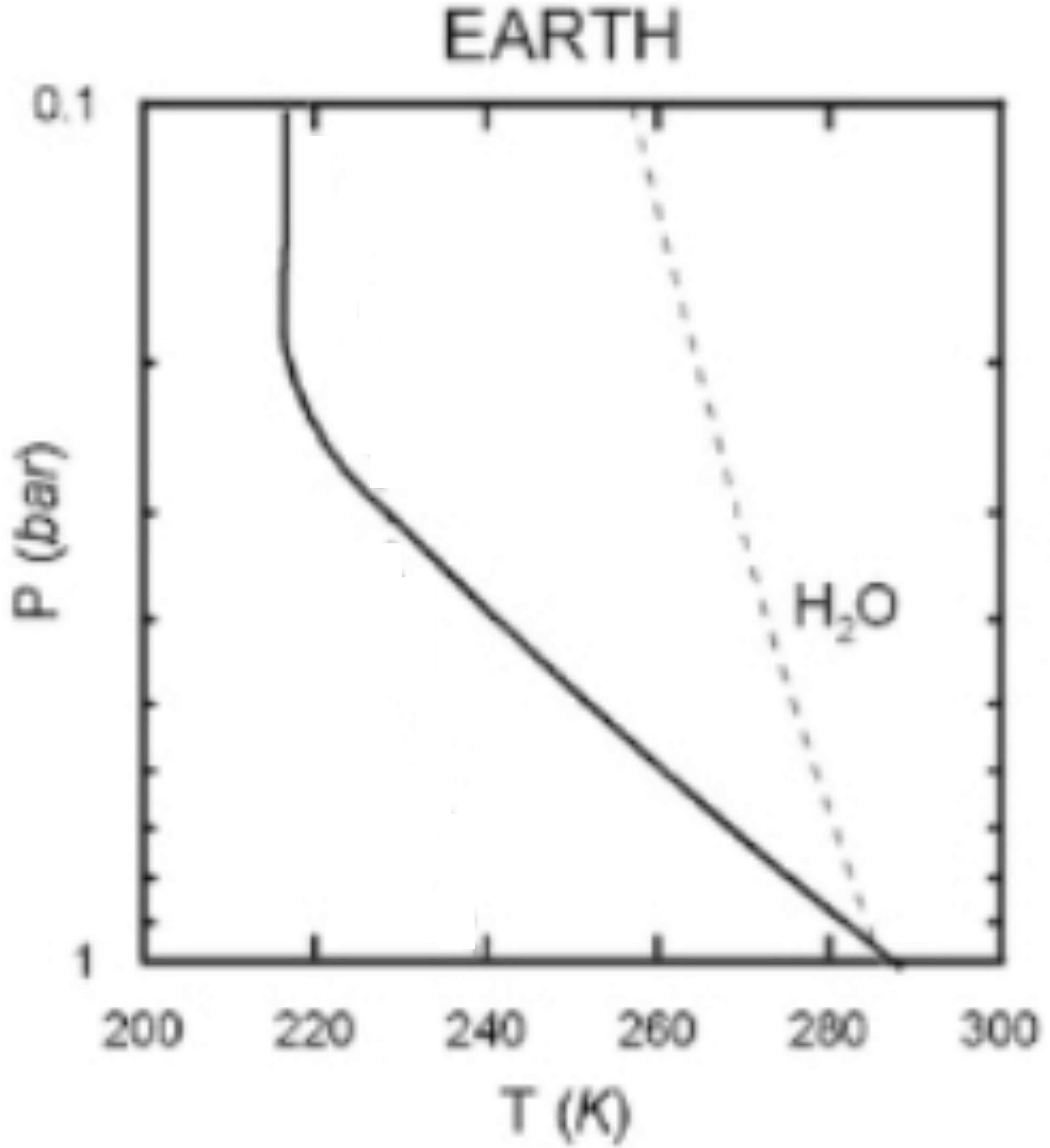
Clouds

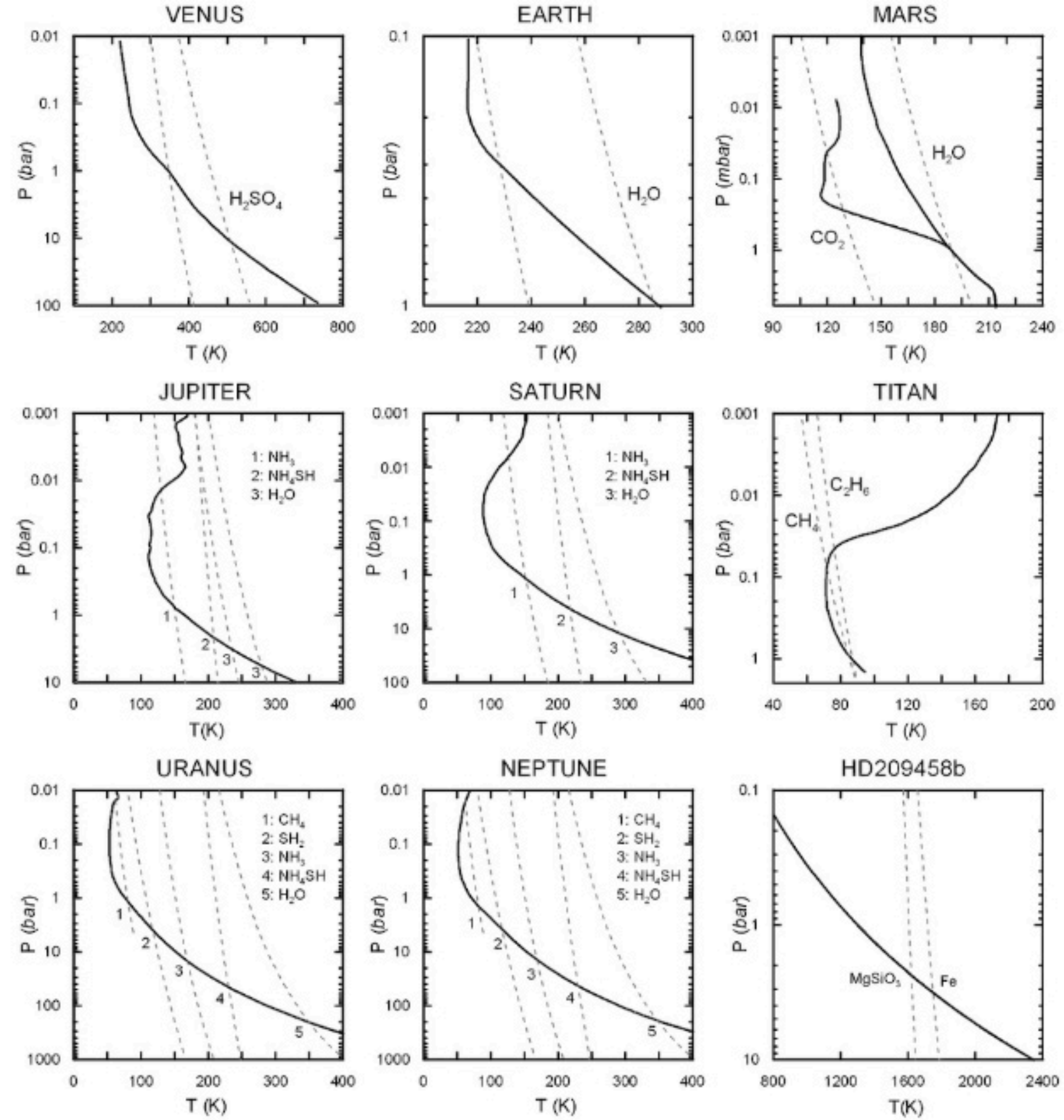
- Clouds play an important role in atmospheric heat balance and thermal structure
- The formation of clouds involves the fields of microphysics and thermodynamics
- Suspended particles can originate from:
  - condension
  - chemical/photochemical reactions
  - outgassing
  - lifting from the surface
  - particle bombardment of atoms and molecules in upper atmosphere

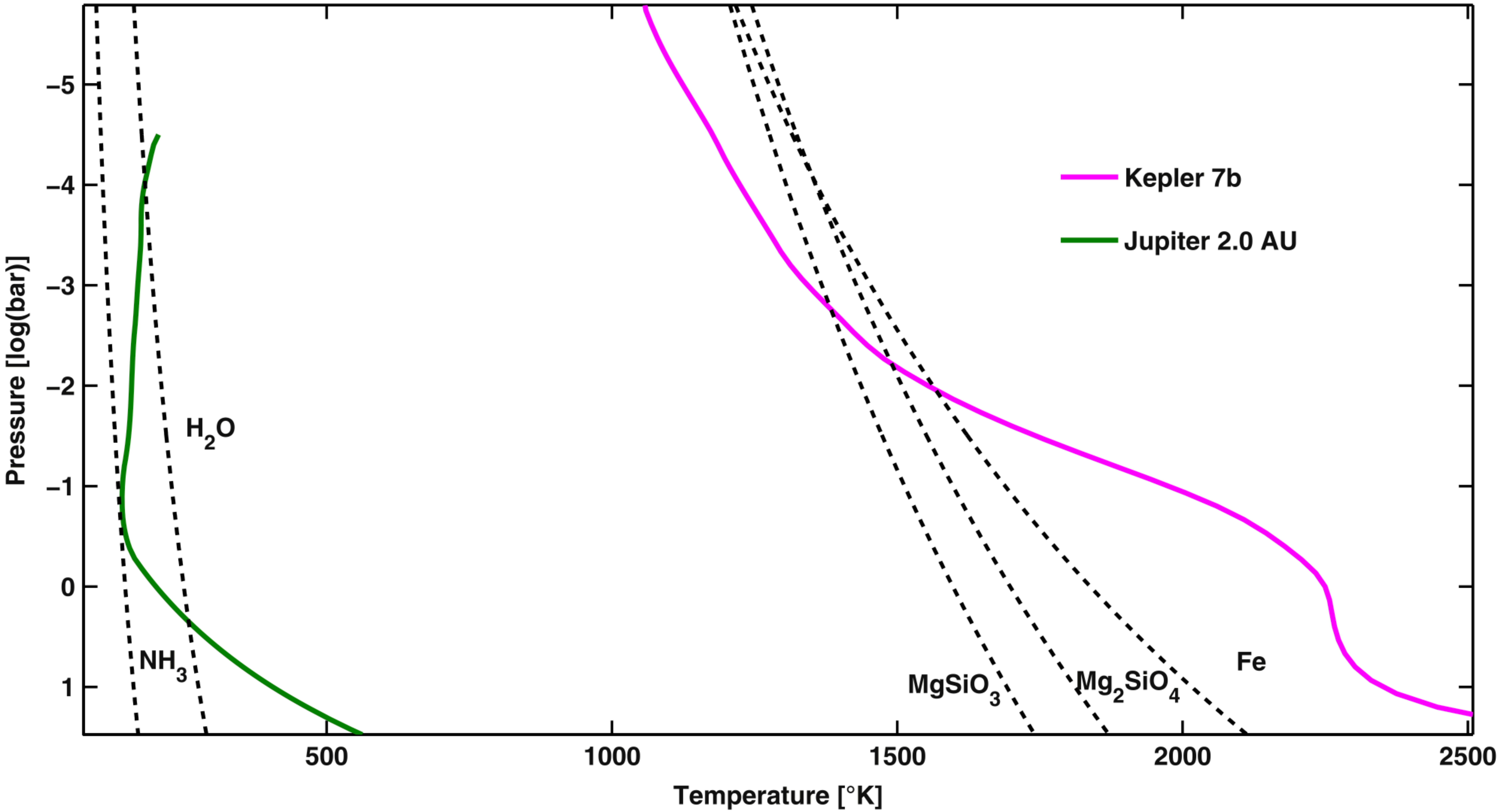


Cloud formation

- Saturation vapor pressure: pressure (at a given temperature) where water (or another condensible) condenses
  - dashed line represents the saturation vapor pressure for water
- Clouds form where the saturation vapor pressure curve is at a higher temperature than the environmental lapse rate
- The two curves cross at the cloud base

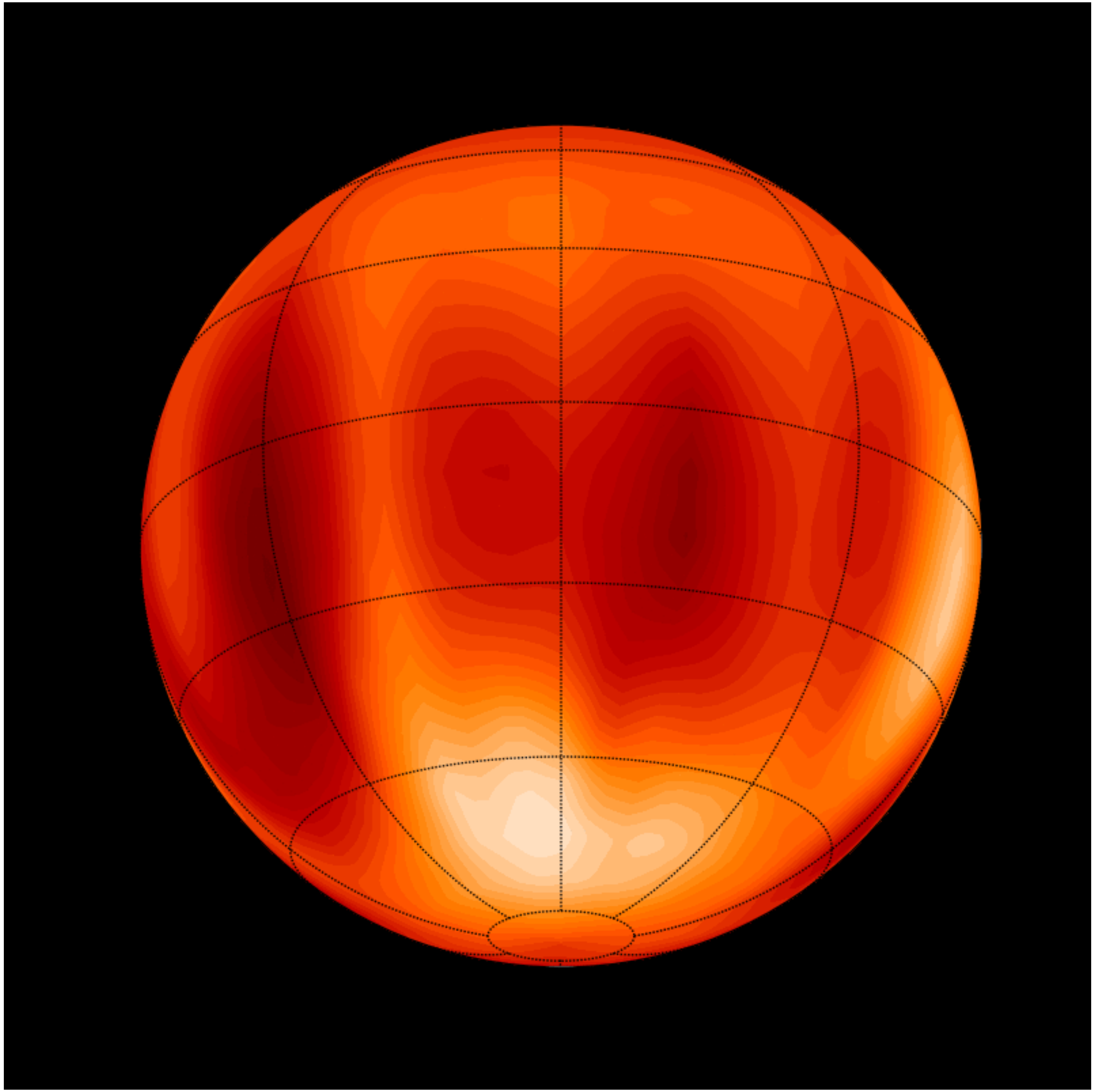



VENUS
EARTH
MARS
JUPITER
SATURN
TITAN
URANUS
NEPTUNE
HD209458b
P (bar)
P (mbar)
T (K)
H_2SO_4
H_2O
CO_2
1: NH_3
2: NH_4SH
3: H_2O
C_2H_6
CH_4
1: CH_4
2: SH_2
3: NH_3
4: NH_4SH
5: H_2O
$MgSiO_3$
Fe



Webber et al. 2015

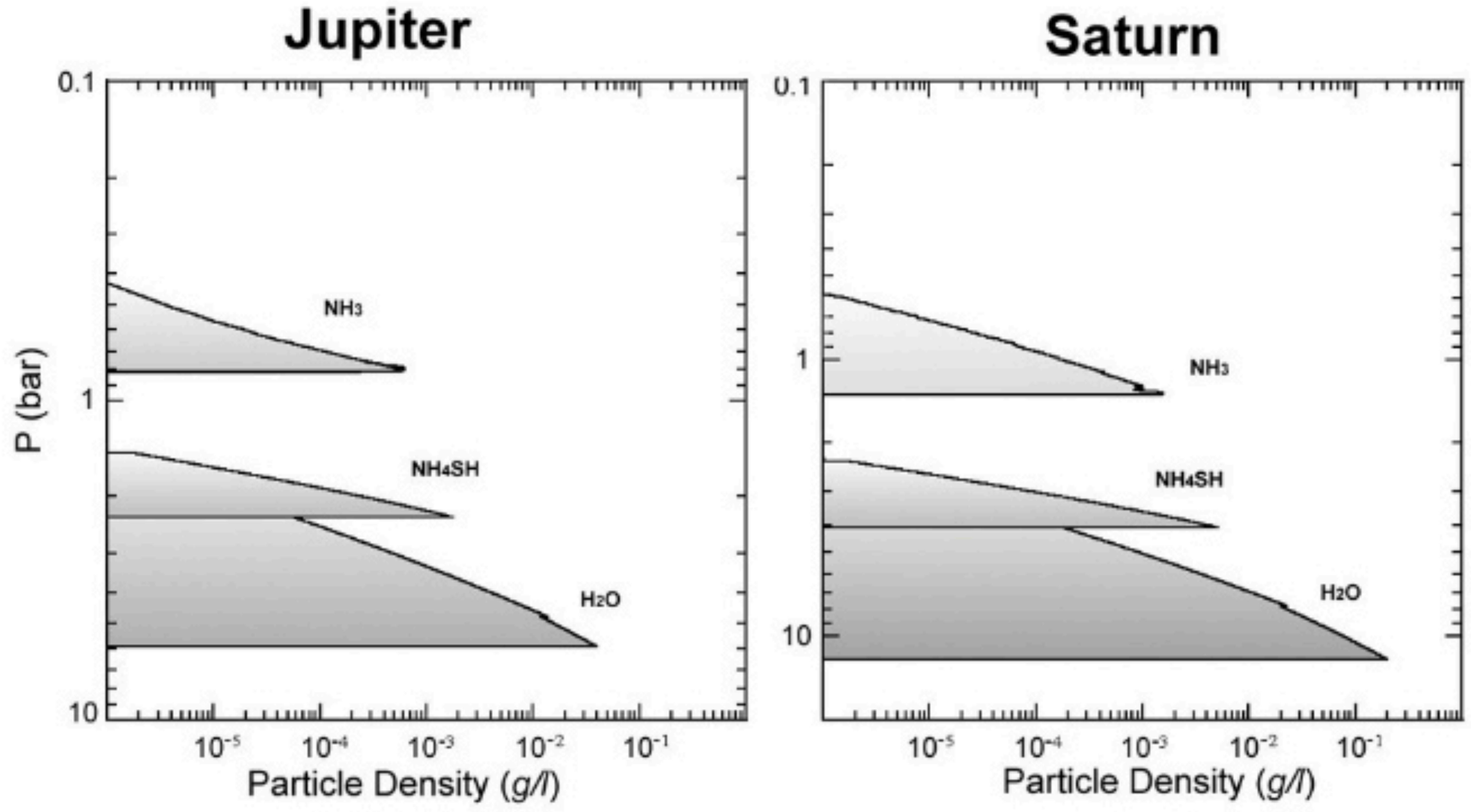

deeper
hotter
denser
NH_3
NH_4HS
H_2O
CH_4 gas
CsCl
RbCl
KCl
LiF
Li_2S
Na_2S
CO gas
Mg-silicates
iron metal liquid
CO gas
Ca-Ti-oxides
Ca-Al-oxides
Jupiter
CH_4 gas
CsCl
RbCl
KCl
CH_4 gas
LiF
Li_2S
Na_2S
CO gas
Mg-silicates
iron metal liquid
Ca-Ti-oxides
Ca-Al-oxides
CO gas
T dwarfs
CO gas
Mg-silicates
iron metal liquid
CO gas
Ca-Ti-oxides
Ca-Al-oxides
L dwarfs
CO gas
Ca-Ti-oxides
corundum
CO gas
L- to M dwarf transition
(c) 2008 K. Lodders



Lehman-16
Crossfield et al. 2014

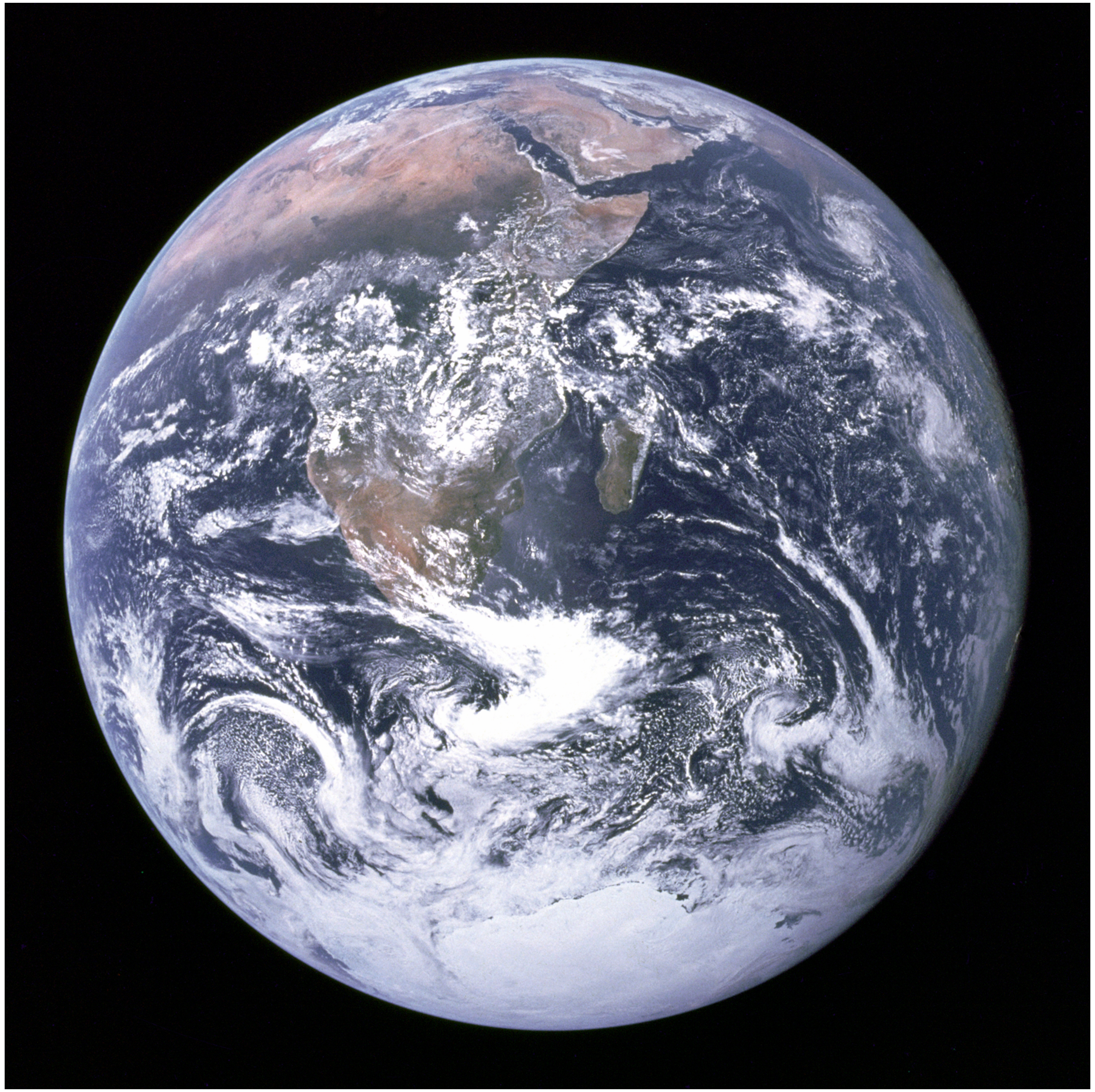
Giant Planets

- Cloud composition and vertical structure for gas giants
  - Assuming solar abundances of reference elements



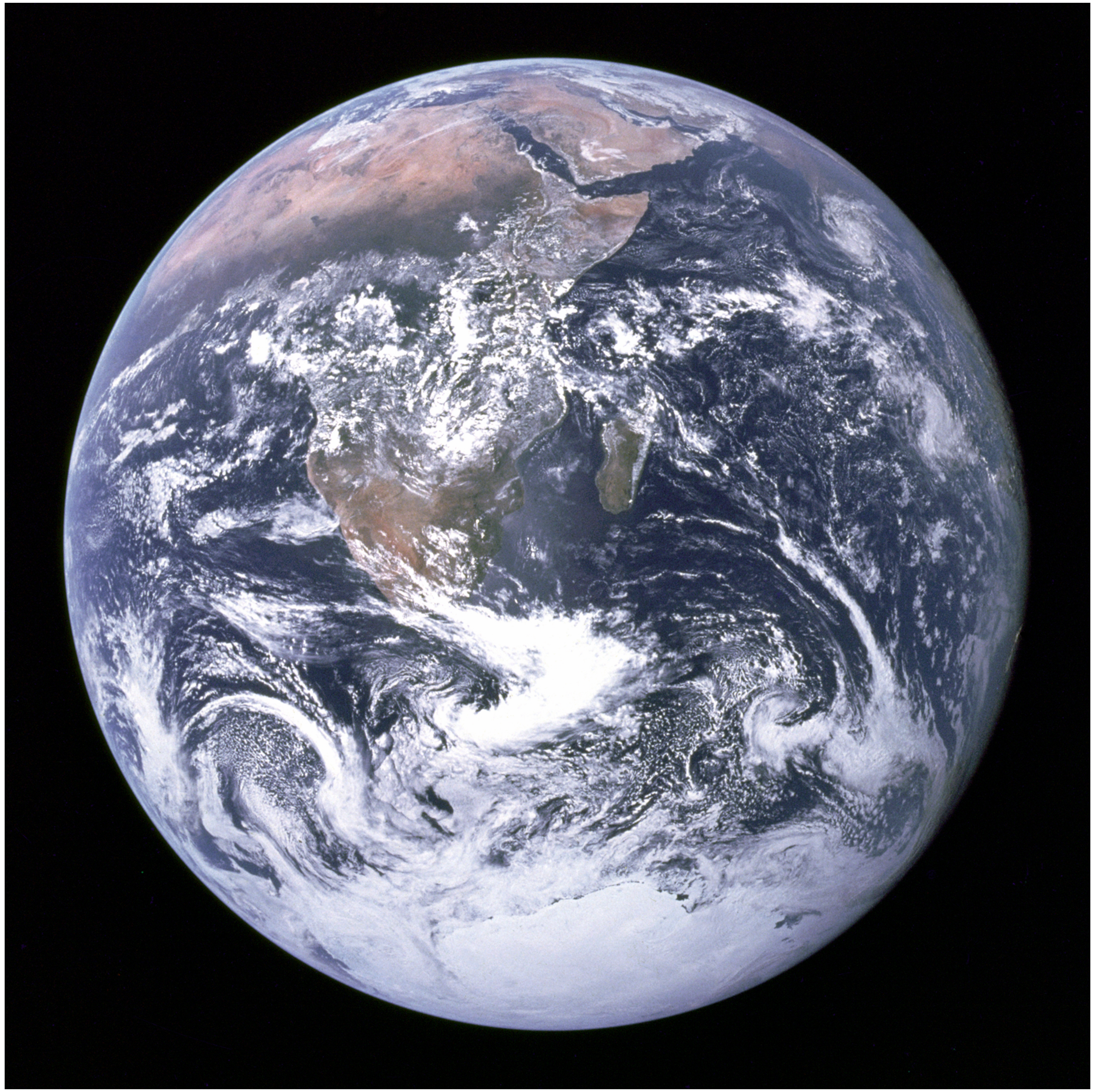
Atmospheric Motions

- Atmospheres obey laws of hydrodynamics valid for any fluid under:
    - spherical geometry
    - planetary rotation
- Open boundary to space at top, lower boundary at surface (sometimes) or “deep atmosphere”



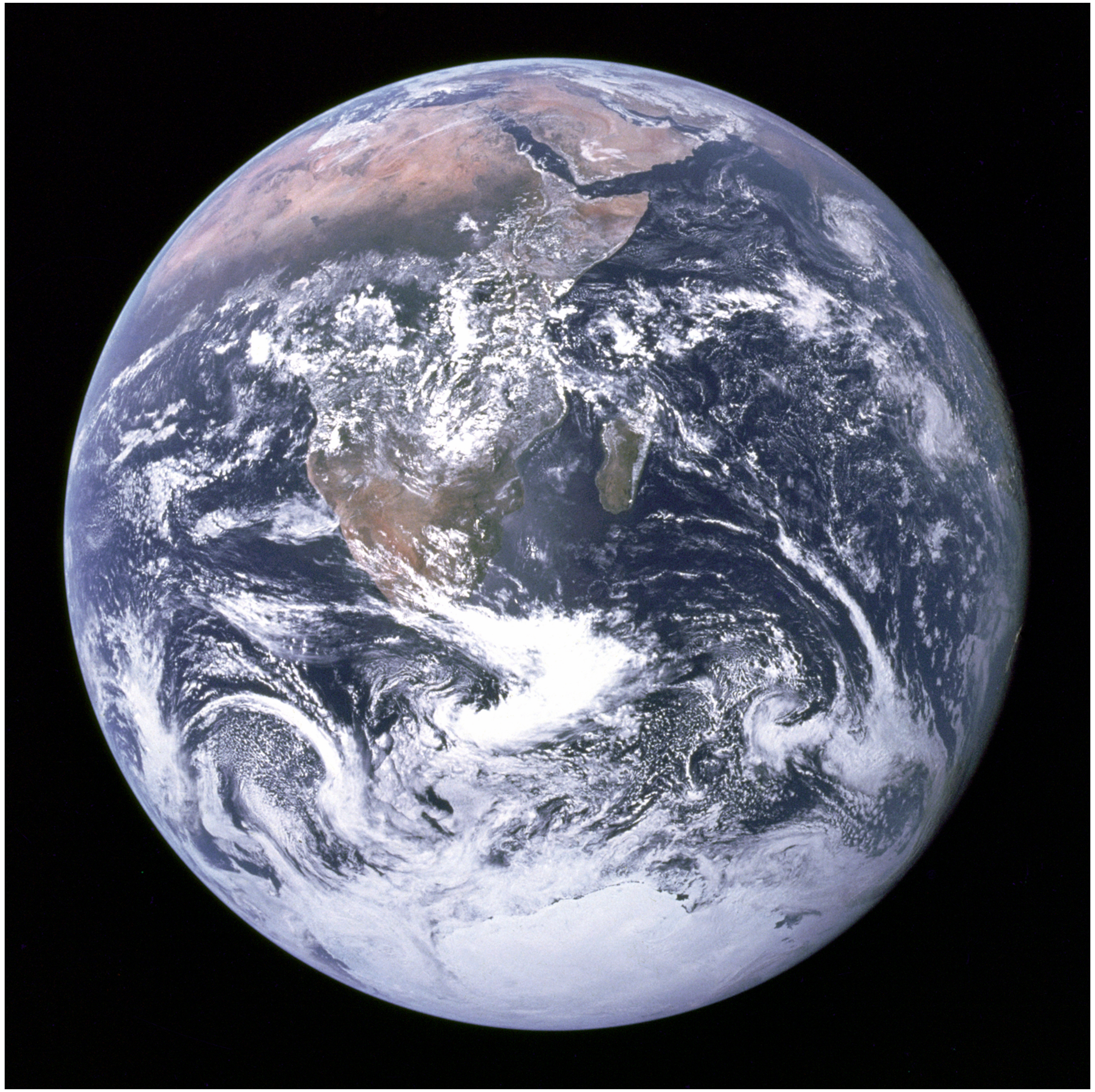
Atmospheric Motions

- External and internal energy sources can drive motions
- Gaseous, compressible fluids that generally obey the ideal gas law
- Mostly electrically neutral



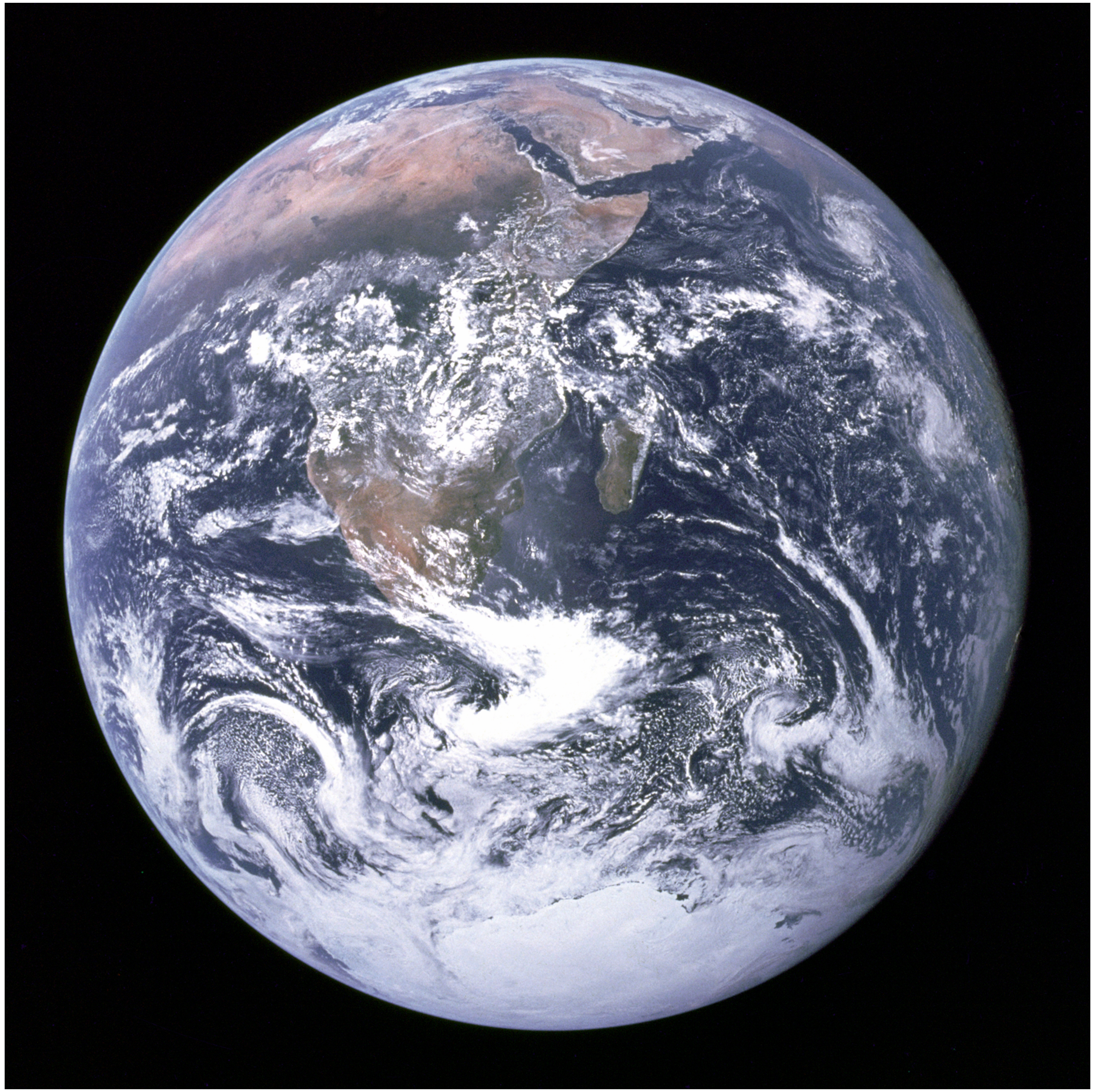
Atmospheric Motions

- Motions in planetary atmospheres are described by:
  - Newton's second law (called the Navier-Stokes equation for continuous fluid motions)
  - laws of thermodynamics
  - continuity equation (mass conservation)
  - equation of state (ideal gas law)
- Generally use spherical coordinates, but sometimes cartesian (where appropriate)



Atmospheric Motions

- Atmospheric motions are described using two classical views:
  - Eulerian: flow is studied (measured) in a fixed point in space relative to a reference frame
    - Example: a Martian lander that is measuring wind speeds, temperature, pressure, etc
  - Lagrangian: motions follow atmospheric flow
    - Example: a small fluid parcel marked with a dye



Atmospheric Motions

- We can relate the rate of change of some field variable (A) following the motion (Lagrangian view) to its rate of changed at a fixed point (Eulerian view)

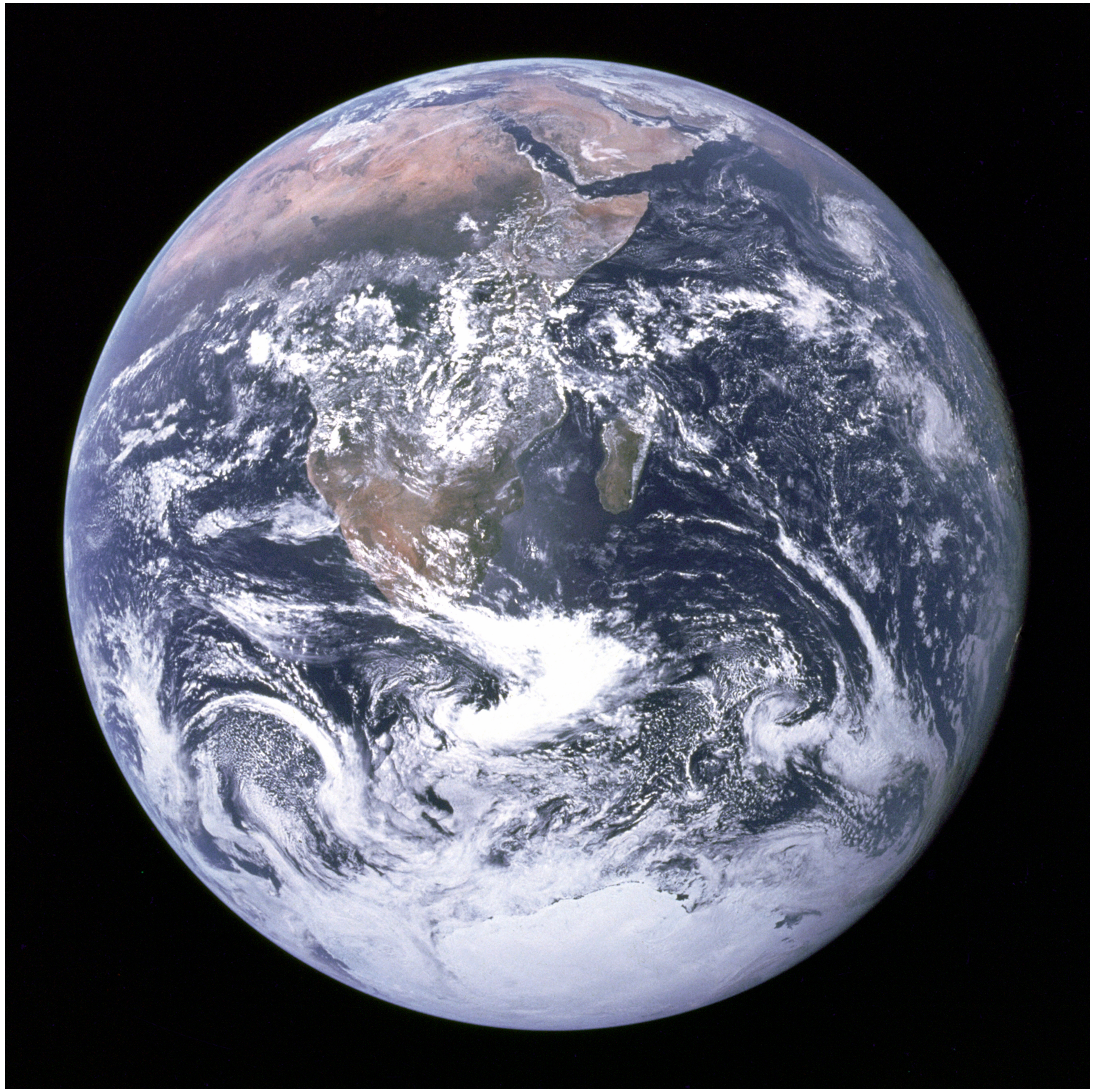
- Take the "total derivative" (also called the "substantive derivative" or "advective derivative" or "material derivative")

  - Accounts for both changes in the fluid at a location, and movement of material (advection)

- $$\frac{dA}{dt} = \frac{\partial A}{\partial t} + \left(v_x \frac{\partial A}{\partial x} + v_y \frac{\partial A}{\partial y} + v_z \frac{\partial A}{\partial z} \right) = \frac{\partial A}{\partial t} + \overrightarrow{v} \cdot \nabla A$$

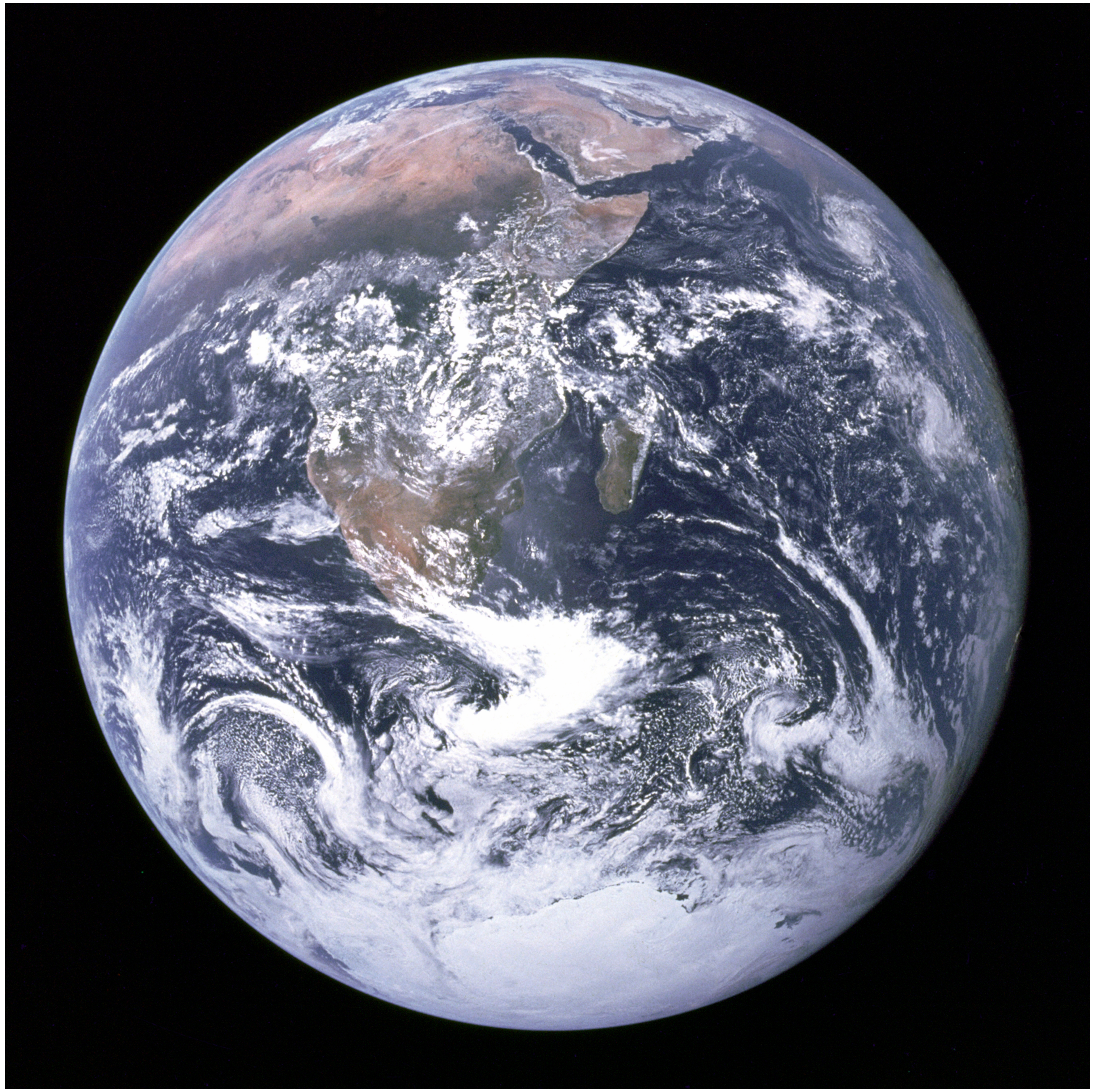
$$\overrightarrow{v} = v_x \hat{x} + v_y \hat{y} + v_z \hat{z}$$

$$v_x = \frac{dx}{dt} \quad v_y = \frac{dy}{dt} \quad v_z = \frac{dz}{dt}$$



Atmospheric Motions

- $\frac{dA}{dt} = \frac{\partial A}{\partial t} + \overrightarrow{v} \cdot \nabla A$
- $\frac{dA}{dt}$: Rate of change with respect to time following motion
- $\frac{\partial A}{\partial t}$: Local rate of change with respect to time at a fixed point
- $\overrightarrow{v} \cdot \nabla A$: Advection term



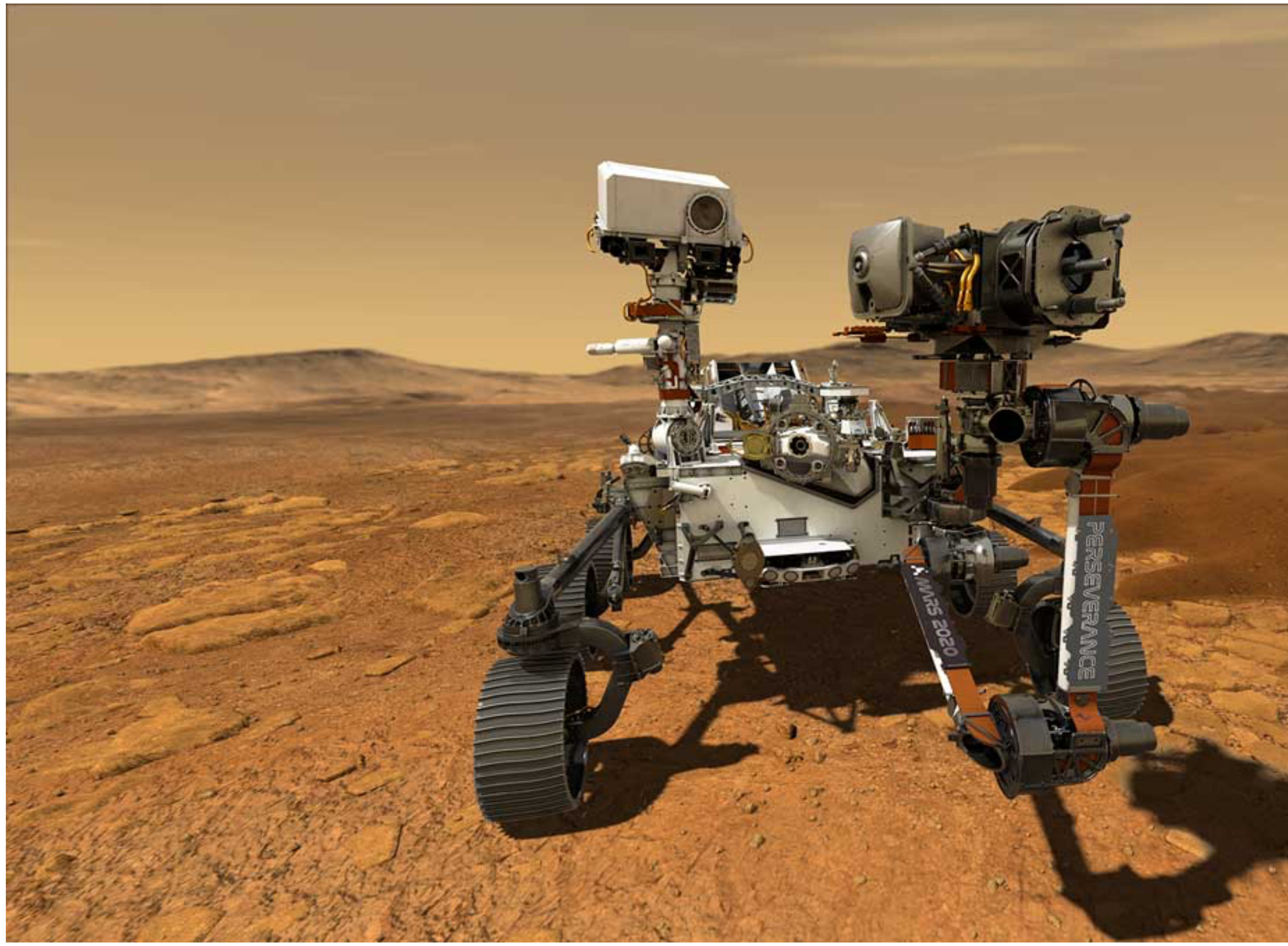
In-class activity: Temperature Change on Mars

- $$\frac{dA}{dt} = \frac{\partial A}{\partial t} + \left(v_x \frac{\partial A}{\partial x} + v_y \frac{\partial A}{\partial y} + v_z \frac{\partial A}{\partial z} \right) = \frac{\partial A}{\partial t} + \overrightarrow{v} \cdot \nabla A$$
  $$\overrightarrow{v} = v_x \hat{x} + v_y \hat{y} + v_z \hat{z}$$

  $$v_x = \frac{dx}{dt} \qquad v_y = \frac{dy}{dt} \qquad v_z = \frac{dz}{dt}$$

- The temperature on the surface of Mars decreases by 3K per 100 km in the eastward direction. A rover moving eastward at 1 km/hr measures a temperature decrease of 1 K/hr. What is the temperature change (in K/hr) measured by a fixed Mars lander that the rover is passing by?

- Hint: pay attention to sign (+ or -)



In-class activity: Temperature Change on Mars

- $$\frac{dA}{dt} = \frac{\partial A}{\partial t} + \left(v_x \frac{\partial A}{\partial x} + v_y \frac{\partial A}{\partial y} + v_z \frac{\partial A}{\partial z} \right) = \frac{\partial A}{\partial t} + \vec{v} \cdot \nabla A$$

- The temperature at a point on the surface of Mars decreases by 3K per 100 km in the eastward direction. A rover moving eastward at 1 km/hr measures a temperature decrease of 1 K/hr. What is the temperature change (in K/hr) measured by a fixed Mars lander that the rover is passing by?

- Luckily this problem is 1-dimensional, so let's just define x as increasing to the East. Also, the quantity we care about is temperature, so let's set A=T:

$$\frac{dT}{dt} = \frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x}$$

In-class activity: Temperature Change on Mars

- $$\frac{dT}{dt} = \frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x}$$

- The first term is how temperature changes as a function of time following the flow, so that's what the rover measures (-1 K/hr) — note the temperature decreases!

- The second term is how temperature changes as a function of time at a fixed point in space: that's what the stationary lander measures, and what we want to solve for.

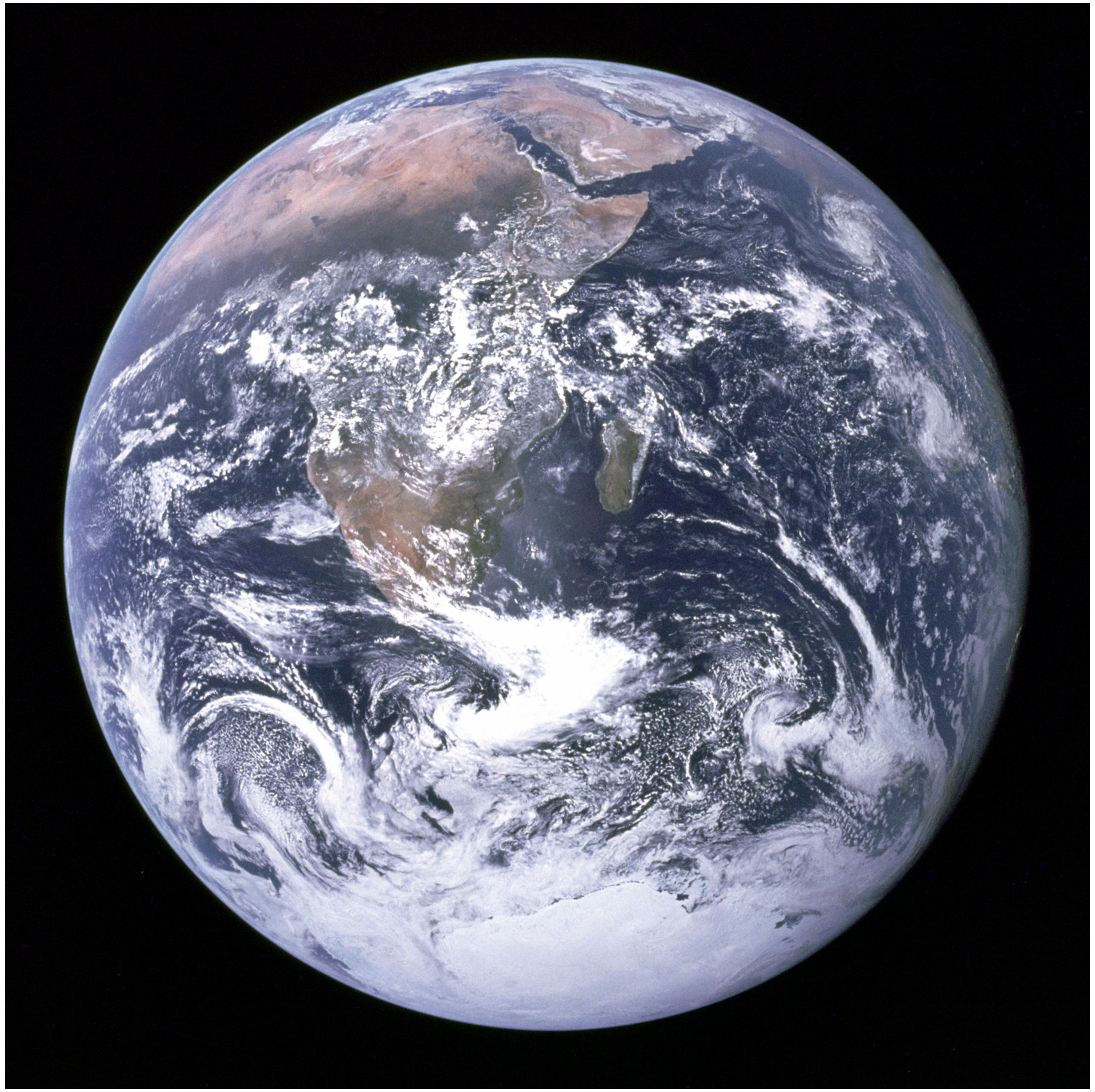
- Finally, the last term includes the velocity of the flow (the 1 km/hr eastward motion of the rover) and the change in temperature as a function of distance (-3K / 100 km)

- Let's solve for the change in temperature at the stationary lander, and plug in numbers:

$$\frac{\partial T}{\partial t} = \frac{dT}{dt} - v_x \frac{\partial T}{\partial x} = (-1\frac{K}{hr}) - (1\frac{km}{hr})\frac{-3K}{100km} = -1\frac{K}{hr} + 0.03\frac{K}{hr} = -0.97\frac{K}{hr}$$

Break

Momentum Conservation



- Use the equation of motion for fluids:
  - Force per unit volume on fluid is equal to sum of external force (ρg) and pressure gradient force
- $$\rho \frac{d\overrightarrow{v}}{dt} = \rho \left[\frac{\partial \overrightarrow{v}}{\partial t} + (\overrightarrow{v} \cdot \overrightarrow{\nabla}) \cdot \overrightarrow{v} \right] = -\nabla P - \rho g$$
- For a fluid with viscosity the equation of motion becomes the Navier-Stokes Equation:

$$\frac{\partial \overrightarrow{v}}{\partial t} + (\overrightarrow{v} \cdot \overrightarrow{\nabla}) \overrightarrow{v} = -\frac{1}{\rho} \nabla P - \overrightarrow{g} + \frac{\eta}{\rho} \nabla^2 \overrightarrow{v}$$

η: dynamic viscosity (cm^2/s)

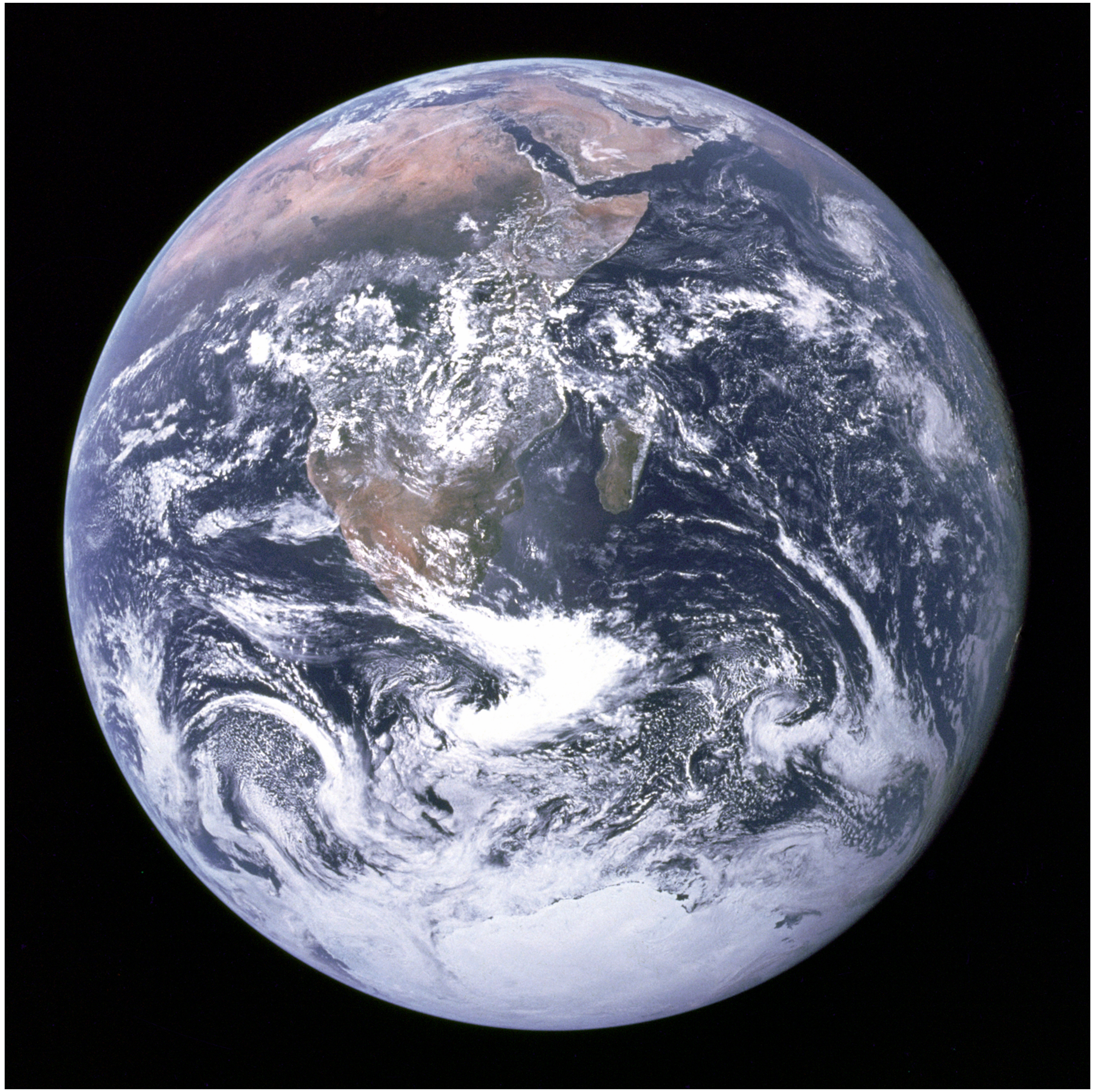
ν: kinematic viscosity (g/cm/s)

$\nu = \eta / \rho$

Momentum Conservation

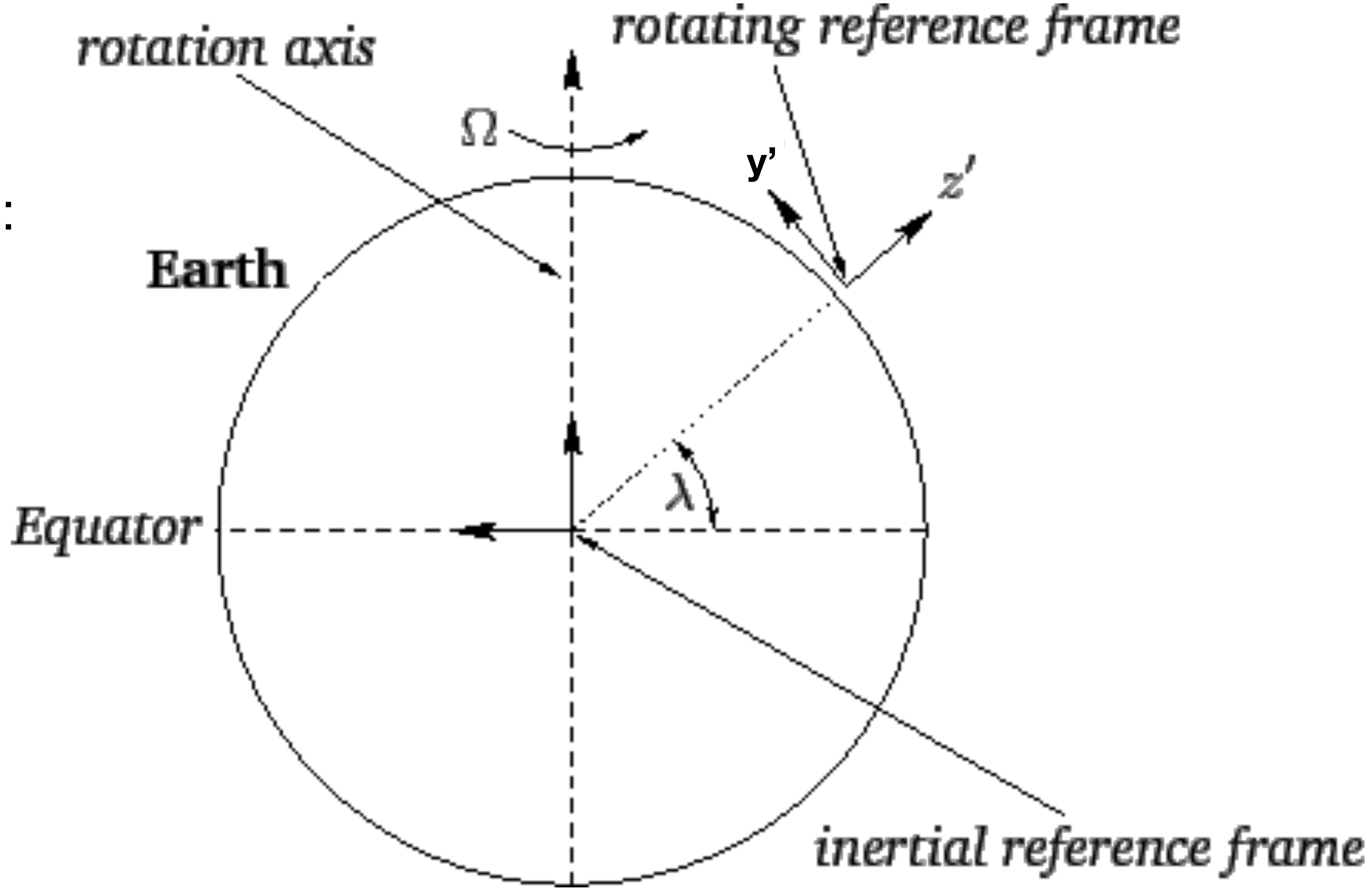
- $\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla})\vec{v} = -\frac{1}{\rho}\nabla P - \vec{g} + \frac{\eta}{\rho}\nabla^2 \vec{v}$
- For an incompressible fluid, $\nabla \cdot \vec{v} = 0$
- In this case, the Navier Stokes equation becomes:

$$\frac{\partial \vec{v}}{\partial t} = -\frac{\nabla P}{\rho} - \vec{g} + \frac{\eta}{\rho}\nabla^2 \vec{v}$$



Rotating Reference Frame

- The rotation of the planet (Ω is angular velocity) is significant for large-scale dynamics
- We need to account for this by transforming to a rotating reference frame
- Align rotating coordinates (x', y', z') with (east, north, up):
- $u = \dfrac{dx'}{dt}$: zonal (east-west) winds
- $v = \dfrac{dy'}{dt}$: meridional (north-south) winds
- $w = \dfrac{dz'}{dt}$: vertical winds



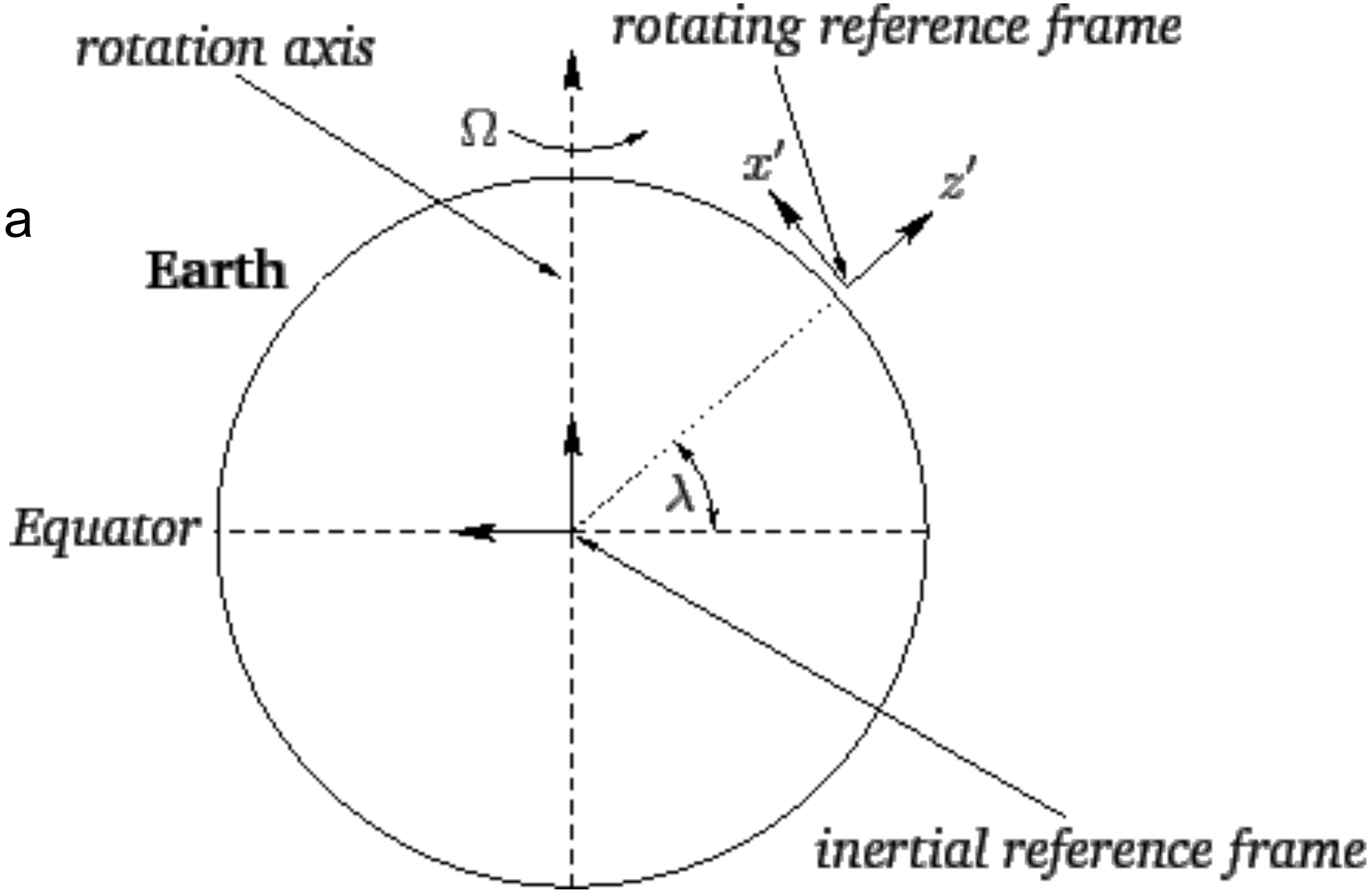
Rotating Reference Frame

- One more transformation to spherical coordinates:

  R_P: planetary radius

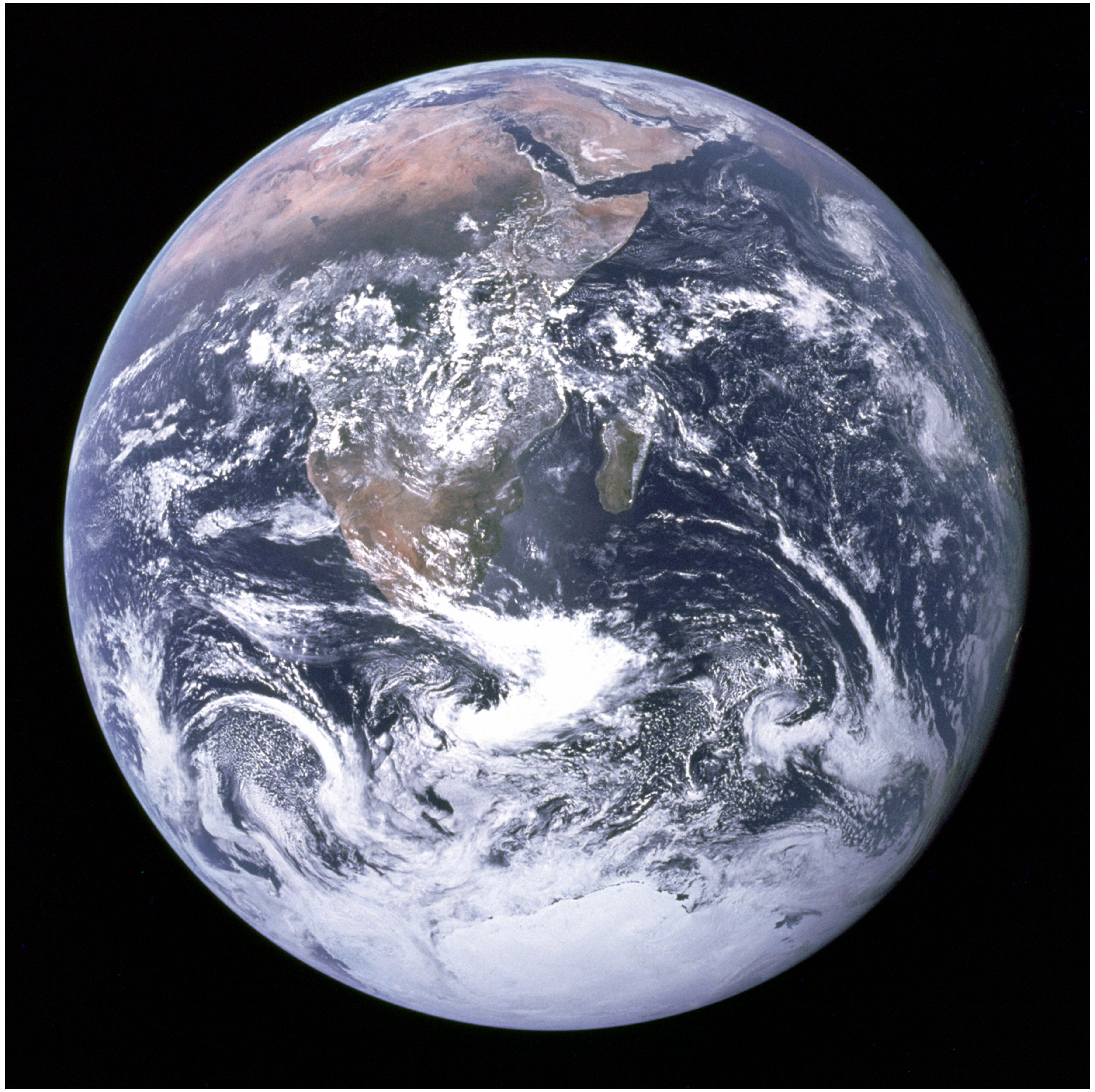
  ϕ: latitude

- We can get get simpler versions of these equations after a bit of math, and making some simplifying assumptions:
  - No longitudinal variation in wind speeds
  - vertical wind ~ 0
  - focus on mid-latitudes
  - frictionless atmosphere



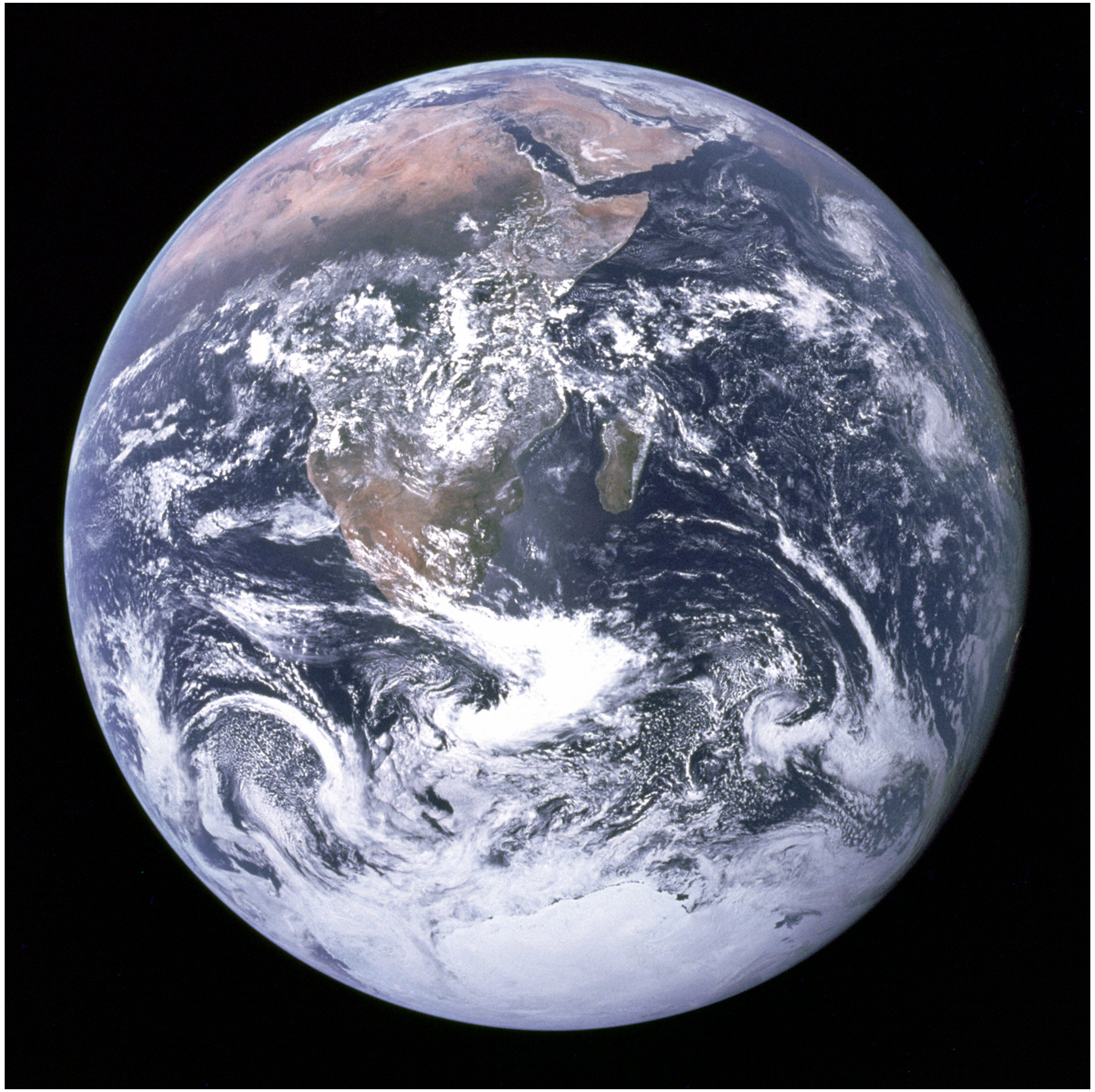
Scale Analysis

- $$\frac{du}{dt} = 2\Omega v \sin\phi - \frac{1}{\rho}\frac{\partial P}{\partial x}$$
- $$\frac{dv}{dt} = -2\Omega u \sin\phi - \frac{1}{\rho}\frac{\partial P}{\partial y}$$
- Define the Coriolis parameter, $f = 2\Omega \sin\phi$
- $$\frac{du}{dt} = fv - \frac{1}{\rho}\frac{\partial P}{\partial x}$$
- $$\frac{dv}{dt} = -fu - \frac{1}{\rho}\frac{\partial P}{\partial y}$$



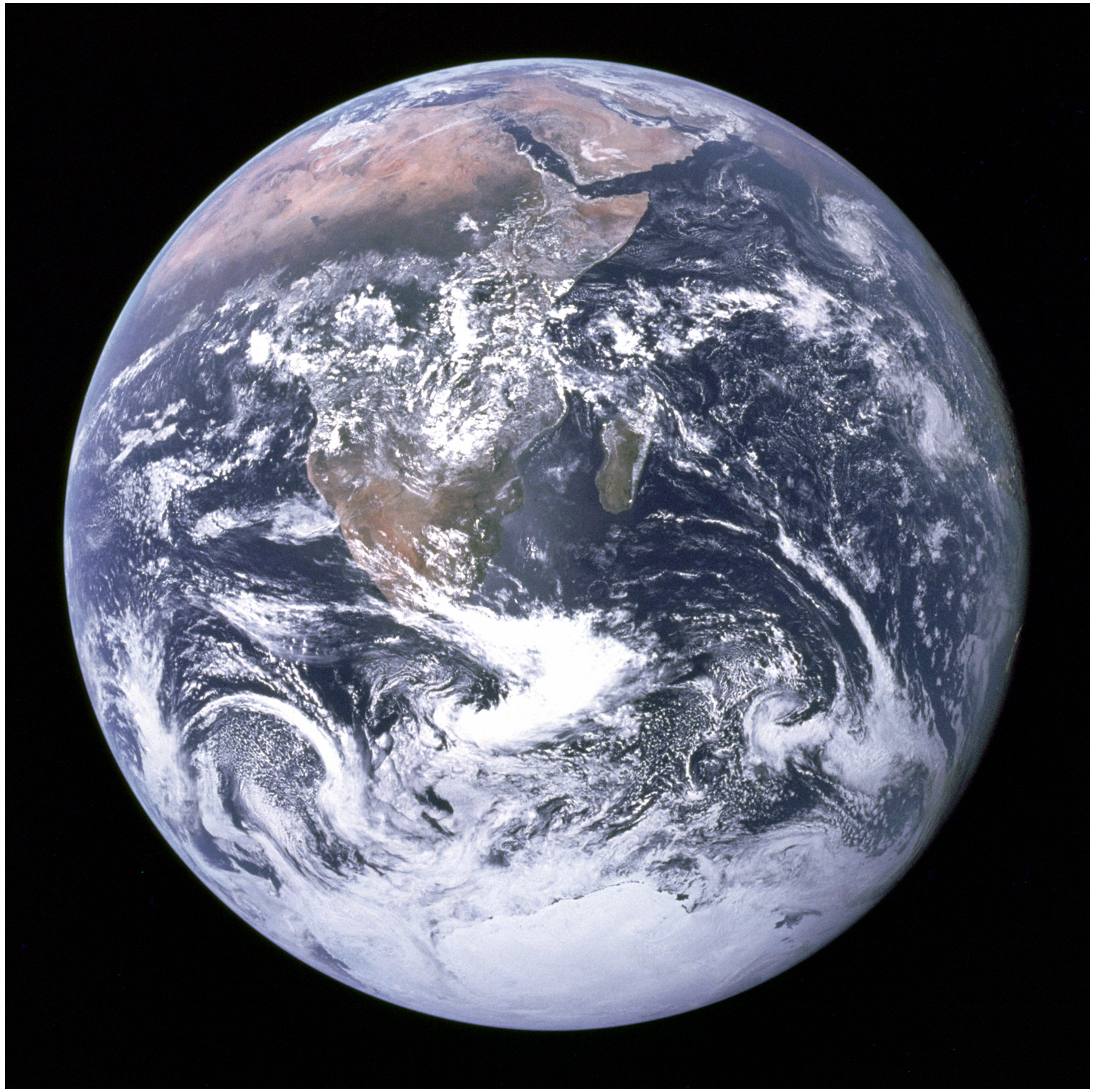
Scale Analysis

- Can define characteristic scales based on observations.
- For example, for Earth at latitude of 45 degrees:
  - $U \approx 10m/s$: Horizontal velocity scale (u or v)
  - $W \approx 1cm/s$: Vertical velocity scale
  - $L \approx 10^6 m$: Length scale
  - $\Delta P/\rho \approx 10^3 m^2/s^2$: horizontal pressure fluctuation scale
  - $L/U \approx 10^5 s$: time scale



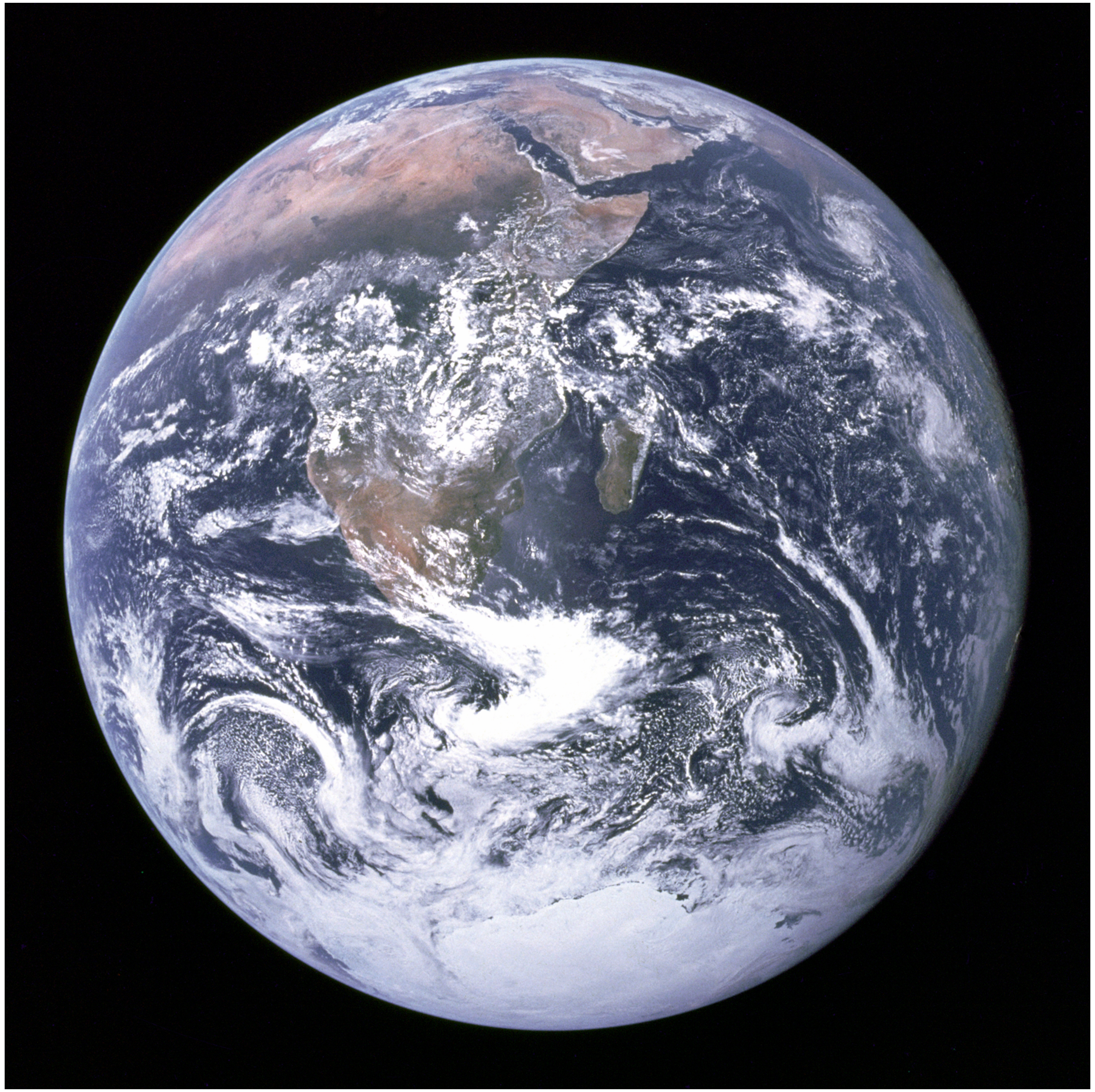
Scale Analysis

- For disturbances at the characteristic (synoptic) scale of 1000 km:
    - $$\frac{du}{dt} \approx \frac{dv}{dt} \approx 0$$
- $$-fv \approx \frac{1}{\rho}\frac{\partial P}{\partial x}$$
- $$fu \approx \frac{1}{\rho}\frac{\partial P}{\partial y}$$
- This is known as the geostrophic relationship
    - approximates the relationship between the pressure field and the horizontal wind field
    - implies that the wind speed is proportional to horizontal pressure gradient
    - As isobars come together, wind intensifies



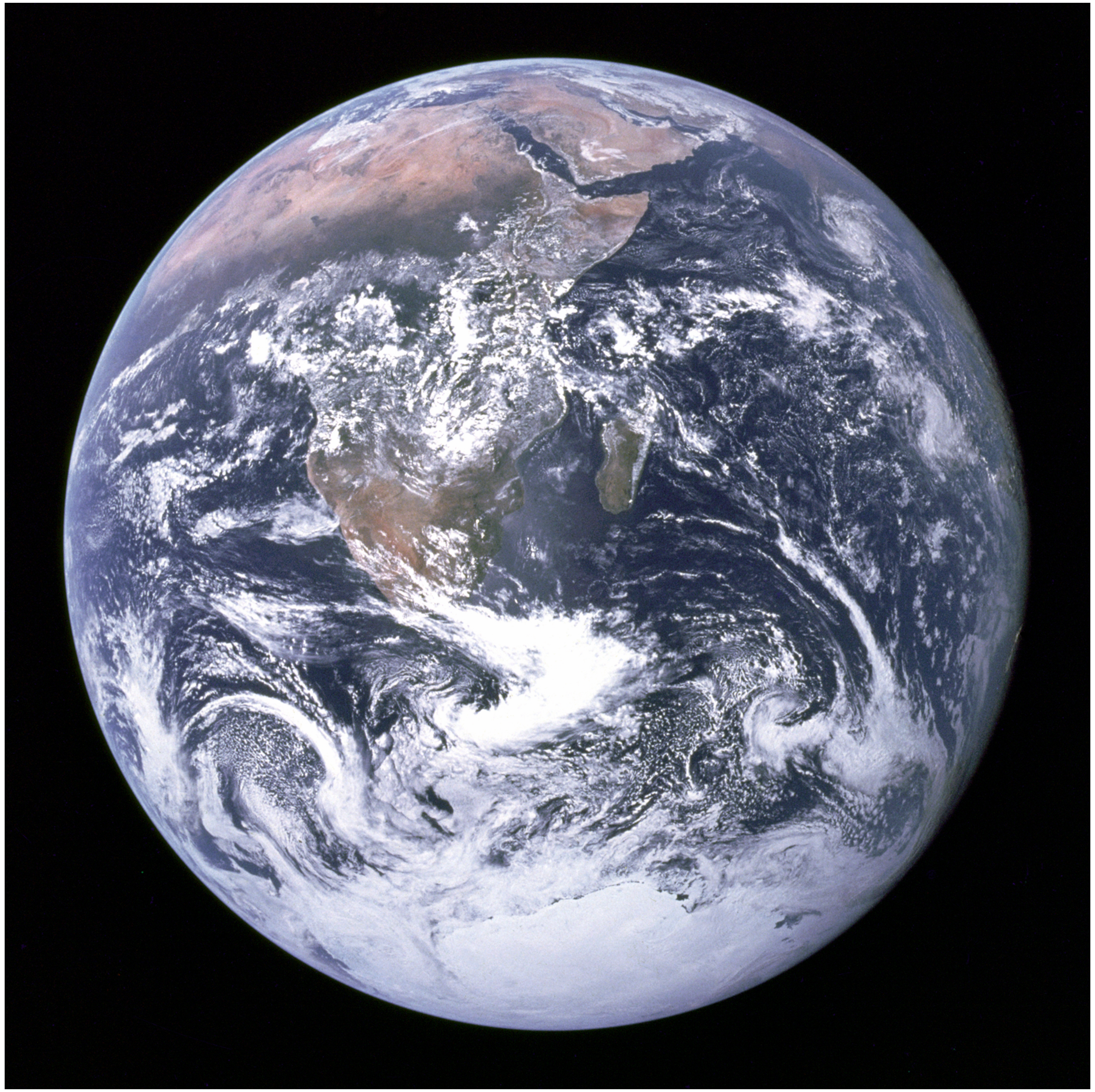
Rossby Number

- The Rossby number is the ratio between the characteristic horizontal wind speed (U) and the Coriolis force:
- $R_0 = \dfrac{U}{fL}$
- In the geostrophic approximation, $R_0 \ll 1$



On Friction and Turbulence

- In the lab, energy is dissipated by transfer from laminar flow to molecules (heat): molecular viscosity
- In a turbulent atmosphere, have analogous situations on a larger scale: ordered flow —> turbulent eddies
- Big eddies —> small eddies —> molecular motion (chain of energy dissipation)

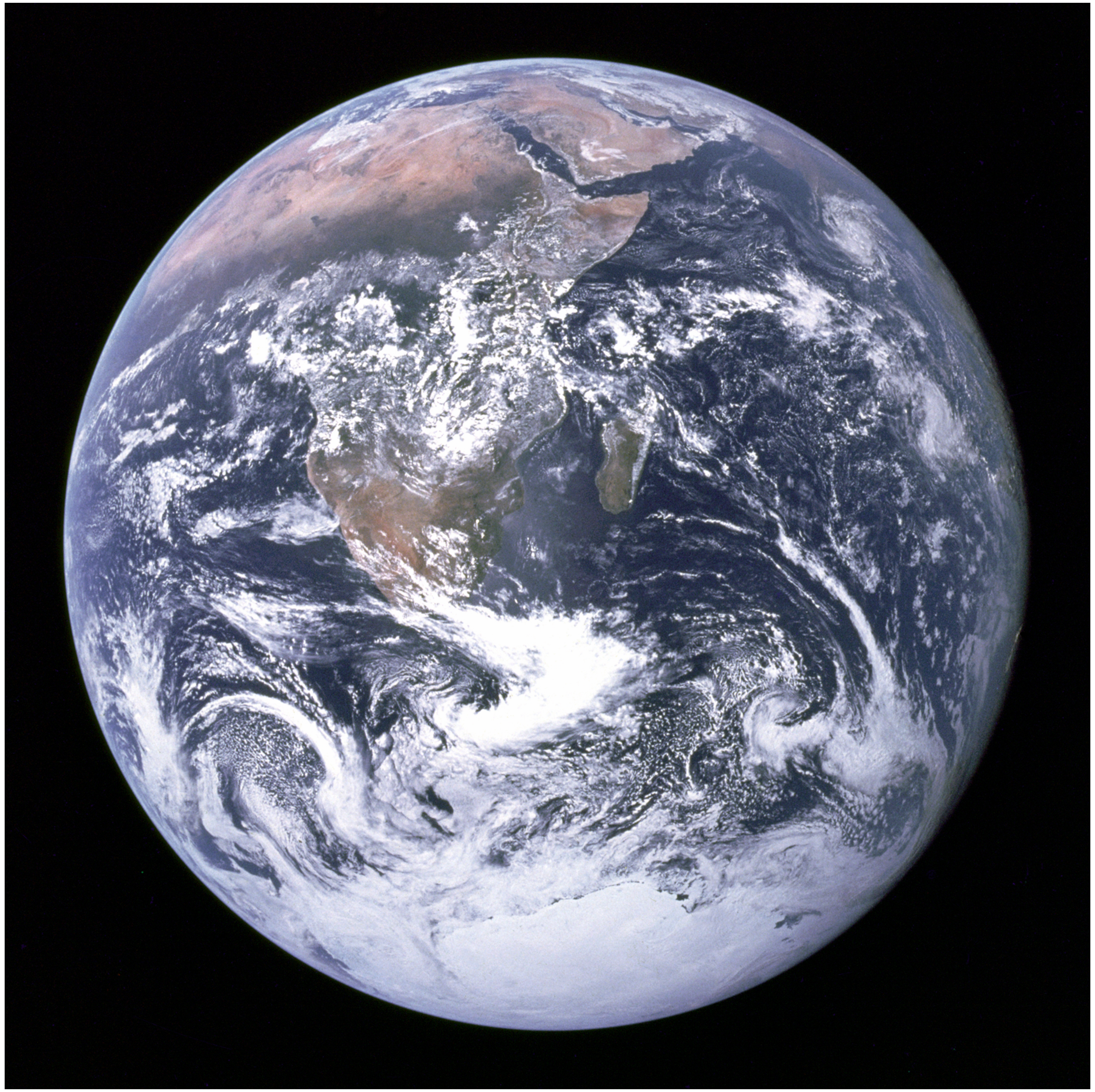


On Friction and Turbulence

- Process of eddy cascade removes kinetic energy from winds and converts it to local heating (described by eddy viscosity)

- operatres on length scale l, the “mixing length” (analogous to mean free path for molecular viscosity)

- eddy viscosity is most important at boundary layer near surface, where u approaches 0

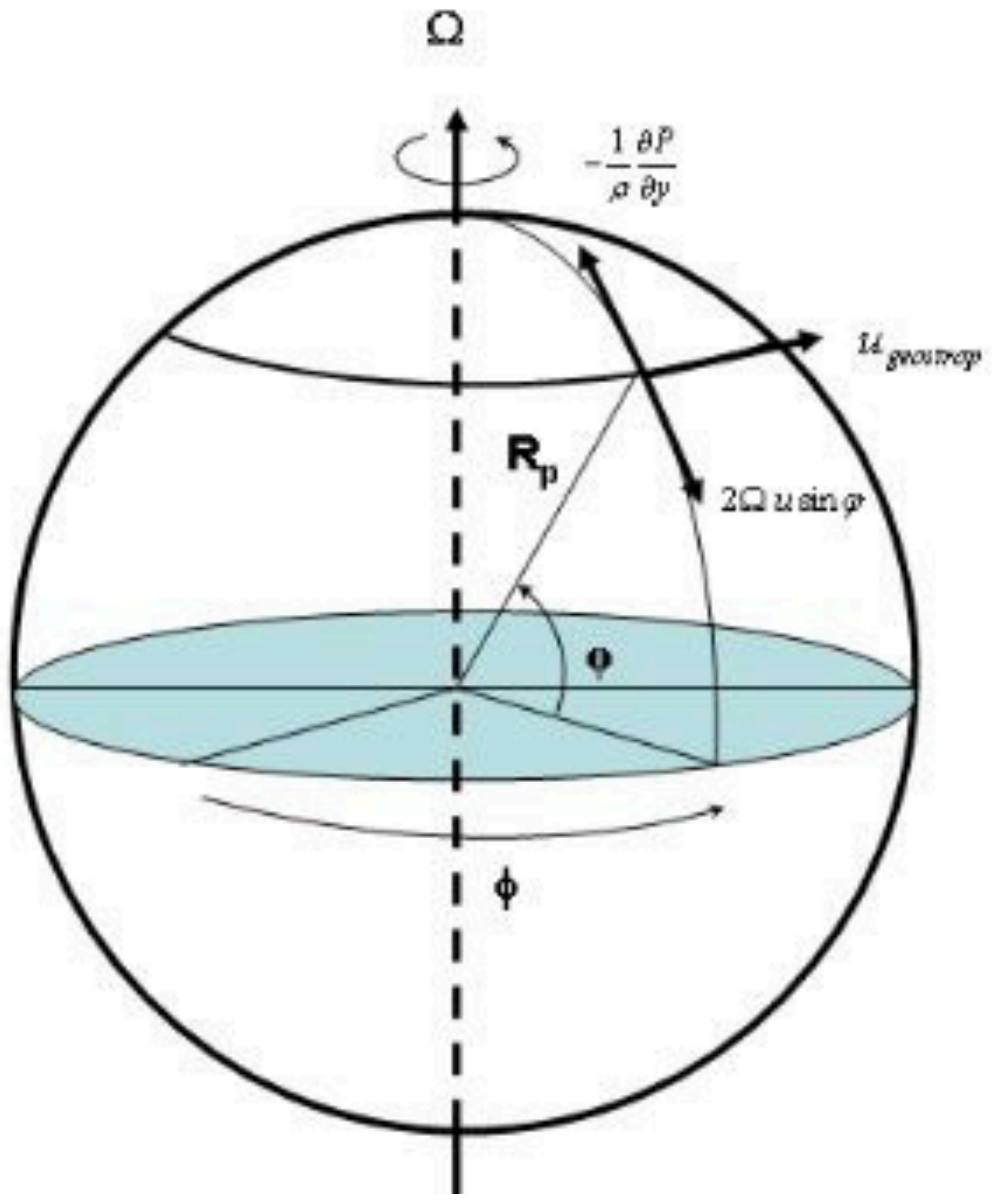


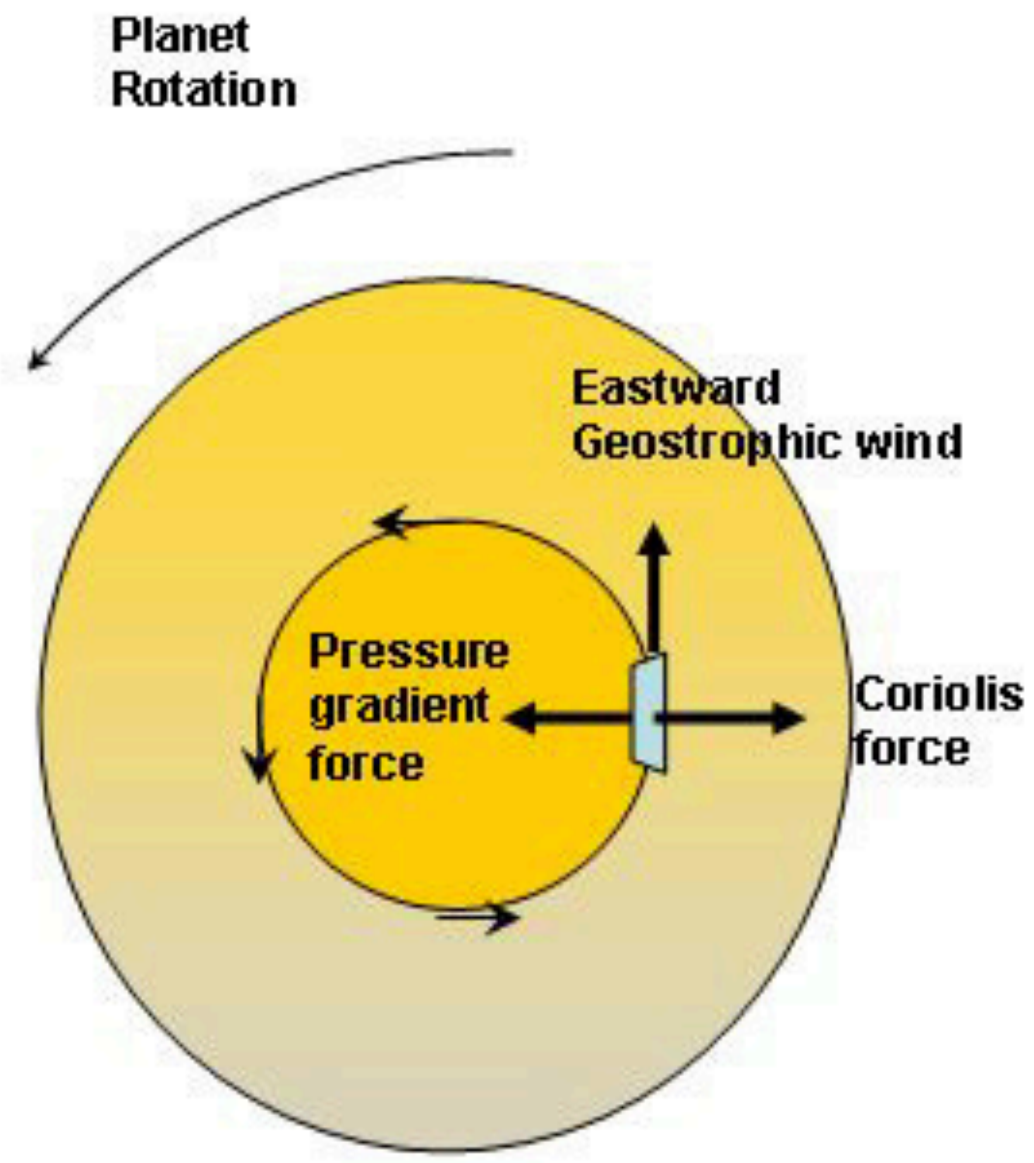
Geostrophic Balance

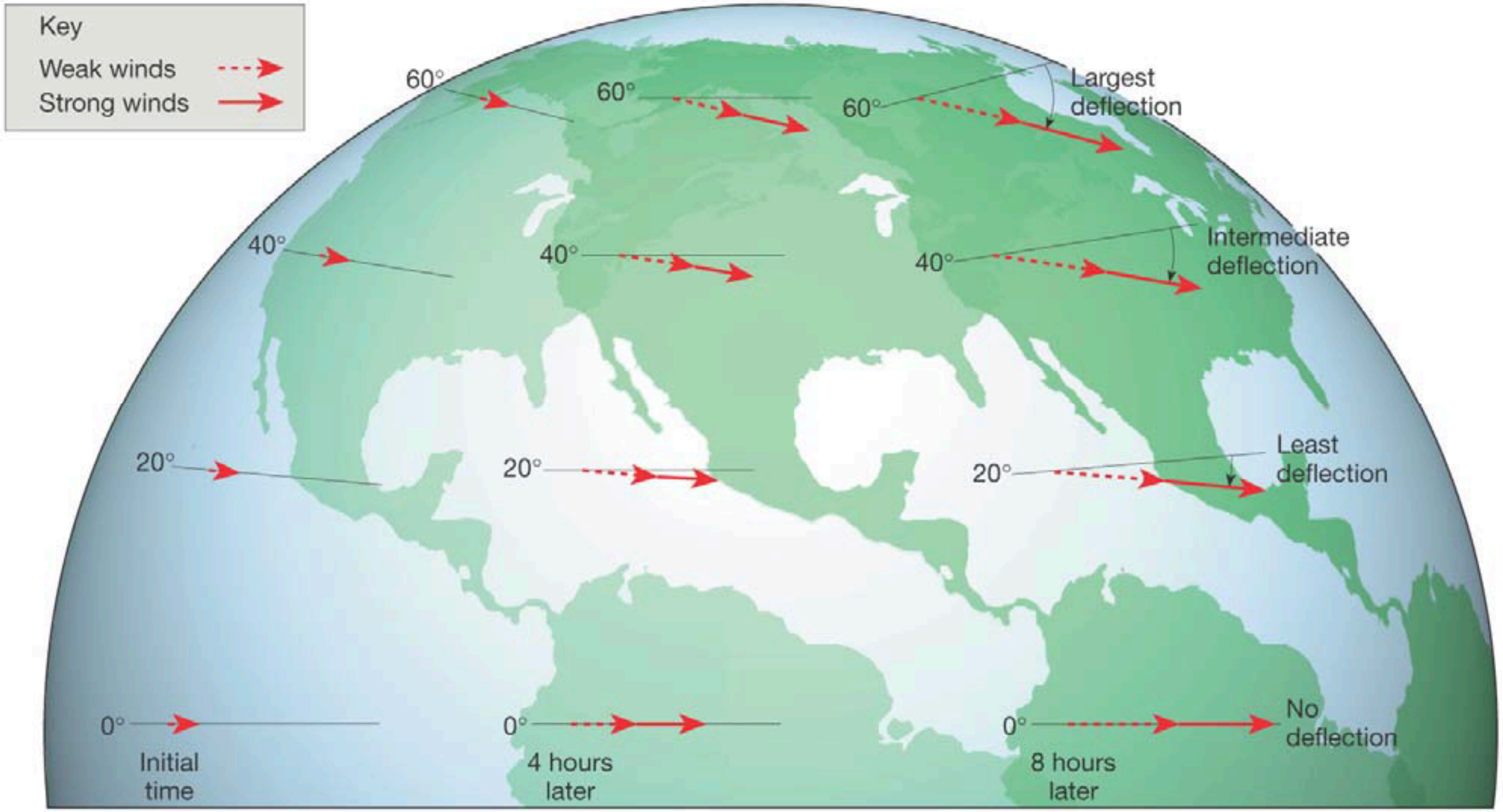
- For rapidly rotating planets (like Earth), pressure gradient force and Coriolis force dominate momentum equation ($R_0 \ll 1$)

- (This breaks down as f goes to 0, like at equatorial latitudes)

  - Coriolis parameter, $f = 2\Omega \sin \phi$



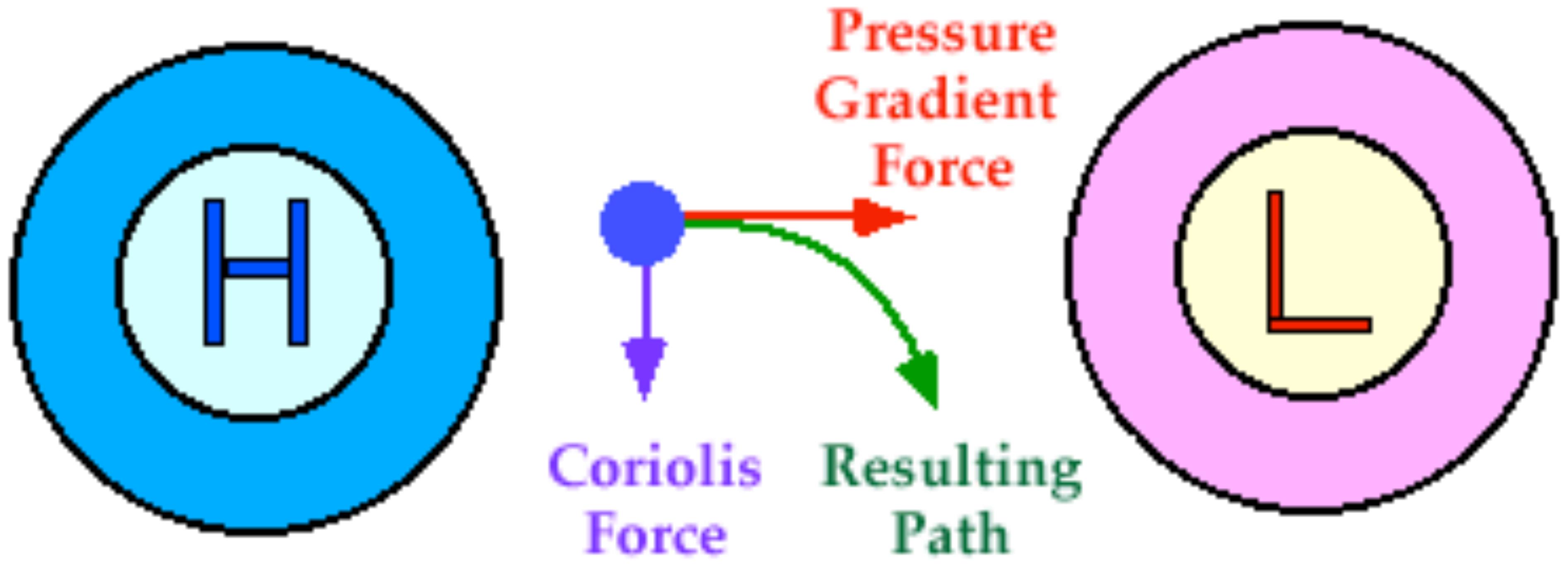


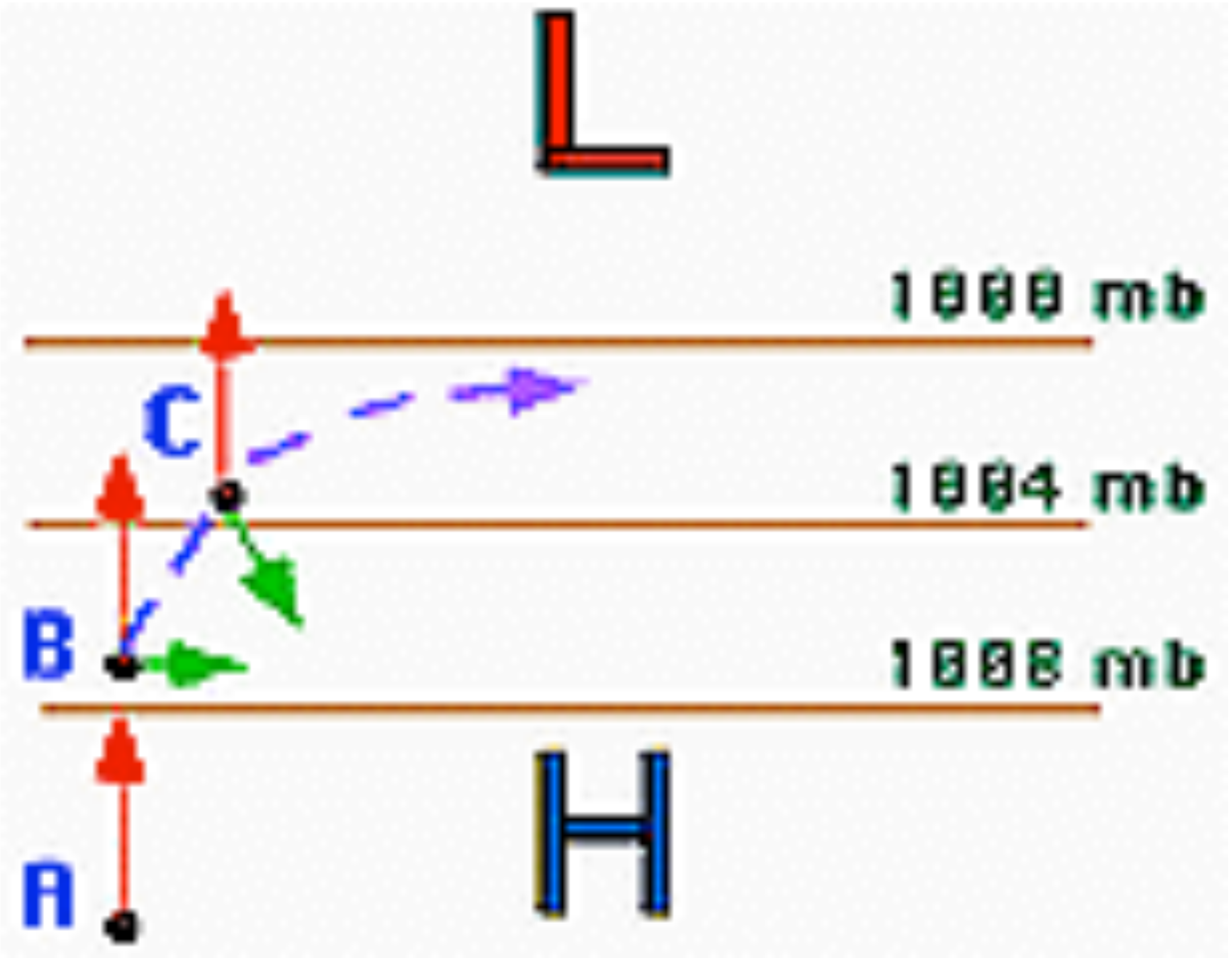


Key
Weak winds
Strong winds
60°
60°
60°
Largest deflection
40°
40°
40°
Intermediate deflection
20°
20°
20°
Least deflection
0°
0°
0°
No deflection
Initial time
4 hours later
8 hours later

Geostrophic Wind

- Wind when there's a balance between Coriolis and pressure gradient forces
    - Air parcel at rest will move from high P to low P because of pressure gradient force
    - As air parcel moves, it is deflected by Coriolis force (to right in Northern hemisphere)
    - Deflection increases until Coriolis force equals pressure gradient force
    - Wind blows parallel to isobars (geostrophic)
    - Can figure out flow motion by looking at pressure distribution





Example

- What is the magnitude of the zonal jet stream here in Las Cruces required given the observed horizontal pressure gradient?

- We know/measure:

- $\phi \approx 30°$ Air density: $\rho = 1kg/m^3$

  Pressure decreases toward the North, pressure gradient is:

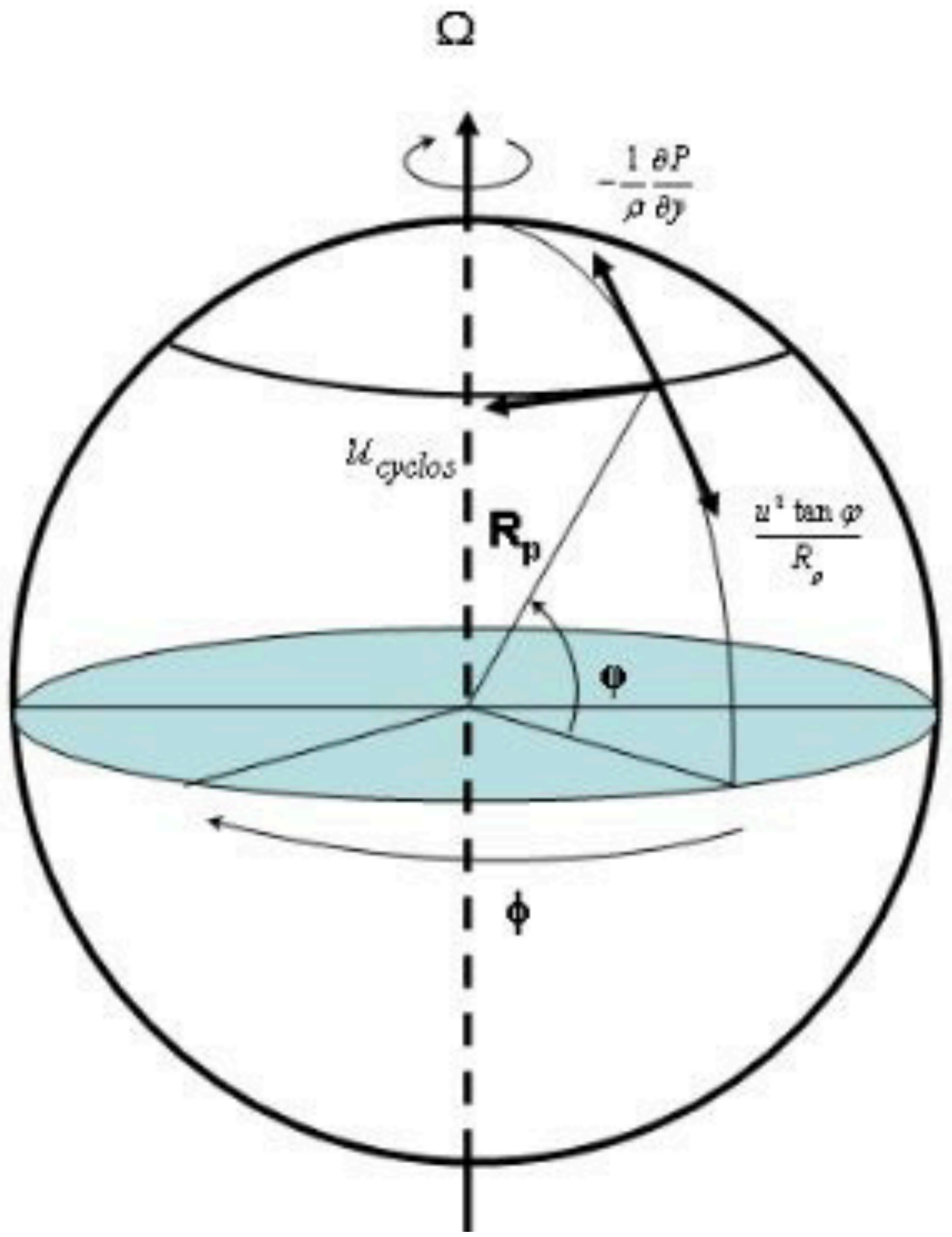
$$\frac{-10mbar}{500km} = \frac{-10^{-3}Pa}{5x10^5m} = -2x10^{-3}Pa/m$$

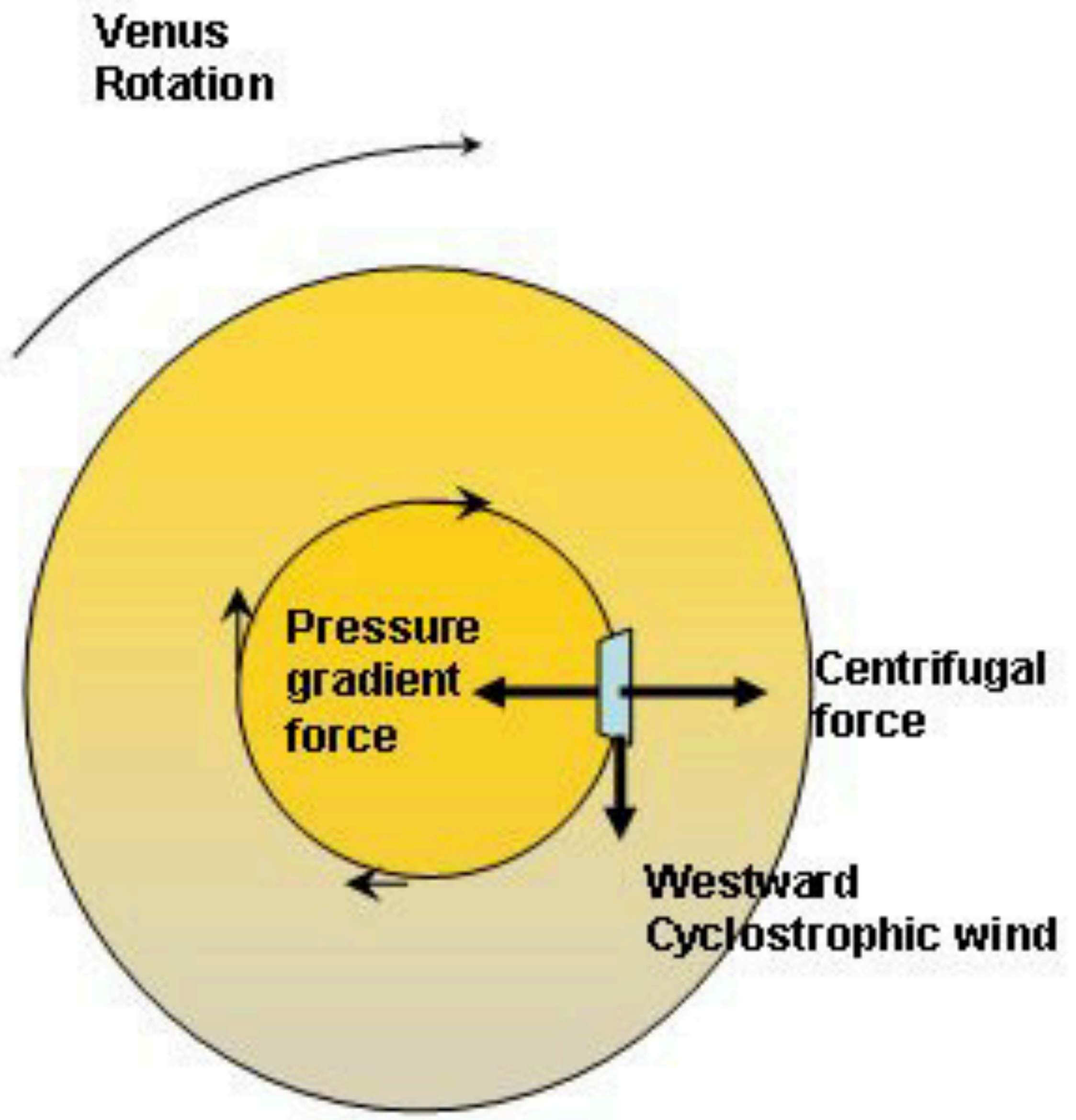
- $f(30°) = 2\Omega \sin 30° = 7.27x10^{-5}$

- $fu = -\frac{1}{\rho}\frac{\partial P}{\partial y}$ $u = -\frac{1}{\rho f}\frac{\partial P}{\partial y} = \frac{2x10^{-3}}{1x7.27x10^{-5}} = 27.5m/s$ About 55 mph

Cyclostrophic Balance

- Slowly rotating bodies (like Venus) have small f, so $R_0 > 1$
    - (also applies to equatorial latitude on faster-rotating bodies)
- In this case, can ignore Coriolis term in momentum equations
    - Dominant terms reflect a balance between pressure gradient force and centrifugal force
- $$u = \sqrt{-\frac{R_p}{\rho \tan \phi} \frac{\partial P}{\partial y}}$$





Cyclostrophic Balance

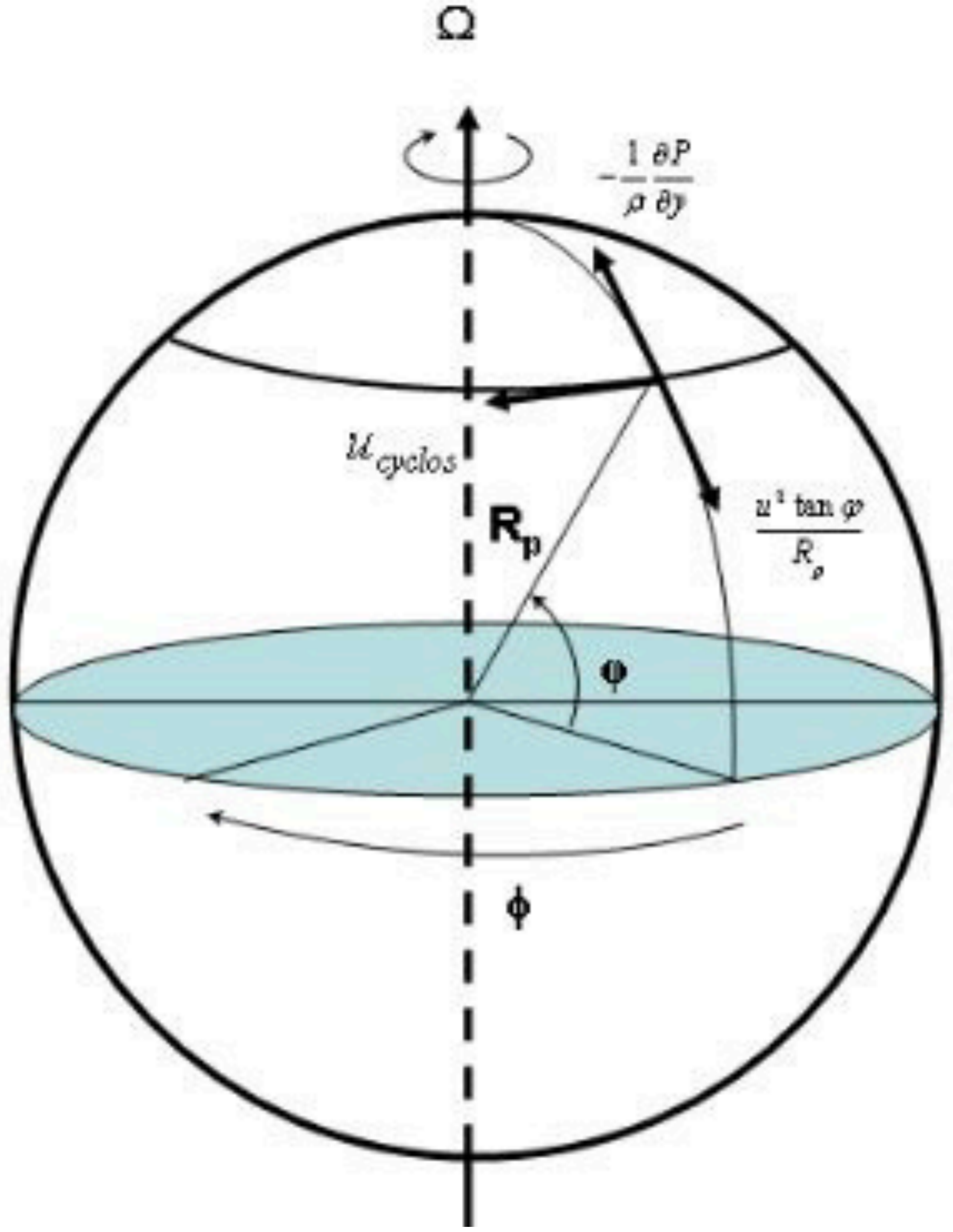
- What if $\frac{\vec{v}^2}{r} \gg f\vec{u}$?

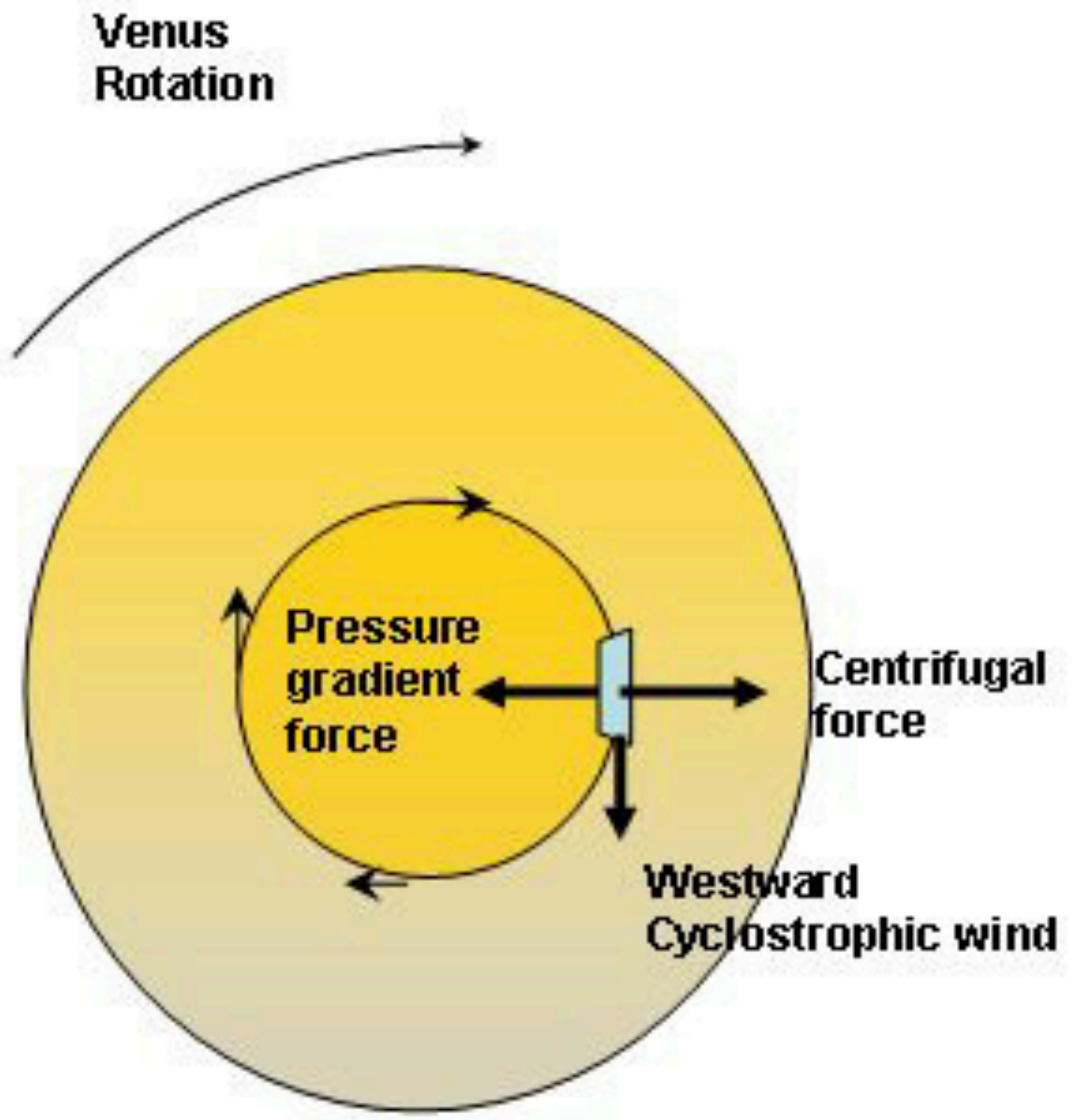
- For example, if we had large wind speeds and small radius of curvature

- Then the pressure gradient force balances the centrifugal force:

- $$\frac{U^2}{R} = -\frac{1}{\rho}\frac{\partial P}{\partial y}$$

- $$U = \left(\frac{R}{\rho}\frac{\partial P}{\partial y}\right)^{\frac{1}{2}}$$





For next time

- Homework 4 due on Wednesday, October 19 at 11:59pm
- Reading: Planetary Science, 3.1.2, 4.5.1-4.5.2