Atmospheric Physics: The Neutral Atmosphere

John W. Meriwether

Department of Physics and Astronomy

Clemson University

Overview of Lecture

Fundamental equations of Atmospheric Physics

Basics of the Earth's atmosphere structure for
80 km to ~ 1000 km:

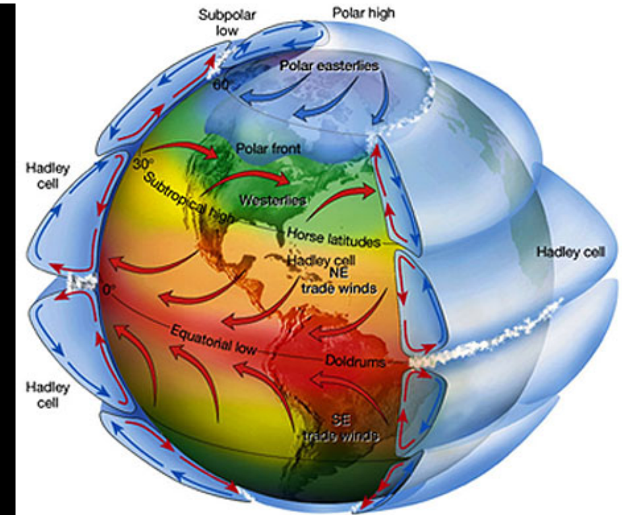
i.e., Mesosphere, Thermosphere, and Exosphere

- Structure & dynamics
- Energy sinks and sources
- Airglow emissions as remote sensing diagnostic
- Waves and tidal winds (if time permits)

Atmospheric Dynamics: The Basics

1) Forces:

- **Pressure gradient** - $\partial P/\partial x$
- **Friction** - $\nu\, \partial^2 U \partial z^2$
- **Gravity** - $\rho\, \mathbf{g}$
- **Electromagnetic** - $e\, \mathbf{E} \times \mathbf{B}$



2) Reference Frames:

- **Inertial** Newtonian Dynamics
- **Non-Inertial** Apparent Forces (Coriolis, centrifugal)

3) Time Tendency:

- **Fixed observer** Material Deriviative
- **Observer "riding" motion** Lagrangian Deriviative

4) Conservation Laws:

- **Mass** m
- **Momentum (force equation)** linear + angular
- **Energy** $1/2mv^2 + \rho C_p T + \rho gz$

5) Scaling of the Equations of Motion:

- **Geostrophic Balance** Rossby Number
- **Turbulence** Reynolds Number

2. Dynamics of Horizontal Flow

Real Forces: are the fundamental forces, e.g.
- Gravitation
- Electricity & Magnetism
- Friction
- Pressure gradient

Apparent Forces: arise due to the acceleration of the reference frame.
- Centrifugal force
- Coriolis force

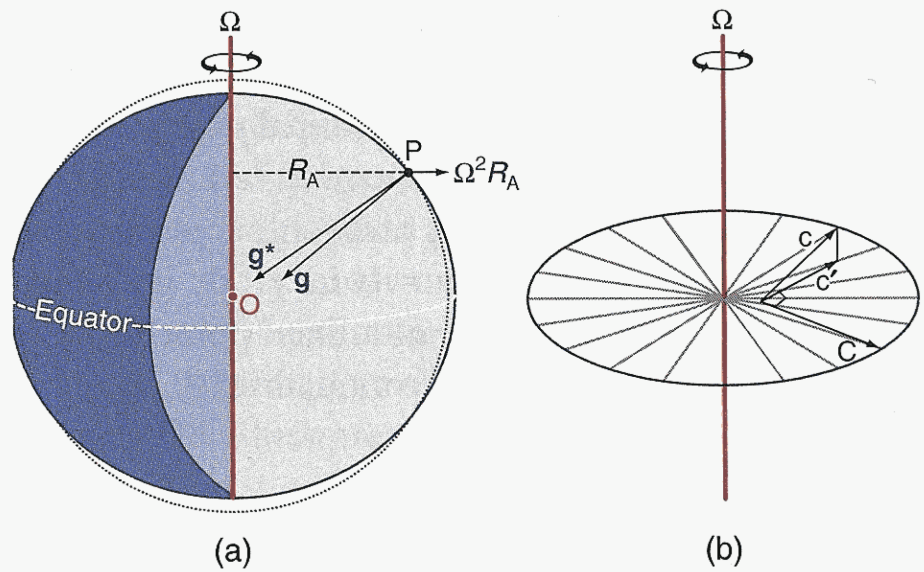


Fig. 7.6 (a) Apparent forces. Effective gravity **g** is the vectorial sum of the true gravitational acceleration **g*** directed toward the center of the Earth O and the *centrifugal force* $\Omega^2 R_A$. The acceleration **g** is normal to a surface of constant geopotential, an oblate spheroid, depicted as the outline of the Earth. The dashed reference line represents a true spherical surface. (b) The Coriolis force C is linearly proportional to c′ the component of the relative velocity c in the plane perpendicular to the axis of rotation. When viewed from a northern hemisphere perspective, C is directed to the right of c′ and lies in the plane perpendicular to the axis of rotation.

Real vs. Apparent Forces

In an inertial (non-accelerating) reference frame Newton's Laws of Motion can be directly applied to a parcel of gas in order to determine its time tendency (acceleration).

Euler's Equation:

m Dv/Dt = - dP/dx + $\rho \mathbf{g}$ + other forces (1-dimensional, x-direction)

Dv/Dt is the material or **advective deriviative** in an inertial reference frame. It can be related to the Lagrangian deriviative ("riding" the parcel) via

D/Dt = - $\partial/\partial t$ + $\mathbf{v}\ \partial/\partial x$, where **v** is the vector velocity.

Real vs. Apparent Forces

In an accelerating reference frame (planet rotating with angular velocity ω), the acceleration produces an **apparent force** to the fixed observer.

This is called the **Coriolis Force**.

The acceleration due to this "fictitious" force is given by:

$Dv/Dt = -2\ \omega \times \mathbf{v}$

The Coriolis Force is always perpendicular to the direction of motion and thus cannot do work on the fluid.

Gravity vs. Gravitation; Or Which Way is Down?

Gravitation:

The force between two objects due to their mass. On the surface of the Earth gravitation is denoted by the vector g* directed toward the center of the Earth.

However, the Earth is rotating with angular acceleration $\Omega = 2\pi$ rad day^{-1} = 7.292×10^{-5} s^{-1} which produces a radial force = $\Omega^2 R$, where R is the radial vector from the axis of rotation.

Gravity: $g = g^* + \Omega^2 R$

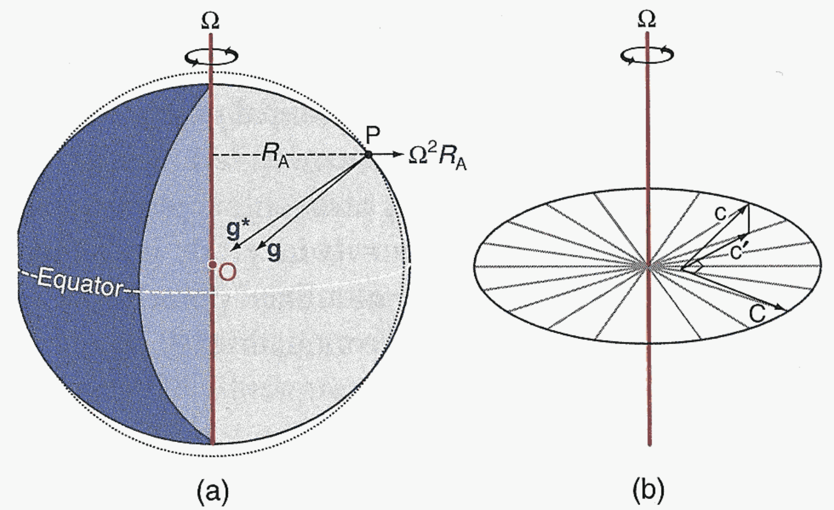


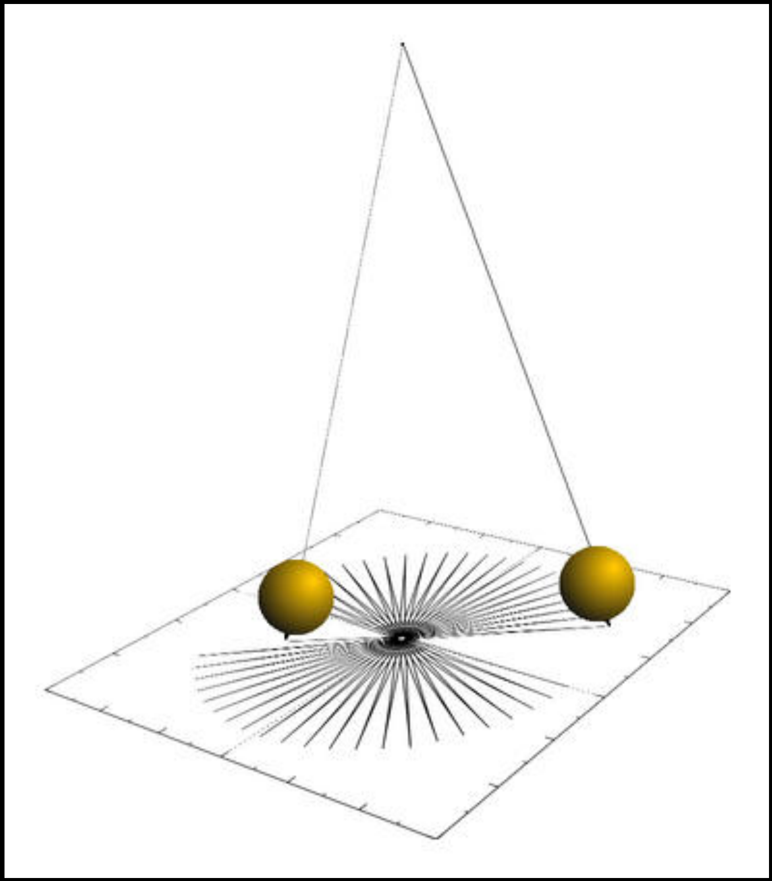
Fig. 7.6 (a) Apparent forces. Effective gravity **g** is the vectorial sum of the true gravitational acceleration **g*** directed toward the center of the Earth O and the *centrifugal force* $\Omega^2 R_A$. The acceleration **g** is normal to a surface of constant geopotential, an oblate spheroid, depicted as the outline of the Earth. The dashed reference line represents a true spherical surface. (b) The Coriolis force C is linearly proportional to **c**′ the component of the relative velocity **c** in the plane perpendicular to the axis of rotation. When viewed from a northern hemisphere perspective, C is directed to the right of **c**′ and lies in the plane perpendicular to the axis of rotation.

Focault Pendulum

The Focault Pendulum is an example of simple harmonic motion in inertial space.

The Focault Pendulum swings back and forth in inertial space while the Earth rotates “underneath” it.

From the point of view of someone watching the motion on the surface of the Earth, it appears that the pendulum rotates. This is inertial motion.



The Pressure Gradient Force

The vertical force balance is known as hydrostatic equilibrium

The vertical force per unit mass:

$$\frac{1}{\rho}\frac{dp}{dz} = -g$$

In general the total pressure force:

$$P = -\frac{\nabla p}{\rho}$$

Horizontal components of the pressure gradient force:

$$P_x = -\frac{1}{\rho}\frac{\partial p}{\partial x} \qquad P_y = -\frac{1}{\rho}\frac{\partial p}{\partial y}$$

The Horizontal Equations of Motion

East-West direction (x, u positive toward East):

$$\frac{du}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + fv + F_x$$

North-South direction (y, v positive toward North):

$$\frac{dv}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial y} - fu + F_y$$

where $F_{x,y}$ is the external force (e.g. friction)

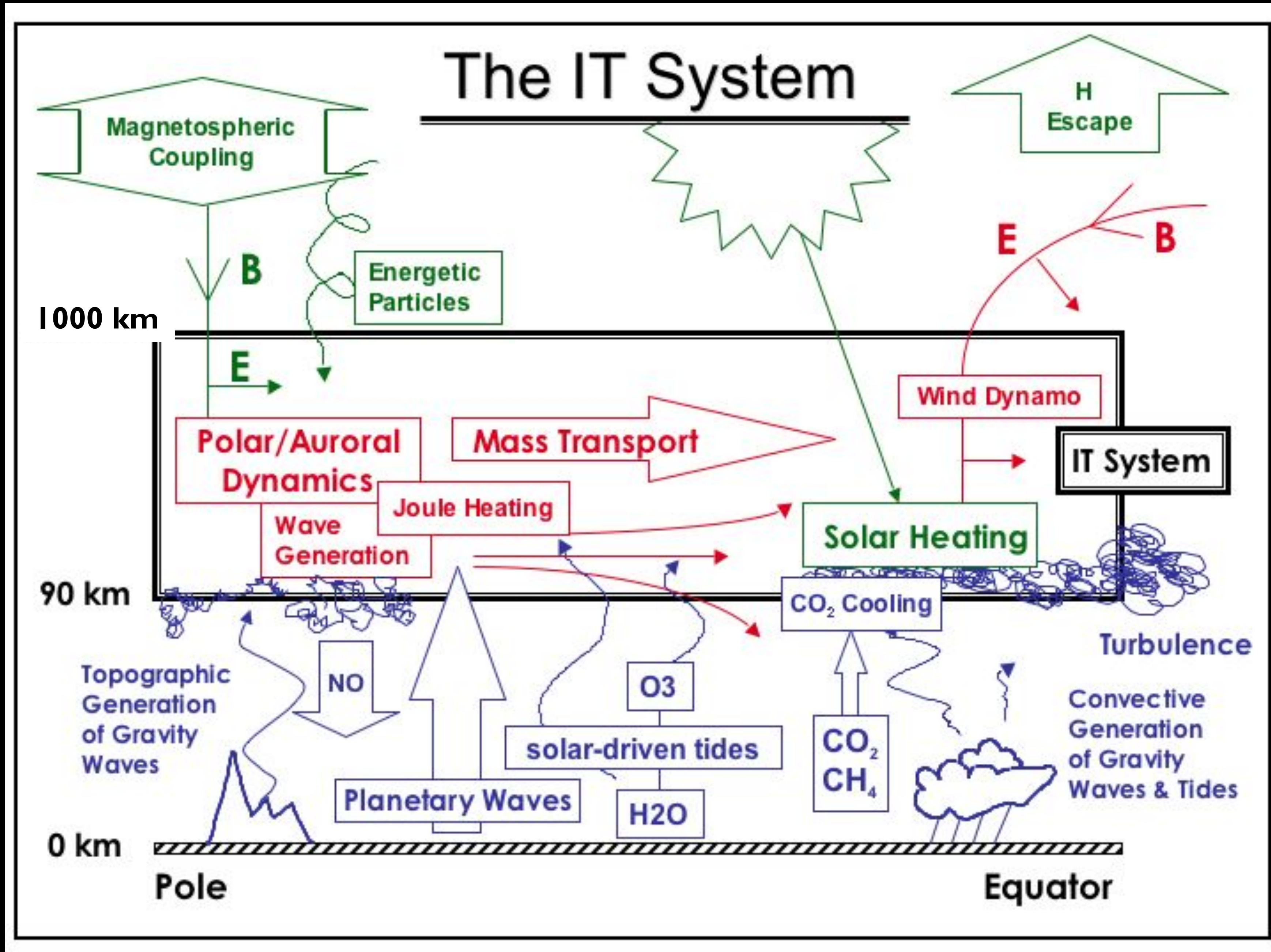
The Horizontal Equations of Motion

Above ~1km altitude (outside the boundary layer) $F_{x,y} = 0$:

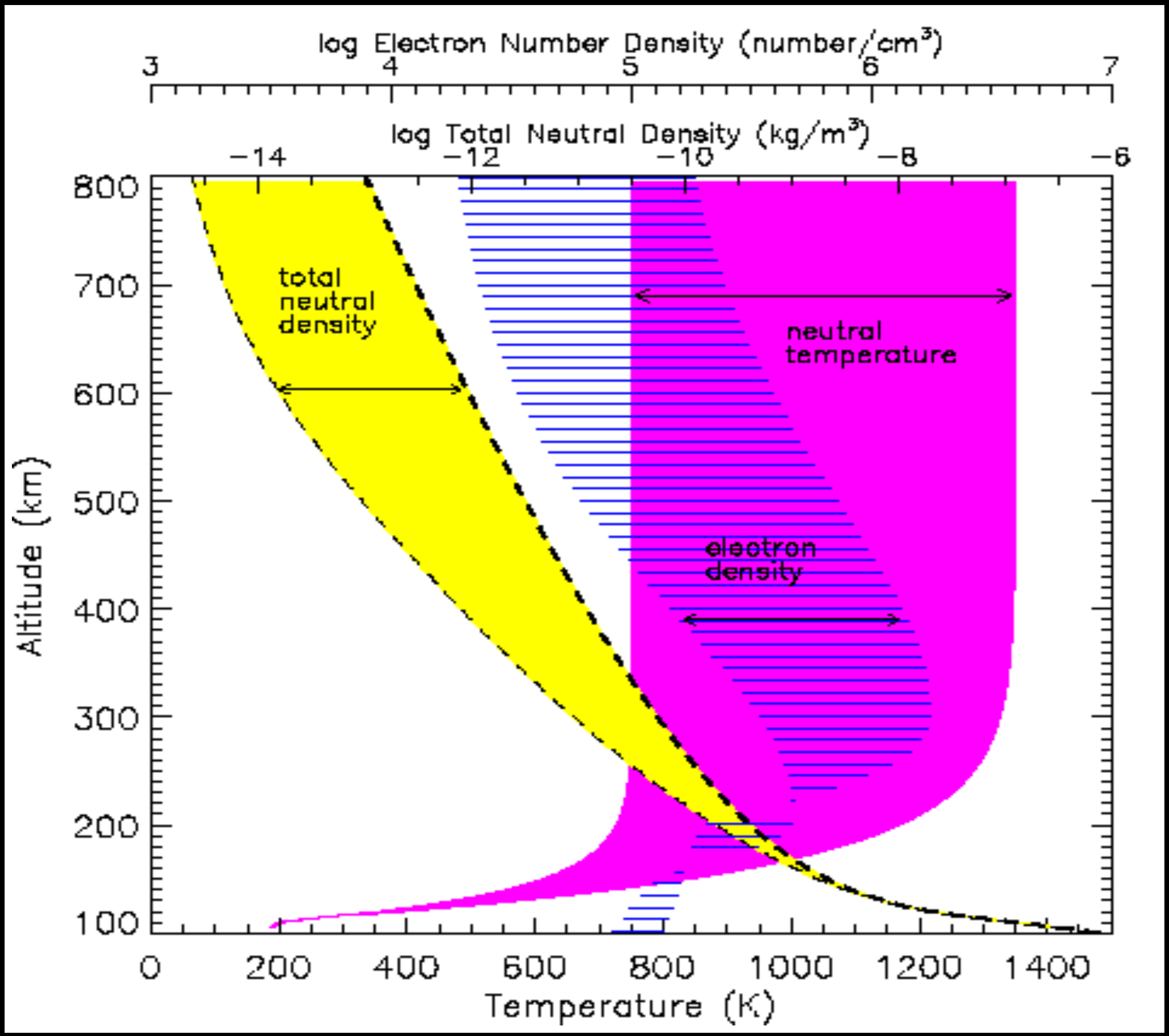
$$-\frac{1}{\rho}\frac{\partial p}{\partial y} = fu \qquad \frac{1}{\rho}\frac{\partial p}{\partial x} = fv$$

Note that there is no tendency or time evolution. This is called the Geostrophic Balance. The wind velocity that exactly solves these equations is known as the Geostrophic Wind.

$$u_g = -\frac{1}{f\rho}\frac{\partial p}{\partial y} \qquad v_g = \frac{1}{f\rho}\frac{\partial p}{\partial x}$$


The IT System
Magnetospheric Coupling
H Escape
B
E
Energetic Particles
1000 km
E
B
Wind Dynamo
Polar/Auroral Dynamics
Mass Transport
IT System
Joule Heating
Wave Generation
Solar Heating
90 km
CO_2 Cooling
Turbulence
Topographic Generation of Gravity Waves
NO
O3
Convective Generation of Gravity Waves & Tides
solar-driven tides
CO_2
CH_4
Planetary Waves
H2O
0 km
Pole
Equator

Solar cycle changes in EUV radiation impact upper atmosphere temperature and density



Neutral Temperature: 2 times

Neutral Density: 50 times

Electron Density: 10 times

The Thermosphere

The Thermosphere:

"…hot sphere…" - from the Greek

The Thermosphere

The Thermosphere is an ENERGY SINK[1]

[1]At least, usually it is.

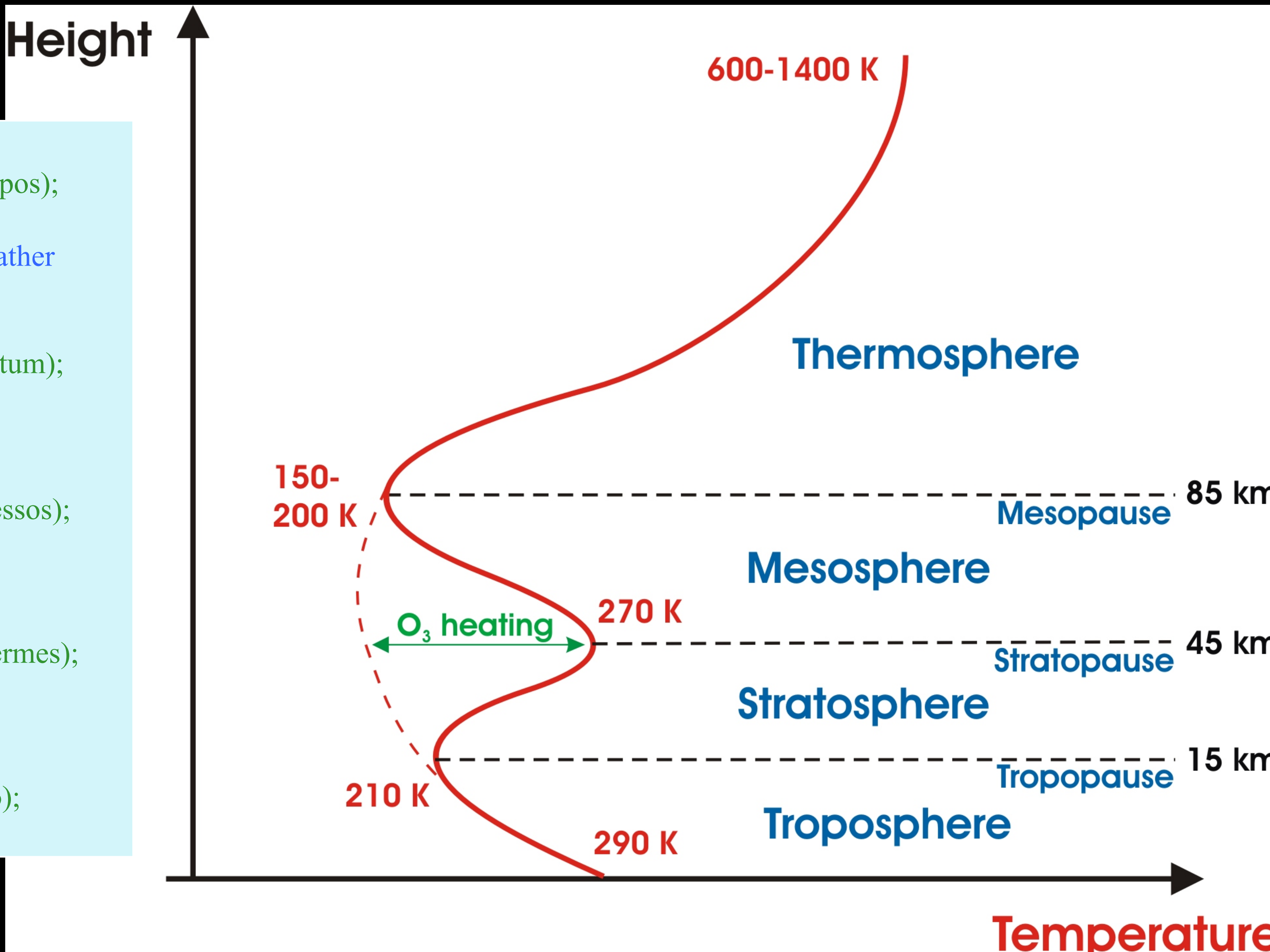
Tropo
(Greek: tropos);
“change”
Lots of weather

Strato
(Latin: stratum);
Layered

Meso
(Greek: messos);
Middle

Thermo
(Greek: thermes);
Heat

Exo
(greek: exo);
outside



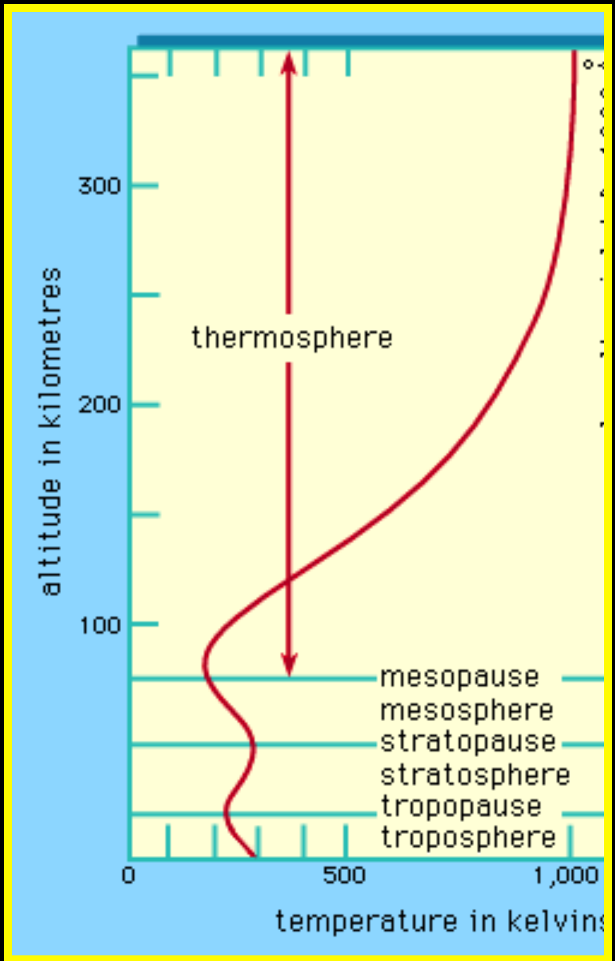
Thermosphere structure

Temperature increases with altitude:
heated by solar (E)UV

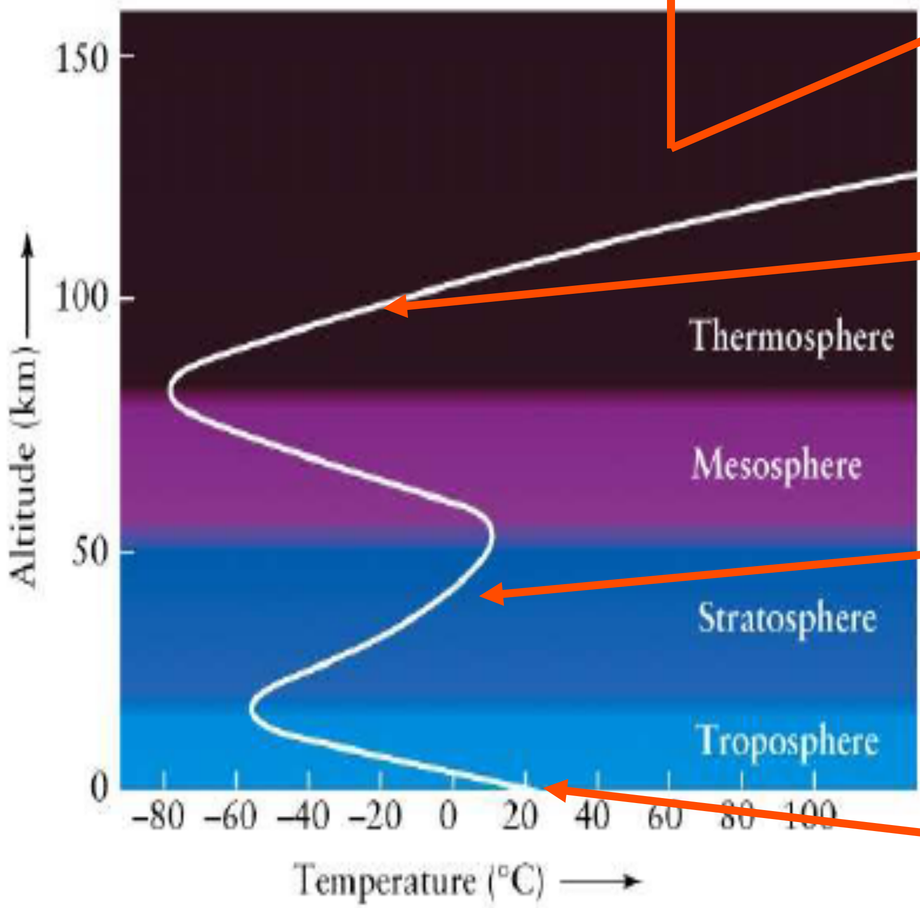
Extends to limit of space
(usefully to ~ 500 km)

Below 100 km, turbulently mixed;
above 100 km, stratified into
layers of atomic species by
molecular diffusion

Thermosphere is electrically
NEUTRAL everywhere!



Big Question: Why does the Atmospheric Temperature vary with Altitude?



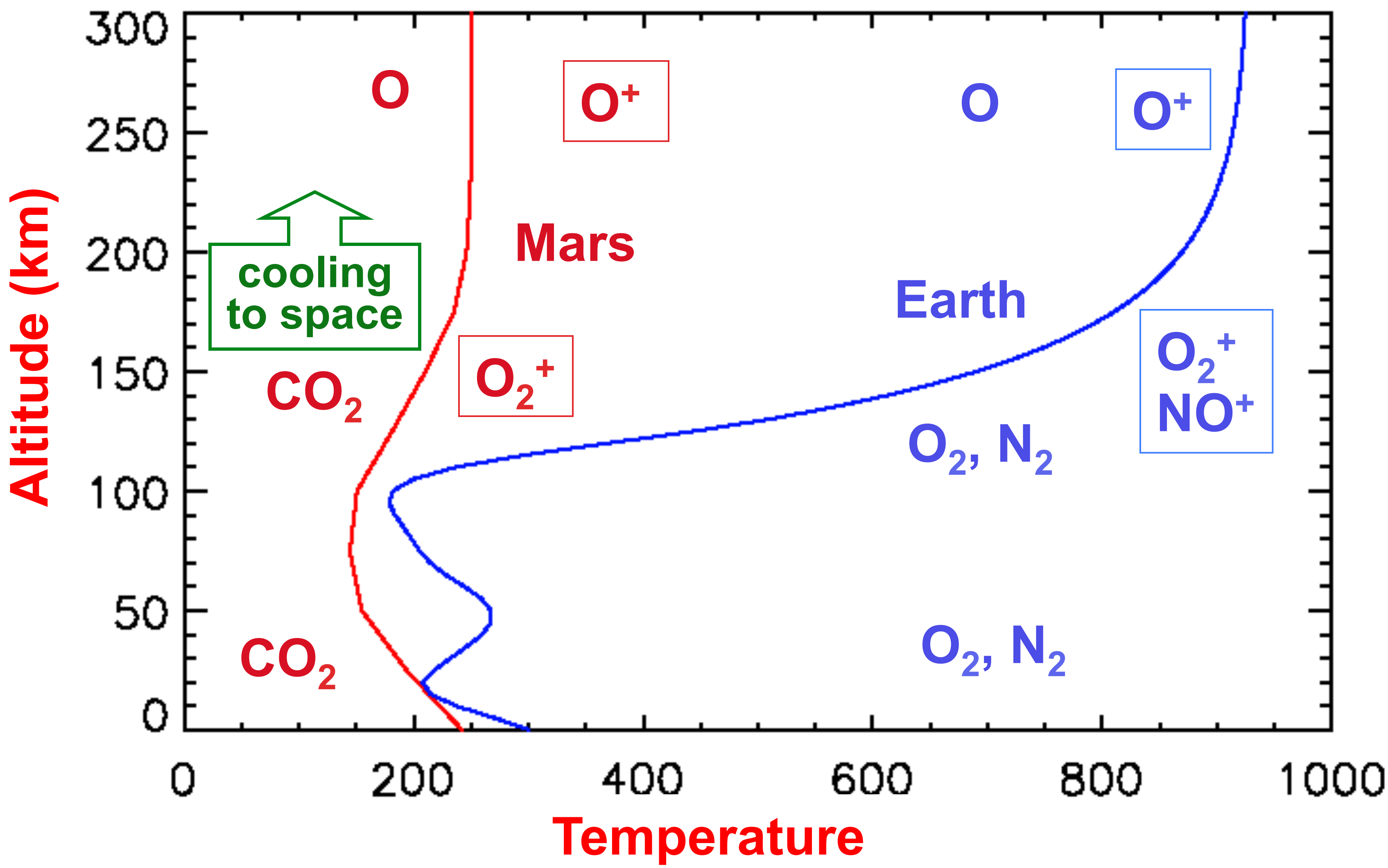
Ionization:
O, N_2, O_2 + sunlight => e + …

Oxygen Heating:
O_2 + sunlight => O + O

Ozone Heating:
O_3 + sunlight => O + O_2

Surface Heating

Earth and Mars: Temperature Structure & Major Atmosphere and Ionosphere Constituents



HEAT SOURCES AND SINKS

Thermosphere - Sources

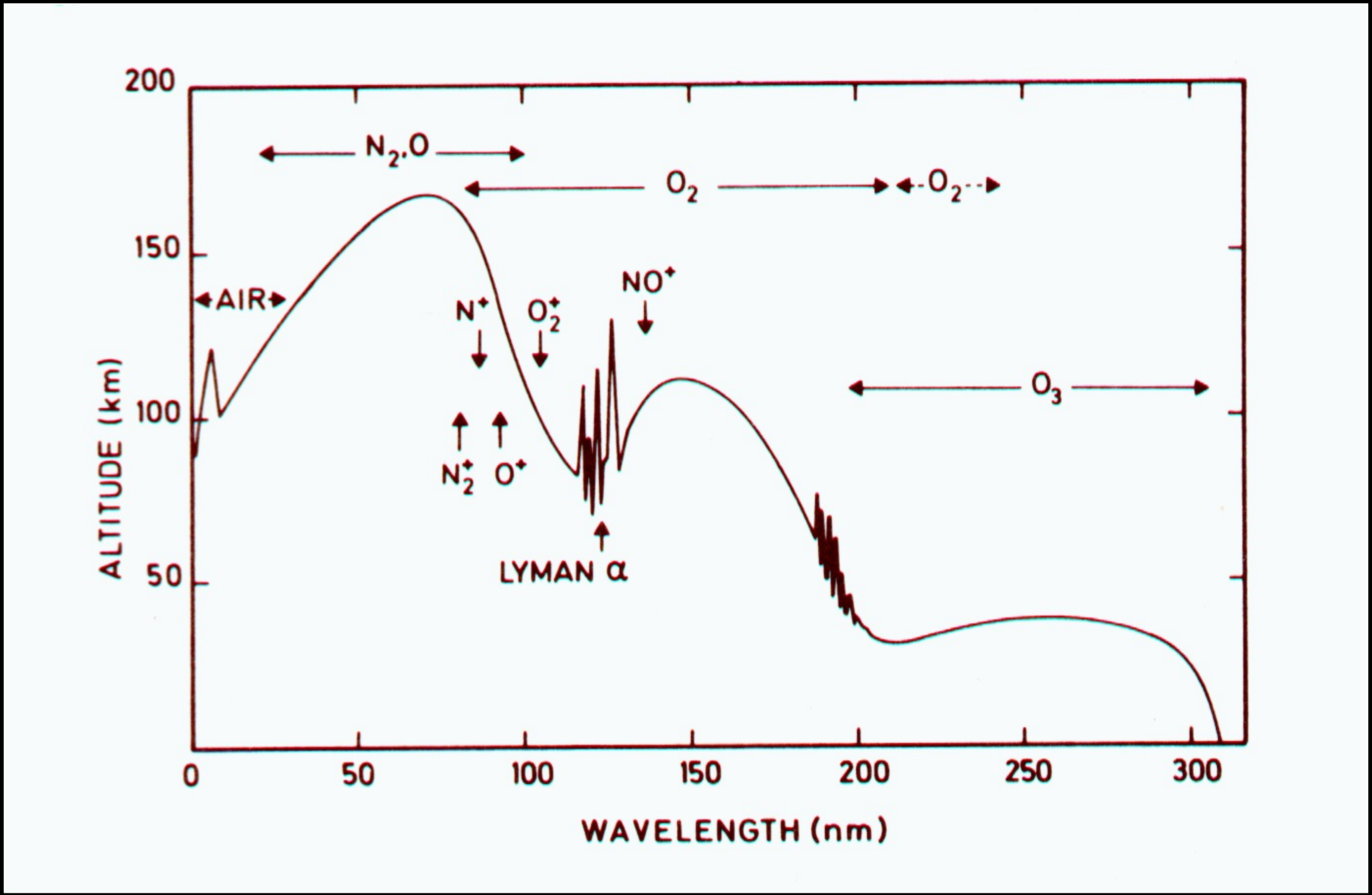
- absorption of EUV (200-1000 Å; photo-ionization of O, N_2, O_2) and UV (1200-2000 Å; photo-dissociation of O_2) radiation;
- photo-ionization and photo-dissociation lead to chemical reactions and collisions that liberate heat.

- dissipation of upward propagating gravity waves (weather systems; flow over topography) and tides (periodic heating).

- joule heating of electric currents (mostly auroral / polar regions)

- particle precipitation (mostly auroral / polar regions)

Absorption of Solar Radiation vs. Height and Species



Thermosphere - Sinks

Thermal conduction (molecular and turbulent) removes heat from thermosphere to mesosphere (here collision frequencies are high enough that polyatomic molecules CO_2, O_3, H_2O can radiate energy away in infrared).

Let Φ = heat flux due to conduction = $k\dfrac{dT}{dh}$

As a first approximation, heat input is balanced by loss due to conduction:

$$Q \approx \frac{d\Phi}{dh} \quad \Rightarrow \quad \Phi \approx \int Q\,dh$$

Therefore

$$\left.\frac{dT}{dh}\right|_z \approx \frac{1}{k}\int_z^{\infty} Q\,dh$$

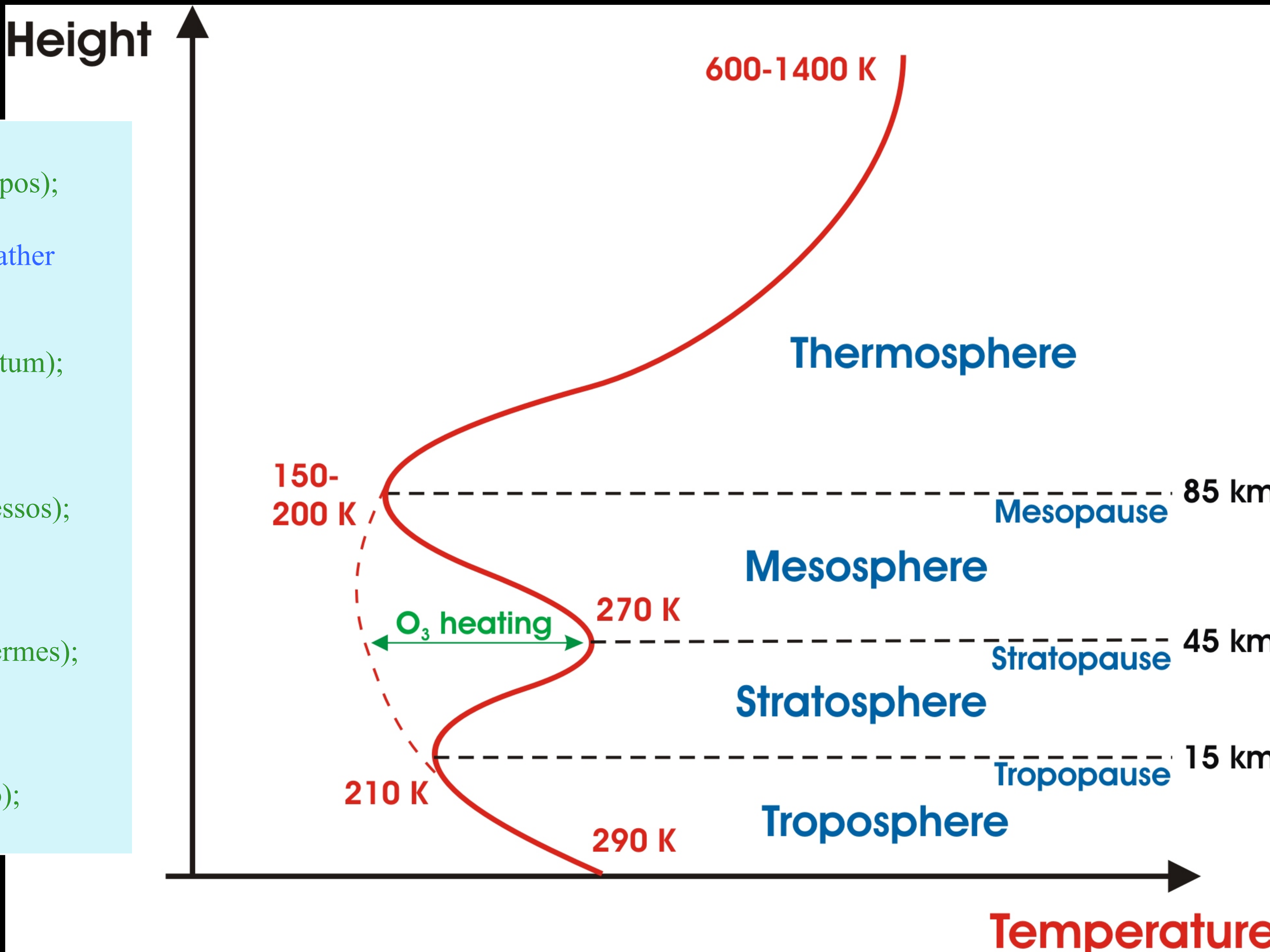
Tropo
(Greek: tropos);
“change”
Lots of weather

Strato
(Latin: stratum);
Layered

Meso
(Greek: messos);
Middle

Thermo
(Greek: thermes);
Heat

Exo
(greek: exo);
outside



Mesosphere - Sources

some UV absorption by O_3 in lower region

heat carried downward from thermosphere
(minor contribution)

Mesosphere - Sinks

infrared radiation by CO_2, O_3, H_2O, OH

Stratosphere - Sources

strong absorption of UV (2,000 - 3000 Å) by O_3
(produces peak in temperature at stratopause)

Troposphere - Sources

•absorption by planetary surface of infrared and visible radiation, and conduction to atmosphere

•atmospheric absorption of terrestrial and solar IR.

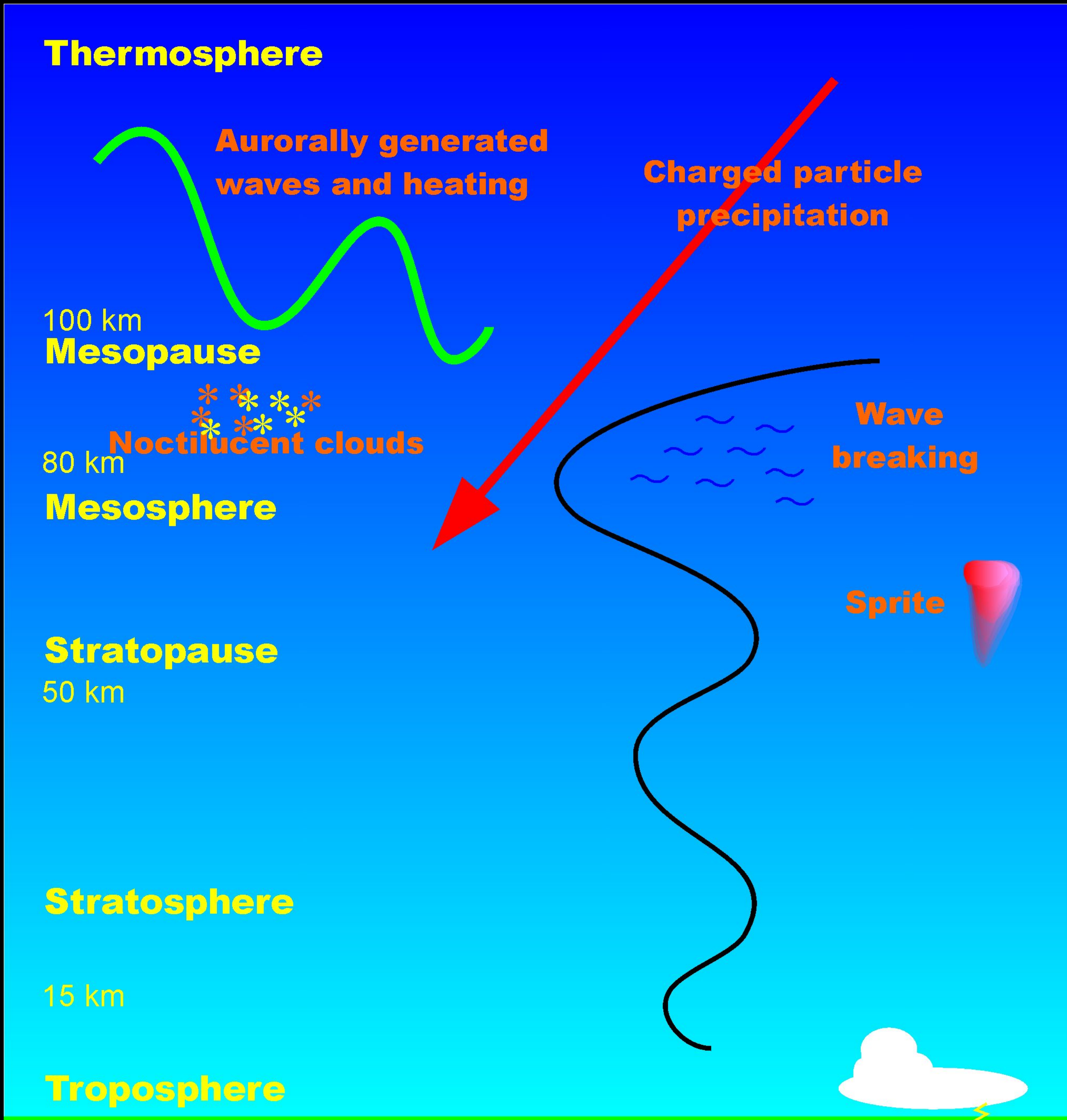
•latent heat release by water

Troposphere - Sinks (and Sources)

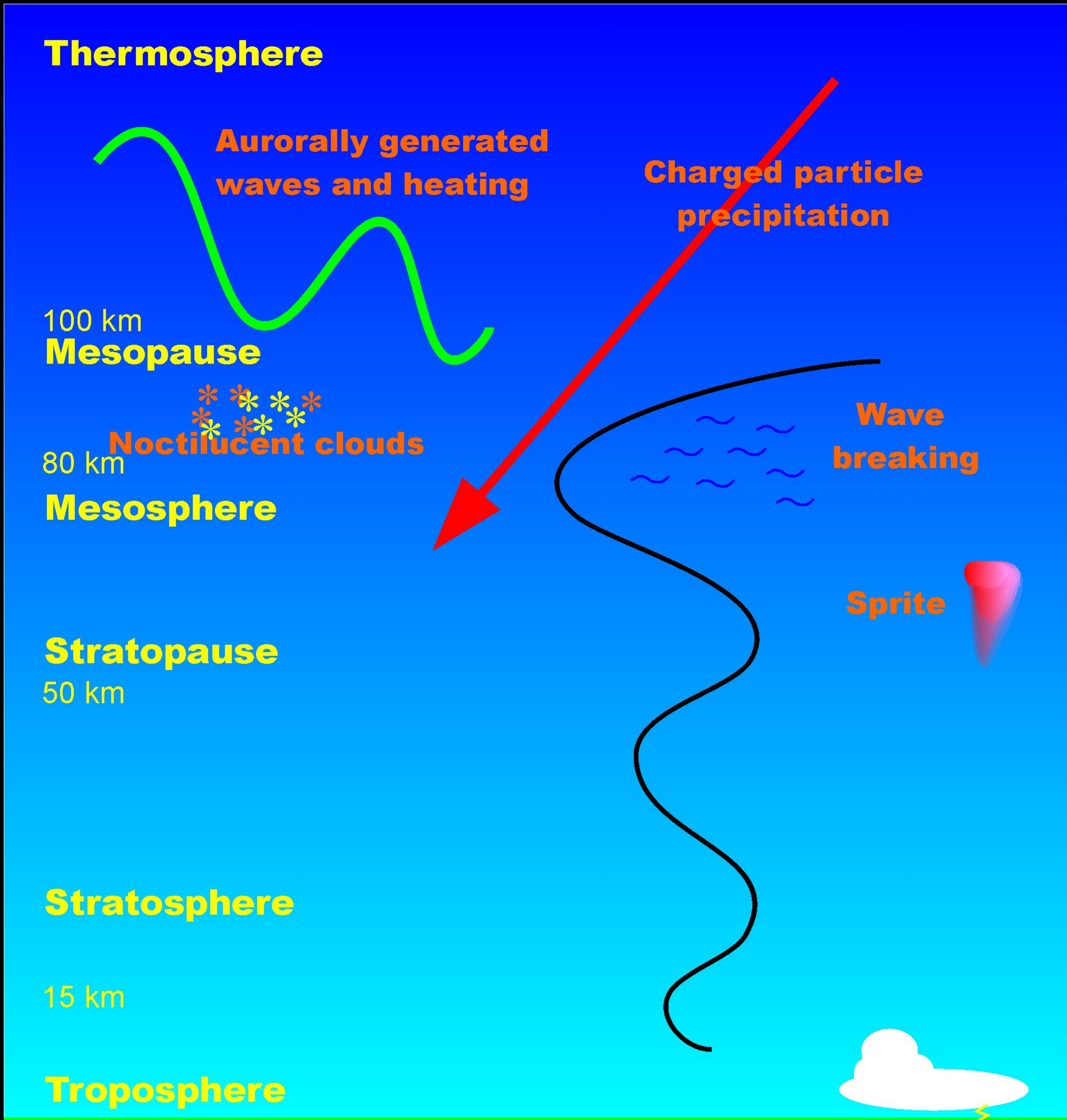
•infrared radiation by surface, atmosphere (absorption)

•evaporation of water

•thermal convection important in transporting heat between different levels



Adapted from Jarvis, Science, 2001



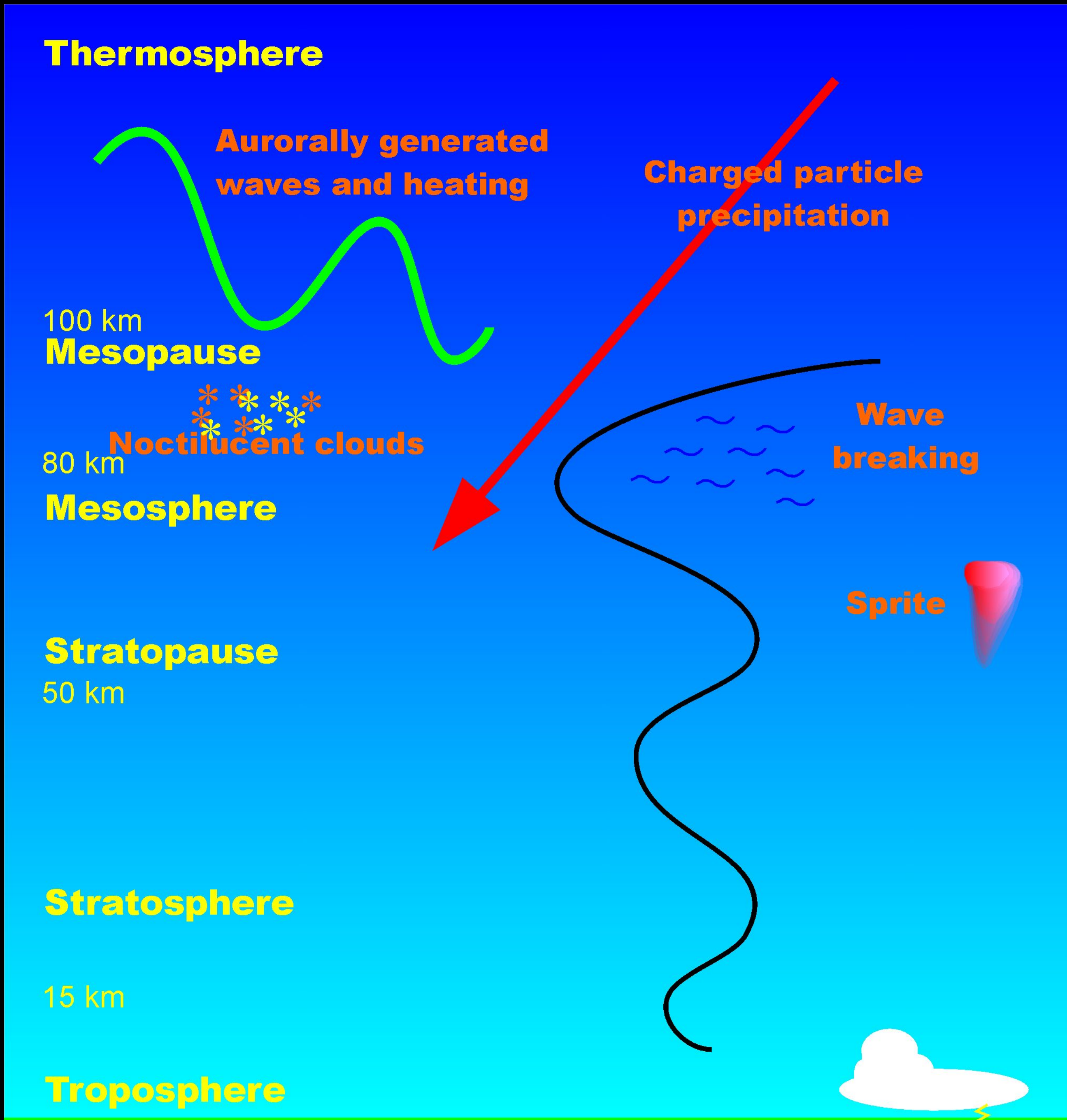
Mesopause
(85 km – 100 km)

transition between heterosphere and homosphere

transition between atmosphere and „space“

BUT: there is no clear borderline, but rather the mesosphere / lower thermosphere is a transition zone, affected from above (space) and below (ground)

Adapted from Jarvis, Science, 2001



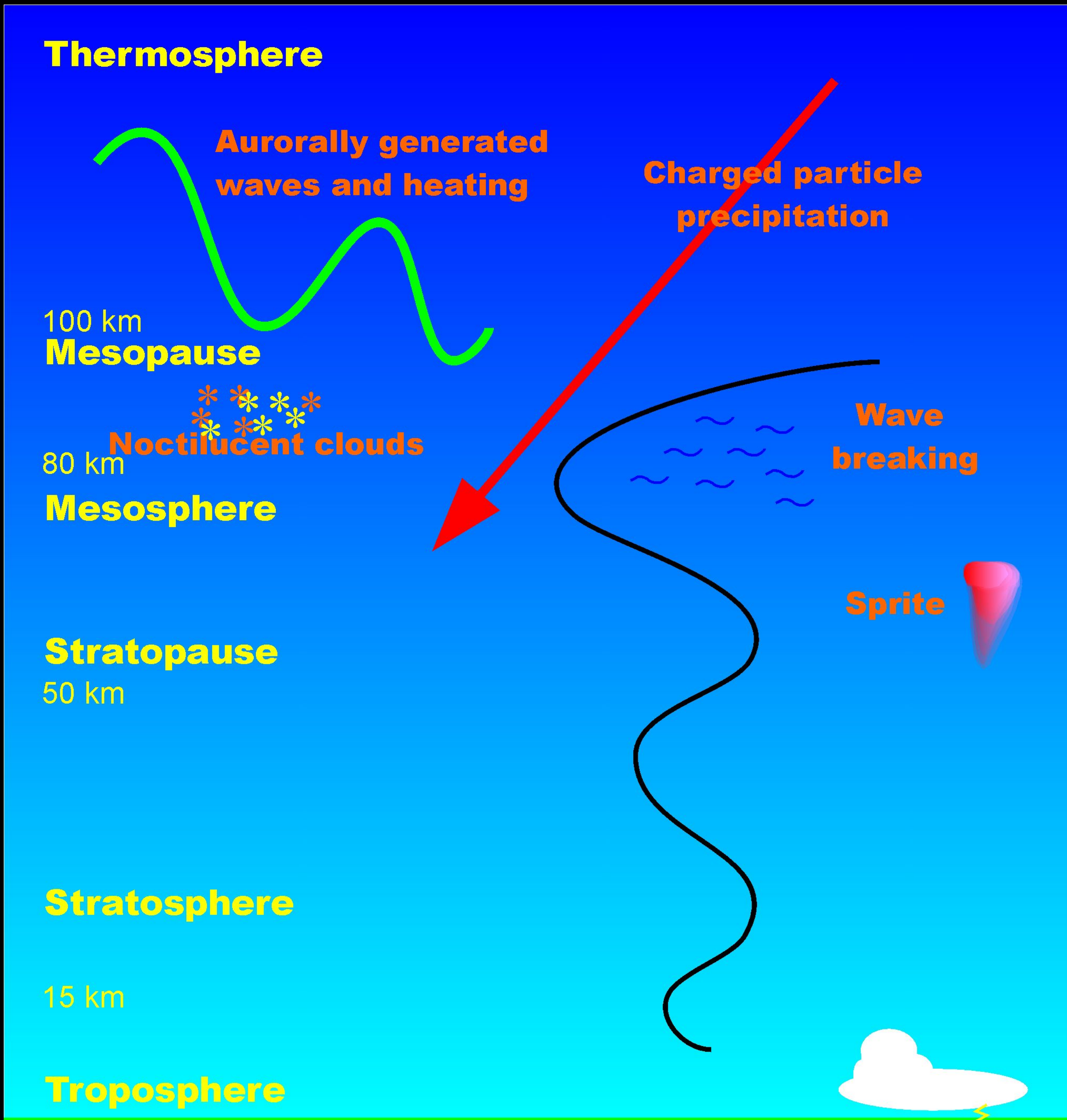
from above:

- solar radiation
- solar and magneto-spheric particles
- meteorites

from below:

- gravity waves
- sprites

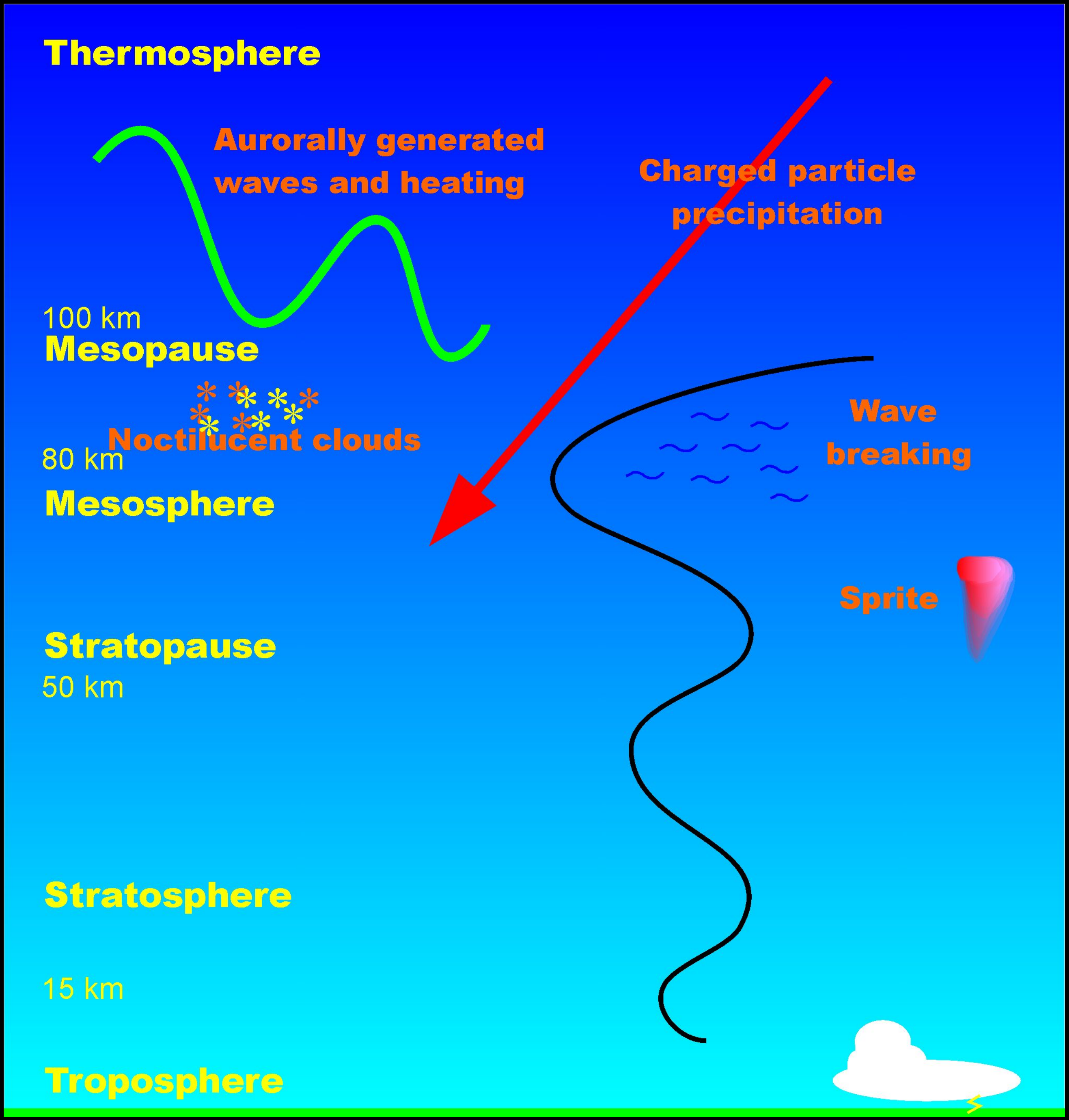
Adapted from Jarvis, Science, 2001



40 km – 150 km:
„ignorosphere“
not accessible by
in-situ measurements

40 km – 80 km
„last frontier“:
until recently not well
covered by remote
measurements

Adapted from Jarvis, Science, 2000



40 km – 150 km:
„ignorosphere"
not accessible by
in-situ measurements

40 km – 80 km
„last frontier":
until recently not well
covered by remote
measurements

UARS, since 1991

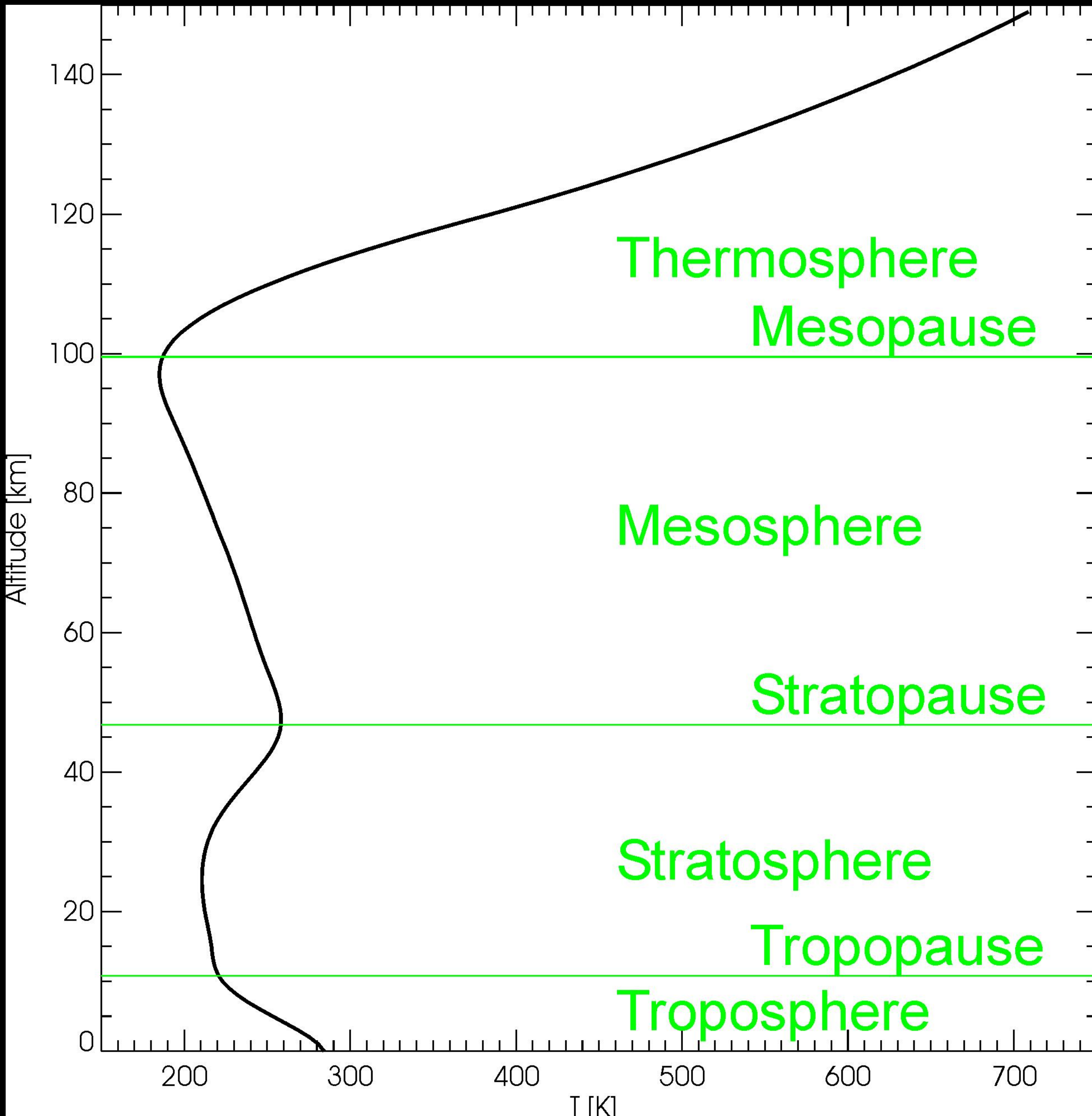
ODIN, since 2001

ENVISAT, since 2002

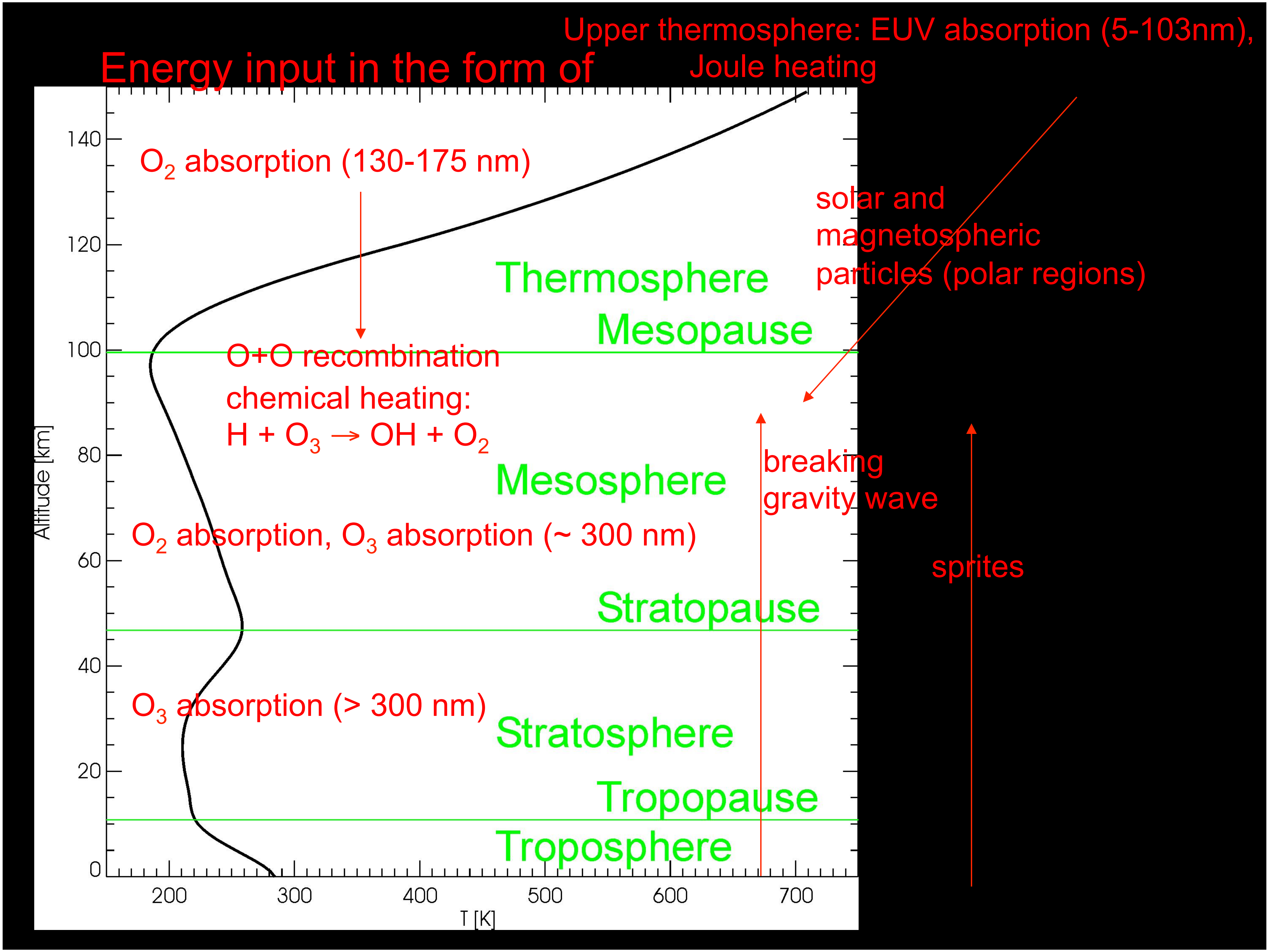
AURA, since 2004

TIMED, ???

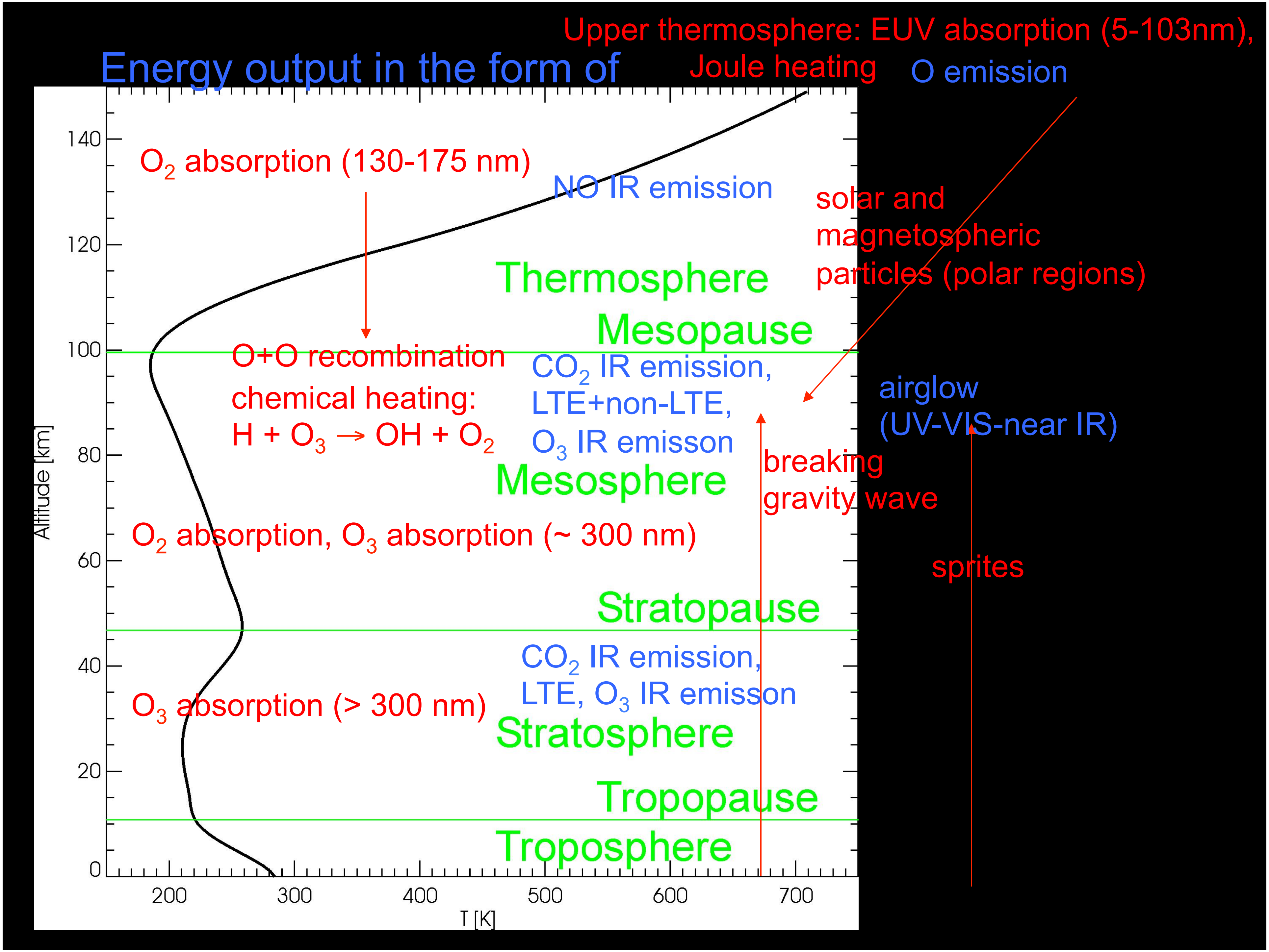
Adapted from Jarvis, Science, 2000



MSIS-90 model result for
October 25, 52°N, 8°E

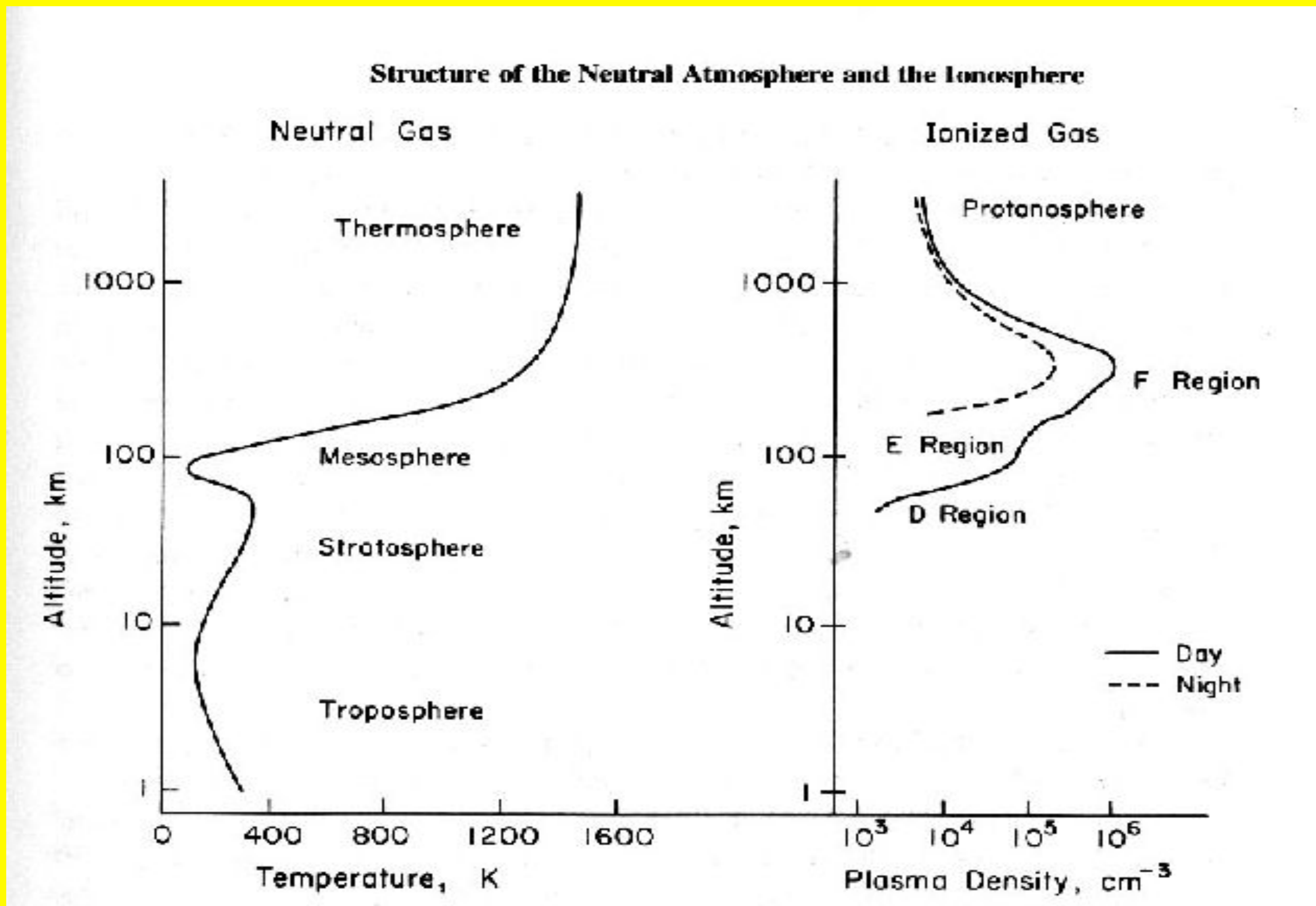


Upper thermosphere: EUV absorption (5-103nm),
Joule heating
Energy input in the form of
O_2 absorption (130-175 nm)
solar and
magnetospheric
particles (polar regions)
Thermosphere
Mesopause
O+O recombination
chemical heating:
$H + O_3 \rightarrow OH + O_2$
breaking
gravity wave
Mesosphere
O_2 absorption, O_3 absorption (~ 300 nm)
sprites
Stratopause
O_3 absorption (> 300 nm)
Stratosphere
Tropopause
Troposphere
Altitude [km]
T [K]
0
20
40
60
80
100
120
140
200
300
400
500
600
700



Upper thermosphere: EUV absorption (5-103nm),
Joule heating
O emission
Energy output in the form of
O_2 absorption (130-175 nm)
NO IR emission
solar and
magnetospheric
particles (polar regions)
Thermosphere
Mesopause
O+O recombination
chemical heating:
$H + O_3 \rightarrow OH + O_2$
CO_2 IR emission,
LTE+non-LTE,
O_3 IR emisson
airglow
(UV-VIS-near IR)
Mesosphere
breaking
gravity wave
O_2 absorption, O_3 absorption (~ 300 nm)
sprites
Stratopause
CO_2 IR emission,
LTE, O_3 IR emisson
O_3 absorption (> 300 nm)
Stratosphere
Tropopause
Troposphere
Altitude [km]
0
20
40
60
80
100
120
140
200
300
400
500
600
700
T [K]

The Two Atmospheres



Thermosphere vs. Ionosphere

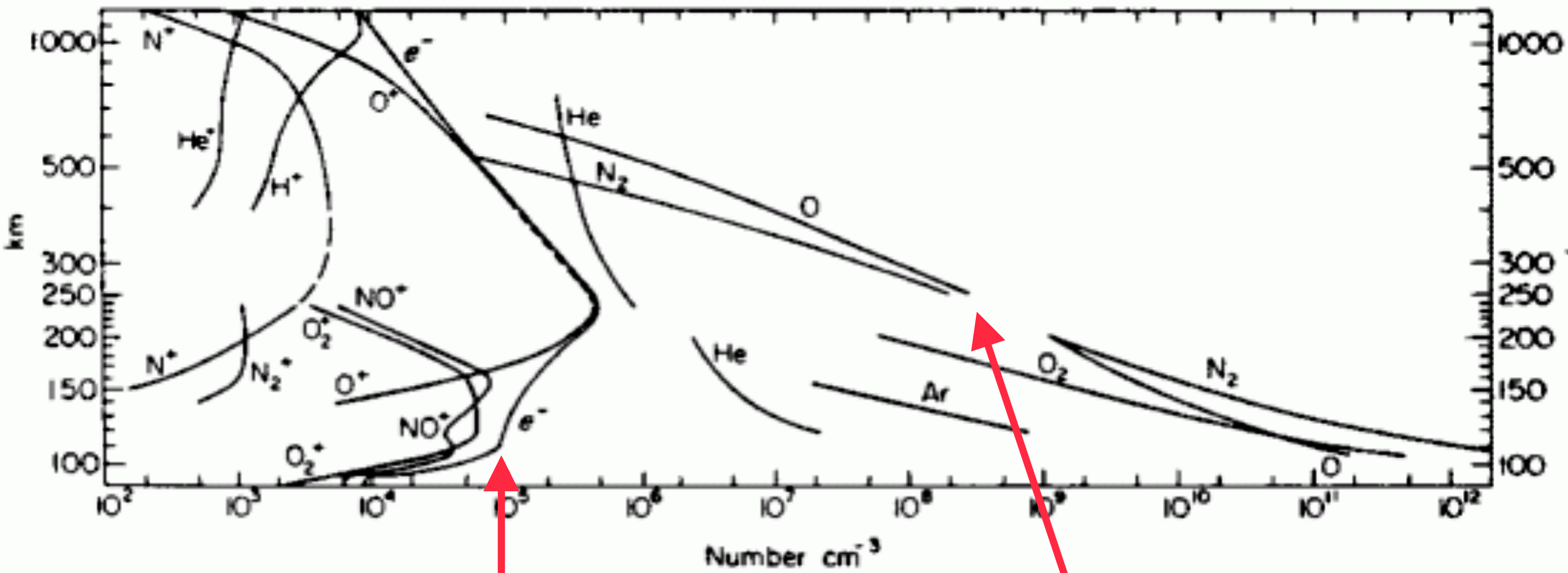
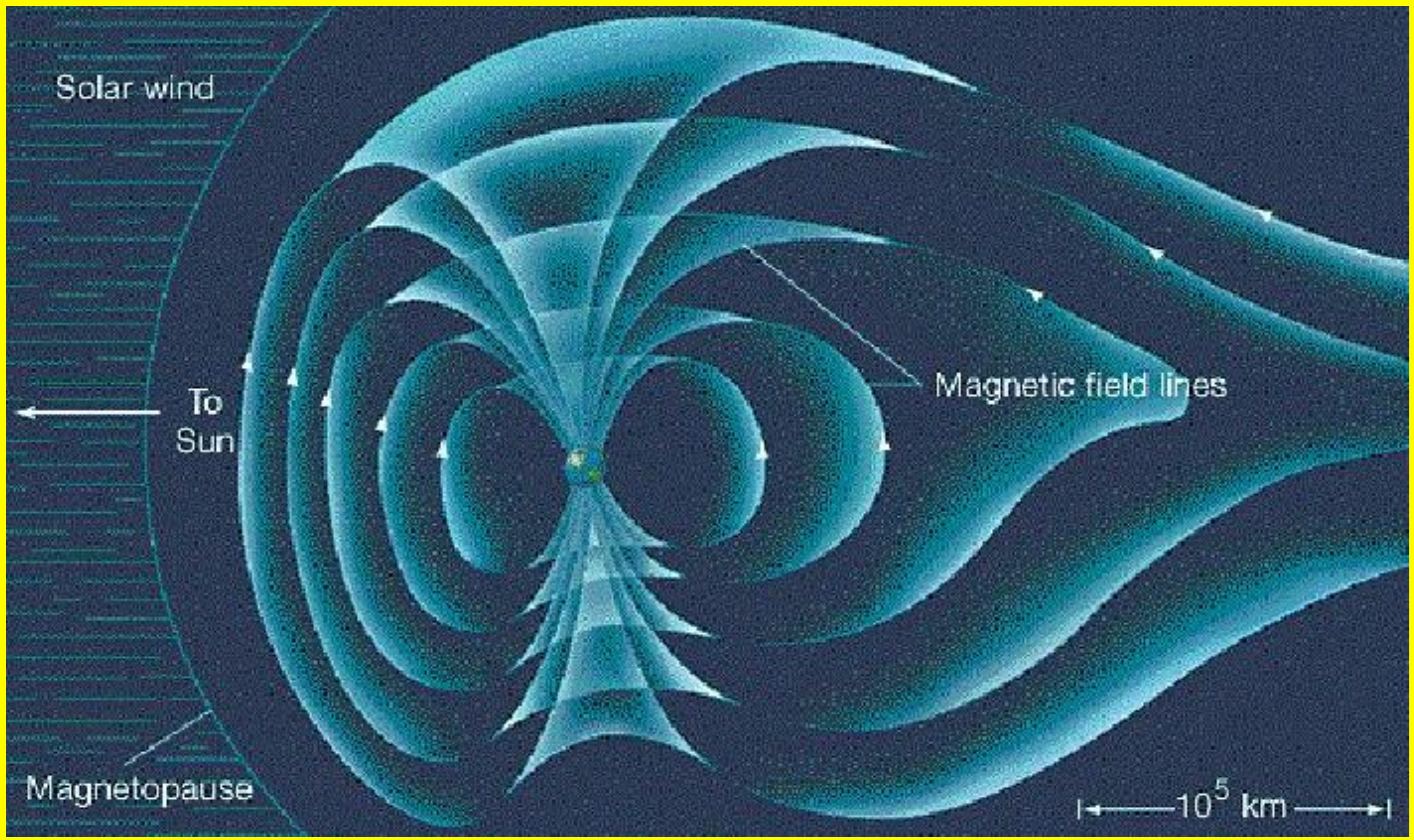


Fig. 1.2. International Quiet Solar Year (IQSY) daytime atmospheric composition, based on

Ionospheric density << Thermospheric density by ~ 1E6

What links them?



The Three[1] Key Equations

The Equation of Motion

F = mA

The Equation of Energy, aka Conservation of Energy

Heat Production + Loss + Transport = 0

The Equation of Continuity, aka Conservation of Mass

Particle Production + Loss + Transport = 0

The Equation of State

$$P = nkT = \rho RT/m = H\rho g$$

[1] *to within an order of magnitude.*

The exosphere?

The exosphere is sometimes defined as the region where the mean free path exceeds the scale height. This occurs ~ 500-600 km.

In the exosphere, escape velocities (and hence ‘production and loss’ begin to become important.

So we will ignore the exosphere here.

The Thermosphere Equations

The Equation of Motion

F = mA

Equation of Motion

- The thermosphere is collision-dominated.
- Basic equations of fluid dynamics may be used, e.g. Navier-Stokes

  (Conrad and Schunk, *JGR* **84**, 1979)
- We resort to Newtonian mechanics, F=mA, to describe the forces acting upon a packet of neutral gas and its rate of change of velocity.

Equation of Motion

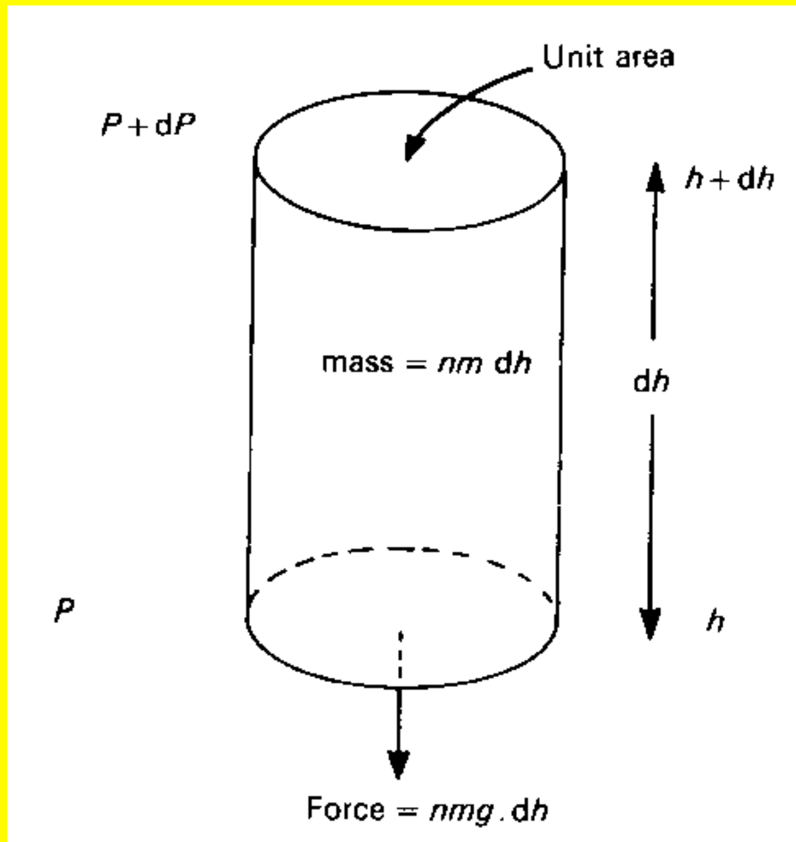
Again, taking a single packet of gas and drawing a force diagram in the Lagrangian[1] frame:

Gravity & Pressure Gradient

Coriolis effects

Ion Drag

Viscosity



[1]i.e., moving with the gas packet

Scale Height

In equilibrium and considering only gravity and the pressure gradient,

$$dP = -nmg\ dh$$

$$dP/dh = -nmg,$$

but $P = nkT$

$$1/P\ dP/dh = -mg/kT = -1/H$$

where $H = kT/mg$ is the 'scale height'

Scale Heights

Height (km) — Scale Height (km)

60	245	29.0	[illegible]	[illegible]	2.55×10[illegible]	7.35
70	173	29.0	1.96×10^{15}	9.4×10^{-8}	4.7×10[illegible]	5.21
80	168	29.0	2.84×10^{14}	1.36×10^{-8}	6.6×10[illegible]	5.08
90	176	28.8	3.9×10^{13}	1.88×10^{-9}	9.5×10^{-1}	5.35
100	208	27.8	6.0×10^{12}	2.8×10^{-10}	1.74×10^{-1}	6.54
120	390	26.1	6.3×10^{11}	2.9×10^{-11}	3.4×10^{-2}	13.1
140	662	24.5	1.07×10^{11}	4.7×10^{-12}	1.04×10^{-2}	24.0
160	926	23.7	4.0×10^{10}	1.52×10^{-12}	5.1×10^{-3}	34.8
180	1115	22.8	2.0×10^{10}	7.7×10^{-13}	3.1×10^{-3}	43.6
200	1230	22.0	1.07×10^{10}	4.2×10^{-13}	1.95×10^{-3}	50.2
220	1305	21.2	6.6×10^{9}	2.7×10^{-13}	1.20×10^{-3}	55.3
240	1356	20.6	4.6×10^{9}	1.70×10^{-13}	8.5×10^{-4}	60.0
260	1400	20.0	3.3×10^{9}	1.12×10^{-13}	6.4×10^{-4}	63.8
280	1430	19.5	2.35×10^{9}	7.9×10^{-14}	4.7×10^{-6}	67.0
300	1455	19.1	1.82×10^{9}	5.7×10^{-14}	3.6×10^{-4}	70.6
320	1472	18.7	1.32×10^{9}	4.3×10^{-14}	2.7×10^{-4}	73.0
340	1485	18.4	1.00×10^{9}	3.1×10^{-14}	2.04×10^{-4}	75.6
360	1491	18.0	7.6×10^{8}	2.3×10^{-14}	1.54×10^{-4}	77.8
380	1496	17.8	5.9×10^{8}	1.78×10^{-14}	1.23×10^{-4}	79.9
400	1500	17.5	4.7×10^{8}	1.38×10^{-14}	9.8×10^{-5}	81.8
450	1500	17.0	2.5×10^{8}	7.2×10^{-15}	5.2×10^{-5}	85.7
500	1500	16.6	1.44×10^{8}	4.1×10^{-15}	2.9×10^{-5}	88.6
600	1500	16.3	4.8×10^{7}	1.32×10^{-15}	1.00×10^{-5}	93.1
700	1500	16.1	1.70×10^{7}	4.6×10^{-16}	3.5×10^{-6}	97.0
[illegible]	[illegible]					

Equation of Motion

Acceleration = Force / unit mass

$$\frac{D}{Dt}\mathrm{U} = g \underbrace{- \frac{1}{\rho}\nabla p}_{\text{pressure gradient}} \underbrace{- 2\Omega \wedge \mathrm{U}}_{\text{Coriolis forcing}} \underbrace{- \upsilon_{ni}(\mathrm{U} - \mathrm{V})}_{\text{ion drag}} \underbrace{+ \frac{1}{\rho}\nabla(\mu \nabla \mathrm{U})}_{\text{viscosity}}$$

$U, \rho, p, \nu_{ni} =$ gas velocity, density, pressure, and the neutral-ion collision freq.

Ω = Earth's angular rotation; V = ion velocity; and μ = viscosity coefficient, g=gravity

Equation of Motion

- Convert from Lagrangian frame to Eulerian[1] frame by means of a transform:

$$\underbrace{\frac{D}{Dt}X}_{\substack{\text{rate of change of X} \\ \text{(a gas parameter)} \\ \text{in the packet of gas}}} = \underbrace{\frac{\partial}{\partial t}X}_{\substack{\text{rate of change of X} \\ \text{at a fixed point on} \\ \text{the Earth's surface}}} + \underbrace{(V.\nabla)X}_{\substack{\text{advection} \\ \text{term}}}$$

[1] i.e. in the frame of the Earth.

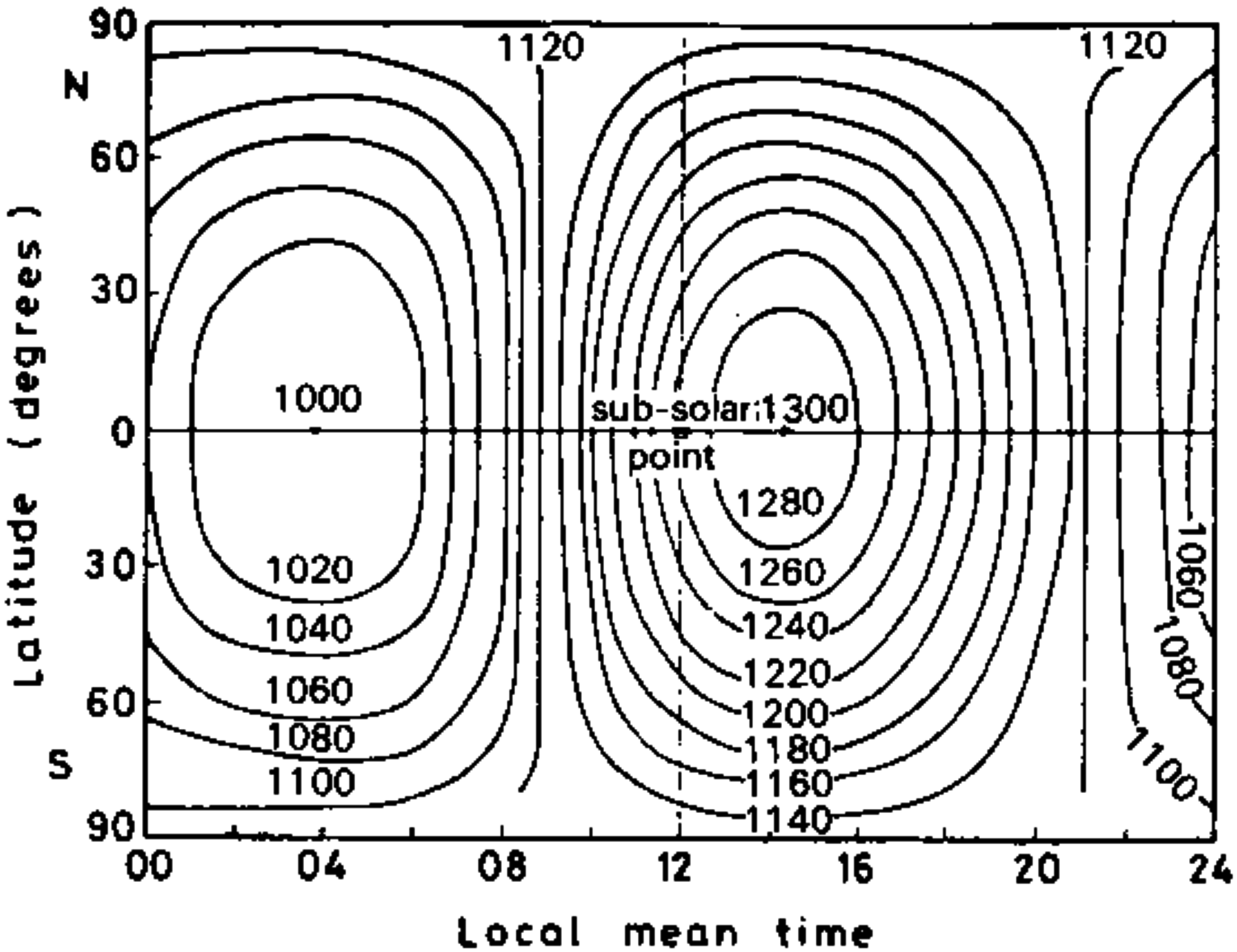
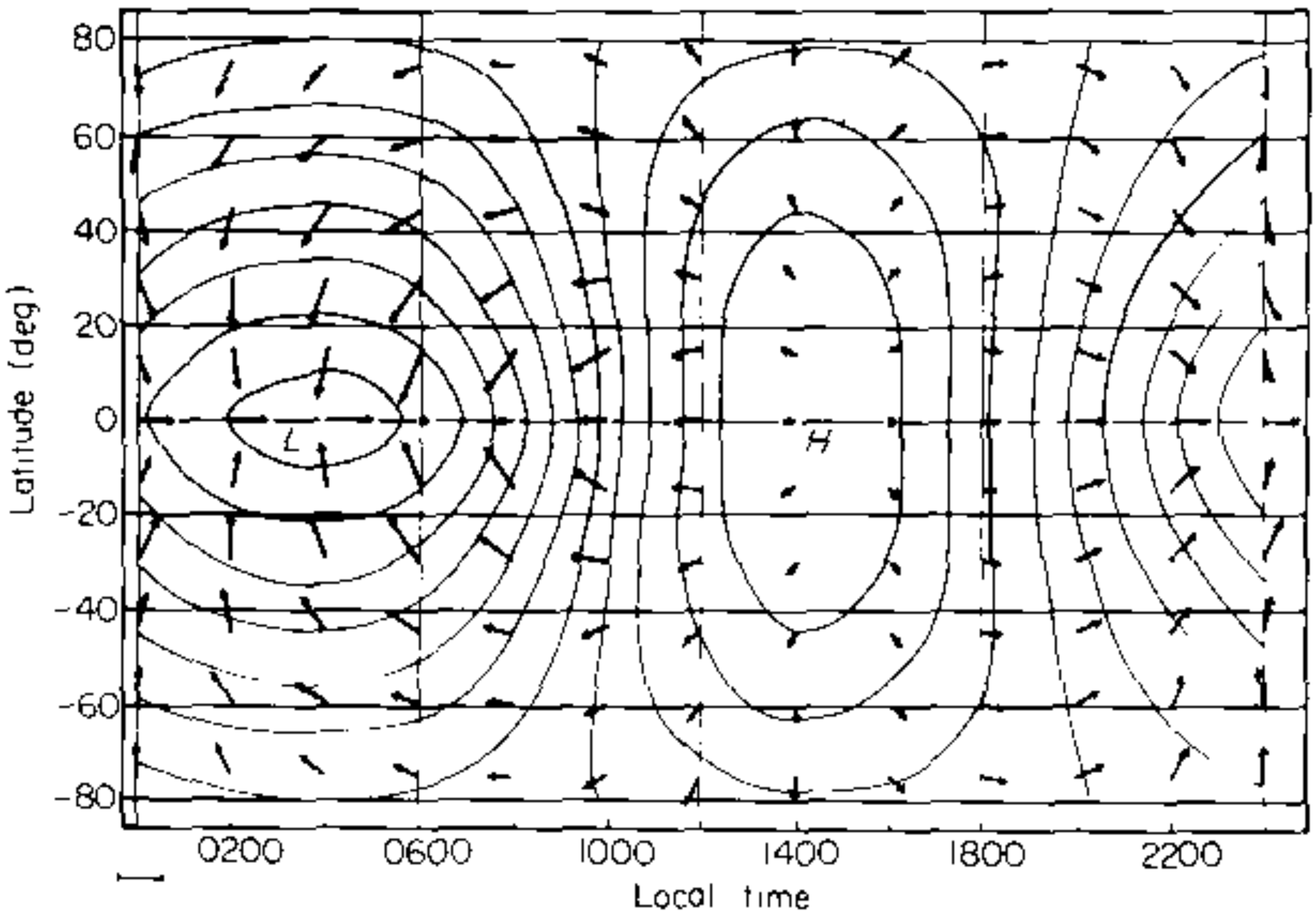


Fig. 4.18 Global temperature distribution in the thermosphere (in K) at the equinox in conditions of medium solar activity. No account is taken of any high-latitude sources of heat, such as energetic particles. (After H. Kohl and J. W. King, *J. Atmos. Terr. Phys.* **29**, 1045, copyright (1967) Pergamon Press PLC; data from J. G. Jacchia, *Smithsonian Contrib. Astrophys.* **8**, 215, 1965)

Thermal Winds



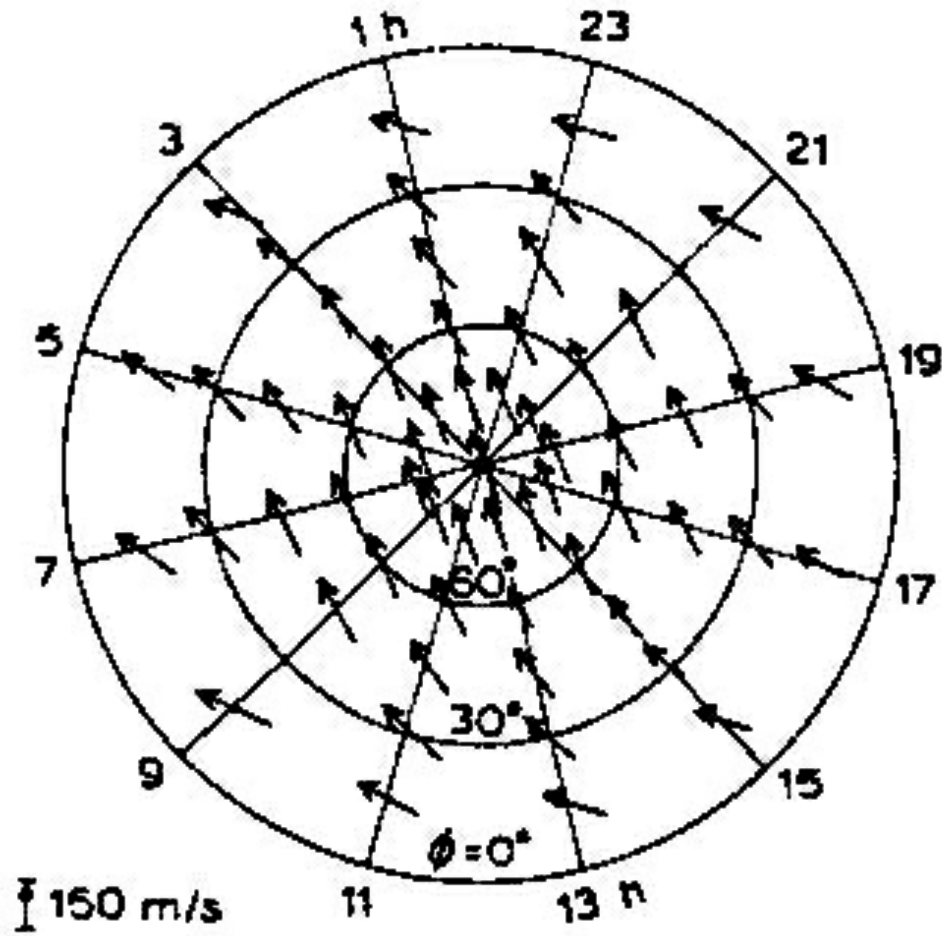


Fig. 4.19 Winds at 300 km, computed from the temperature distribution of Fig. 4.18.

The Thermosphere Equations

The Equation of Motion

F = mA

The Equation of Energy, aka Conservation of Energy

→ **Heat Production + Loss + Transport = 0**

The Equation of Continuity, aka Conservation of Mass

Particle Production + Loss + Transport = 0

The Equation of State

P = nkT

Energy Equation

Heat Source Mechanism:

Absorption of Solar UV/EUV/soft X-ray radiation on the dayside

- Photodissociation e.g. $O_2 + h\upsilon \rightarrow O + O$
- Ionisation e.g. $NO + h\upsilon \rightarrow NO^+ + e^-$

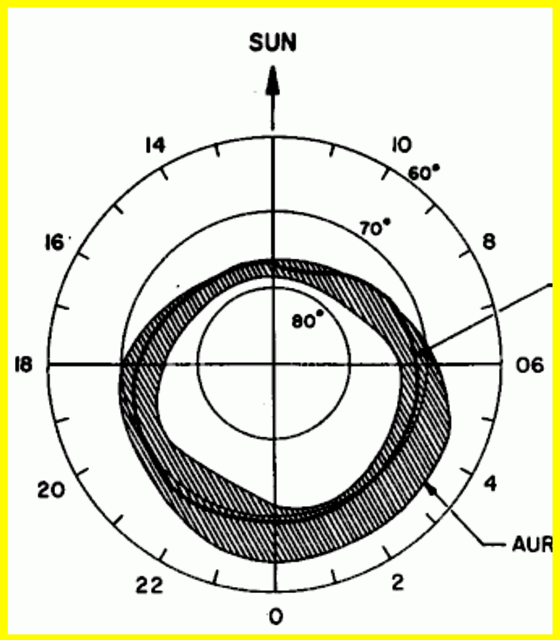
Secondary local heating from excess energy:,
e.g. vibrational, rotational, elastic collision, etc

Energy Equation

Heat Source Mechanism:

Energetic charged particles injected from the magnetosphere

- Mostly electrons
- Spiralling down 'open' magnetic field lines around auroral oval



Energy Equation

Heat Source Mechanism:

Joule Heating and Lorentz Forcing

- Ions accelerated by crossed E and B fields (right hand rule)
- Joule heating: macroscopic motions of ions and neutrals do not coincide → frictional heating
- Lorentz Forcing: microscopic motions of ions and neutrals do not coincide → collisional momentum transfer

Energy Equation

Heat Source Mechanism:

Wave Dissipation

Waves from a variety of sources will dissipate through turbulence, viscosity, resonance, etc. Possible sources of wave dissipation are:

- Thermospheric Tides
- Gravity Waves aka Atmospheric Gravity Waves aka Travelling Atmospheric Disturbances
- MHD waves

Energy Equation

Loss Mechanism:

Radiation

The principal mechanism of thermospheric heat loss.

- Auroral (spectral, e.g. N_2 and N_2^+ molecular emissions and Oxygen lines @ 630 nm and @557 nm)
- Airglow (e.g. O, OH)

Energy Equation

Heat Transfer Mechanism:

Molecular Conduction

- Thermospheric temperature becomes asymptotic > 400 km due to rapid thermal conductivity
- Heat flux $\propto$ temperature gradient, $\Phi \propto \nabla T$

Energy Equation

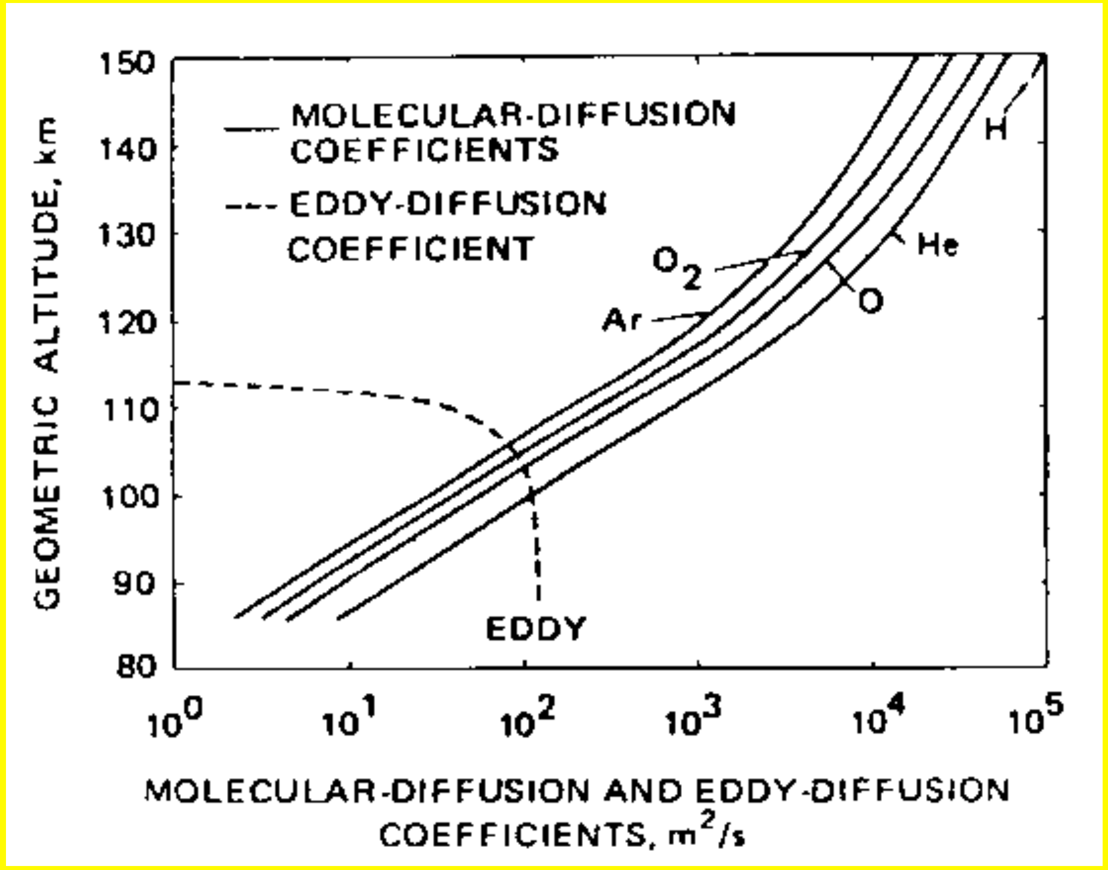
Heat Transfer Mechanism:

Eddy Transport

- Important (dominant) below turbopause
- Transports heat down to mesosphere ~ 50 km

Energy Equation

Diffusion Coefficients



Energy Equation

Heat Transfer Mechanism:

Winds (Advection)

- Neutral winds will transport energy
- Chemical transport by neutral winds will allow species to be created by, e.g. dissociation, and moved elsewhere before recombination

Energy Equation

We take a single packet of gas and examine its energy (density):

$$\varepsilon = \underbrace{\overbrace{c_P}^{\text{specific heat at constant pressure}} T}_{\text{internal energy}} + \underbrace{\frac{V^2}{2}}_{\text{kinetic energy}}$$

Energy Equation

Rate of change of energy (density) of single packet of gas is given by:

$\partial\varepsilon/\partial t$ = Heat source rate

+ Heat loss rate

+ Heat transport rate

The Thermosphere Equations

The Equation of Motion

F = mA

The Equation of Energy, aka Conservation of Energy

Heat Production + Loss + Transport = 0

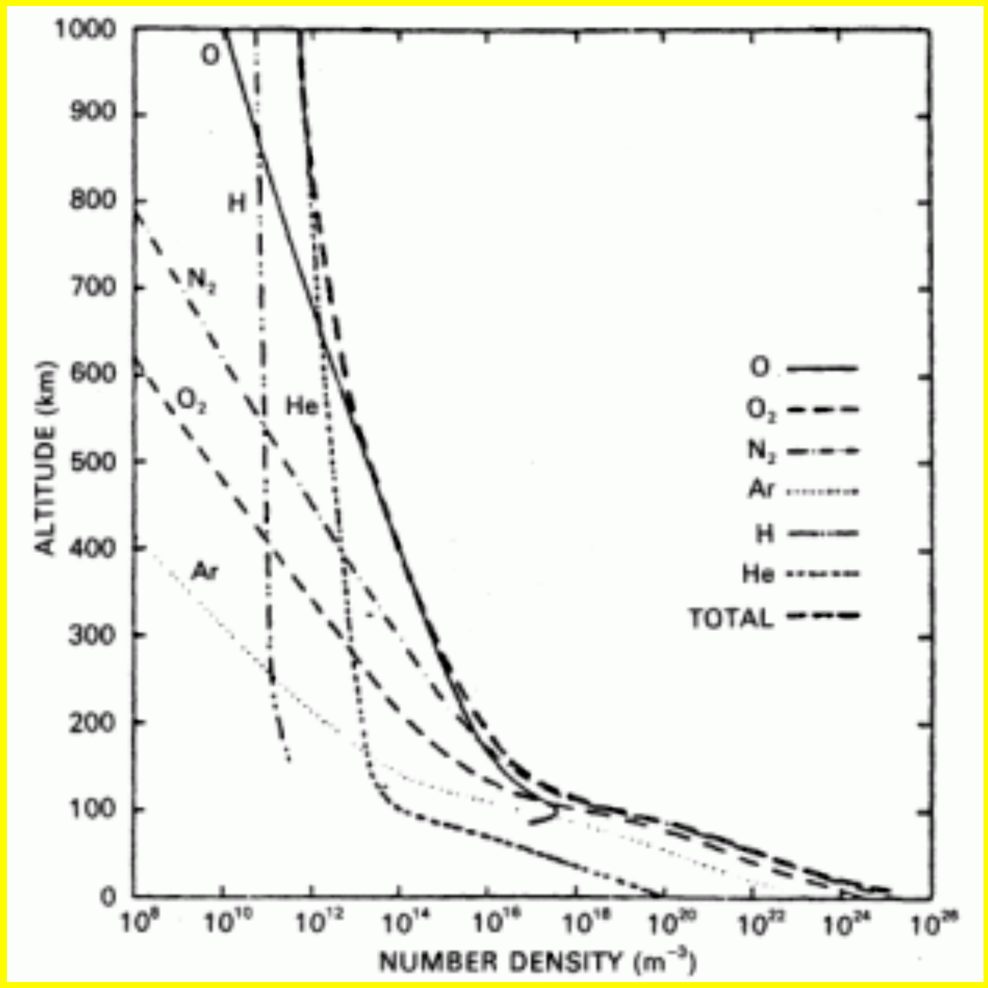
The Equation of Continuity, aka Conservation of Mass

→ **Particle Production + Loss + Transport = 0**

The Equation of State

$P = nkT = \rho RT/m = H\rho g$

Thermosphere species



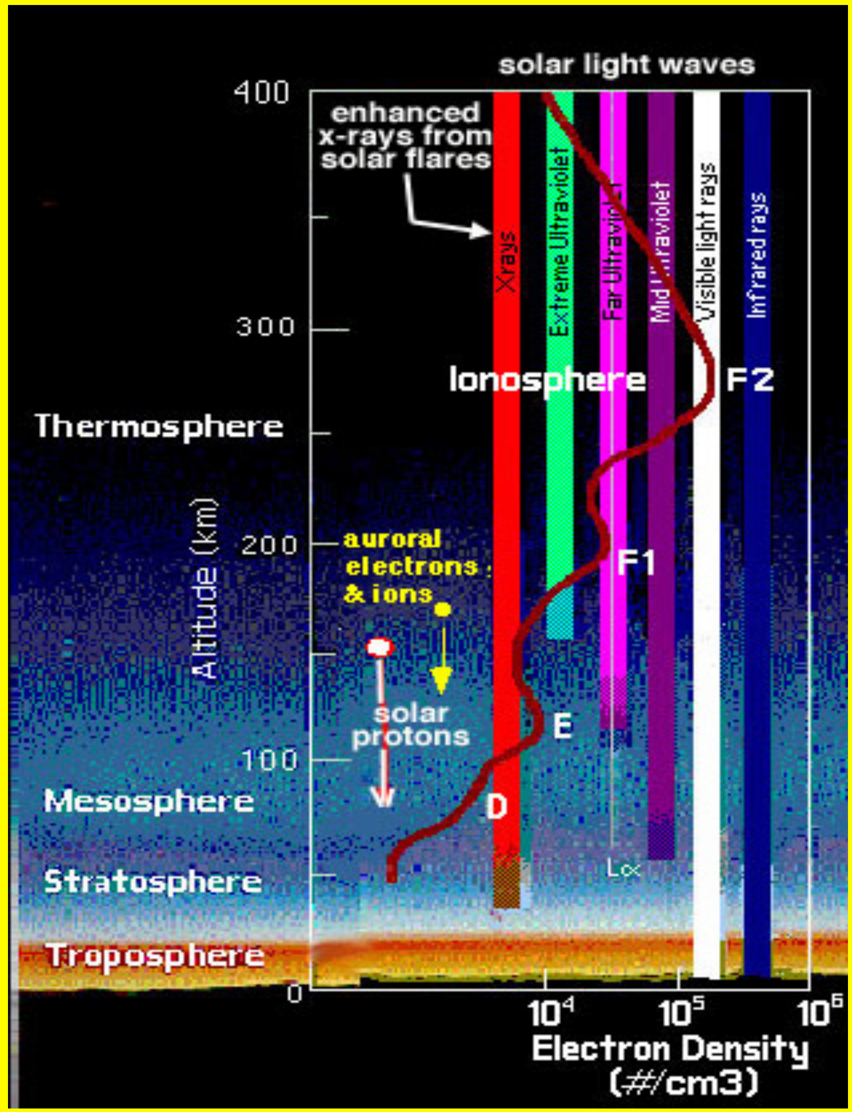
Major species

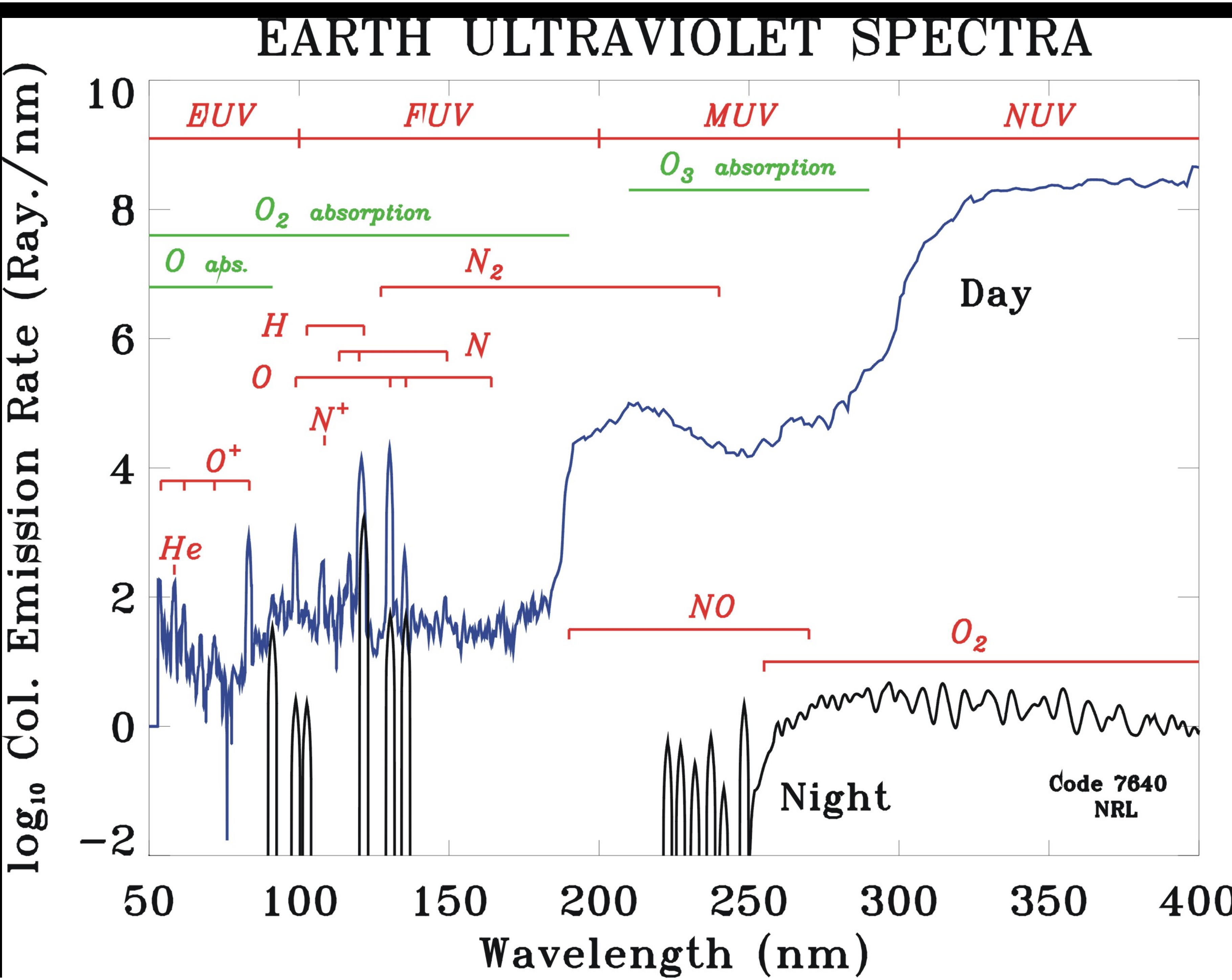
- O, O_2, N_2, Ar, He, H

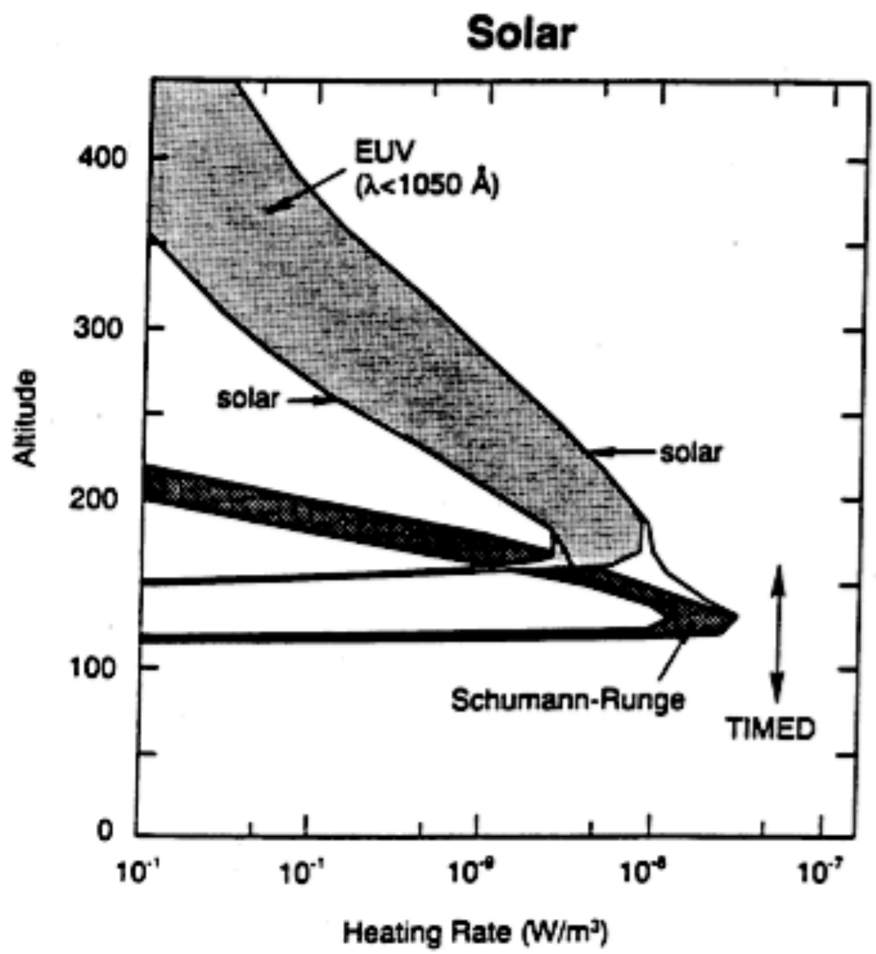
Minor species

- NO – significant in cooling

Solar Radiation Absorption



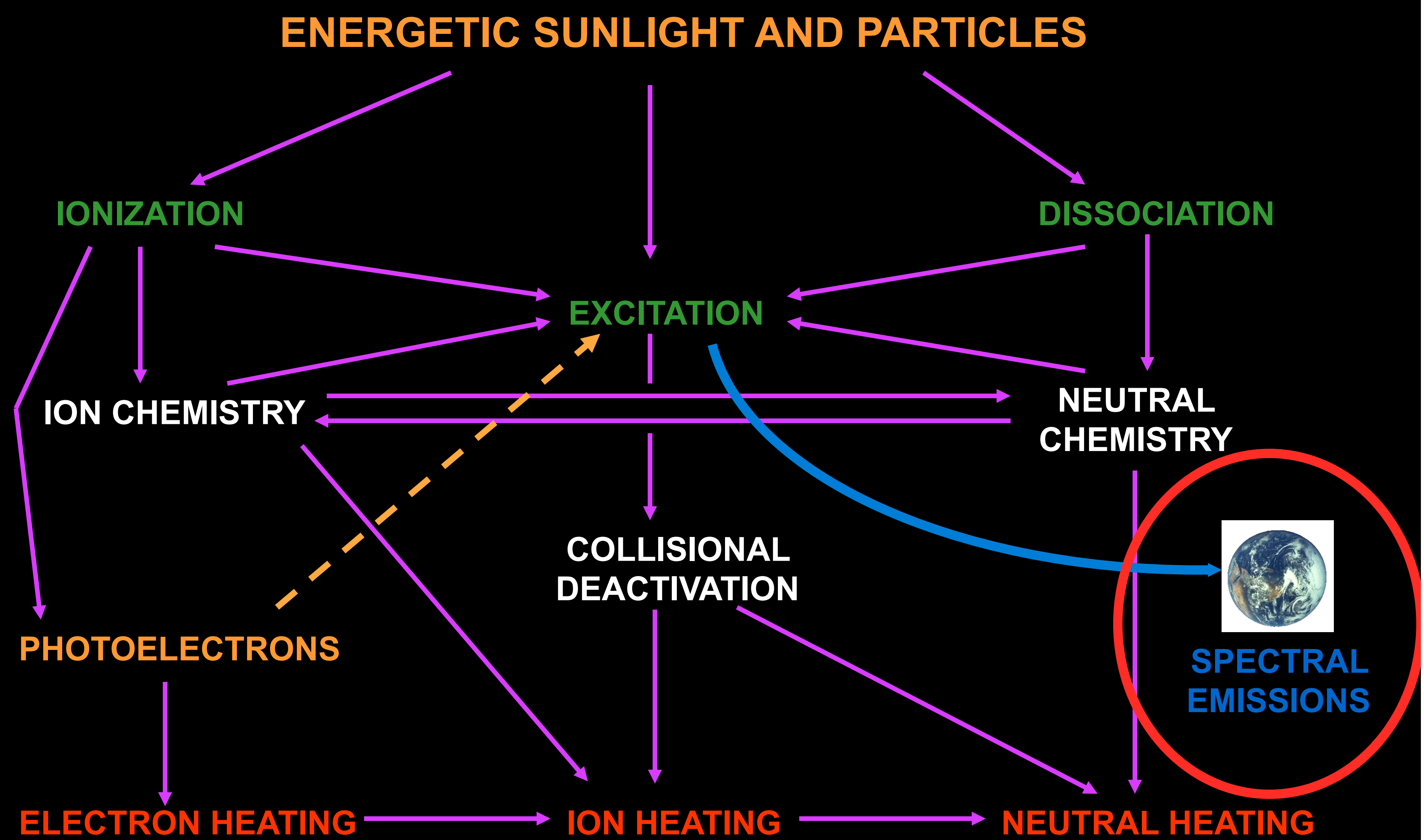

EARTH ULTRAVIOLET SPECTRA
$\log_{10}$ Col. Emission Rate (Ray./nm)
Wavelength (nm)
EUV
FUV
MUV
NUV
O_3 absorption
O_2 absorption
O aps.
N_2
H
N
O
N^+
O^+
He
Day
NO
O_2
Night
Code 7640
NRL
10
8
6
4
2
0
−2
50
100
150
200
250
300
350
400



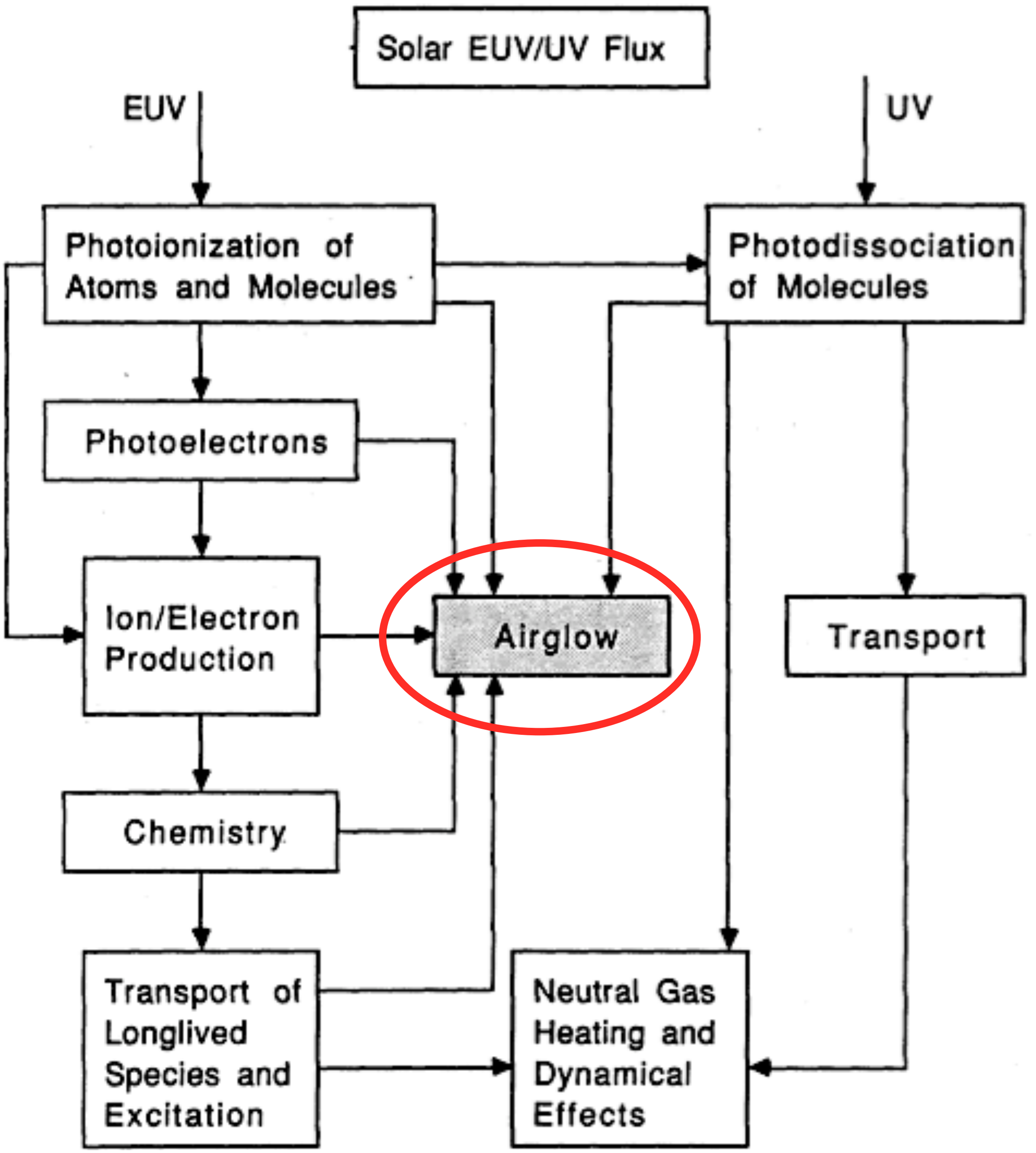
Altitudinal profiles of heating rates due to solar EUV and UV absorption. The shaded regions indicate the range of variations with solar activity. The TIMED Mission investigates the region of maximum energy deposition.

EUV portion of solar spectrum particularly variable

Solar Energy in the Upper Atmosphere



BASIC THERMOSPHERIC PHOTOCHEMISTRY



Photochemical systems (complicated!)

- Major species (O, O_2, N_2)
- Reservoir molecules (H_20, H_2)
- Metastable neutrals
- Permitted excited states
- Odd hydrogen family
- Odd oxygen family
- Odd nitrogen family
- Metallic neutrals and ions
- Major and minor ionic species
- Metastable ions
- Cluster ions
- Tracer species

Brief Historical Outline

1868 Anders Angstrom discovers green line is present in the night sky even when no aurorae are present

1920's Robert John Strutt (4th Baron Rayleigh) begins investigations [Note: he is referred to as the "airglow Rayleigh"; his father John William Strutt, 3rd Baron Rayleigh, is the "scattering Rayleigh"]

1923 John McLennon & G.M. Shrum identify green line to be due to atomic oxygen

1929 Vesto Melvin Slipher discovers sodium layer (a contribution to airglow)

1931 Sydney Chapman suggests airglow is result of chemical recombination

1939 Chapman suggests reaction cycle to sustain sodium nightglow

1950 term "airglow" coined after other atmospheric emissions are identified

1956 SAR arc discovered by Barbier over France

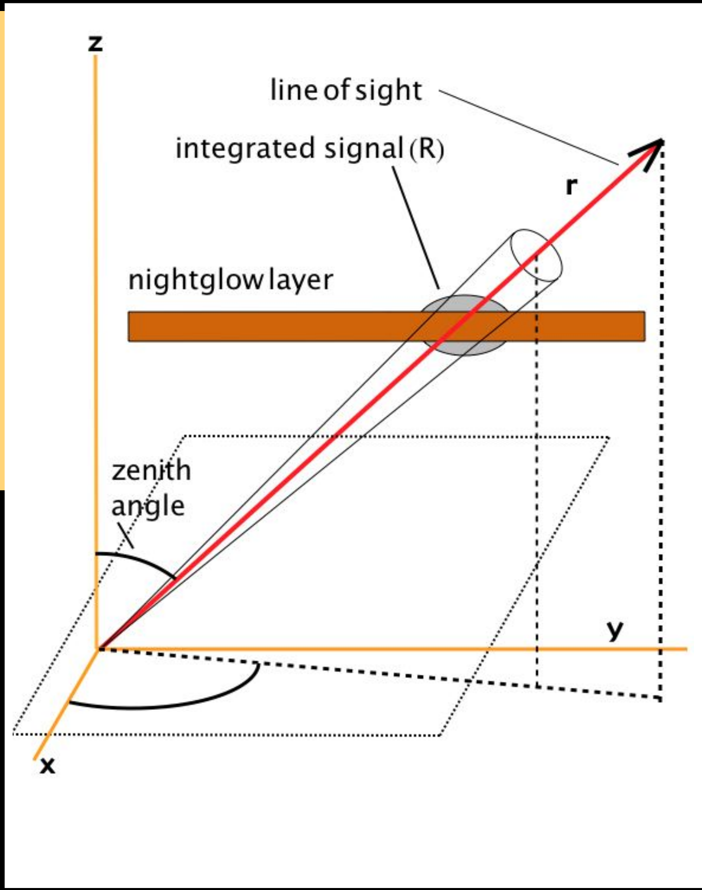
The Rayleigh is a unit of surface brightness

1 R $=10^{10}$ photons/(m^2column)/sec/ster or

$1.58\times10^{-11}/\lambda$ W (cm^2column)/sec/ster

where λ is the wavelength in nm.

The surface brightness for an extended source is independent of the distance of the observer and is represented by the column (of unit cross section) integration of the omni-directional volume emission rate within the extended airglow layer.



Typical airglow brightnesses 10-300 R

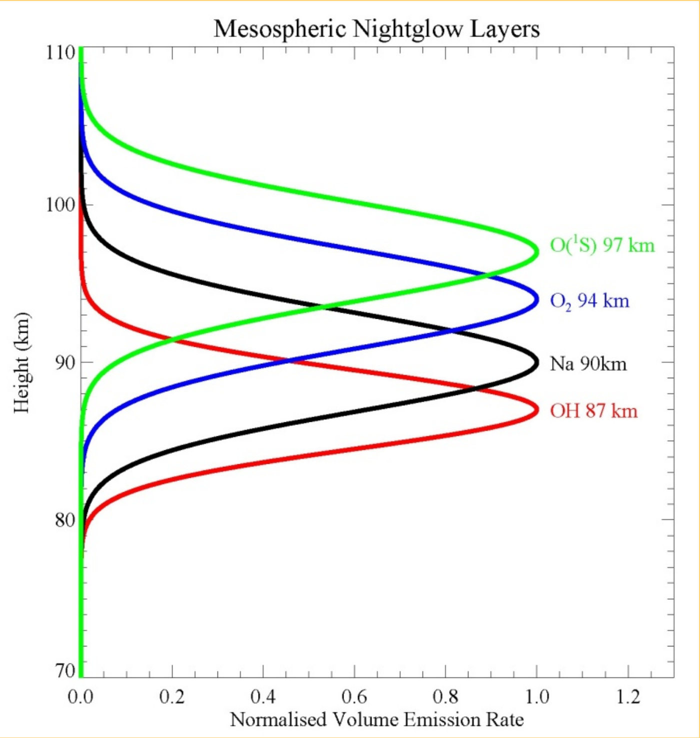
auroral 1-100 kR

The airglow and aurora observed from space

Another example of airglow and aurora

All-sky imager measurements in the mesosphere : GWs, Bores

Typical Airglow emissions in the mesosphere:

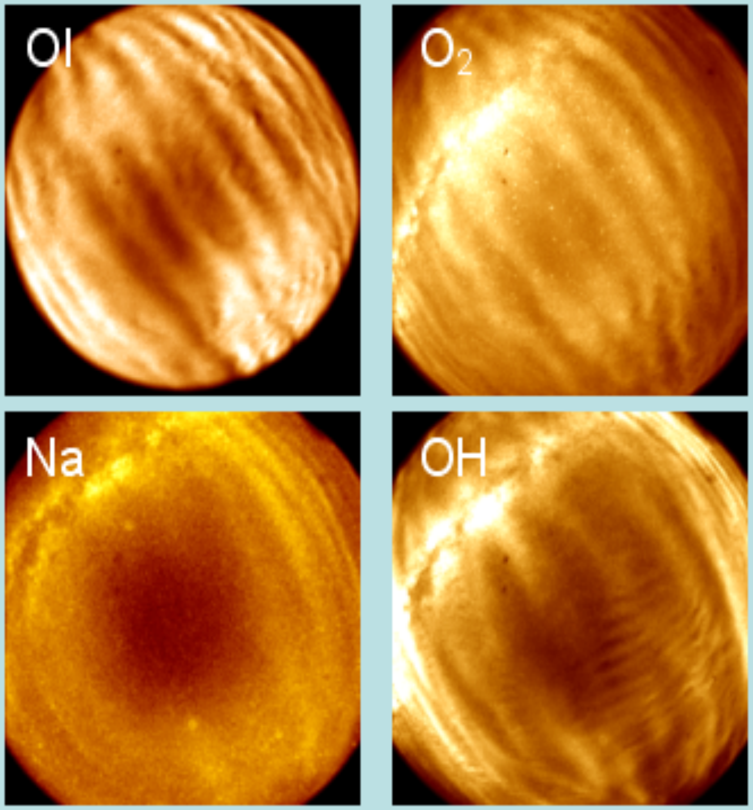


1. **Hydroxyl (OH).** Numerous Meinel bands range from visible to the infrared.

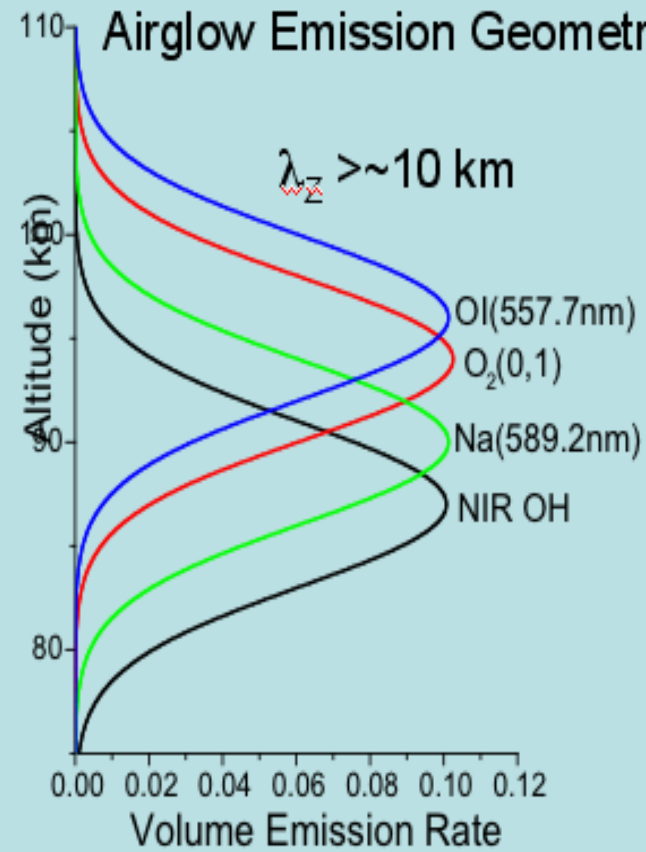
2. **Neutral Sodium (Na).** Line doublet 589.0 & 589.6 nm.

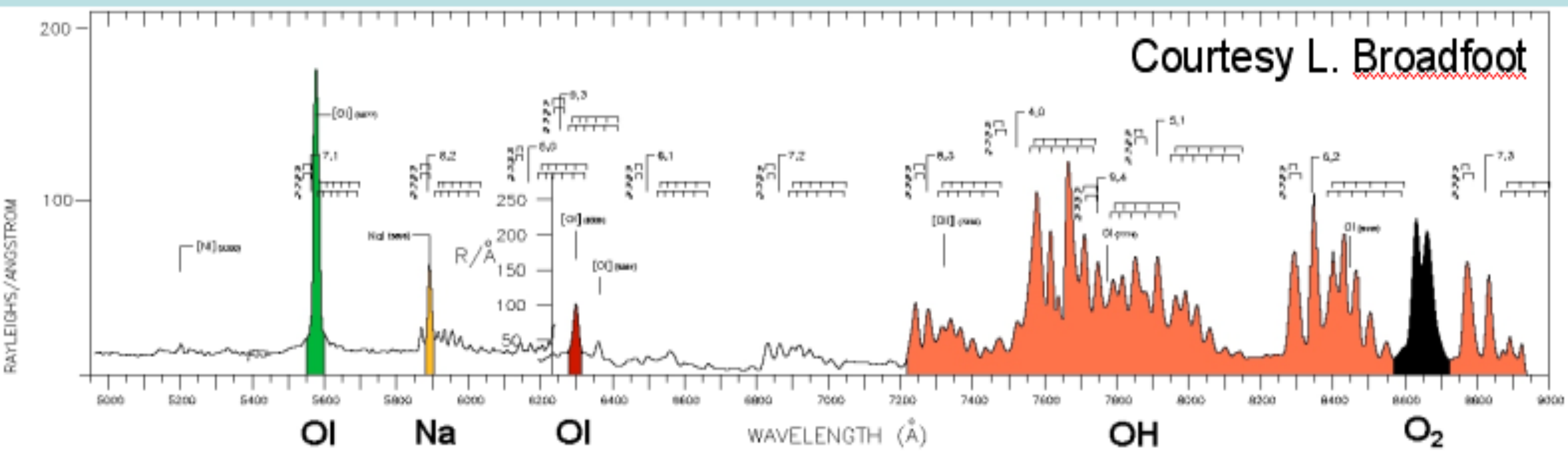
3. **Molecular Oxygen (O2).** O_2(0-1) band is centered at 866.0 nm.

4. **Neutral atomic oxygen ($O(^1S)$).** Line at 557.7 nm.
Most comes from the mesosphere near 96 km via the three-body Barth reaction



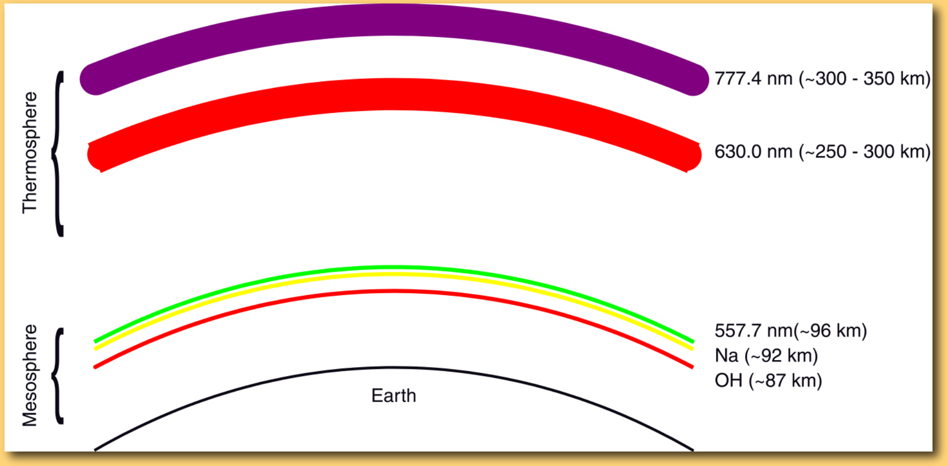
Bear Lake Obs. June 4-5, 2002

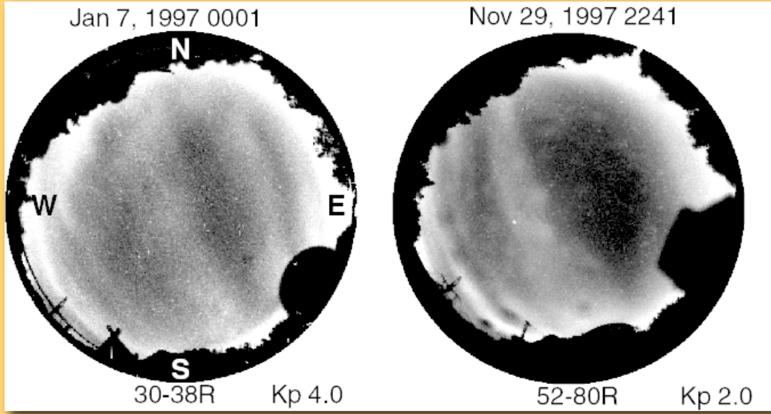




Airglow Measurements

λ_c (nm)	Emission	Applications
541.0	Background	Background sky emissions
557.7	Greenline	Mesospheric studies Equatorial spread-F
589.0	Sodium	Mesospheric studies Meteor trail studies
630.0	Redline	Thermospheric studies Equatorial spread-F
777.4	Near IR	Thermospheric studies Equatorial spread-F
882.8	Broadband OH	Mesospheric Studies





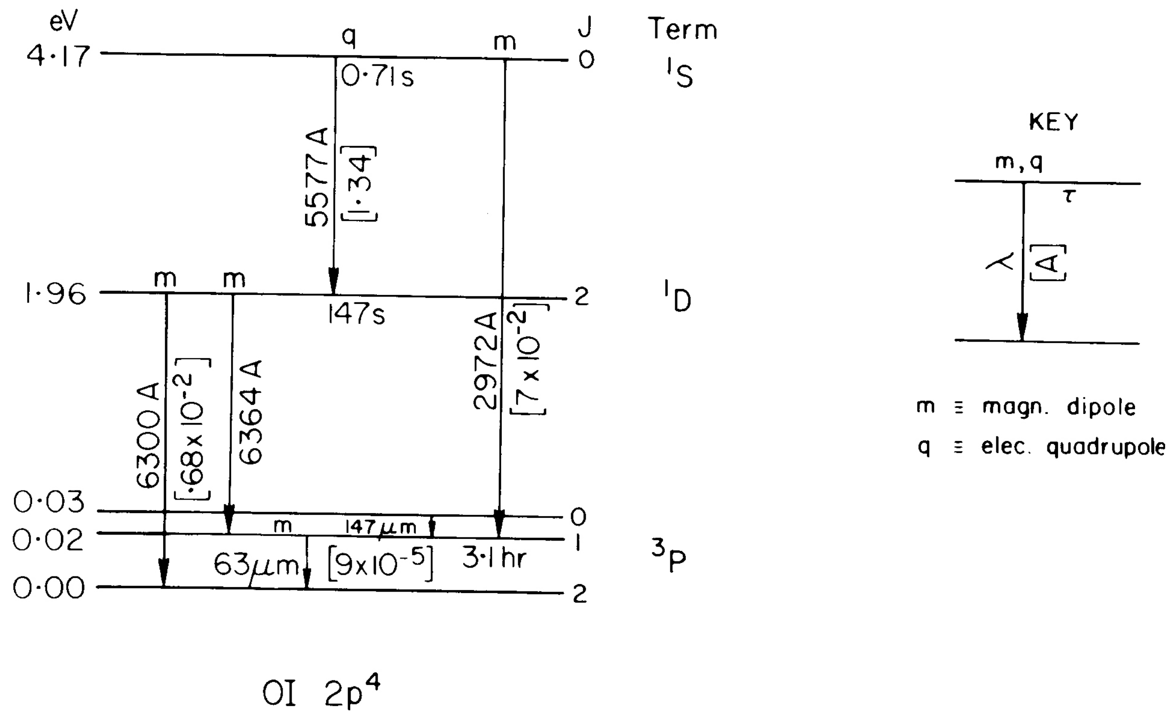


Fig. 6.3 Ground configuration, $1s^2 2s^2 2p^4$, of O I, showing term and level splitting. The diagram gives transition probabilities A ($\sec^{-1}$) for the forbidden transitions, the dominant multipole term (m or q) in the transitions, the wavelengths, and mean lifetime τ of the levels. The level splitting of the ^3P term is exaggerated. The transition probability for $^3P{-}^1D$ is the total: the ratio for $\lambda 6300/\lambda 6364$ is $\frac{3}{1}$. [Transition probabilities from R. H. Garstang: (1968), in "Planetary Nebulae," *I.A.U. Symp.* **34**, 143; (1969), *Liège Colloq.*, p. 35; (1951), *M.N.R.A.S.* **111**, 115.]

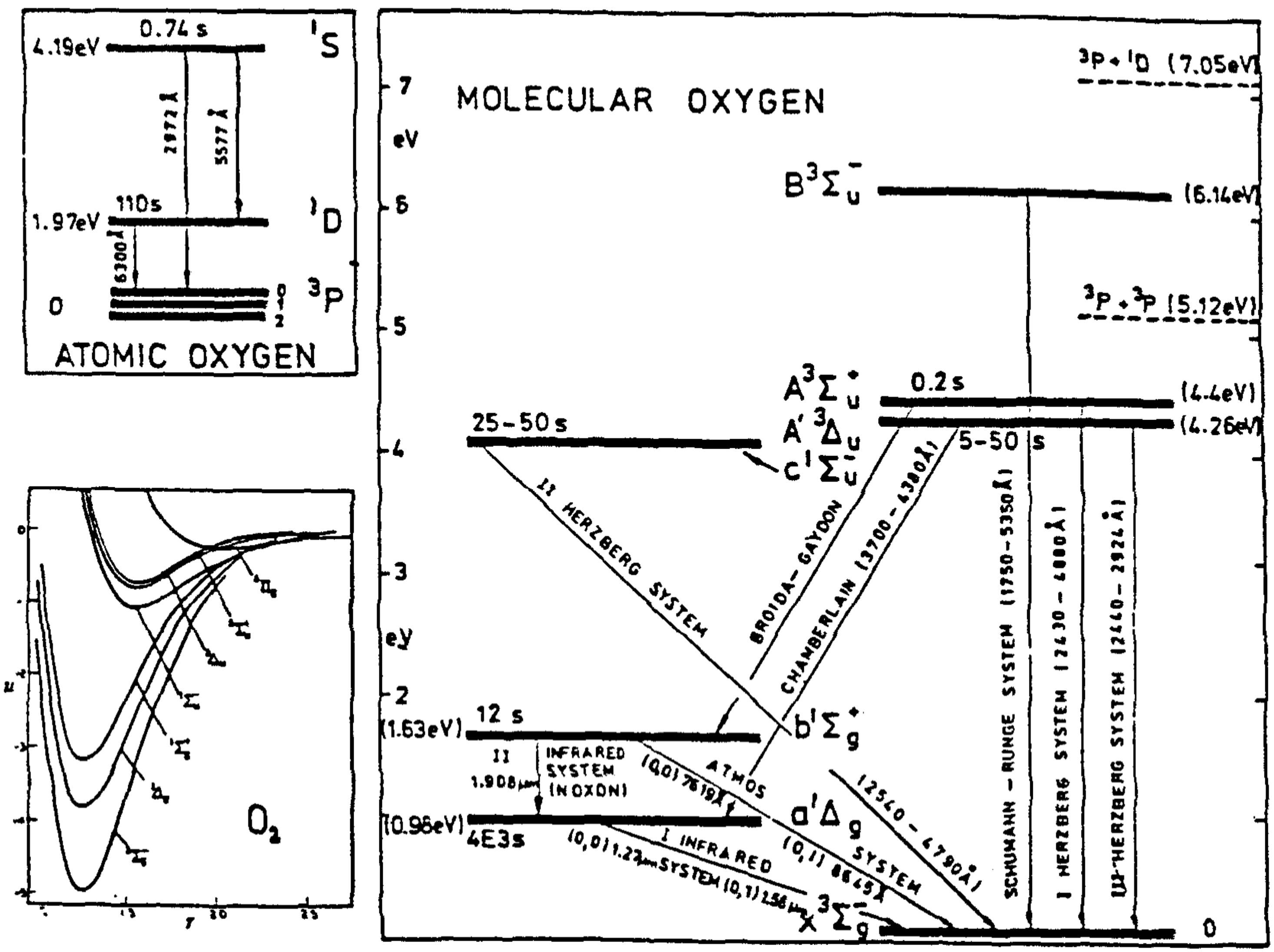
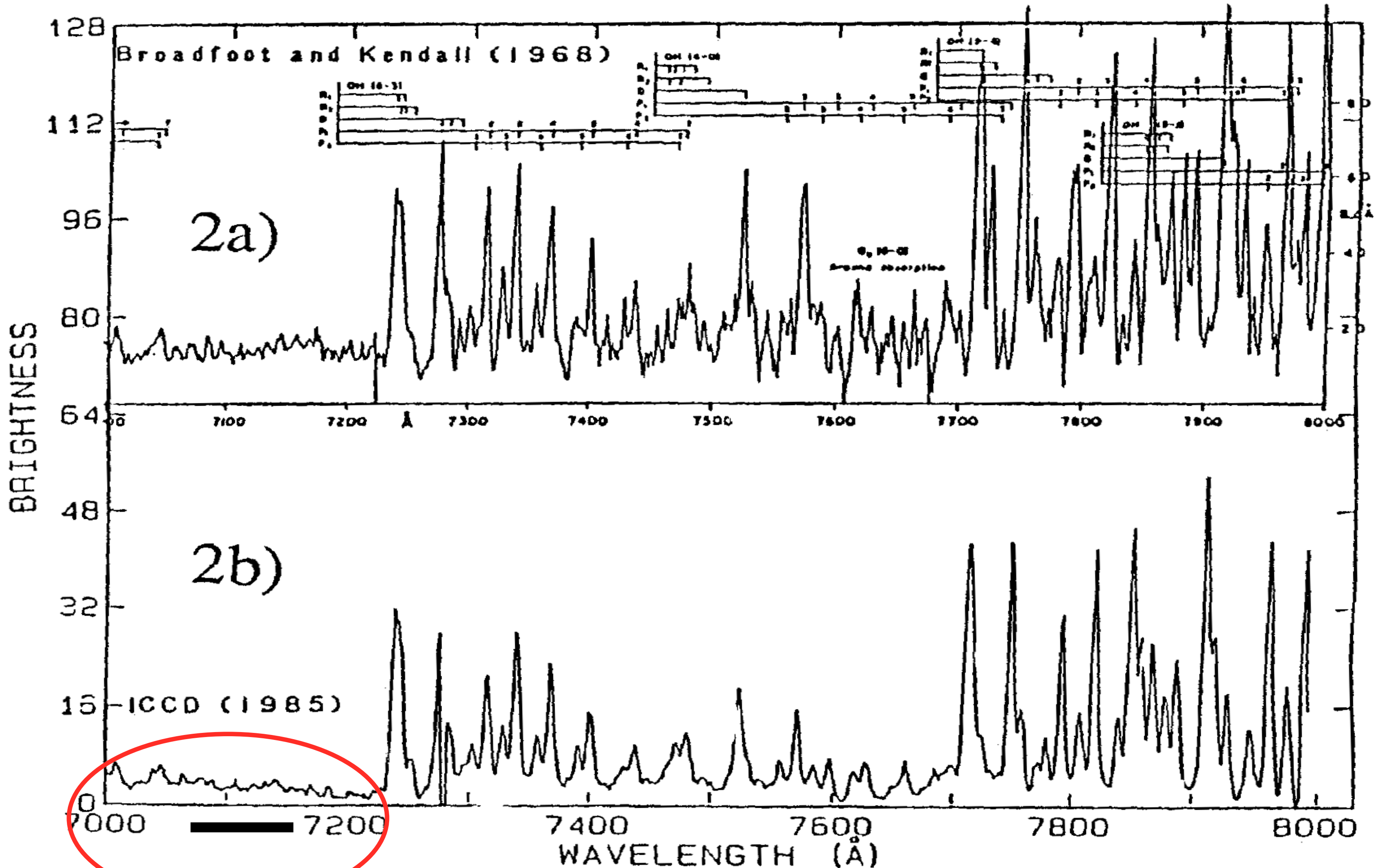


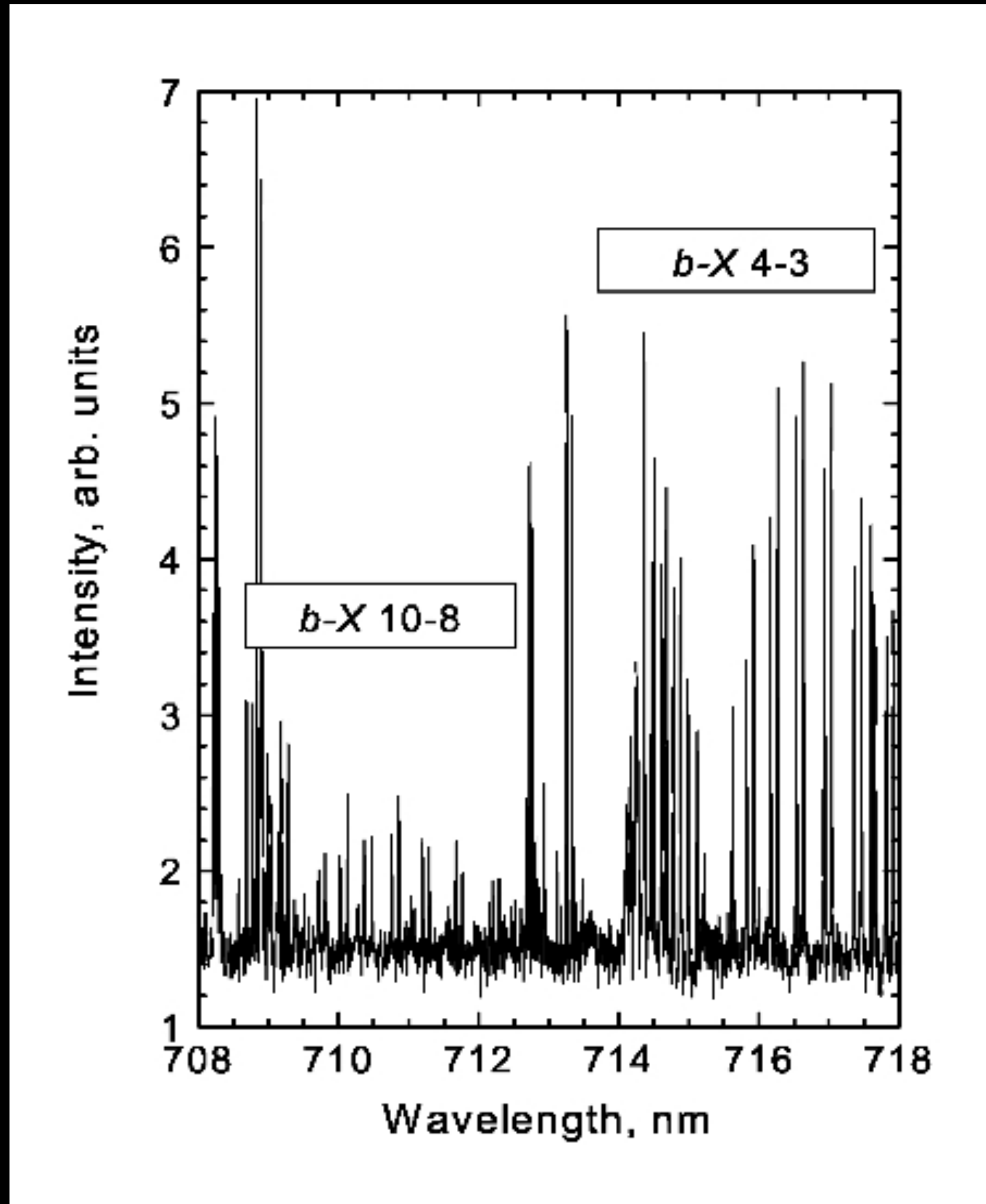
Fig. 6. Energy level diagram of molecular and atomic transitions of oxygen [from *Greer et al.* 1987]



ig. 2*a*. Airglow spectra obtained by Broadfoot at Kitt Peak with a 1m spectrophotometer [*Broadfoot and Kendall*, 968], and (b), airglow spectra obtained by L. B. Broadfoot at Kitt Peak with a 0.5 m charge coupled device imaging pectrograph. Only a few minutes integration was necessary [from *Sharp*, 1986].

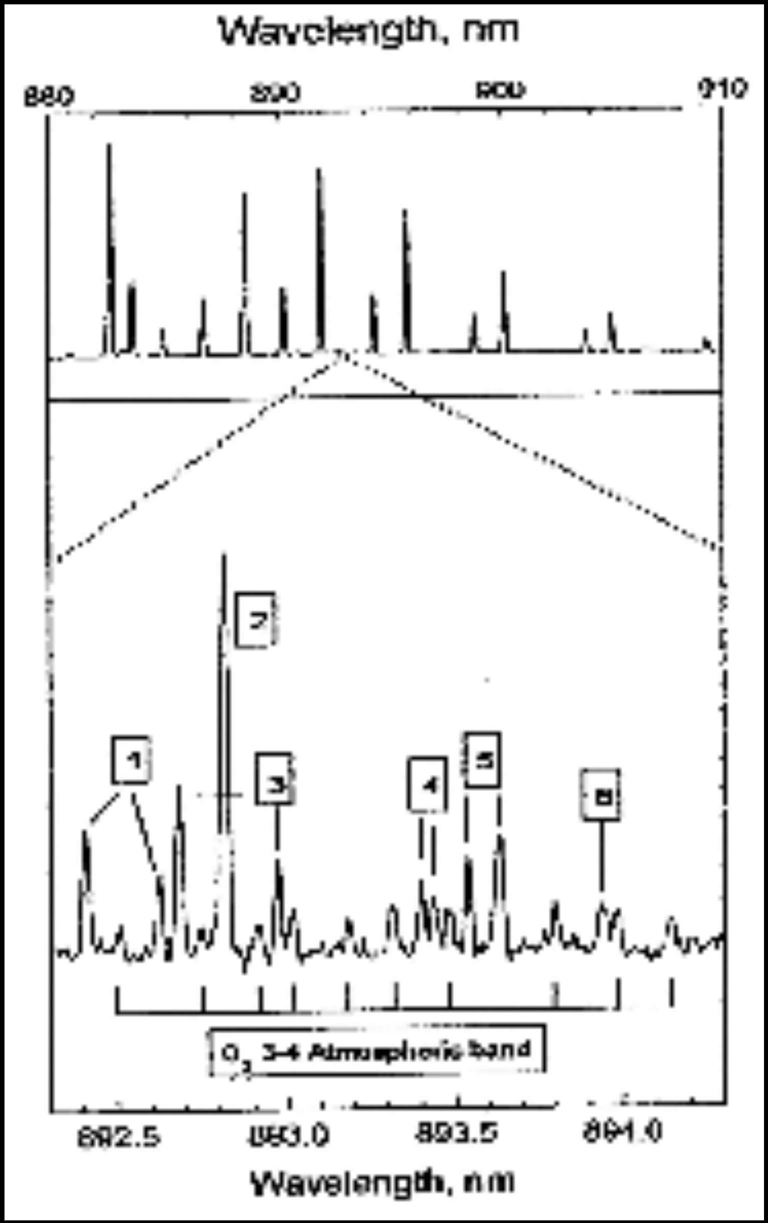
An example of nightglow spectra obtained
by a Fastie-Ebert spectrometer - 1960s technology

An example of today' s technology obtained with the Keck telescope high resolution spectrograph



Modern spectrograph technology can observe very weak spectral features in the nightglow.

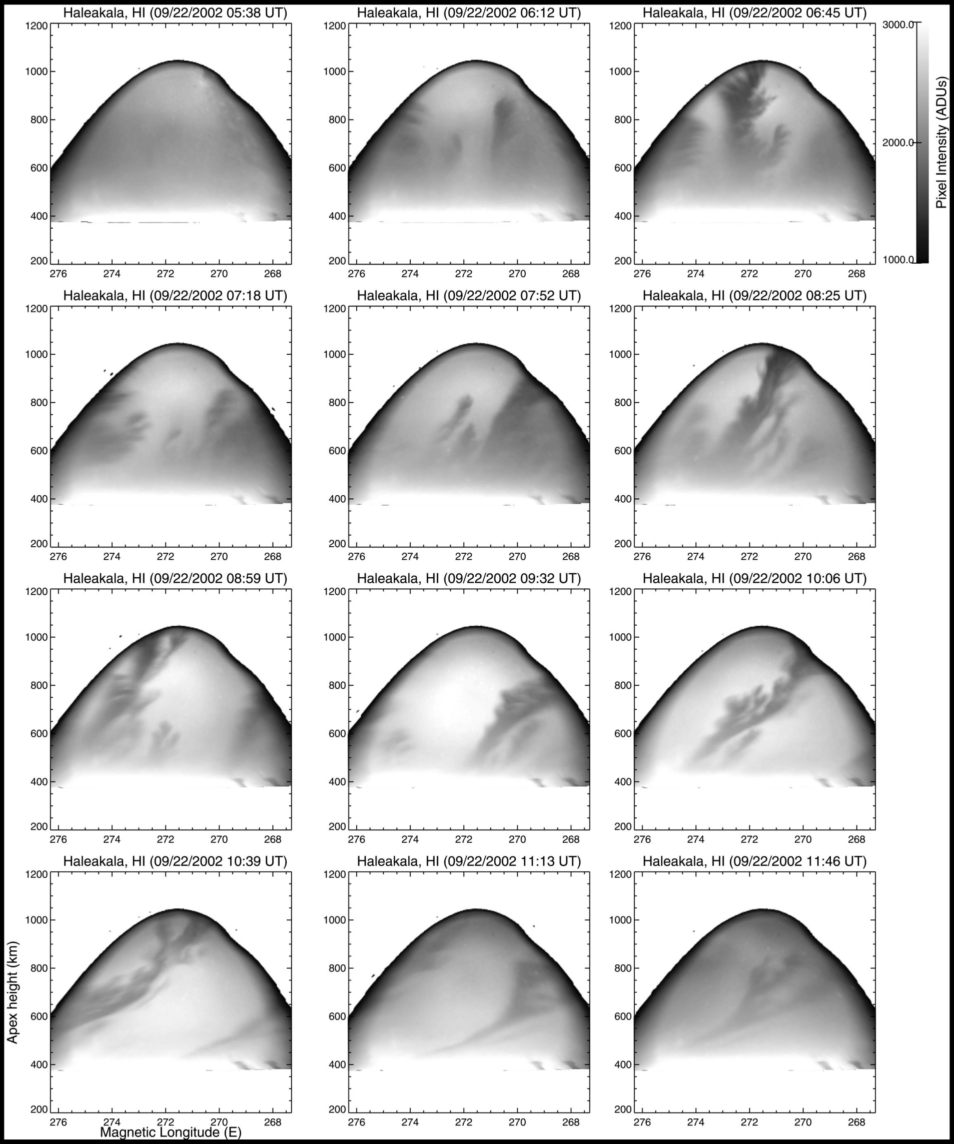
The Keck telescope gets excellent nightglow spectra every night!



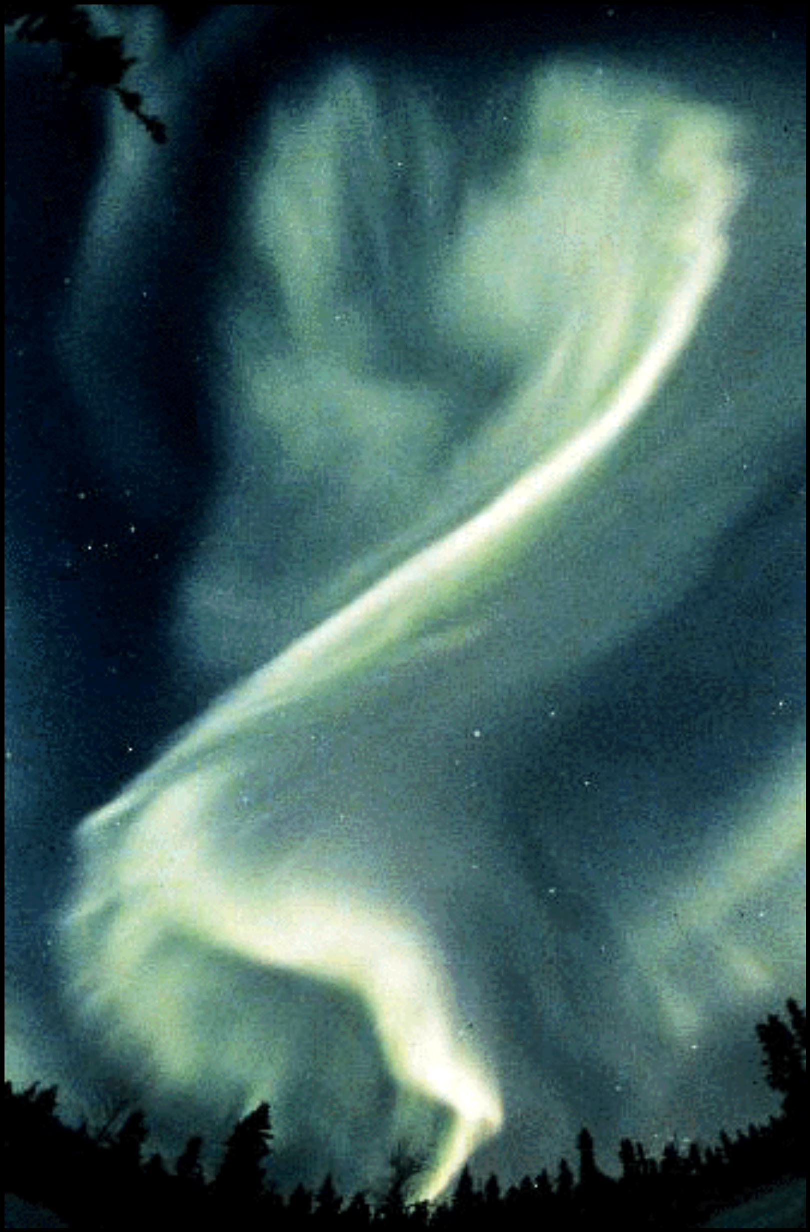
Imaging examples

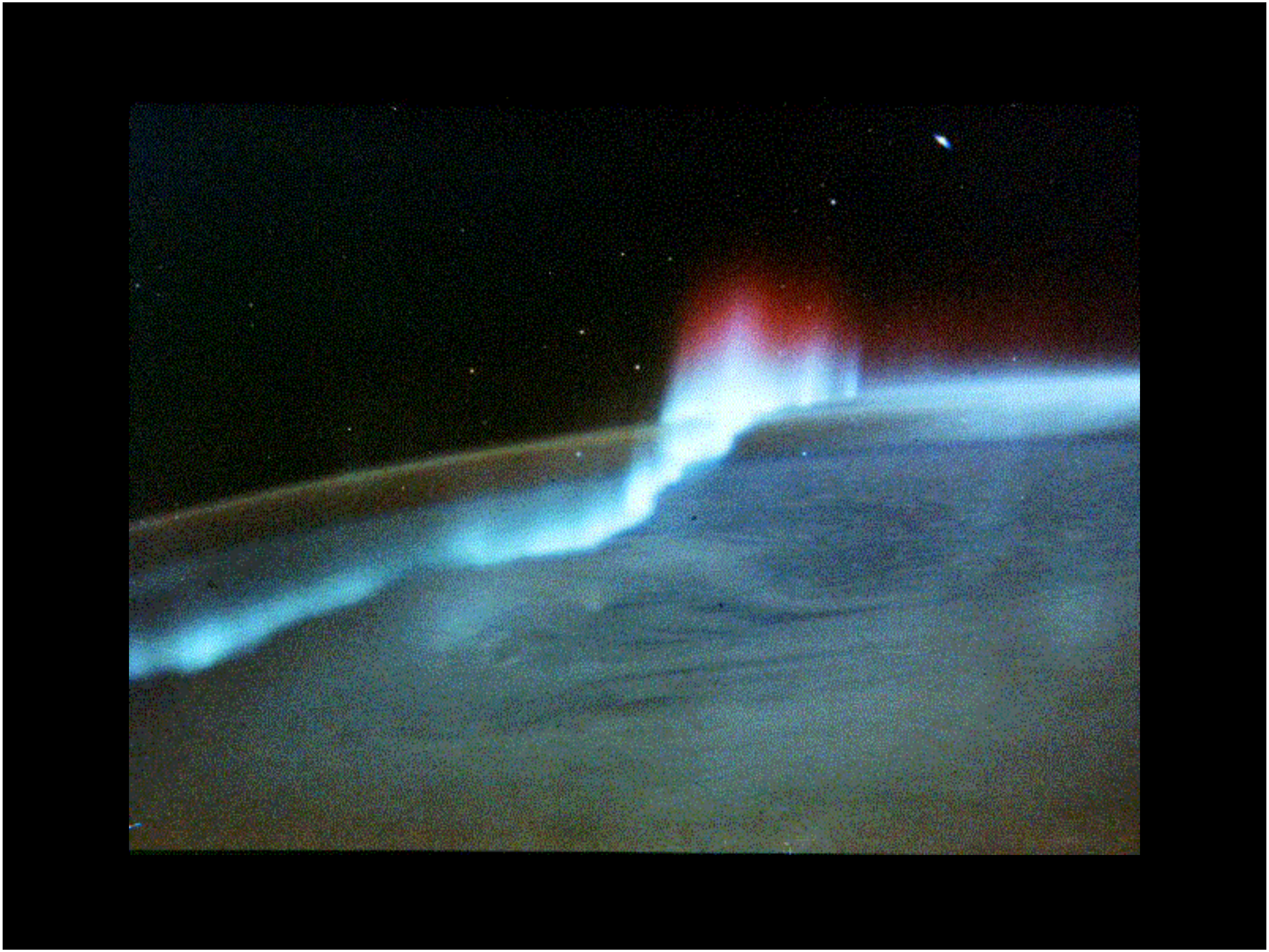
- All-sky imagers provide excellent documentation of the behavior of the nightglow or aurora.
- Very useful for dynamical studies of waves within the mesosphere region.

Holes within the Ionosphere layer lead to communication problems



In contrast to airglow, aurora can be very bright!





Thermospheric Chemistry

The dominant neutral species are O, O_2, N_2, and He in the topside thermosphere

The dominant ion species (by a long way) is O^+ – nitrogen has a very small photodissociation cross-section

Airglow production processes are divided into three types:

- *Dayglow* (when entire atmosphere is illuminated by the Sun) is the brightest airglow due to the importance of RESONANT and FLUORESCENT processes but it is overwhelmed by direct and scattered sunlight

- *Twilightglow* (when only the upper atmosphere is illuminated) is the most readily-observable airglow from the ground
  - -The observer is in darkness
  - -no Rayleigh scattering of sunlight by the dense lower atmosphere
  - -upper atmosphere is still illuminated
  - -is not as bright as dayglow
  - CHEMILUMINESCENCE (see below) is the dominant process;

however, the nightglow contributes more light than starlight to the total luminosity of the night sky

Airglow is due to emission from excited states formed by processes resulting (directly or indirectly) from solar radiation.

These processes include:

- **RESONANCE:**
- **FLUORESCENCE:**
- **PHOTOIONIZATION:**
- **PHOTODISSOCIATION:**
- **INELASTIC COLLISIONS:**
- **CHEMILUMINESCENCE:**
- **EXCITATION by COSMIC RAYS**

RESONANCE:

Emitted light wavelength is the same as that absorbed resulting from excitation by the absorption of solar radiation

Example is the scattering of solar radiation by Na atoms that occurs during twilight.

$$Na(^1S) + h\nu \Rightarrow Na(^2P) \Rightarrow Na(^1S) + h\nu(590,596\ nm)$$

FLUORESCENCE:

emitted light is at lower frequency, i.e. a different color, resulting from excitation by the absorption of solar radiation

An example would be the phenomenon of the Ring continuum that tends to fill the valleys of Fraunhofer structure in the dayglow or twilight.

PHOTOIONIZATION:

emitted light is from the excited states of neutral or ionized fragments caused by solar radiation

$O_2 + h\nu$ (EUV) => $O + O^*$

O^* => $O + h\nu$

or

$O_2 + h\nu$ (EUV) => $O + O^+(^2D) + e$

$O^+(^2P)$ => $O + h\nu$ (732 nm)

INELASTIC COLLISIONS:

emitted light results from excitation caused by the impact of high energy ("hot") electrons that are produced in photoionization

[NOTE: This is the same process that causes the luminous aurora but in that case the "hot" electrons come from the magnetosphere through interactions with the solar wind.]

CHEMILUMINESCENCE:

emissions result from chemical reactions mainly between oxygen and nitrogen atoms and molecules and OH molecules at a height between 100 and 300 km.

Solar radiation energy breaks molecules apart during the day, and it is their recombination, which is accompanied by the emission of light, that generates the nightglow.

$H + O_3 => OH^* + O_2$

$OH^* => OH^{**} => OH^{***}$

OH rotational-vibronic emissions very prevalent within the visible spectral region.

EXCITATION by COSMIC RAYS

(high energy radiation and particles from outside the solar system)

makes a small contribution to airglow as well.

Table 2.2 Emissions of some excited species in the middle atmosphere

Lower state	Excited state	Radiative lifetime (s)	λ (angstrom)	Name
$O(^3P)$	$O(^1D)$	110	6300	Red line
$O(^1D)$	$O(^1S)$	0.74	5577	Green line
$O_2(X^3\Sigma_g^-)$	$O_2(a^1\Delta_g)$	2.7(3)	12700+	Infrared atmospheri bands
$O_2(X^3\Sigma_g^-)$	$O_2(b^1\Sigma_g^+)$	12	7619+	Atmospheric bands
$O_2(X^3\Sigma_g^-)$	$O_2(A^3\Sigma_u^+)$	1	2600-3800	Herzberg bands
$OH(X^2\Pi)_{v=0,1,..}$	$OH(X^2\Pi)_{v=9,8,..}$	6(-2)	$<$28007	Meinel bands
$N(^4S)$	$N(^2D)$	9.36(4)	5200	
$N(^4S)$	$N(^2P)$	12	3466	
$N_2(X^1\Sigma_g^+)$	$N_2(A^3\Sigma_u^+)$	2	2000-4000	Vegard-Kaplan bands
$NO(X^2\Pi)$	$NO(A^2\Sigma^+)$	2(-7)	2000-3000	γ bands

Neutral-Ion Chemistry

$N_2^+ + O \rightarrow N(^2D) + NO^+$

$NO^+ + e^- \rightarrow N(^2D) + O\ (80\%)$
$\rightarrow N(^4S) + O\ (20\%)$

$N_2^+ + e^- \rightarrow N(^4S) + N(^4S)\ (10\%)$
$\rightarrow N(^4S) + N(^2D)\ (90\%)$

$N^+ + O_2 \rightarrow NO^+ + O$

$N^+ + O_2 \rightarrow O_2^+ + N(^4S)$

$N^+ + O \rightarrow O^+ + N$

Dissociative recombination

- Fast reactions

Neutral-Ion Chemistry

$O_2^+ + e^- \rightarrow O + O$

Dissociative recombination

- Fast reactions

$O_2^+ + N(^4S) \rightarrow NO + O$

$O_2^+ + NO \rightarrow NO^+ + O_2$

$O^+ + O_2 \rightarrow O_2^+ + O$

$O^+ + N_2 \rightarrow NO^+ + N(^4S)$

Charge Exchange

$NO^+ + O_2 \rightarrow O_2^+ + N_2$

$NO + h\nu_{Lyman\alpha} \rightarrow NO^+ + e^-$

$T_1 = 0.667\ T_i + 0.333\ T_n$; T_i is ion temperat
and $T_R = (T_i + T_n)/2$.

Neutral-Neutral Chemistry

$$O_2 + h\nu \rightarrow O + O$$

$$O + O + M \rightarrow O_2 + M$$

$$O + OH \rightarrow O_2 + H$$

$$O + HO_2 \rightarrow O_2 + OH$$

$$O + O \rightarrow O_2 + h\nu$$

$$N(^2D) + O_2 \rightarrow NO + O$$

$$N(^4S) + O_2 \rightarrow NO + O$$

$$N(^2D) + O \rightarrow N(^4S) + O$$

$$N(^4S) + NO \rightarrow N_2 + O$$

$$N(^2D) + e^- \rightarrow N(^4S) + e^-$$

$$N(^2D) + NO \rightarrow N_2 + O$$

$$N(^2D) \rightarrow N(^4S) + h\nu$$

$$NO + h\nu \rightarrow N(^4S) + O$$

$$NO + h\nu_{\mathrm{Lyman}\alpha} \rightarrow NO^+ + e^-$$

Ionising Radiation

- Solar radiation
  - primary ionisation source
- Electrons (from the solar wind)
  - important only at high latitudes
- Protons and $\alpha-$particles (from the solar wind)
  - too penetrative! absorbed in mesosphere or below.
- Bremsstrahlung X-rays from solar wind
  - too penetrative! absorbed in mesosphere or below.

Photodissociative Reactions

$$O_2 + h\nu \rightarrow O + O$$

$$NO + h\nu \rightarrow N(^4S) + O$$

$$NO + h\nu_{Lyman\alpha} \rightarrow NO^+ + e^-$$

Tides and Winds Terminology

In the upper thermosphere, solar heating of the thermosphere itself instigates horizontal winds flowing from the dayside to the nightside.

The Earth's rotation implies that these are 'tidal' – however we refer to them as 'winds, since…

…in the lower thermosphere (< ~ 120 km), winds propagate upwards from the mesosphere, which are referred to as (thermospheric) 'tides'

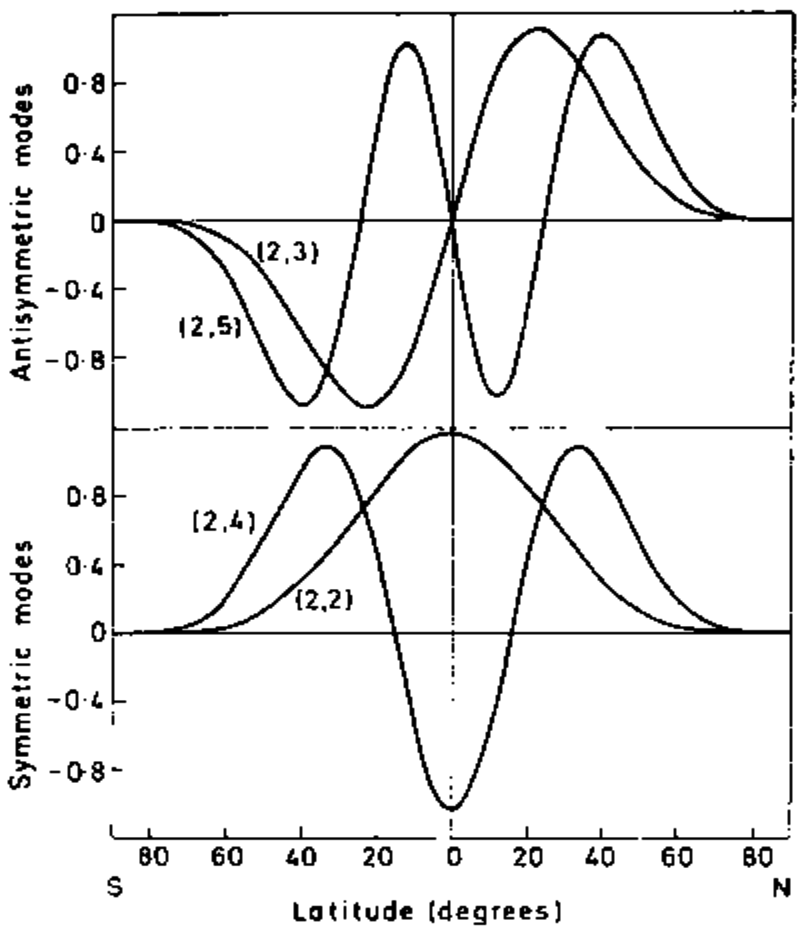
Tides and Winds

The sun (and moon) will cause tidal effects that propagate westwards, due to heat and gravity

The solar forcing and natural modes (Hough modes) of oscillation (c.f guitar string) will combine to give tidal modes, called "migrating tidal modes".

Hough function (n,m): n cycles per day, m-n nodes between the poles.

The dominant tidal modes (in order) are solar-diurnal, solar-semidiurnal (heating-drive), and lunar-diurnal (gravity-driven).

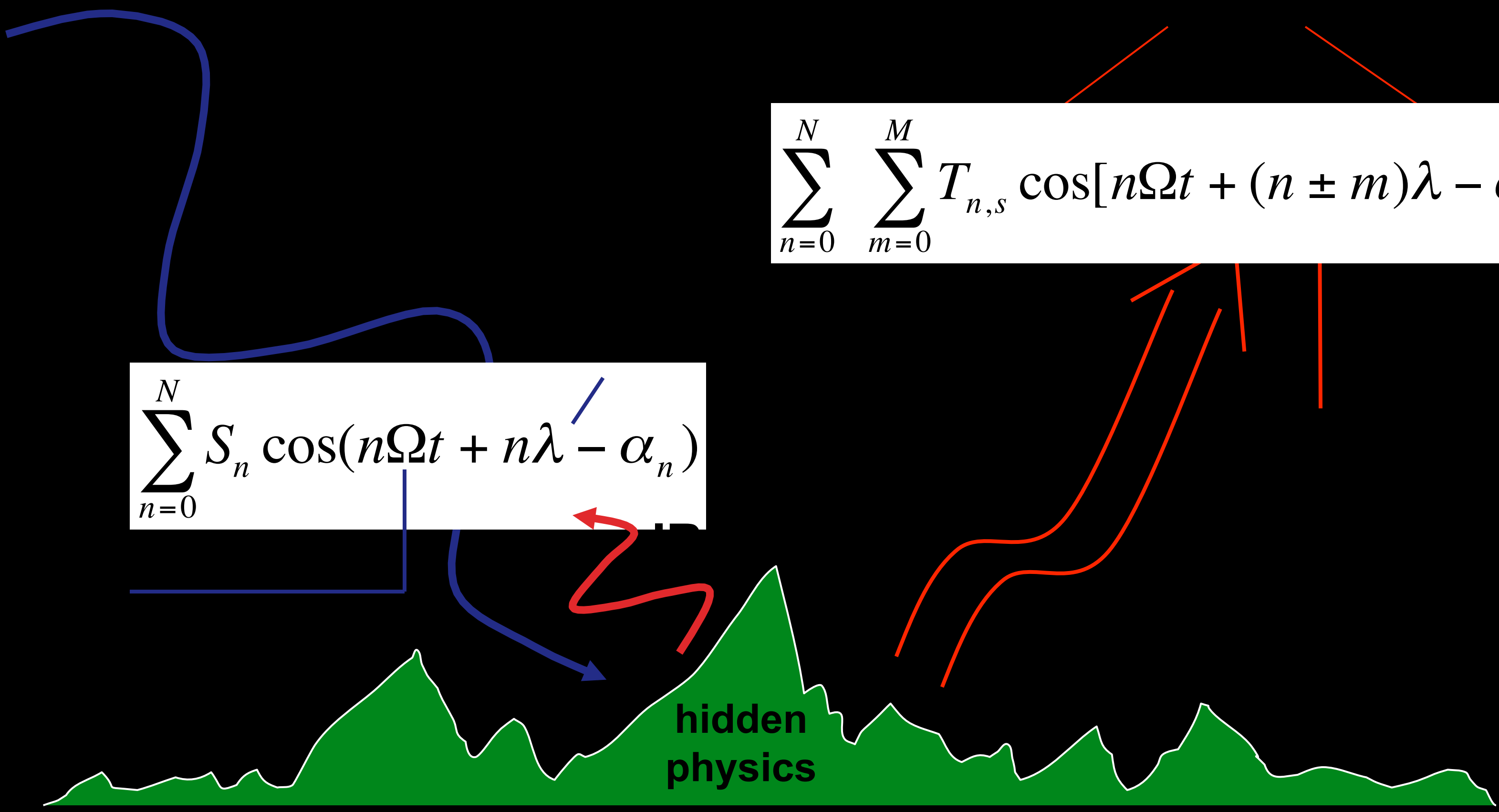


4.16 Hough functions for the two antisymmetric and symmetric modes of the semi-diurnal tide. (After J. V. Evans, *Proceedings of Internationa* *Solar–Terrestrial Physics*, Boulder, Colorado, 1976)

A spectrum of thermal tides is generated via topographic/ land-sea modulation of periodic solar radiation absorption:

$$\sum_{n=0}^{N} \sum_{m=0}^{M} T_{n,s} \cos[n\Omega t + (n \pm m)\lambda - \phi_{n,m}]$$

$$\sum_{n=0}^{N} S_n \cos(n\Omega t + n\lambda - \alpha_n)$$



$$\sum_{m=0,1,2,\ldots}^{M} S_m \cos(m\lambda - \beta_m)$$

Superrotation

- Early satellite data showed that the equatorial thermosphere super-rotates in the evening sector
- Averaged eastward zonal flow ~ 150 m/s @ 350 km, 50 m/s @ 200 km, most pronounced @ 2100-2400 LT
- Is this associated with the solar heating?

Thermospheric Waves

Waves propagate from any disturbance.

The restoring forces are both gravity vertically (e.g. ocean waves) and compression horizontally (e.g. sound wave): hence ‘acoustic gravity waves’, ‘atmospheric gravity waves’ (AGWs), or more generally, ‘travelling atmospheric disturbances’ (TADs).

Thermosphere Waves

Wave propagation tends to be along 'wave guides'

An obvious wave guide is the pressure gradient of the atmosphere (c.f. ocean waves)

Phase propagation is upwards.

Thermosphere Waves

A disturbance will generally create a 'family' of TADs; Large Scale and/or Medium Scale TADs

LS-TADs originate from magnetically conjugate auroral disturbances in the thermosphere.

λ ~ 1000s km, $\tau \sim 10$s min, v ~ 100s m/s, particle motion ↔

MS-TADs originate from the middle atmosphere.

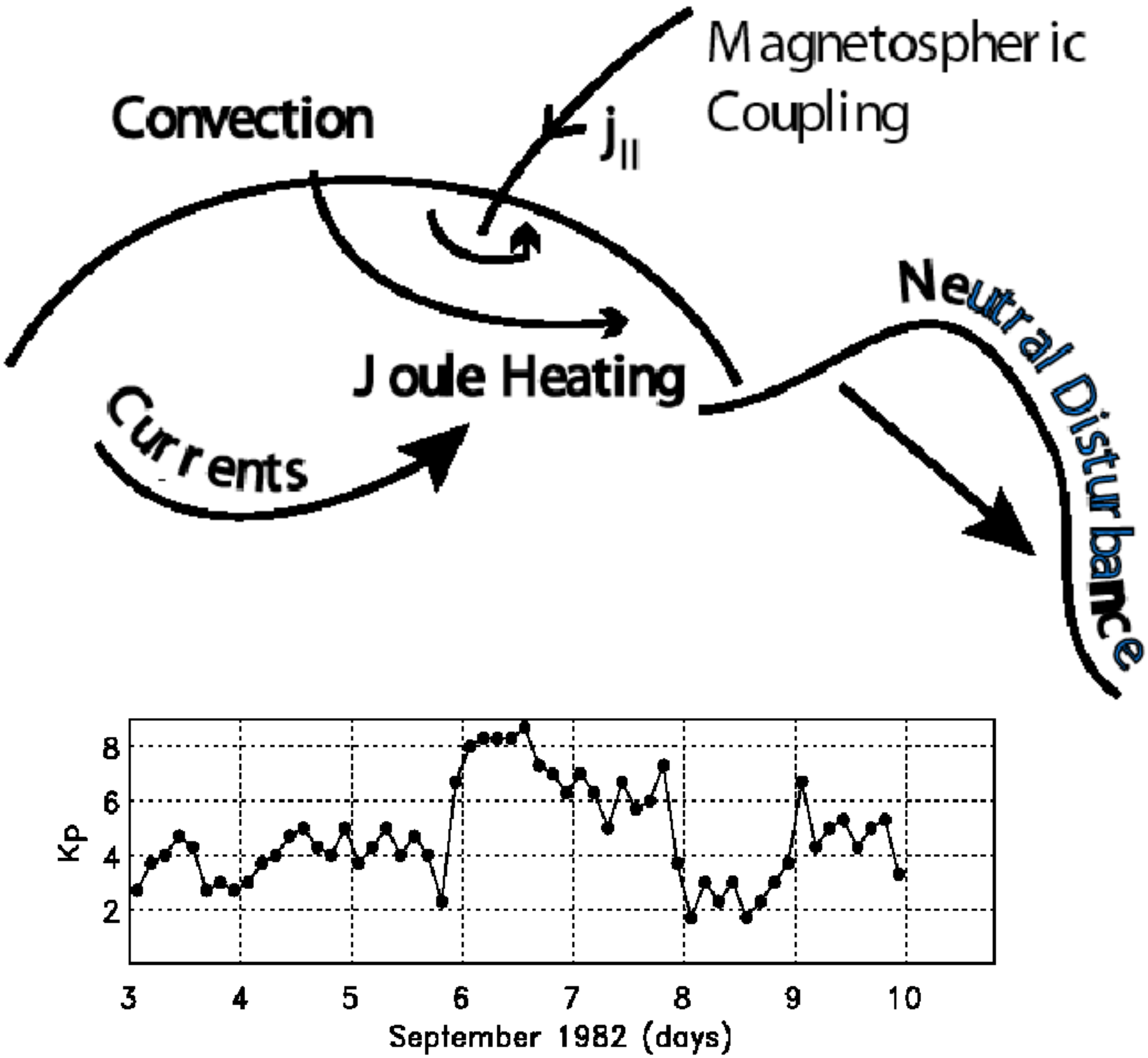
λ ~ 10s km, $\tau \sim$ mins, v ~ 10s m/s, wavefront ~ 45°

Large Scale TADs

What is the triggering disturbance?

Large electric fields in the polar regions drive the ionosphere through ExB forcing

The ionosphere ‘rubs against’ the pseudo-stationary thermosphere



Magnetospheric Coupling
Convection
$j_{\parallel}$
Joule Heating
Currents
Neutral Disturbance
8
6
4
2
Kp
3
4
5
6
7
8
9
10
September 1982 (days)

Joule vs. Lorentz

At high altitudes and/or large electric fields, Joule heating is dominant by ~ order of magnitude

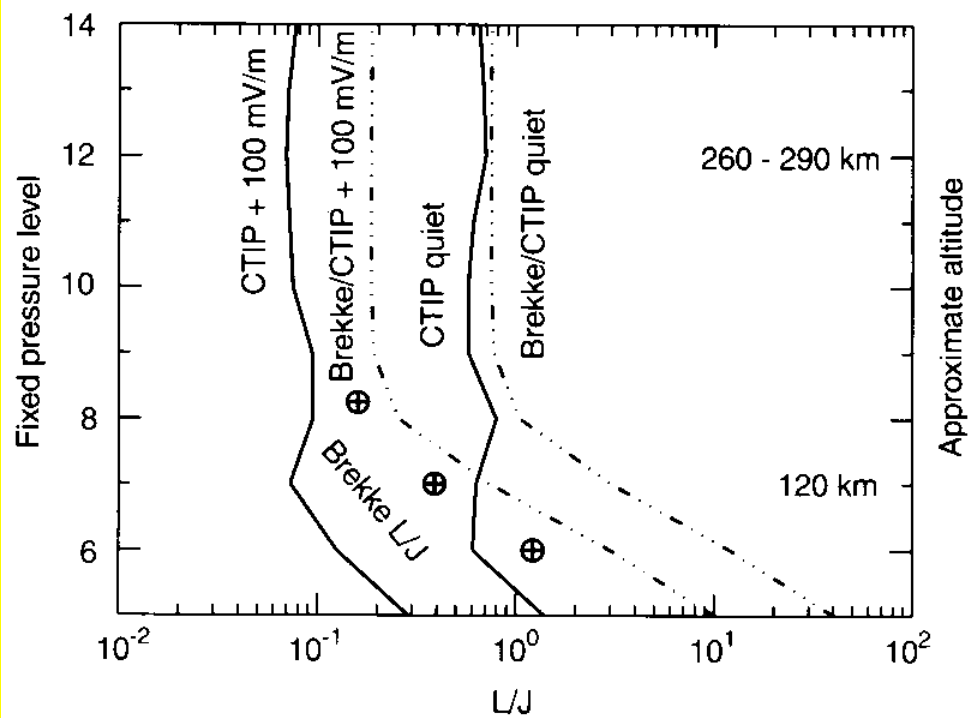


Fig. 3. Plot of the ratio of Lorentz forcing to Joule heating against height at latitude 70°N, longitude 162°E, Day 1. The *two solid lines* show the coupled model results for (a) quiet atmosphere, and (b) during the 100 mV/m enhanced electric field. The *broken lines* show results from the extrapolation of the Brekke formula, Eq. (4), for both quiet and enhanced atmospheres, whilst the *three discrete points* are the Brekke results

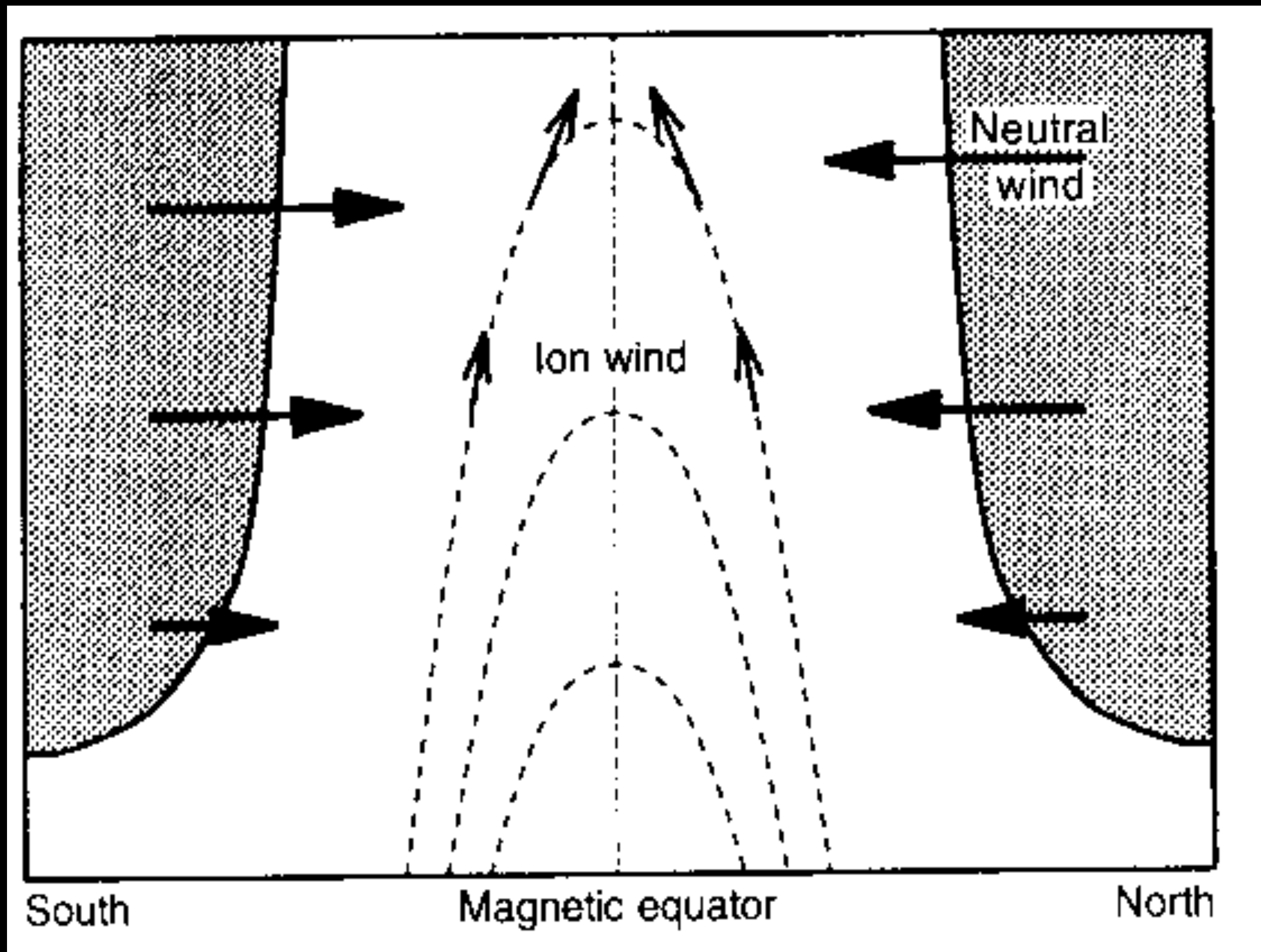
Observing T?Ds

Motion of the thermosphere is difficult to image.

We rely on a proxy: the movement of the embedded ionosphere, which reflects and refracts radio waves. However…

…ions are constrained to spiral about field lines.   Thus, horizontal motion of the thermosphere will result in a vertical component to the motion of the ionosphere (in the general case where $0 < \text{dip angle} < 90$)

TAD/TID coupling



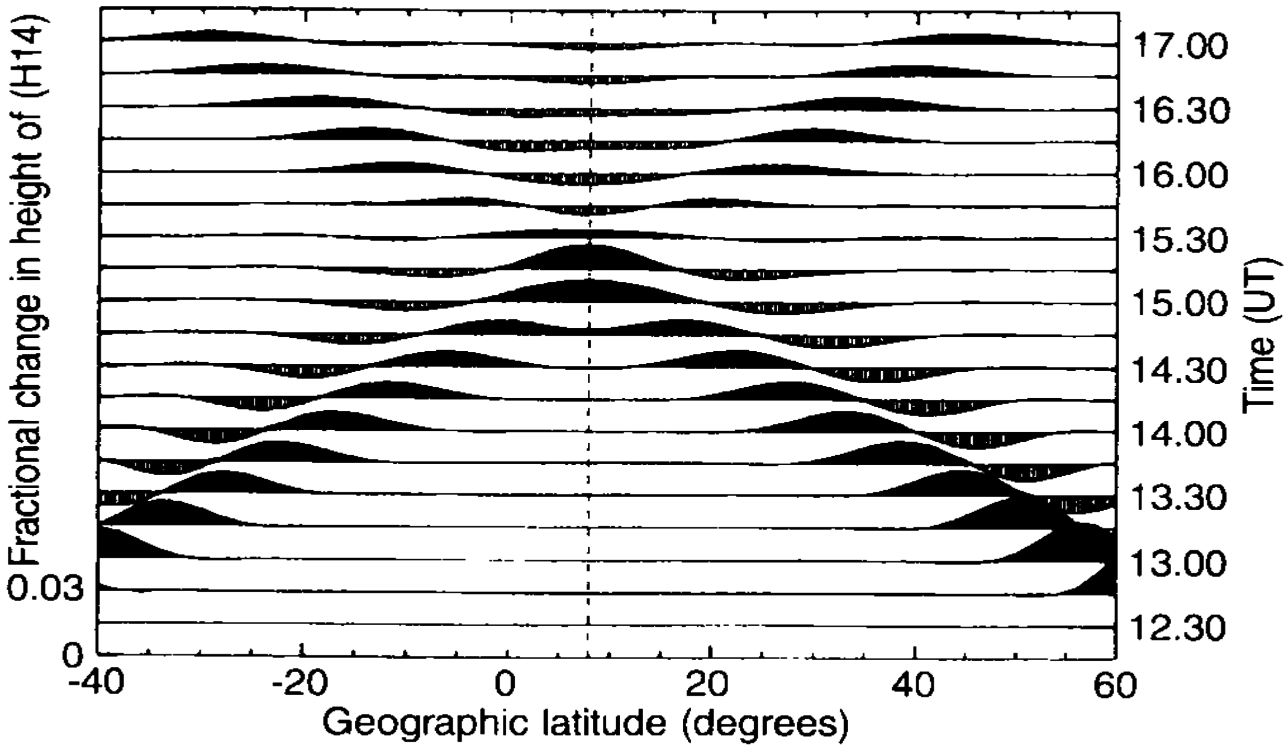


Fig. 1. Change in the height, relative to steady state conditions, of a fixed pressure level at approximately 380 km (just below the F2 peak). An increase in the height of the fixed pressure level is shown in *heavy shading*, whilst a decrease is shown by *light shading*. The AGW is shown at 20 times from 12.15 UT to 17.00 UT; each plot is offset up the y-axis for clarity. The *vertical dashed line* denotes the magnetic equator

hmF_2 signature of TAD

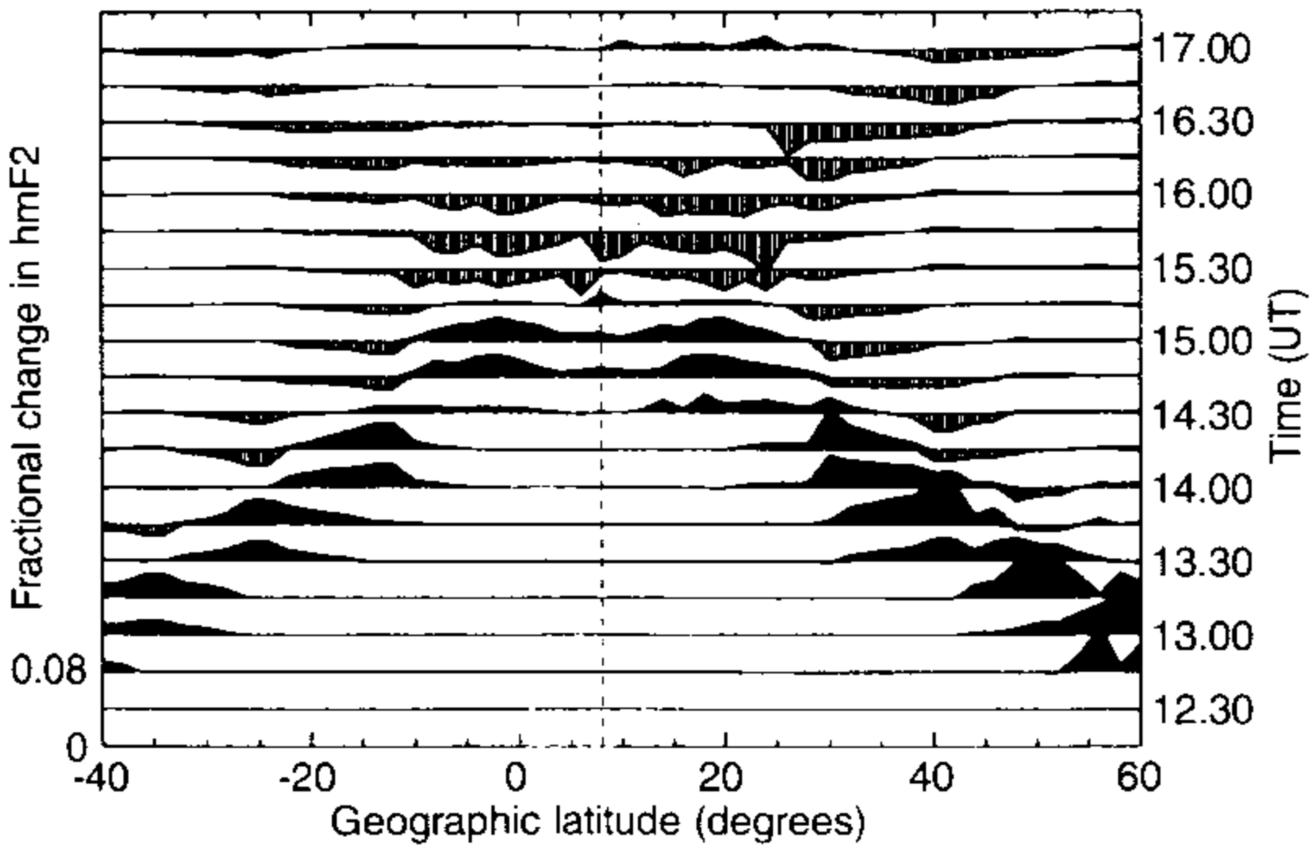


Fig. 4. Change in hmF2 (the height of the F2 peak), relative to steady-state conditions. The format of the plots is identical to that of Fig. 1

NmF2 signature of TAD

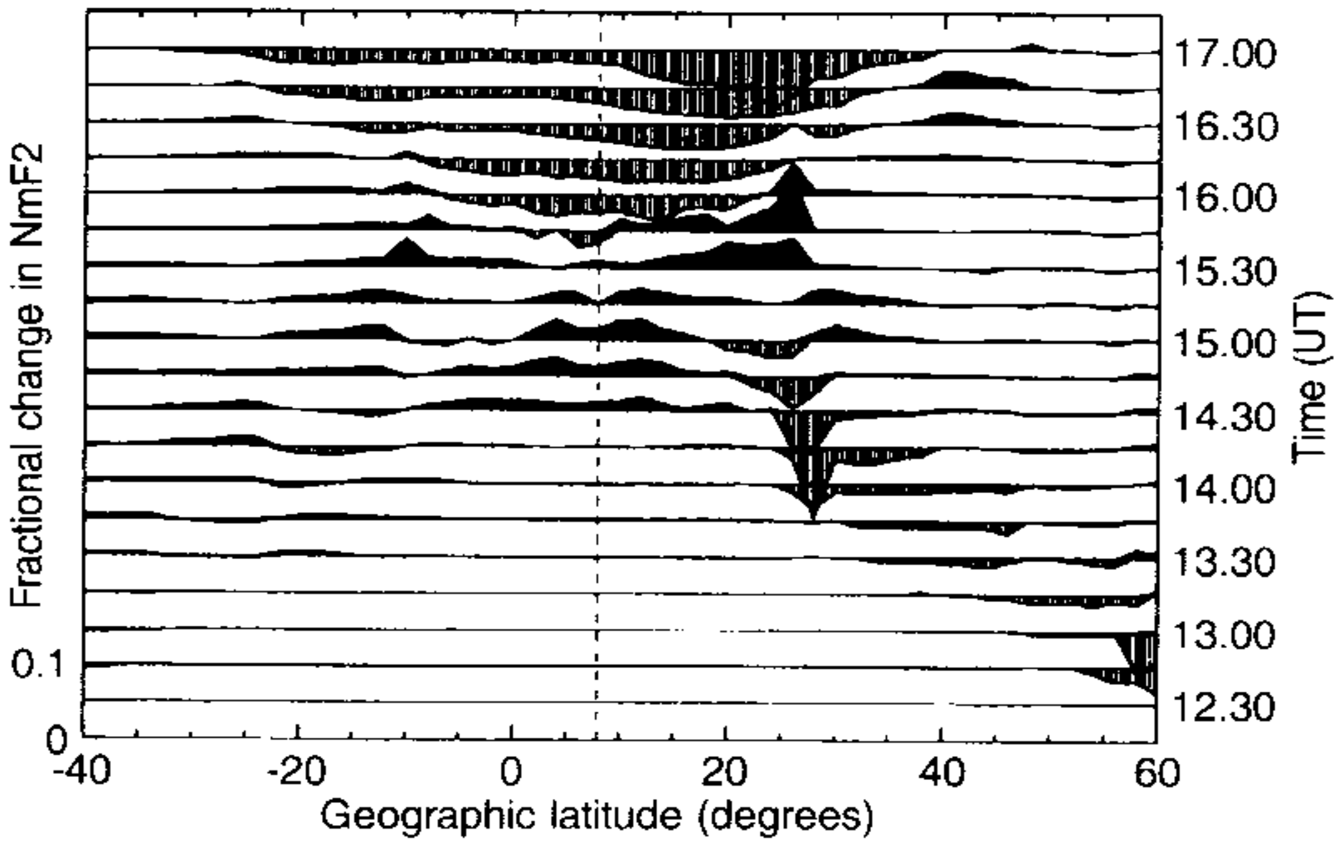


Fig. 5. Change in NmF2 (the density of the F2 peak), relative to steady-state conditions. The format of the plots is identical to that of Fig. 1

Polar Vortices / Flywheel

Ions driven by a large electric field can accelerate to ~ km/s

Lorentz forcing will impart momentum to the neutral gas

The polar thermosphere can thus 'spin up' into a flywheel, retaining its momentum, and driving the ionosphere long (~hours) after the strong electric field conditions have vanished.

Suggested Quick References

The Earth's Ionosphere, Kelley,
ISBN 0124040136, Academic Press

The Solar-Terrestrial Environment, Hargreaves,
ISBN 052142737I, Cambridge University Press

STEP Handbook of Ionospheric Models, ed. Schunk,
Utah State University

Ionospheres   Schunk and Nagy

Questions for the future

- Energy budget issues not complete
  - How much energy transferred to above as opposed to the solar source?
  - What influence does "hot atoms" have upon the ITM system? Recent discovery demonstrates importance
- Coupling issues regarding plasma and waves
  - Do we understand all of the physics associated with the ion-neutral coupling within the ITM system?
  - Do we understand the ITM dynamics, especially regarding the interface with the lower atmosphere where waves break and turbulence structure is strongly developed.

And finally, one last word:

- The Earth's ITM system is certainly complex with many diverse phenomena.
  - Can we improve our skill in modeling the response of the ITM system to external forcing re
    - solar flares, CME events, geomagnetic storm activity
    - Weak and strong levels of solar flux activity
    - meteor strikes, hurricane and tornado events
    - and the ever-constant onslaught of GW and tidal wave structures onto the ITM system.