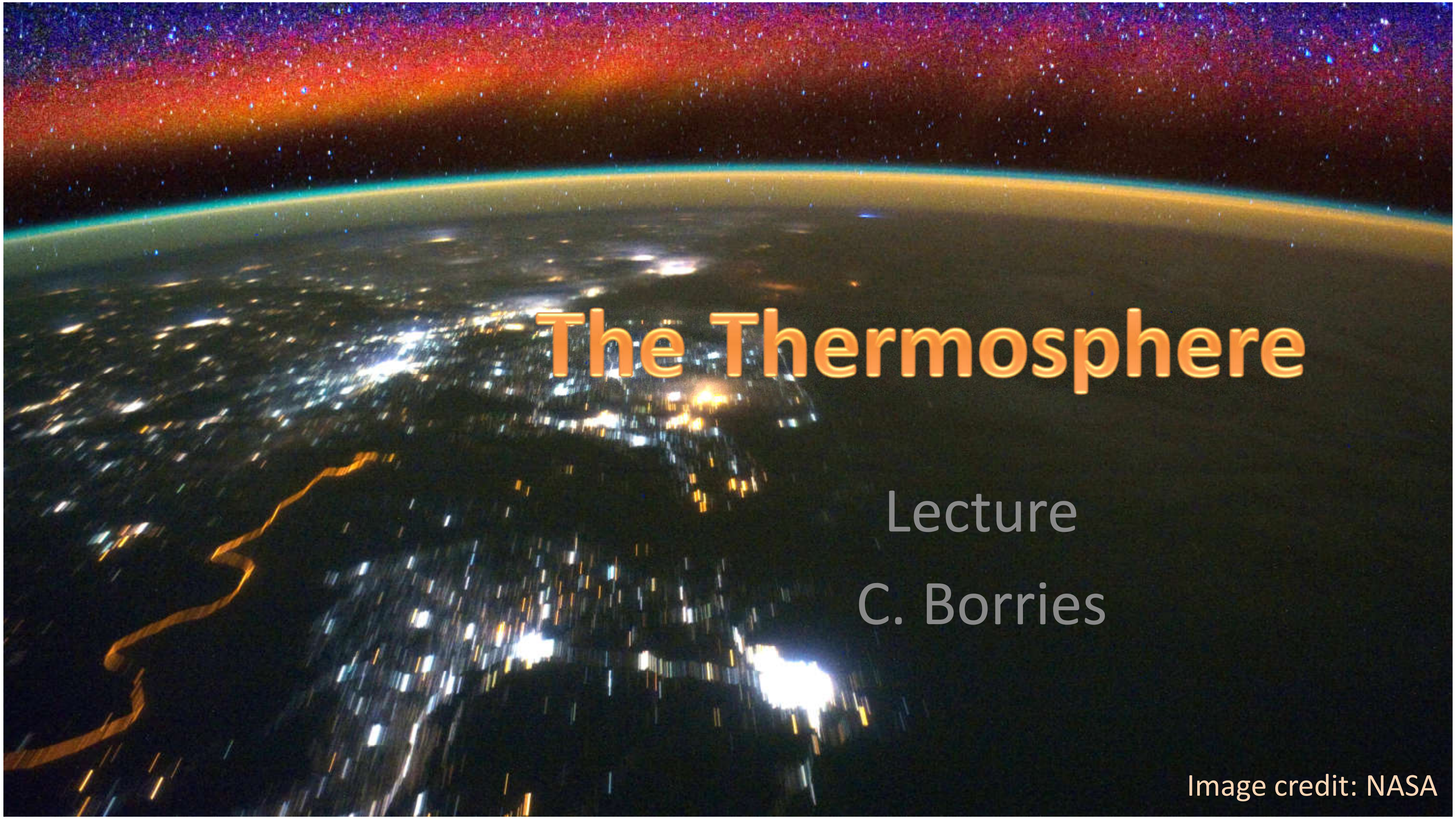
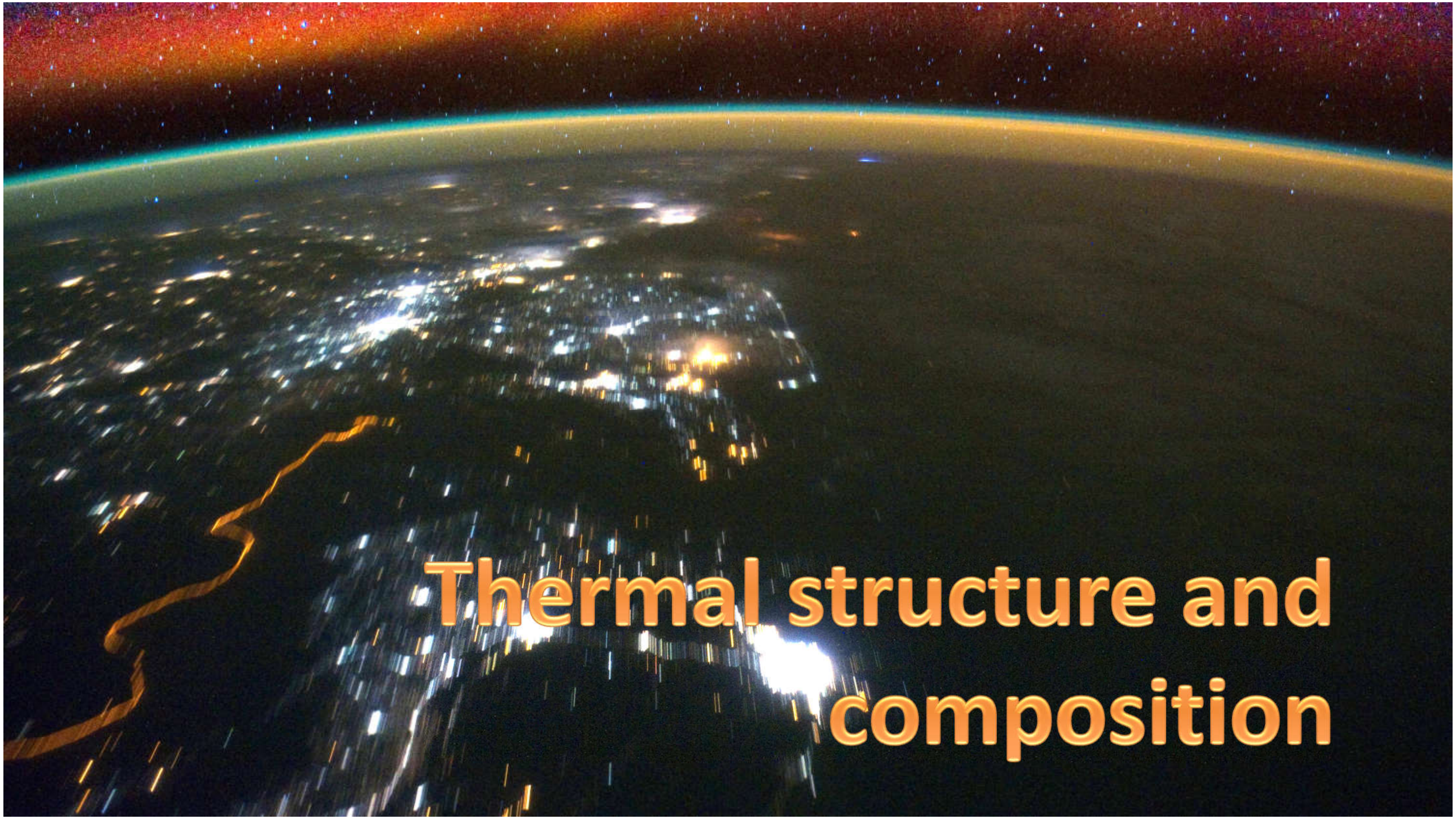

The Thermosphere
Lecture
C. Borries
Image credit: NASA

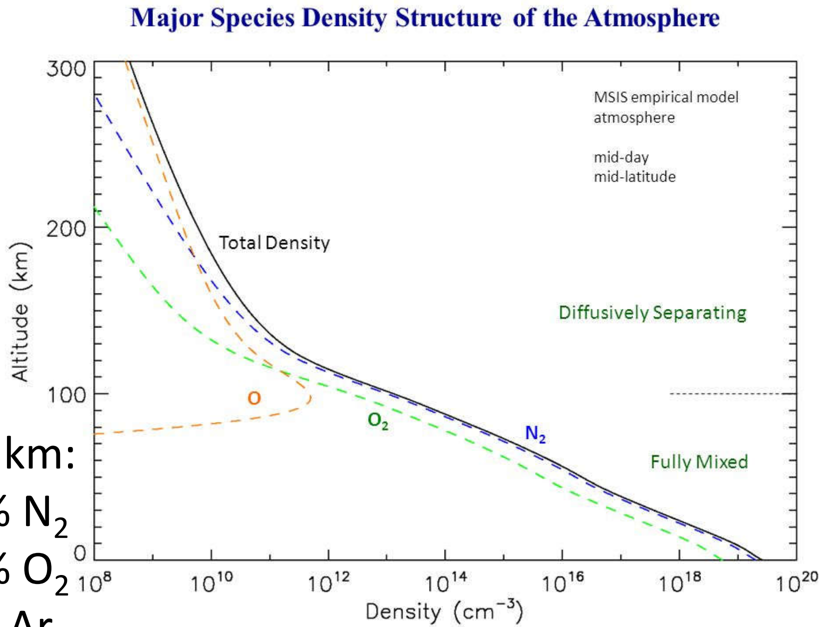
Outline

I. Thermal structure and Composition
II. Energy sources and sinks
III. Dynamics
IV. Thermosphere variability
V. Satellite drag


Thermal structure and
composition

Composition

Main constituents (300 km):
78% **O**, 21% **N_2**, 1% **O_2**, **He, H**



H < 80 km:

- 78% N_2
- 21% O_2
- 1 % Ar

➔ **Molecular diffusion**

Barometric height equation:

$$n_i(h) = n_i(h_0)\frac{T(h_0)}{T(h)}\exp\left\{-\int_{h_0}^{h}\frac{dz}{H_i(z)}\right\},$$

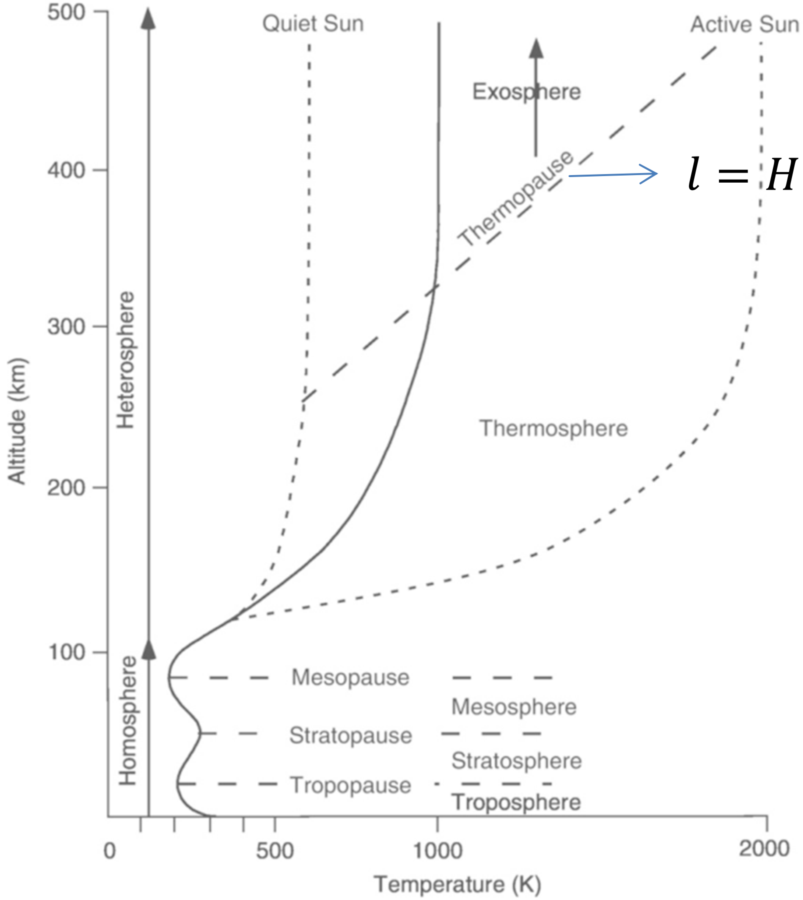
$$H_i(h) = \frac{kT(h)}{m_i g(h)}$$

Hydrostatic Equation:

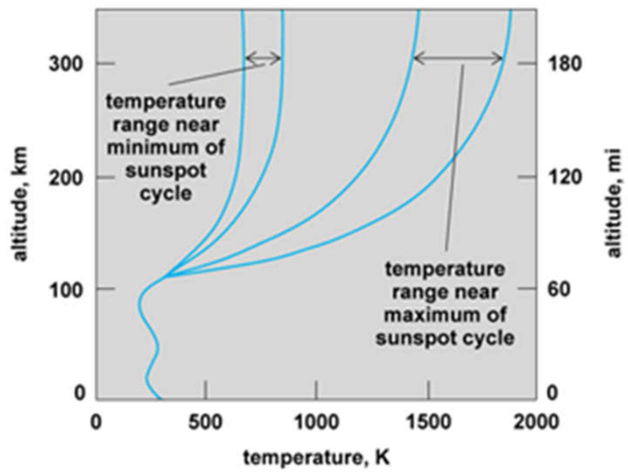
$$\sum_i \frac{dp_i}{dz} = -\sum_i n_i m_i g$$

Thermal structure

Image: Catling & Kasting (2017) after Banks and Kockarts (1973)



$$l = H = \frac{kT_\infty}{\bar{m}\bar{g}}$$



https://doi.org/10.1036/1097-8542.722200

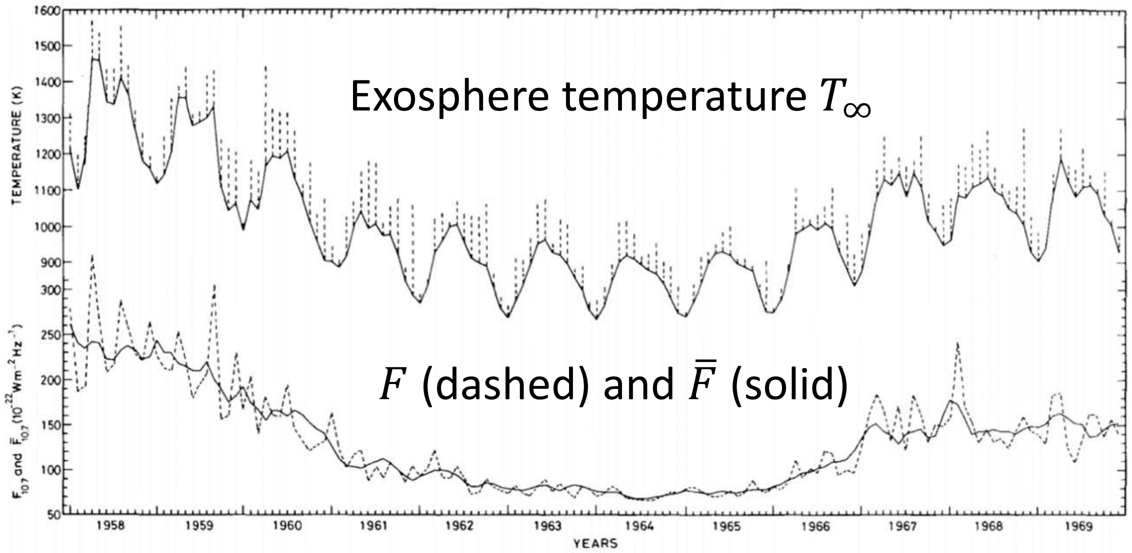
Thermal structure

Approximation: Bates' temperature profile

- $T(h) = T_\infty - \left(T_\infty - T(h_0)\right)e^{-s(h-h_0)}$

Kockarts (1981):

- $T_\infty = a + b\bar{F} + c(F - \bar{F}) + \Delta T + f(t)$



- h_0, $T(h_0)$: constants
- T_∞: exospheric temperature
- $\bar{F}$: solar decimetric flux averaged over several solar rotations, usually three
- F: F10.7 taken one day before the day to which T_∞ corresponds
- ΔT: correction for geomagnetic effects (particle precipitation or Joule heating)
- $f(t)$: semi-annual variation expressed in function of the day count in the year

Kockarts (1981)

Thermal structure

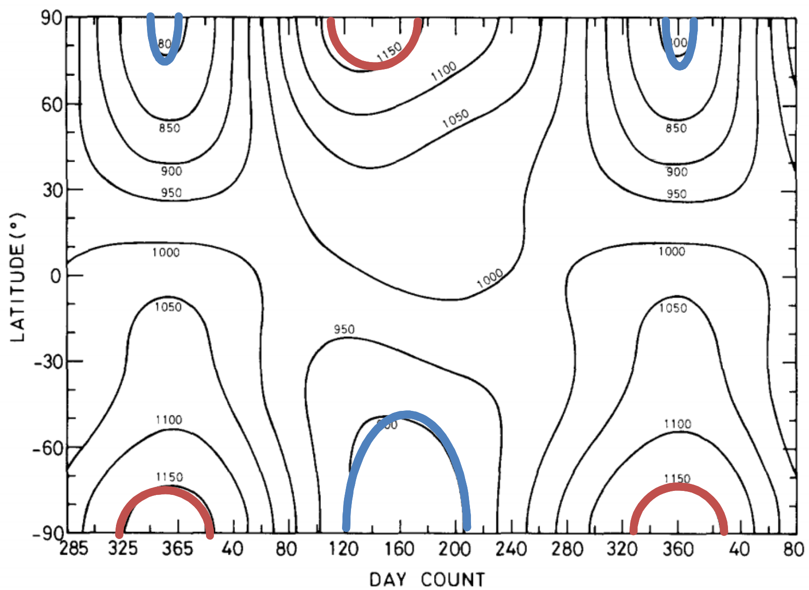
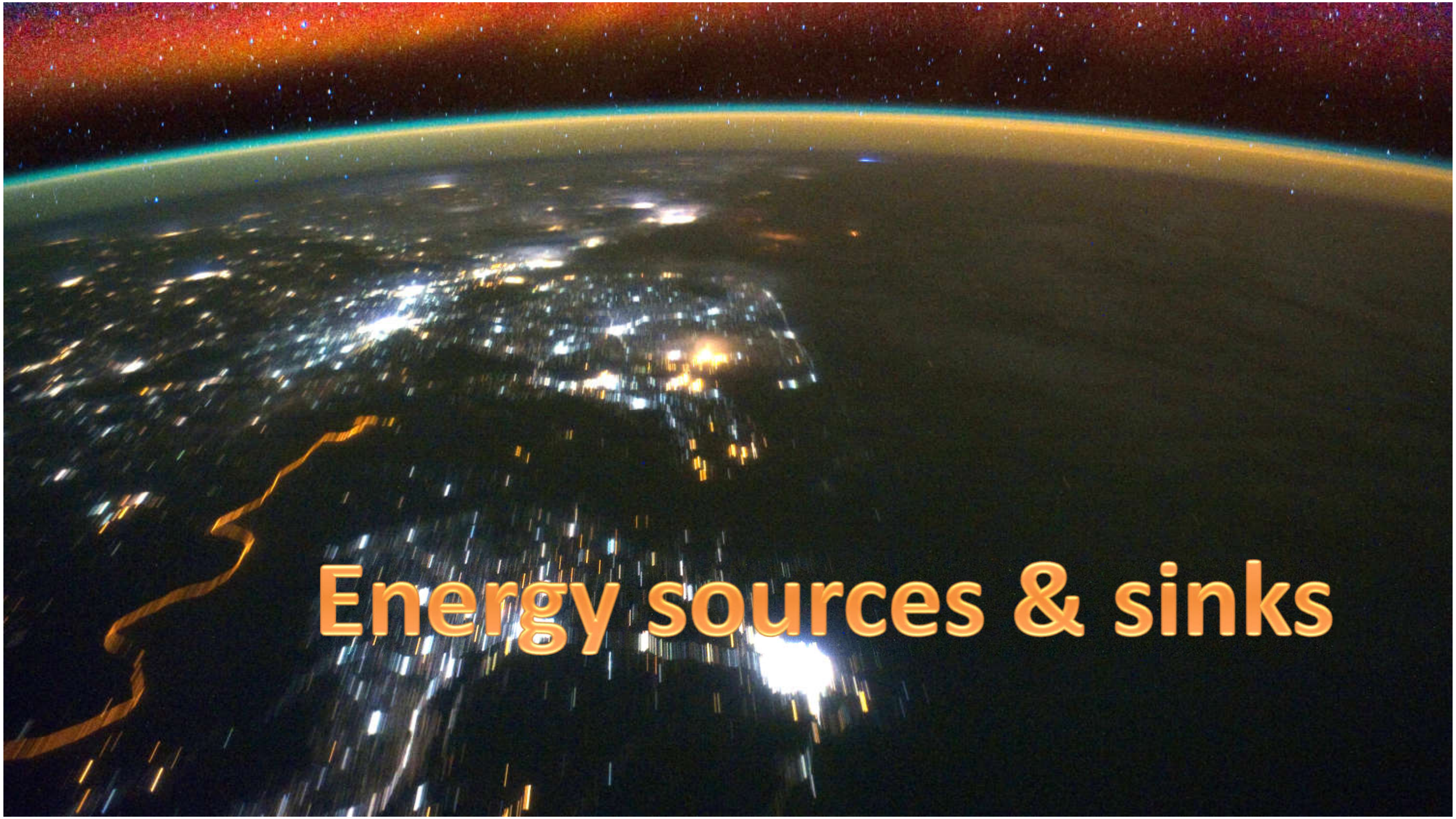


Fig. 2. Isopleths of daily averaged thermopause temperature for $F_{10.7} = \bar{F}_{10.7} = 150 \times 10^{-20}$ Wm^{-2} Hz^{-1} and $K_p = 0$.

Kockarts (1981)

- Thermopause temperature varies in an annual cyle
- This depends on the solar insolation


Energy sources & sinks

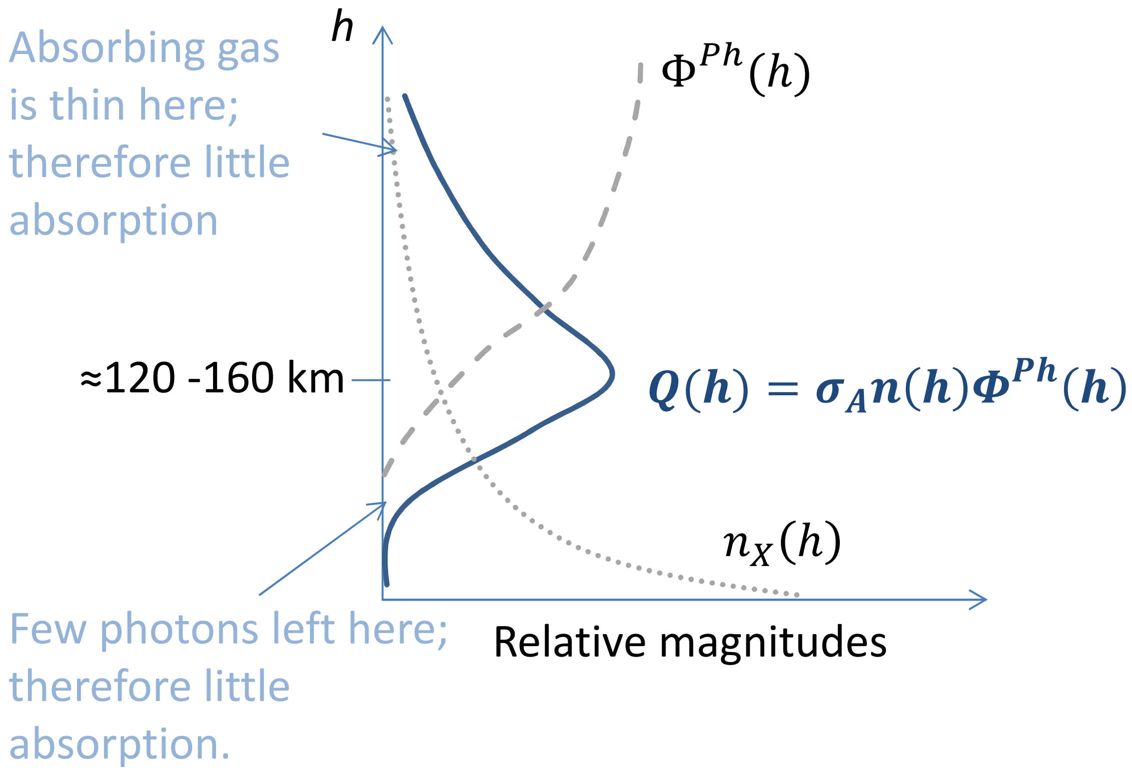
Thermosphere energy sources and sinks

Energy Source	Energy Sink
Absorption of UV (120-200 nm) dissociating O_2	Thermal downward conduction into the mesosphere
Absorption of EUV (20 -100 nm) O, $O_{2,}$ N_2	IR cooling by NO and CO_2 (after geomagnetic storms only)
Joule Heating by Auroral electrical currents	
Particle precipitation from magnetosphere	
Internal redistribution from advection and adiabatic heating (Dissipation of upward propagating waves: tides, planetary waves, gravity waves)	Internal redistribution from advection and adiabatic cooling

Absorption of solar energy

Three factors determine the **rate of solar radiation absorption per volume**, $Q = \left.\frac{dN_{Ph}}{dV\,dt}\right|_h$:

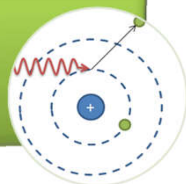
- $\Phi^{Ph}(h)$: No. of photons (photon flux)
- $\mathrm{n}(h)$: No. of absorbing atoms/ molecules,
- σ_A: cross-section, (Efficiency of absorption)



Energy absorption processes

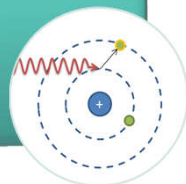
- Process producing new charged particles
- Reaction force comes from within the atom
- $O_2 + \mathrm{h}\nu \rightarrow {O_2}^{+} + e^{*}$

Ionisation



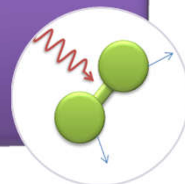
- Atoms absorb energy without ionisation
- The orbital electrons are raised to the next energy level
- $O + \mathrm{h}\nu \rightarrow O^{*}$

Excitation

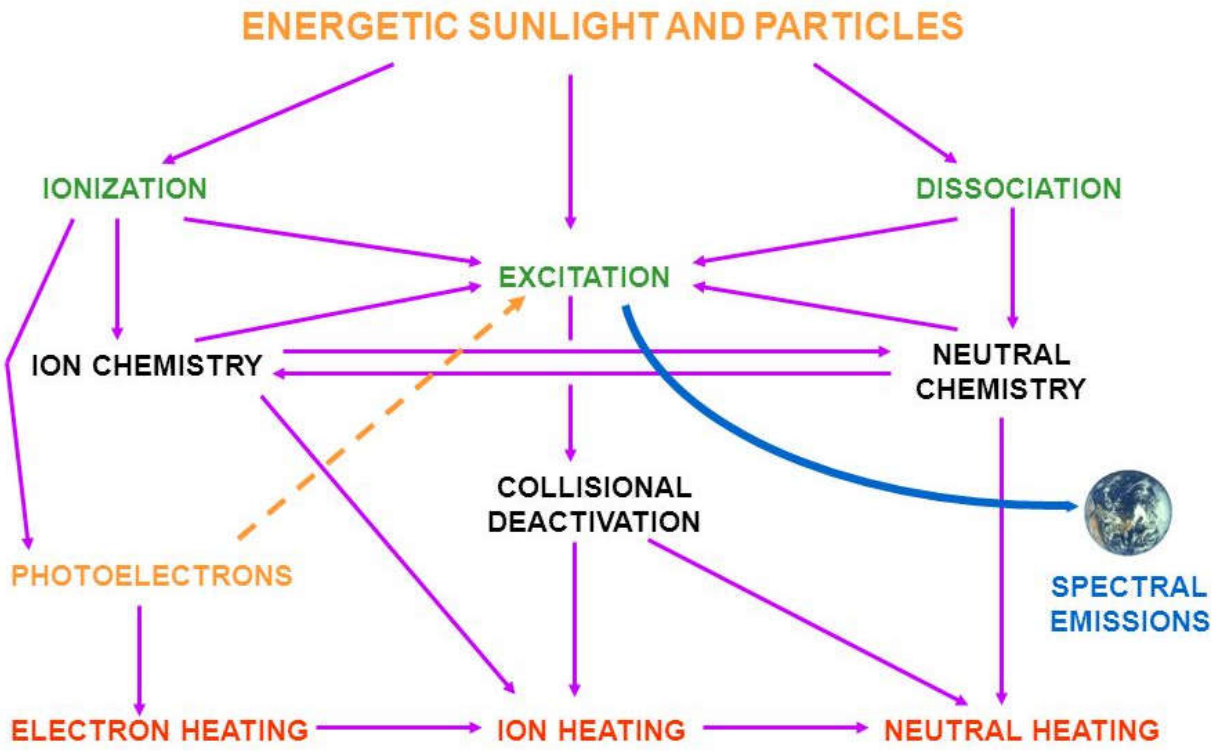


- Separation of charged particles which already exist in a compound
- $N_2 + \mathrm{h}\nu \rightarrow N + N$

Dissociation



Thermosphere heating



Primary absorption processes in the thermosphere

Photodissociation (λ ≤ 242 nm)

- $O_2 + Photon\ (\lambda \leq 242\ nm) \rightarrow O + O$

Photoionisation (λ ≤ 103 nm)

- $O + Photon\ (\lambda \leq 91\ nm) \rightarrow O^+ + e$
- $N_2 + Photon\ (\lambda \leq 80\ nm) \rightarrow {N_2}^+ + e$
- $O_2 + Photon\ (\lambda \leq 103\ nm) \rightarrow {O_2}^+ + e$

Dissociative photoionisation (λ ≤ 72 nm)

- $N_2 + Photon\ (\lambda \leq 49\ nm) \rightarrow N^+ + N + e$

- Collision between photon and gas particle depends on collision cross section
- Each species and absorption process has own absorption cross section
- The absorption cross section depends on the energy of the photon

Primary absorption processes in the thermosphere

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Dissociative photoionisation (λ ≤ 72 nm)

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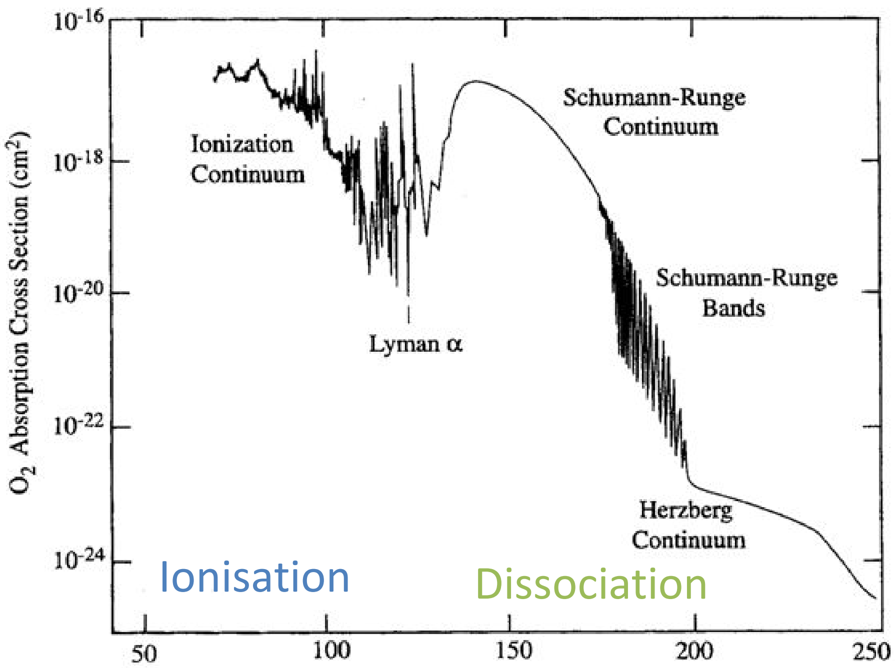
O_2 absorption cross



Chapman function

- describes the attenuation of solar radiation by an exponential atmosphere.
- $q^E(h) = E_{Ph} Q(h)$
  $$= \left(\frac{h_p c_0}{\lambda}\right) \sigma_A n(h) \Phi^{Ph}(h)$$
- $q^E(h) = \sigma_A n(h) \Phi^E{}_\infty e^{-\tau(h)}$
- $q^E(h) = q^* \exp\{1 - z^* - \sec\chi\, e^{-z^*}\},$
  $$z^* = \frac{h - h^*{}_{max}}{H}$$

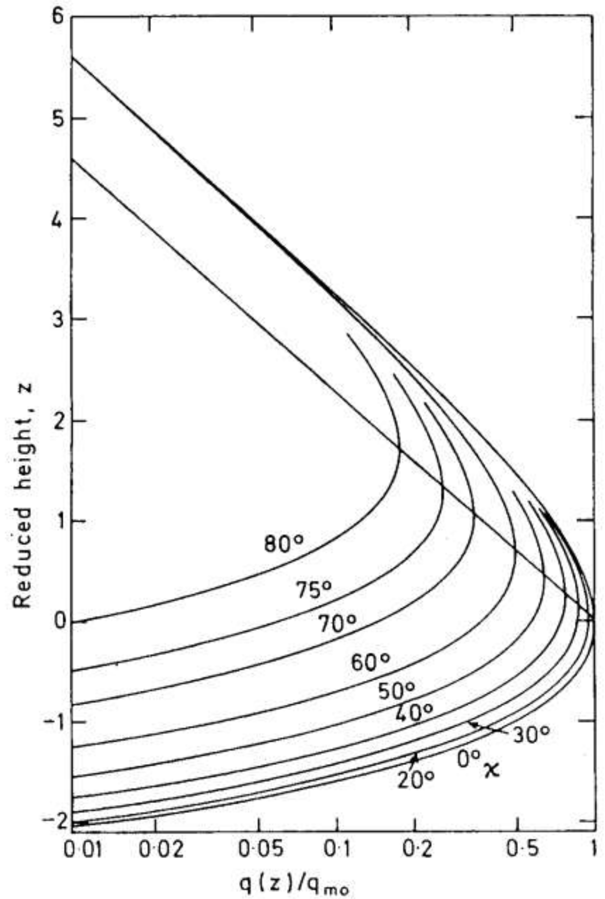


Figure 1.5. The Chapman production function. (After T. E. VanZandt and R. W. Knecht, in *Space Physics* (eds. LeGalley and Rosen). Wiley, 1964.)

Particle Heating

- Mainly electron precipitation causes heating
- Heating due to proton precipitation is smaller because of less power
- Localized source of heating, which is highly variable
- Dissociative recombination

$$N_2 + e^* \to N + N(^4S,^2D,^2P) + e$$

- Dissociative ionisation

$$e + N_2 \to N^+ + N + 2e$$

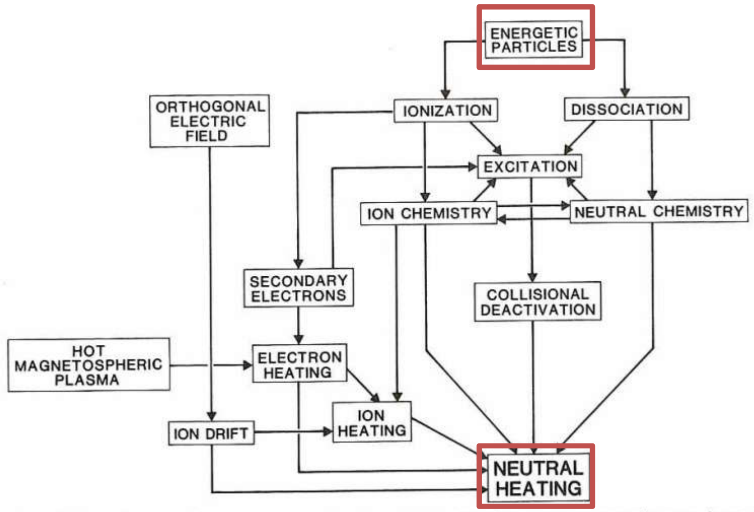
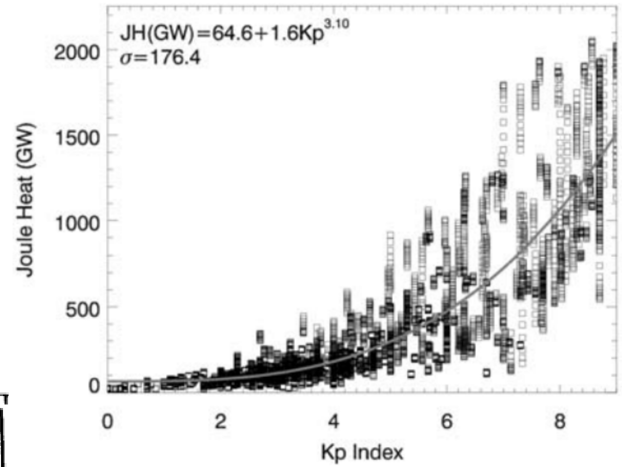


Fig. 1. Flow chart of sources and processes leading to neutral gas heating.

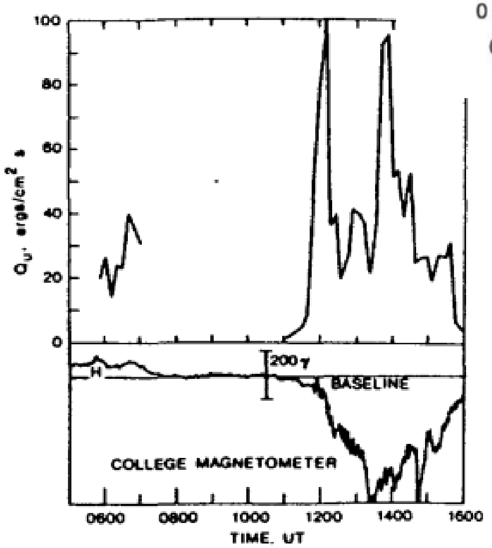
Rees et al. (1983)

Joule/ Frictional Heating

- $q_J = \sigma_P(\mathcal{E} - u_n \times B)^2$
- roughly proportional to the Pedersen conductance at high latitudes
- High latitude phenomenon
- Energy deposition from the magnetosphere
- Correlation with geomagnetic perturbations



Lu et al. (2010)

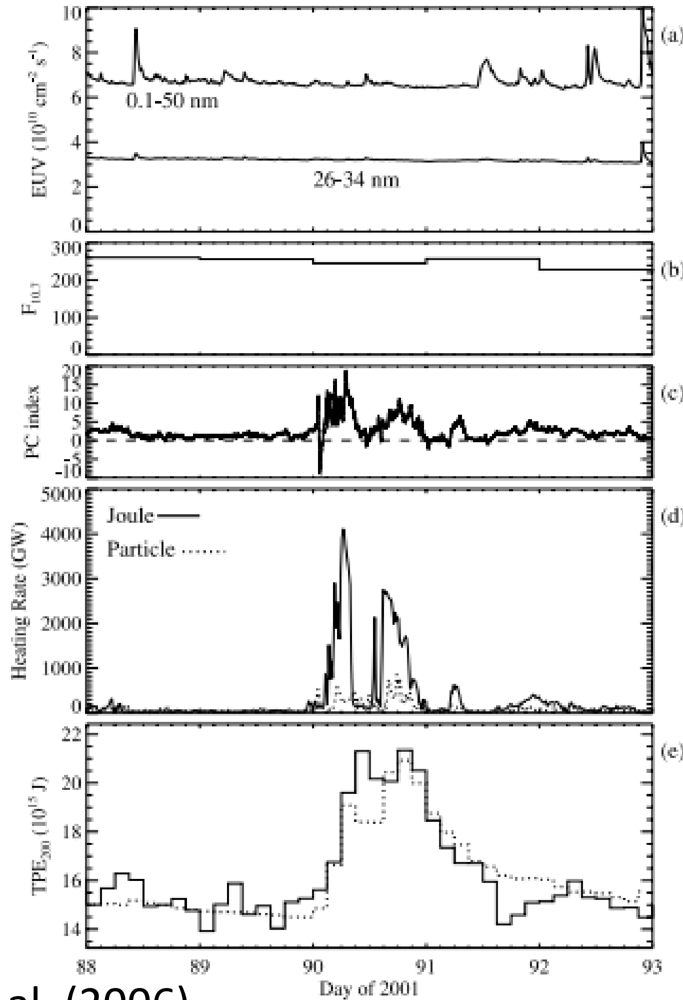


Brekke (1982)

Fig. 7 Height-integrated Joule heating rate compared with simultaneous magnetic variations. (After [18].)

Joule heating vs. precipitation

- Both are Auroral processes
- Joule heating is more intensive than particle heating
- Joule heating large scale
- Particle heating small scale



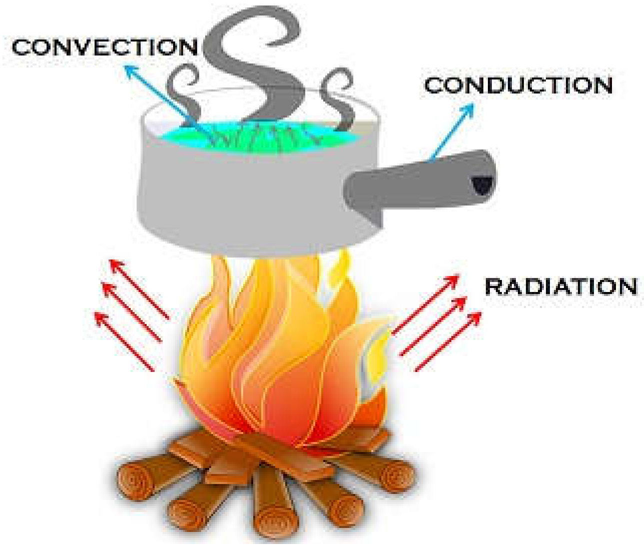
Wilson et al. (2006)

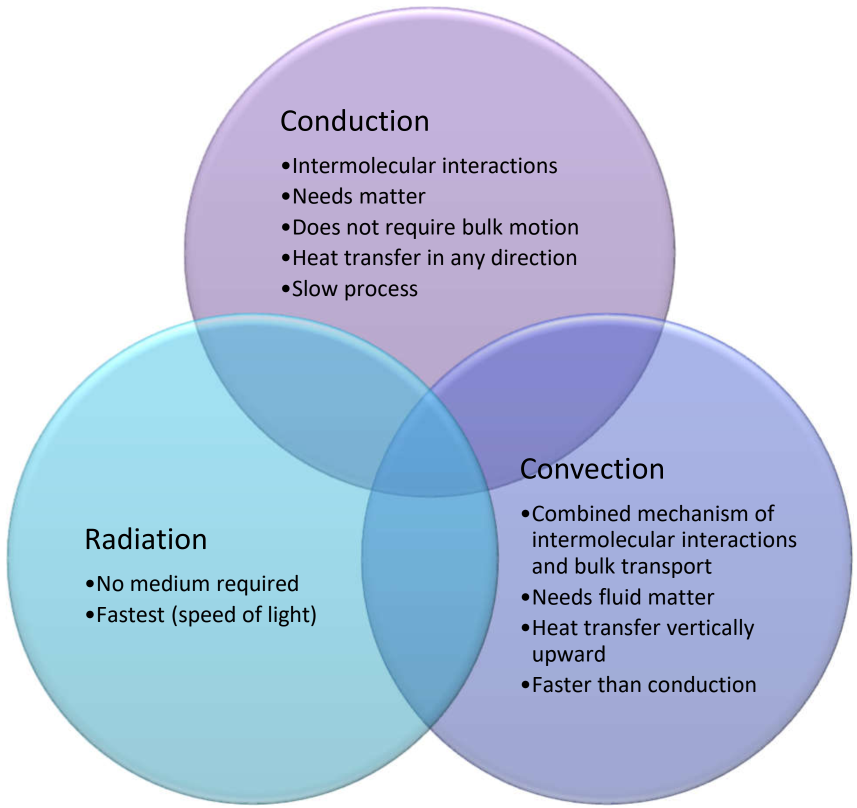
Thermosphere heating

- Heating efficiency (h≥300 km)
- $\eta^w = \frac{q^W}{q^E} = \frac{q^w}{\sigma^A n \Phi^E{}_\infty}$
- Transformation of first law of thermodynamics yields temperature increase per time
- $\frac{\Delta T}{\Delta t} = \frac{q^w}{nk(1+\frac{f}{2})} = \frac{\eta^w \sigma^A \Phi^E{}_\infty}{k(1+\frac{f}{2})}$

- Calculating the temperature change with normal thermosphere condition parameters results in a significantly higher value than observed
- →There must be efficient processes reducing the temperature

Molecular heat transfer





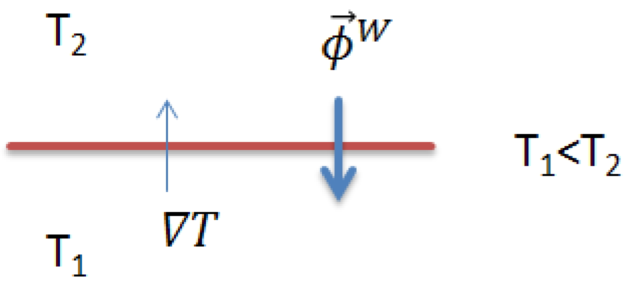
Conduction

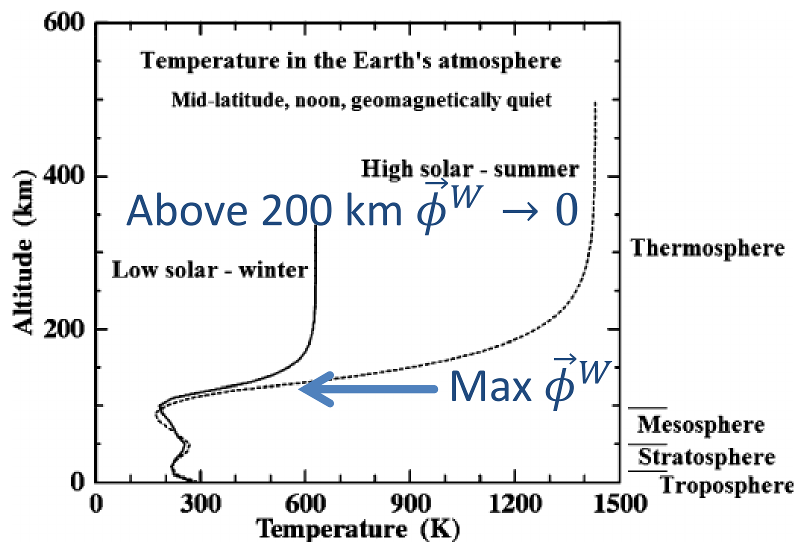
- The heat flux is proportional to the temperature gradient

$$\vec{\phi}^W = -\kappa \nabla T$$

- κ: thermal conductivity
- Heat flux is in the direction of decreasing temperature (basis for minus sign)
- The heat flux causes change of heat in a volume in a certain time

$$d^W = -\nabla \vec{\phi}^W$$

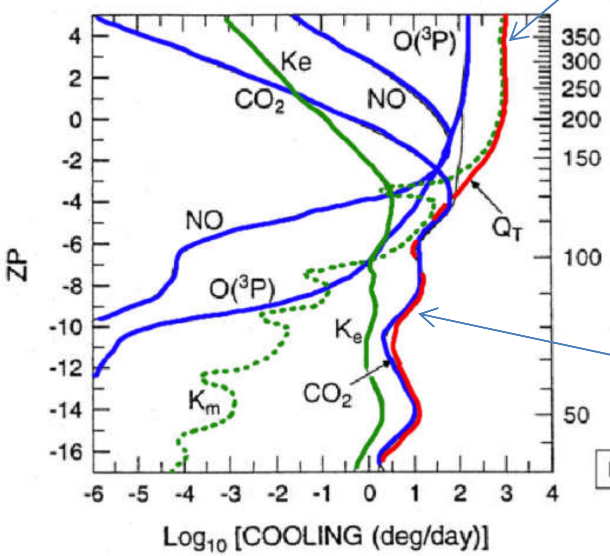




Conduction and Radiative Cooling

- Thermal conduction (molecular and turbulent) removes heat from the thermosphere to the mesosphere
- During quiet conditions, radiative cooling is small in the upper thermosphere
- **Molecular conduction determines the thermosphere temperature profile shape**
- During storms, NO cooling can increase by two orders of magnitude

$Q_T \approx K_m$

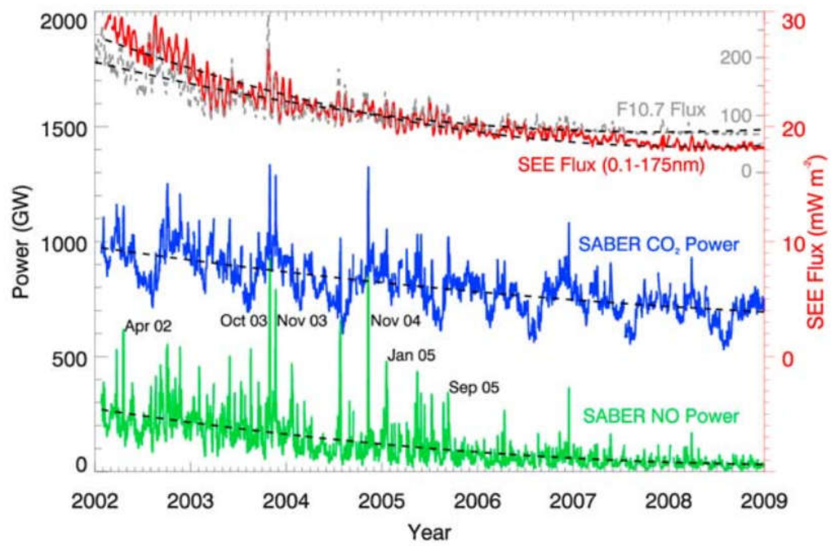


Roble, 1995

- Q_T total neutral heating rate
- K_m molecular thermal conduction
- K_e eddy thermal conduction
- NO cooling at 5.3 mm
- CO_2 total CO_2 rate
- O(^{3}P) fine structure cooling by O
- IR total of O, NO, CO_2
- In the mesosphere collision frequencies are high enough that polyatomic molecules CO_2, O_3, H_2O can radiate energy away in infrared

Radiative cooling

- Heat is converted into IR radiation
- Counteractive to heating processes
- efficient radiative cooler for the thermosphere:
  - NO 5.3 µm (emission maximizes between 100 and 200 km and mostly occurs at high latitudes)
  - CO_2 15 µm (mainly below 130 km)
  - O 63 µm
- Evident seasonal variation in the CO_2 cooling rate
- Spikes associated with storms



Lu et al. (2010)

Heat equation

- $$\rho c_p \frac{\partial T}{\partial t} \cong q^w - l^w + d^w$$
  $$= \eta^w q^E - l^w - \mathrm{div}\vec{\phi}^w$$
- {Temp. Change}={Heating}-{Cooling}-{Conduction}

- Partial, non-linear differential equation
- Depends on composition
- Can be solved only numerically