INFRARED RADIANCE IN THE MESOSPHERE AND LOWER THERMOSPHERE: WHAT'S “UP” AND WHY BOTHER?

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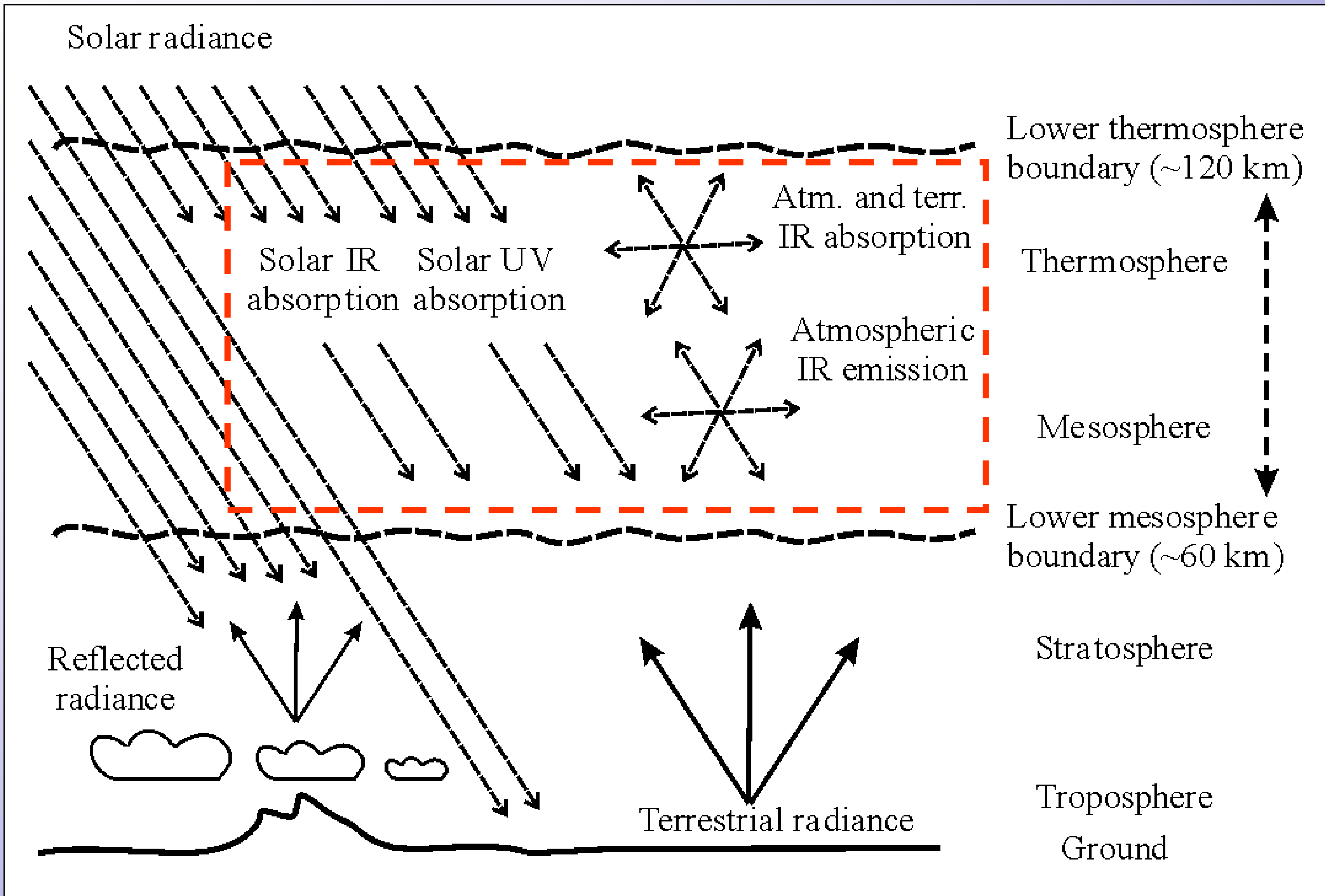
Overview

- Object of study: Mesosphere/Lower Thermosphere (MLT)
- Mechanisms of infrared radiance formation in MLT
- Non-local thermodynamic equilibrium (non-LTE)
- Non-LTE models for CO_2, O_3, H_2O
- Radiative cooling/heating of MLT
- Infrared observations of the MLT area
- Mesospheric temperature and polar mesospheric clouds
- MLT and satellite observations of the lower atmosphere

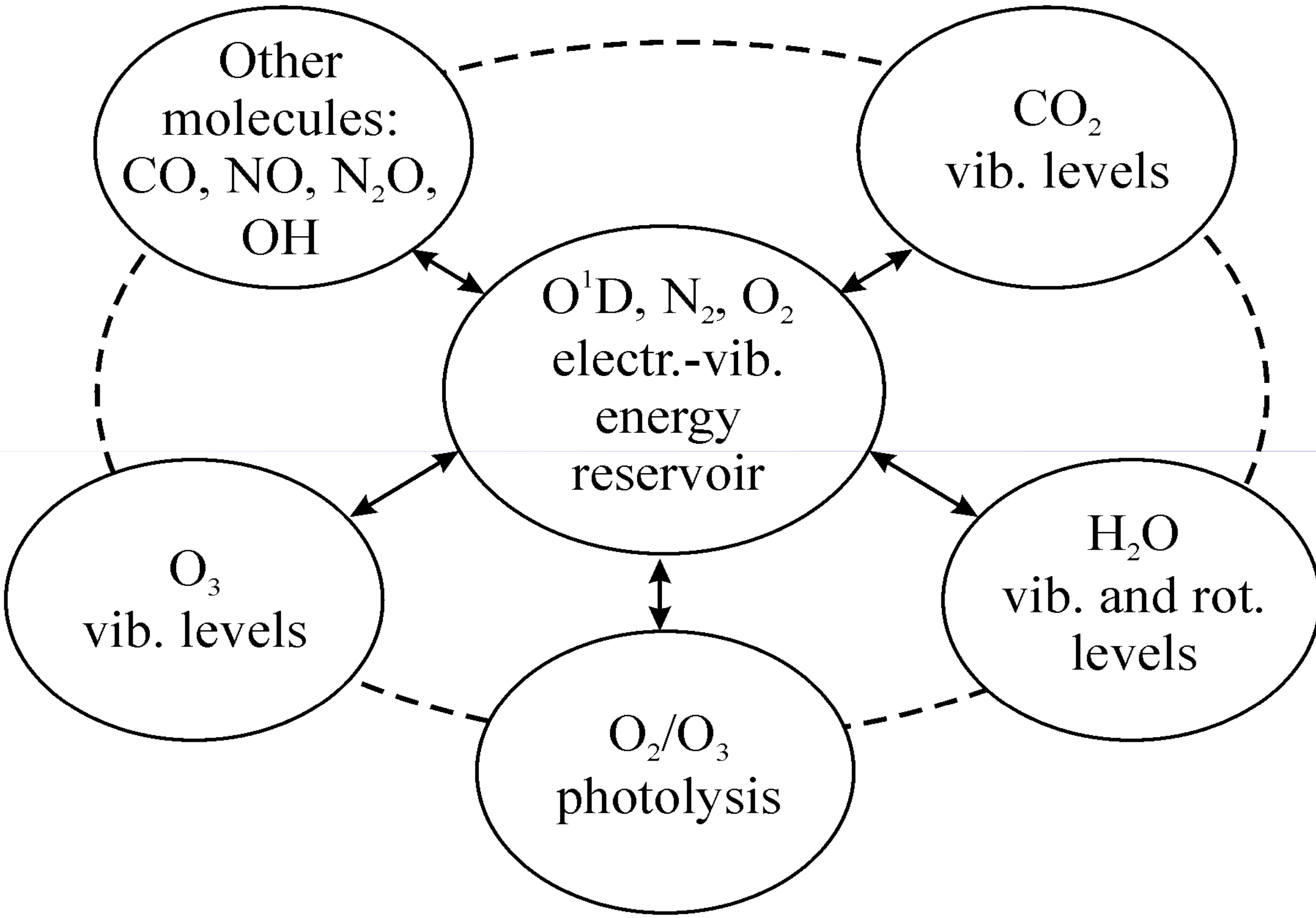
Why bother?

- MLT is a "gateway" between the lower atmosphere and space.
- MLT is sensitive to solar influence and to the radiance coming from below.
- Anthropogenic changes in greenhouse gases may change this input.
- Noctilucent clouds observed in polar MLT in the summer time are very sensitive to temperature changes and there are debates on their role as a "miner's canary" for global changes.
- MLT area absorption and emission in molecular bands affects the atmospheric observations of other areas.

Object of Study: IR radiance in MLT



Energy Exchange Between Atmospheric Molecules



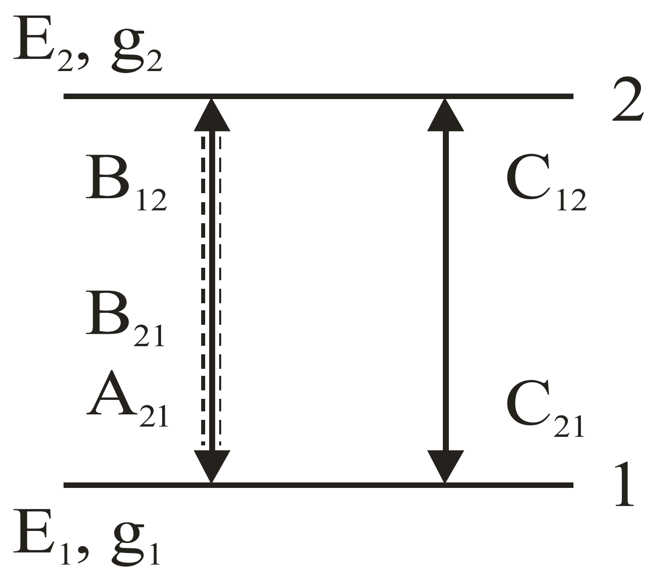
Formulation of the Problem

- Infrared radiance absorption/emission corresponds to vibrational excitation/de-excitation of the molecules.
- To estimate the energetic characteristics of the given area or to interpret the infrared observations in MLT one needs to know the vibrational levels populations.

BUT !!!

- In the upper atmosphere the collisions between the molecules are **not** frequent and the populations are **not** defined by local temperature.
- Breakdown of Local Thermodynamic Equilibrium (LTE).
- Special methodology is applied (non-LTE modeling).

LTE and non-LTE: two-level atom



$$
\begin{cases}
(\underbrace{A_{21} + B_{21}\bar{J}}_{R_{21}} + C_{21})\, n_2 = (\underbrace{B_{12}\bar{J}}_{R_{12}} + C_{12})\, n_1 \\[2ex]
n_1 + n_2 = n
\end{cases}
$$

LTE and non-LTE

$$\begin{cases} (\underbrace{A_{21} + B_{21}\bar{J}}_{R_{21}} + C_{21})\, n_2 = (\underbrace{B_{12}\bar{J}}_{R_{12}} + C_{12})\, n_1 \\ n_1 + n_2 = n \end{cases}$$

$R << C$

$R_{21}n_2 \sim R_{12}n_1$

$$n_2 C_{21} = n_1 C_{12}$$

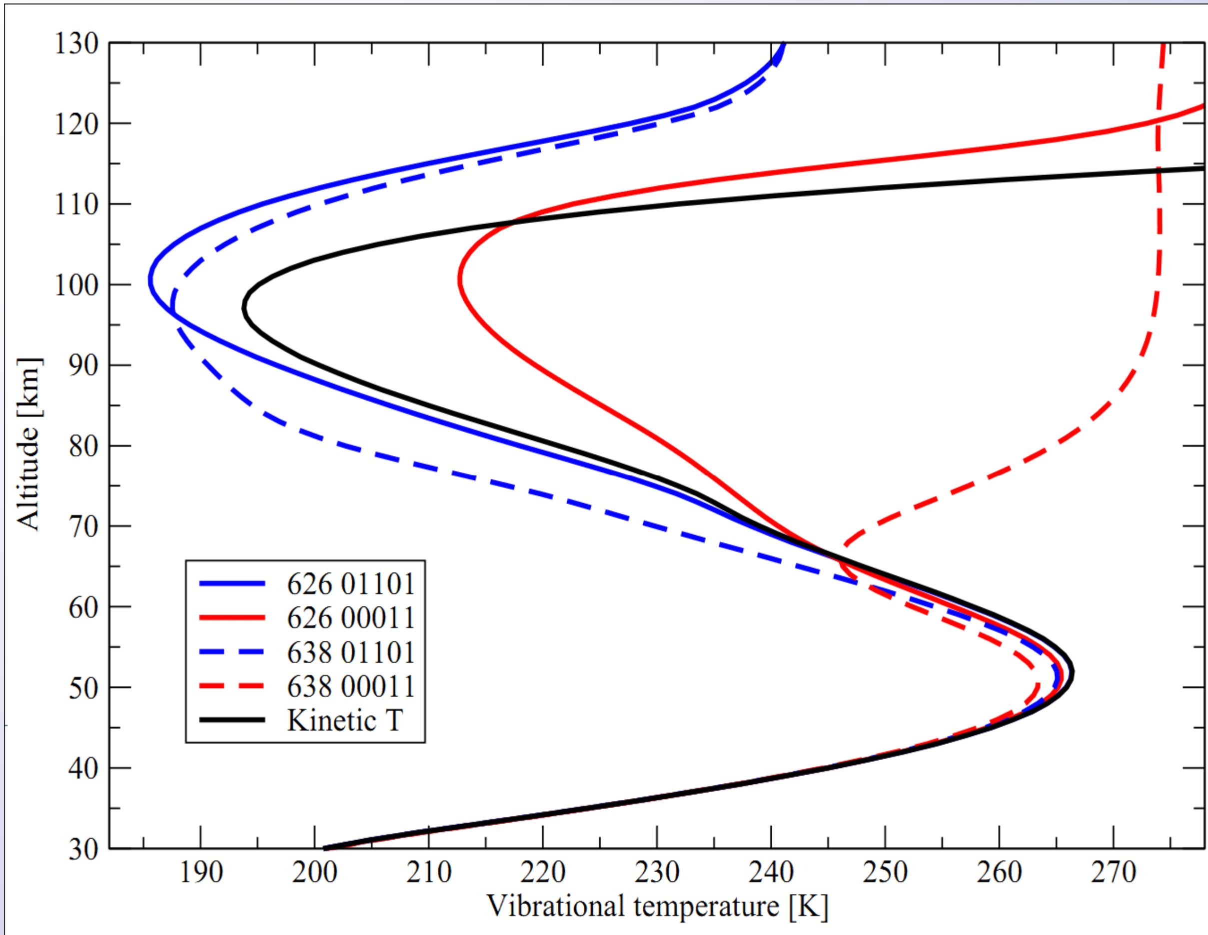
$$\frac{n_2}{n_1} = \frac{g_2}{g_1}\, e^{-\frac{E_2 - E_1}{kT}}$$

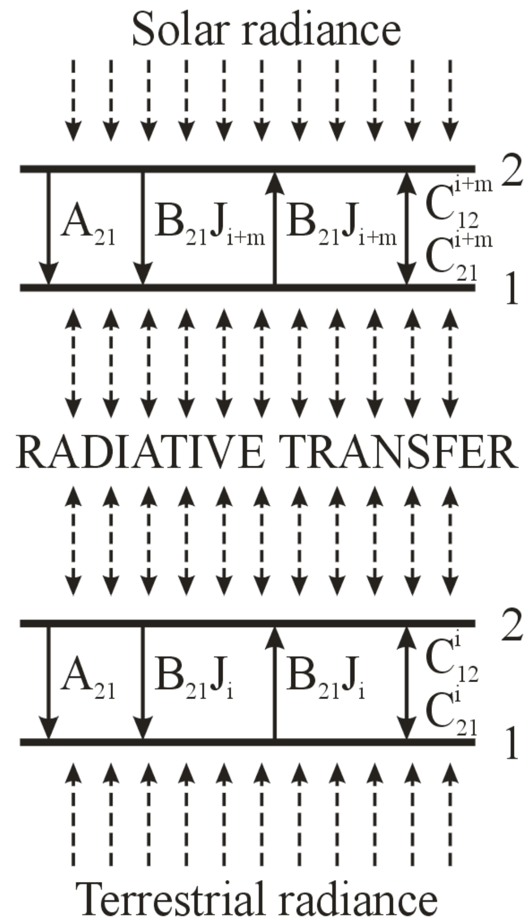
LTE

Otherwise - non-LTE !!!

J is non-local

Non-LTE populations: vibrational temperatures





$$\frac{n_l}{n_0} = \frac{g_l}{g_0} \cdot e^{-(E_l - E_0)/kT_{vib}}$$

$T_{vib}=T_{kin}$: LTE

$T_{vib}\neq T_{kin}$: non-LTE

Cooling/heating rates

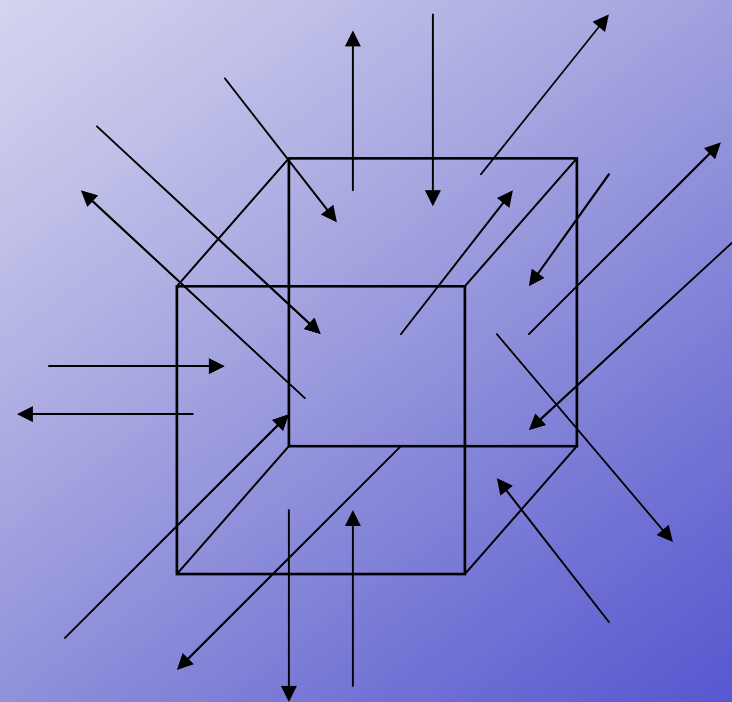
Radiative cooling/heating = radiative flux divergence

in W/m³:

$$H(z) = \frac{1}{4\pi} \int_{\Omega} \int_{-\infty}^{+\infty} \mu \frac{dI_{\mu\nu}(z)}{dz} d\nu$$

in K/day:

$$h(z) = H(z) \cdot \frac{24 \cdot 60 \cdot 60}{C_p(z)\rho(z)}$$



CO_2, O_3, and H_2O: three most "interesting" atmospheric molecules

- The vibrational levels of all 3 molecules are in non-LTE in MLT.

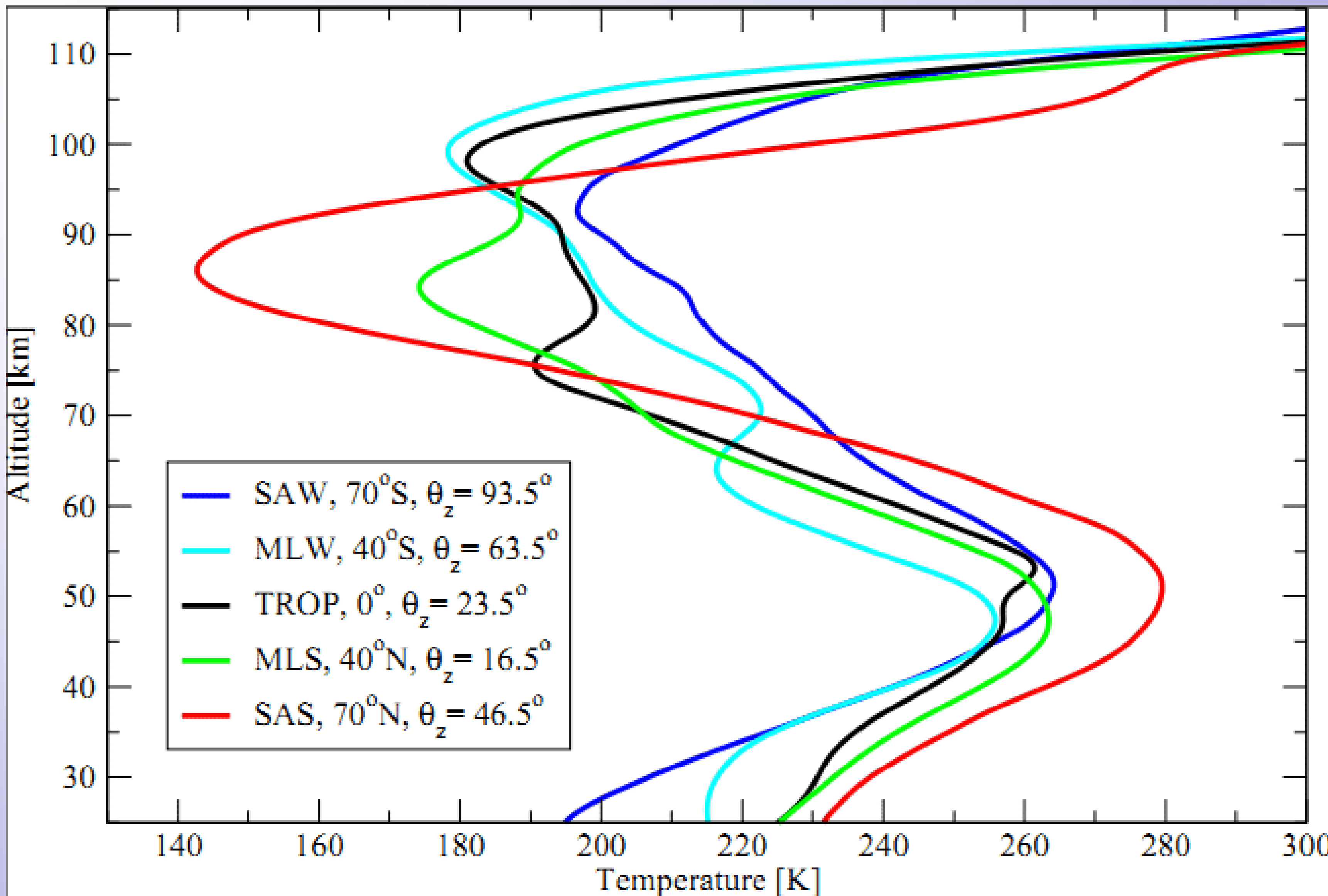
- CO_2(15 μm) is the main cooler in MLT.

- O_3(9.6 μm) is the second in importance.

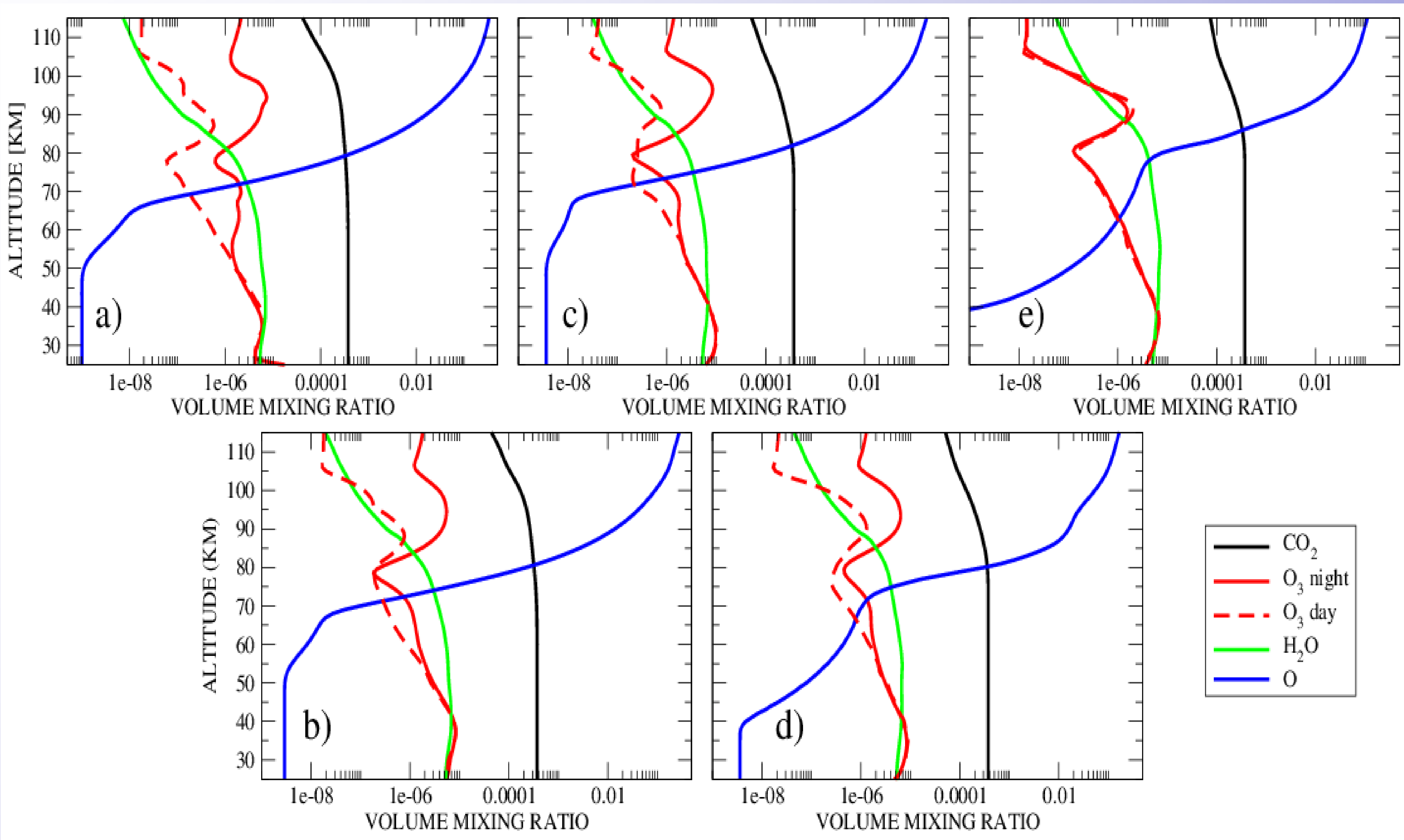
- O_3 and O_2 photolysis in UV forms $O(^1D)$, $O(^3P)$ and electronically and vibrationally excited O_2 coupled with H_2O.

- H_2O **rotational** band is the third in importance. However, the non-LTE model is still required for the H_2O retrievals from the 6.3 μm radiance measurements.

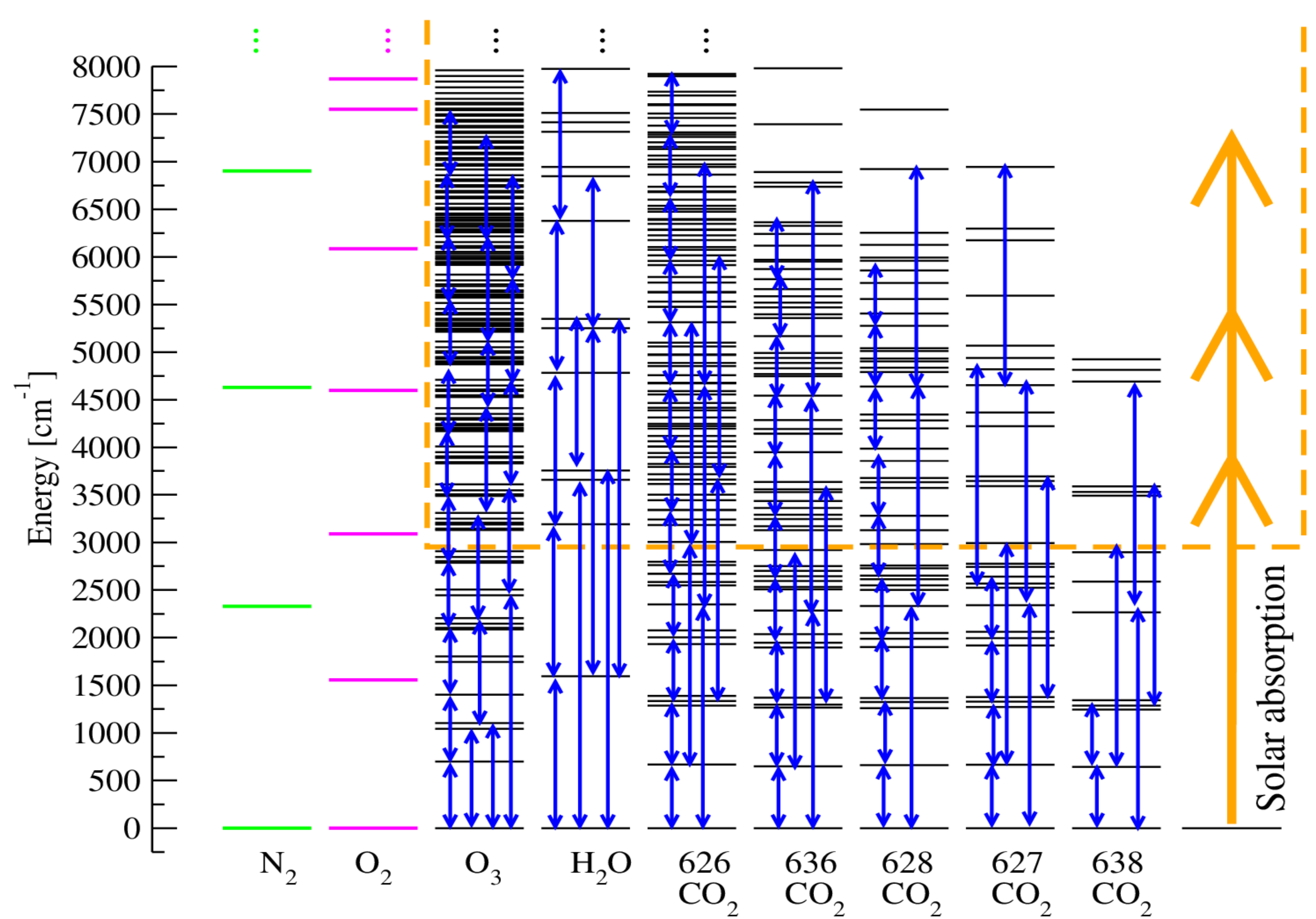
Five test atmospheric models: temperature profiles



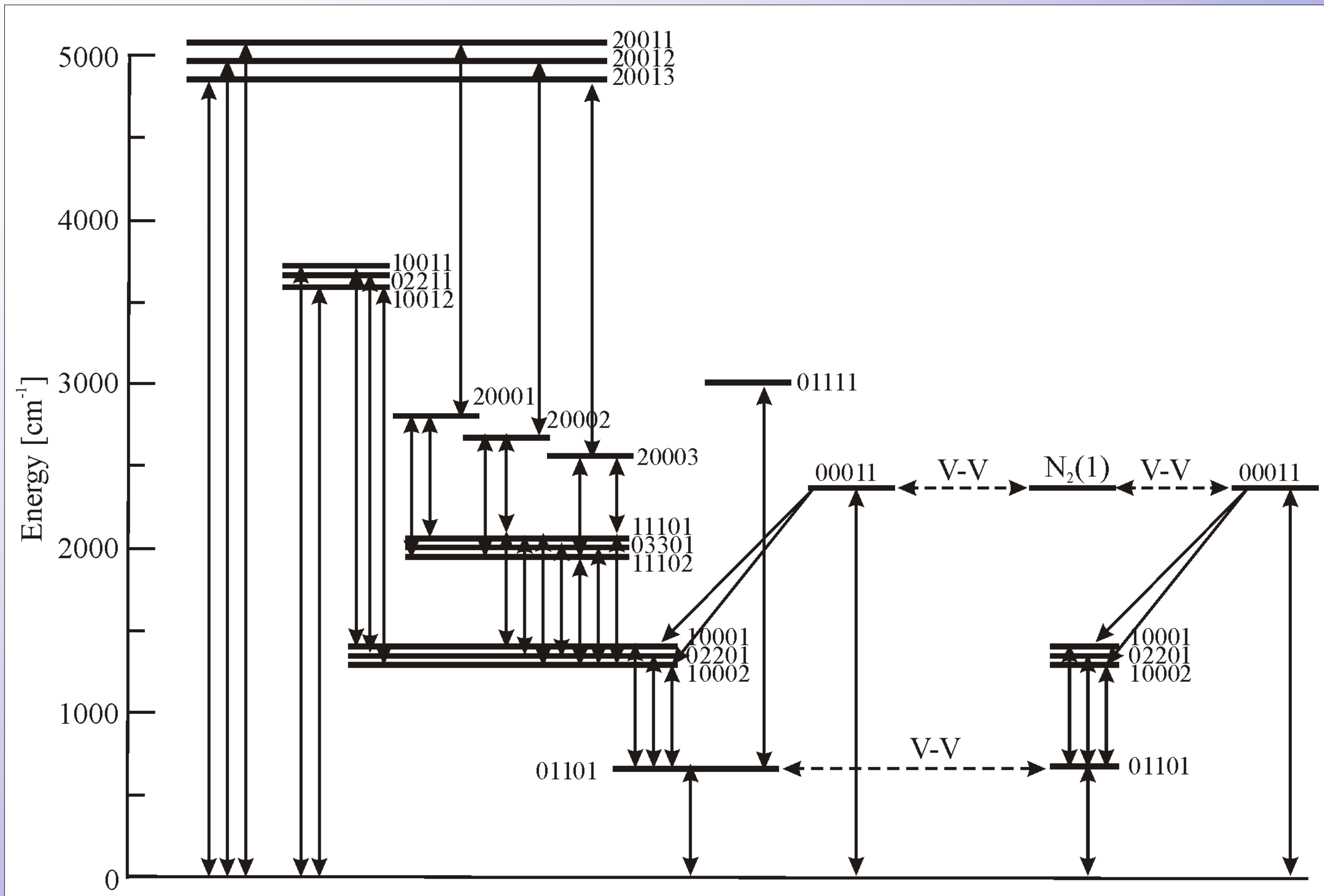
Five test atmospheric models: volume mixing ratios



Non-LTE calculations: ALI-ARMS research code



Vibrational levels and transitions for CO_2



$CO_2(v_2)$ levels pumping and quenching

$$CO_2(\nu_2) + O(^3P) \xleftrightarrow{k'_{VT}} CO_2(\nu_2 + 1) + O(^3P)$$

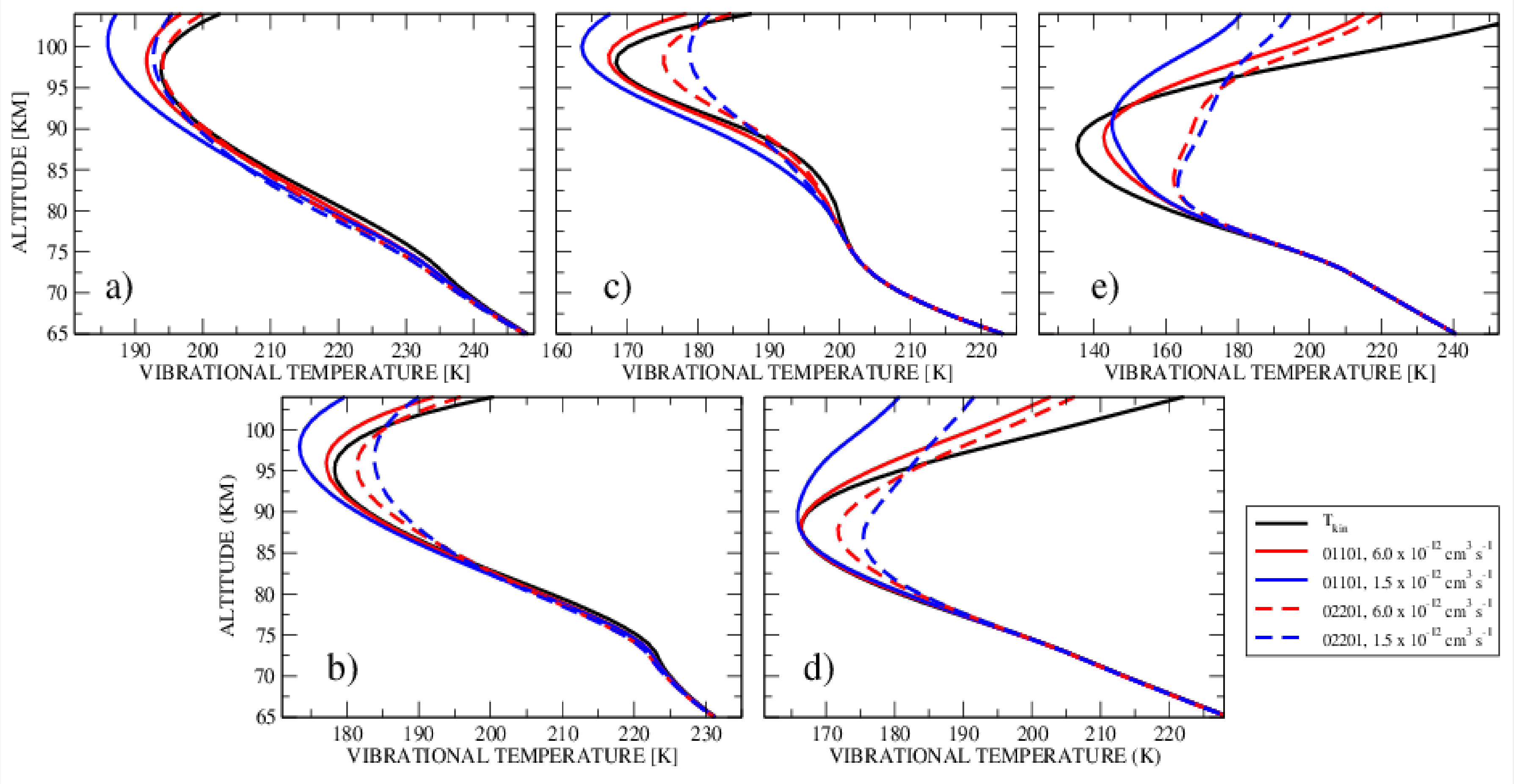
$$CO_2(\nu_2 + 1) \rightarrow CO_2(\nu_2) + h\nu(667cm^{-1})$$

$CO_2(v_2)$-O quenching rate coefficient, $k_{VT}(CO_2\text{-}O)$

$k_{VT}\{CO_2\text{-}O\}$ [cm^3s^{-1}]	Reference	Comments
$3–30 \times 10^{-14}$	Crutzen (1970)	First guess
2.4×10^{-14}	Taylor (1974), Center (1973)	Laboratory measurements
5.0×10^{-13}	Sharma and Nadille (1981)	Atmospheric retrieval
1.0×10^{-12}	Gordiets et al. (1982)	Numerical experiment
2.0×10^{-13}	Kumer and James (1983)	Atmospheric retrieval
2.0×10^{-13}	Dickinson (1984); Allen (1980)	Laboratory measurements
5.2×10^{-12}	Stair et al. (1985)	Atmospheric retrieval
3.5×10^{-12}	Sharma, (1987)	Atmospheric retrieval
$3–9 \times 10^{-12}$	Sharma and Wintersteiner (1990)	Atmospheric retrieval
1.5×10^{-12}	Shved et al. (1991)	Laboratory measurements
1.3×10^{-12}	Pollock et al. (1993)	Laboratory measurements
5.0×10^{-12}	Ratkowski et al. (1994)	Atmospheric retrieval
5.0×10^{-13}	Lilenfeld (1994)	Laboratory measurements
1.5×10^{-12}	Vollmann and Grossmann (1997)	Atmospheric retrieval
1.4×10^{-12}	Khvorostovskaya et al. (2002)	Laboratory measurements
1.8×10^{-12}	Castle et al. (2006)	Laboratory measurements
6.0×10^{-12}	Gusev et al. (2006)	Atmospheric retrieval
1.5×10^{-12}	Huestis et al. (2008)	Recommended value

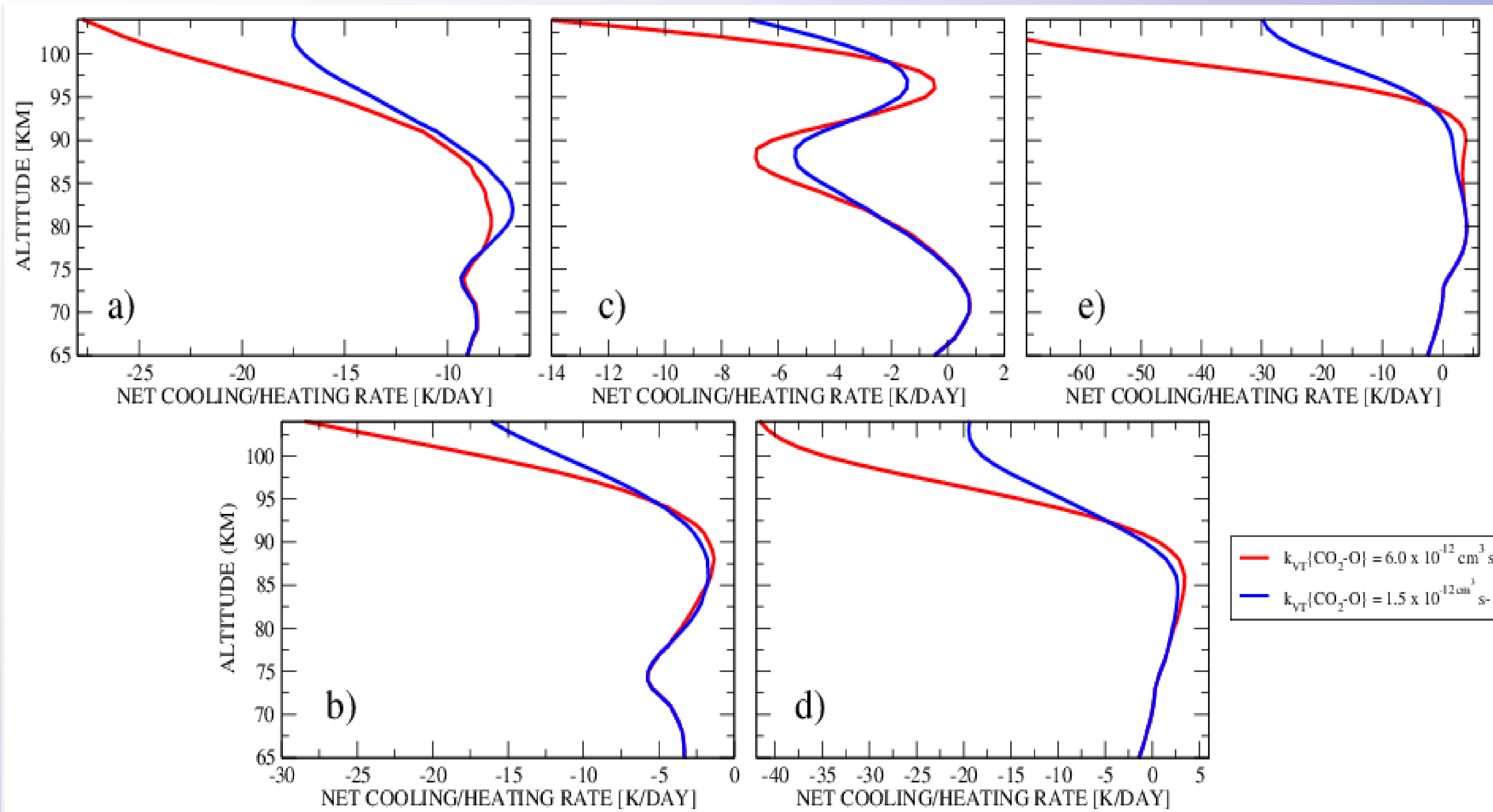
- $k_{VT}(CO_2\text{-}O)$ is **crucial** for estimating the h(z) in MLT and for T(z) retrievals from the 15µm radiance.
- However, there's a **factor of 4** difference between the lab and atmospheric measurements (see table).
- The next slide shows the effect of $k_{VT}(CO_2\text{-}O)$ on the $CO_2(v_2)$ levels

$CO_2(v_2=1)$ and $CO_2(v_2=2)$ levels populations



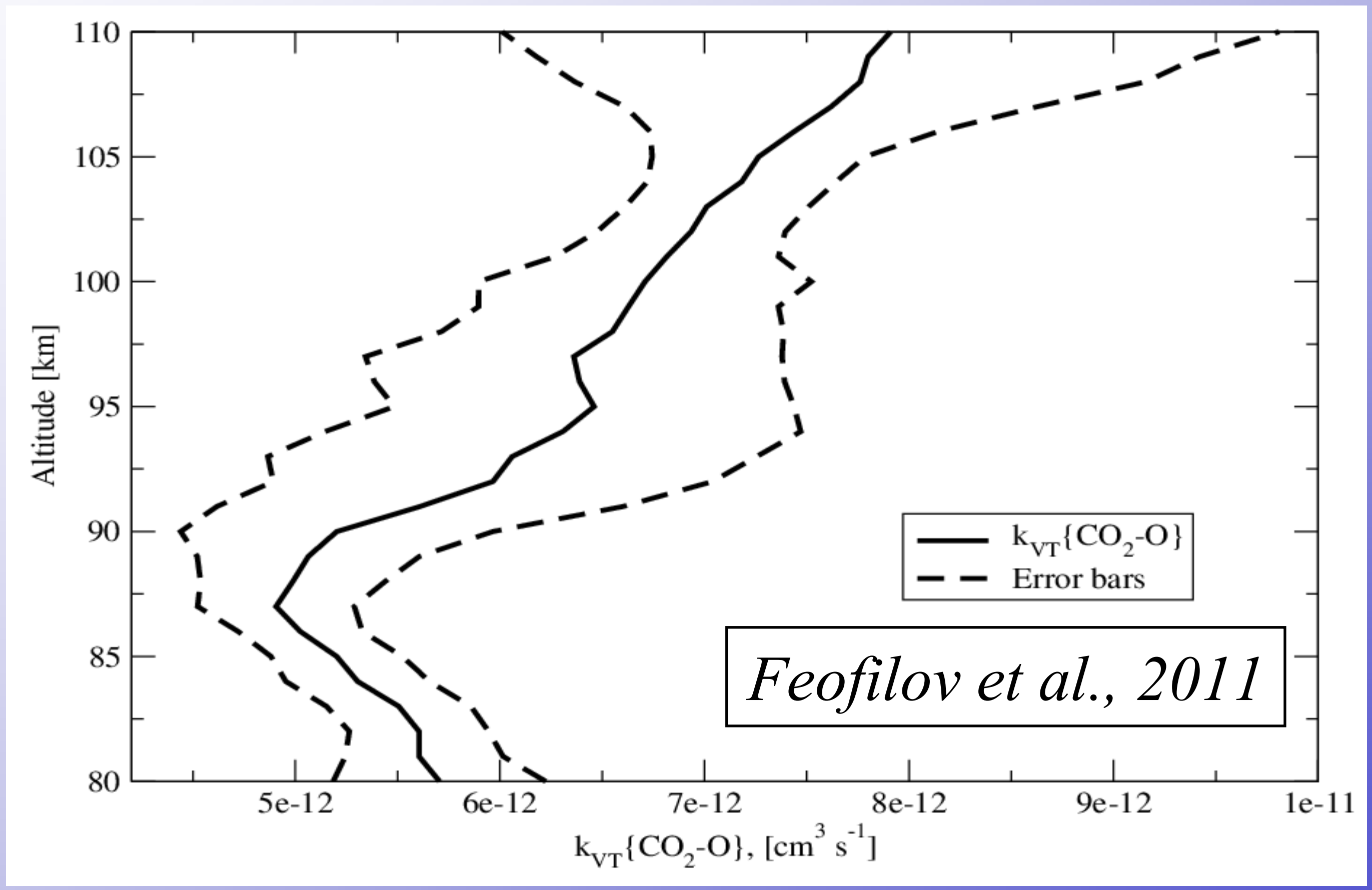
Note two sets of curves calculated for two values of $CO_2(v_2)$-O quenching rate coefficient

CO_2 cooling/heating rates



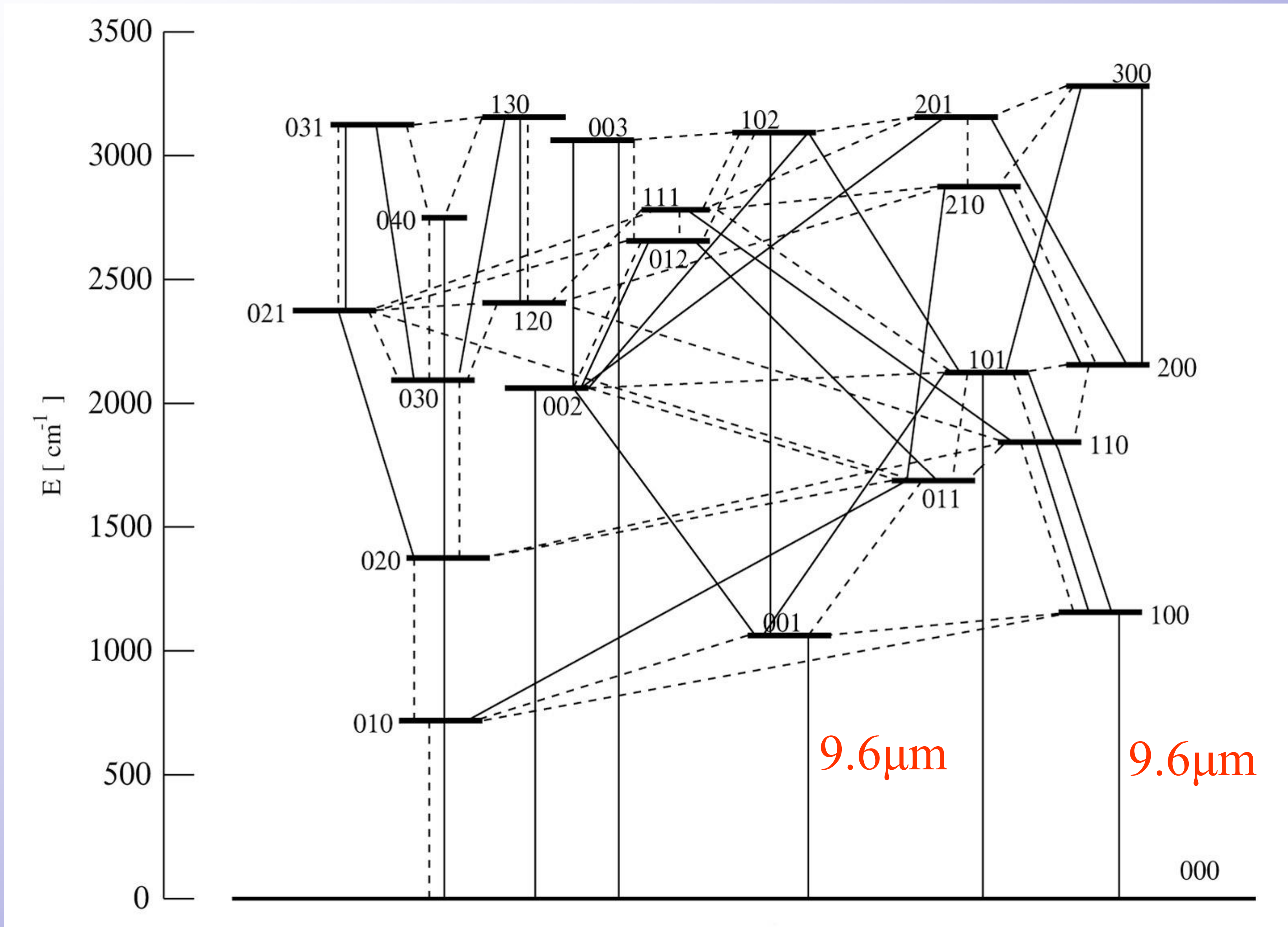
Note two sets of curves calculated for two values of $CO_2(v_2)$-O quenching rate coefficient

$k_{VT}(CO_2\text{-}O)$ retrieved from overlapping satellite and lidar measurements

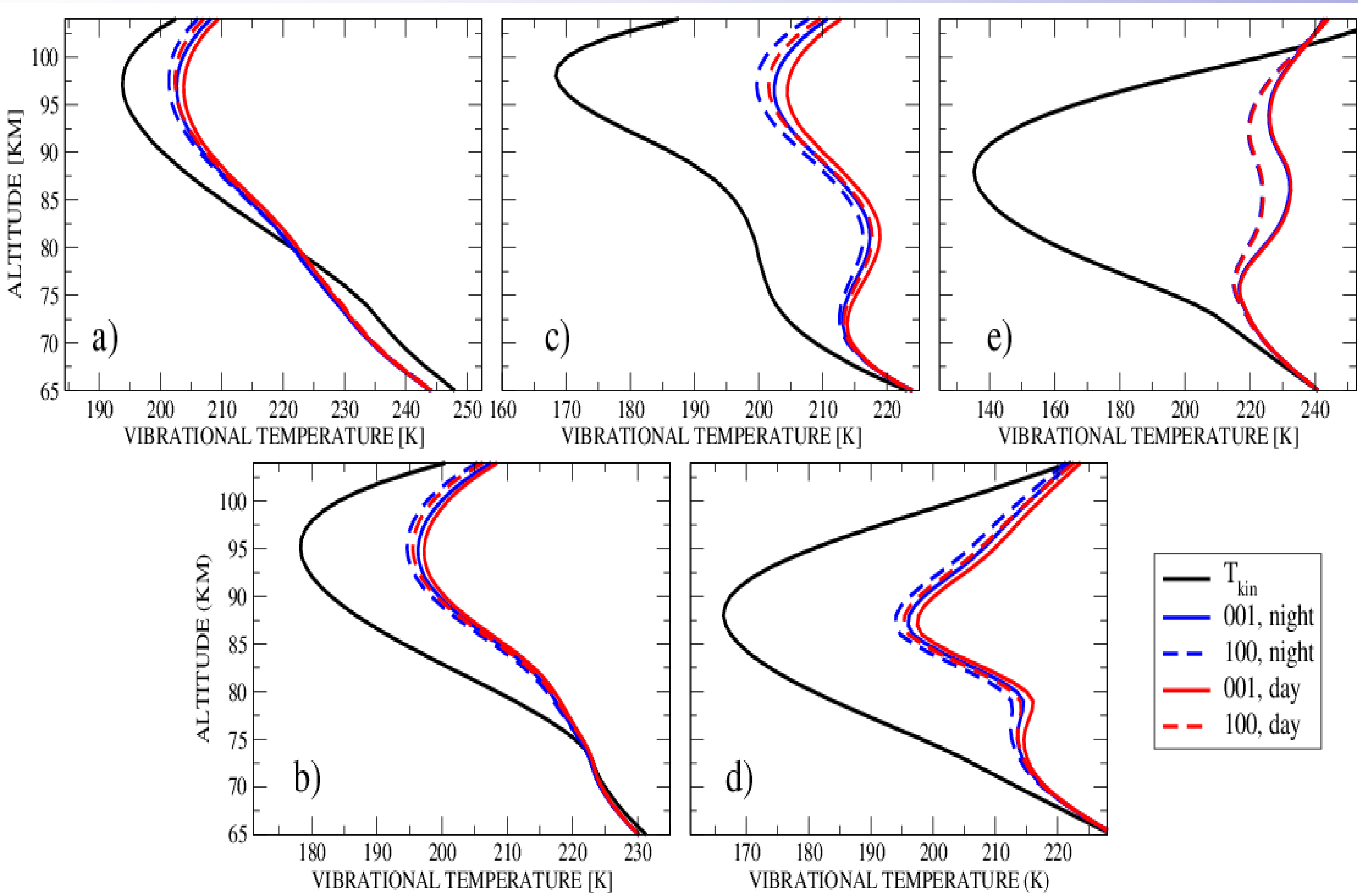


Possible explanation: in the real atmosphere the oxygen atoms are "non-thermal" or "hot" serving as an additional source of $CO_2(\nu_2)$ excitation

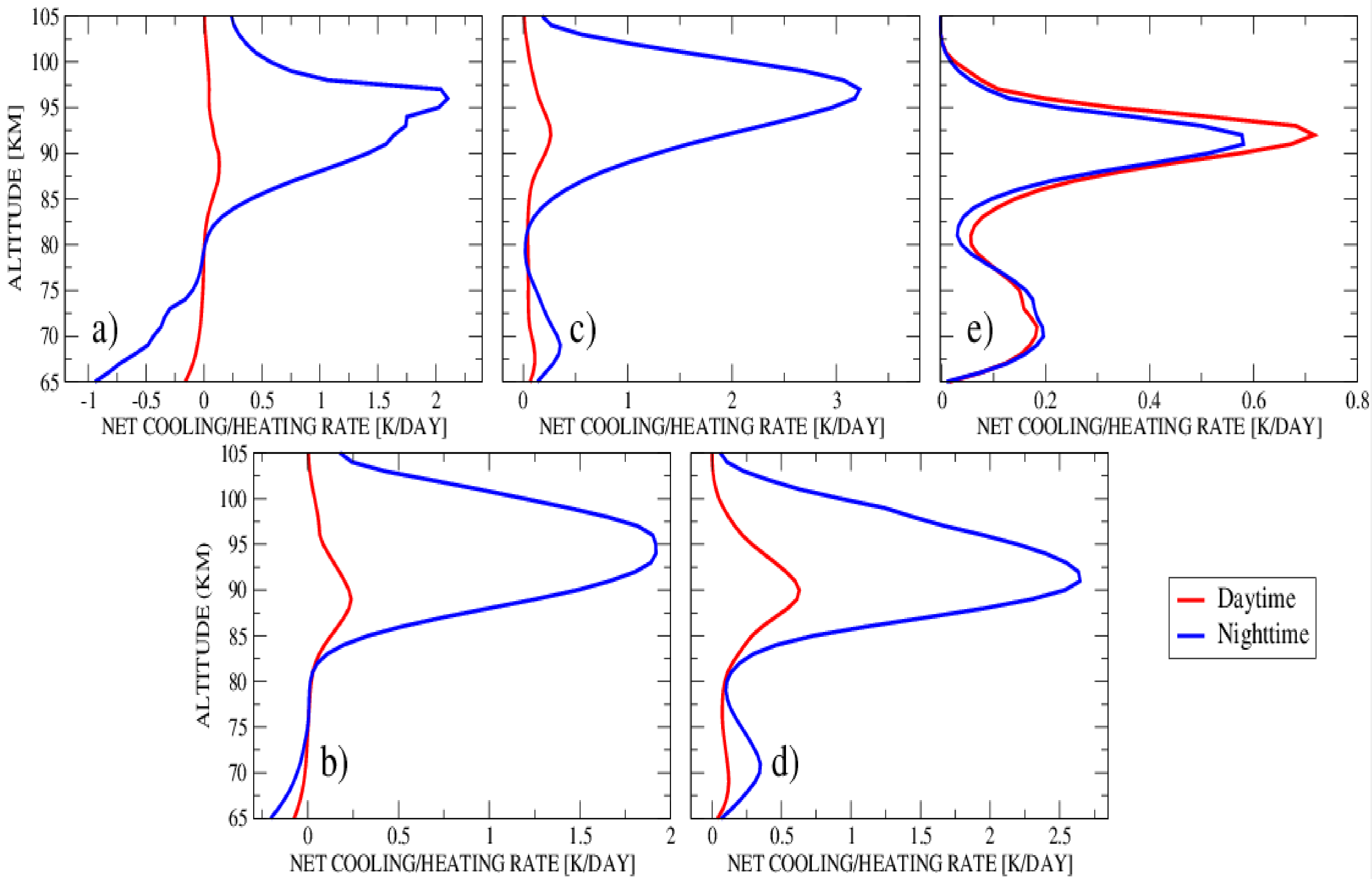
O_3 levels and transitions



Non-LTE effects in O_3

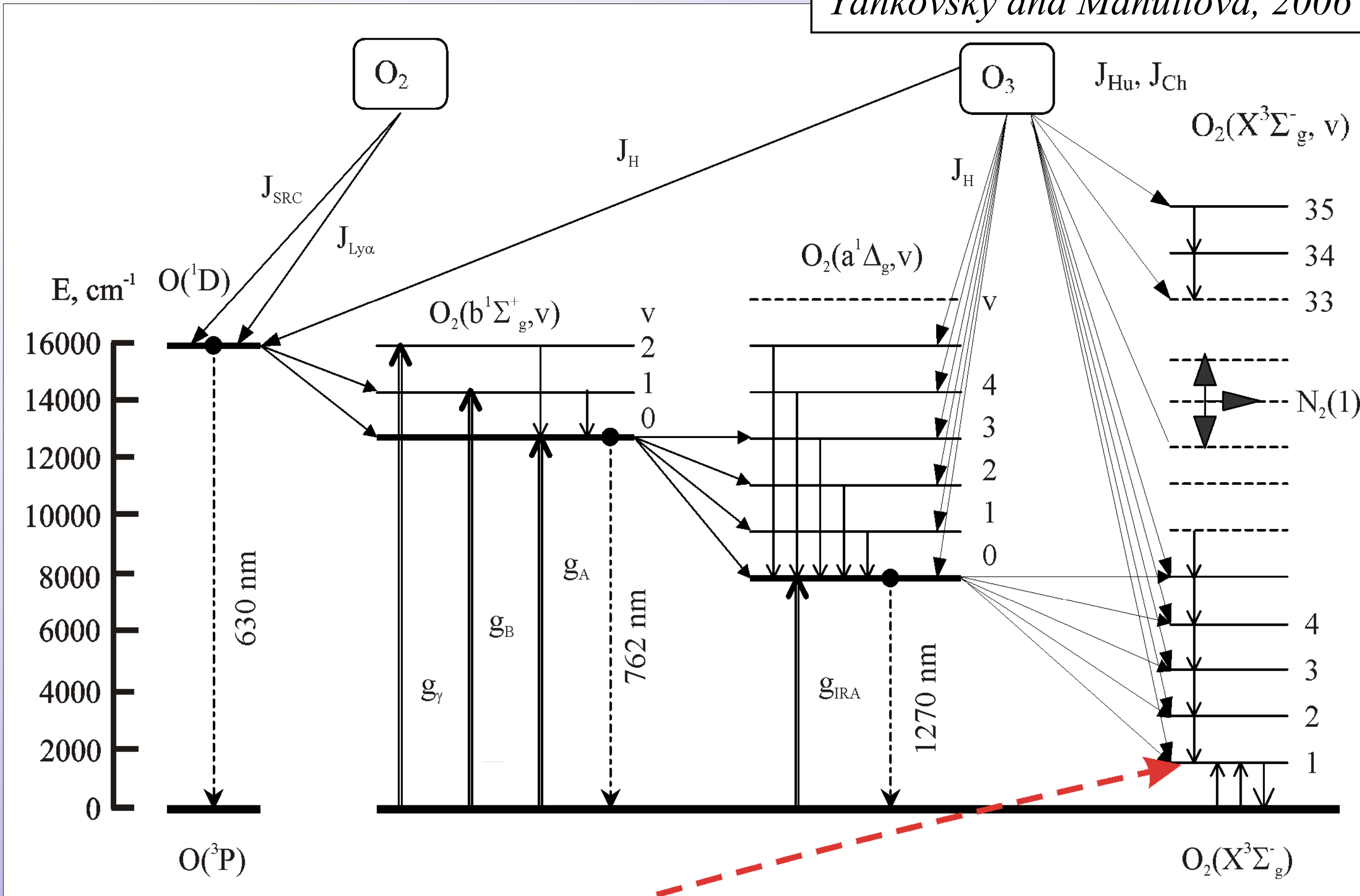


O_3 cooling/heating rates



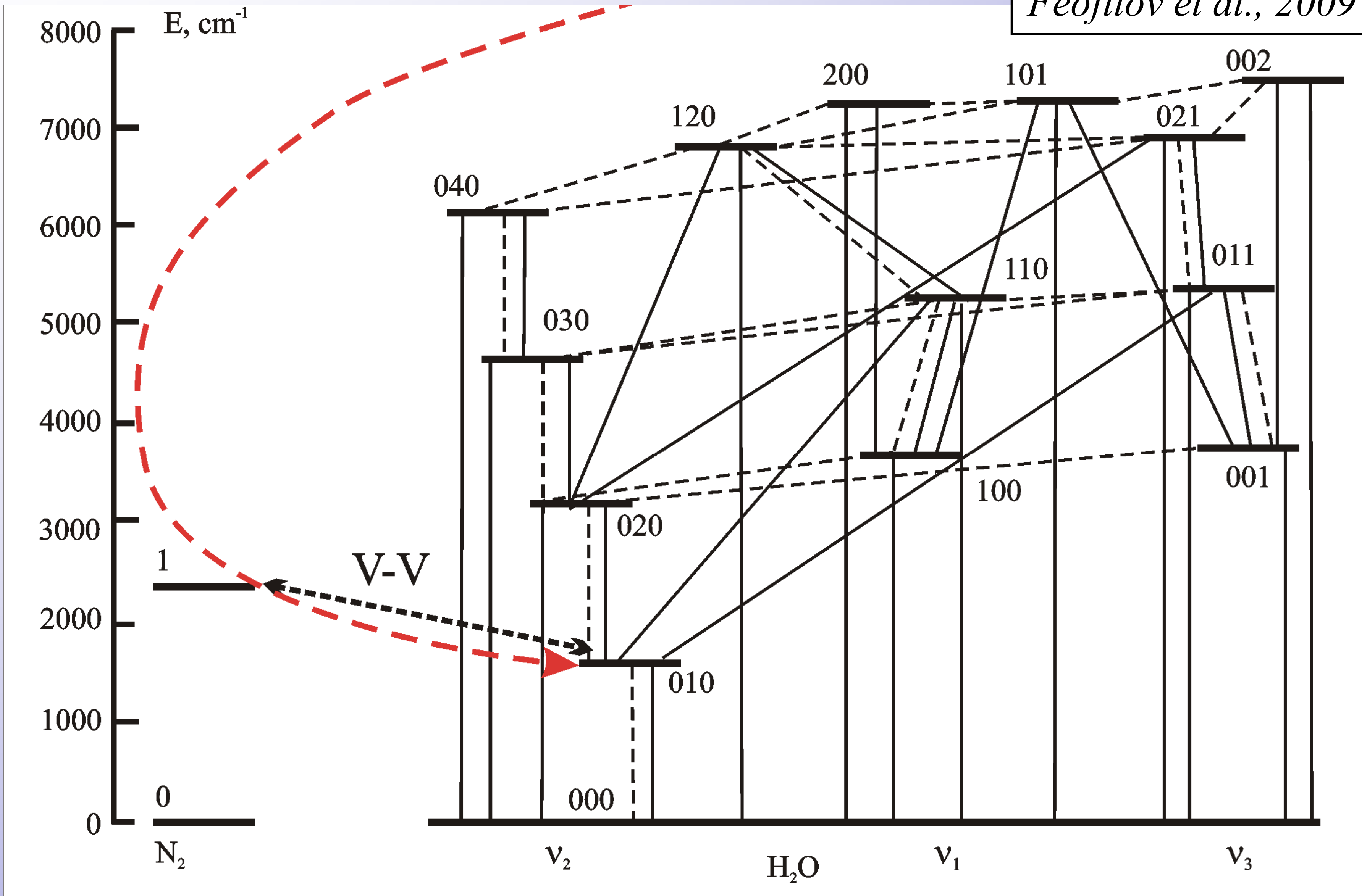
O_2/O_3 photolysis products

Yankovsky and Manuilova, 2006

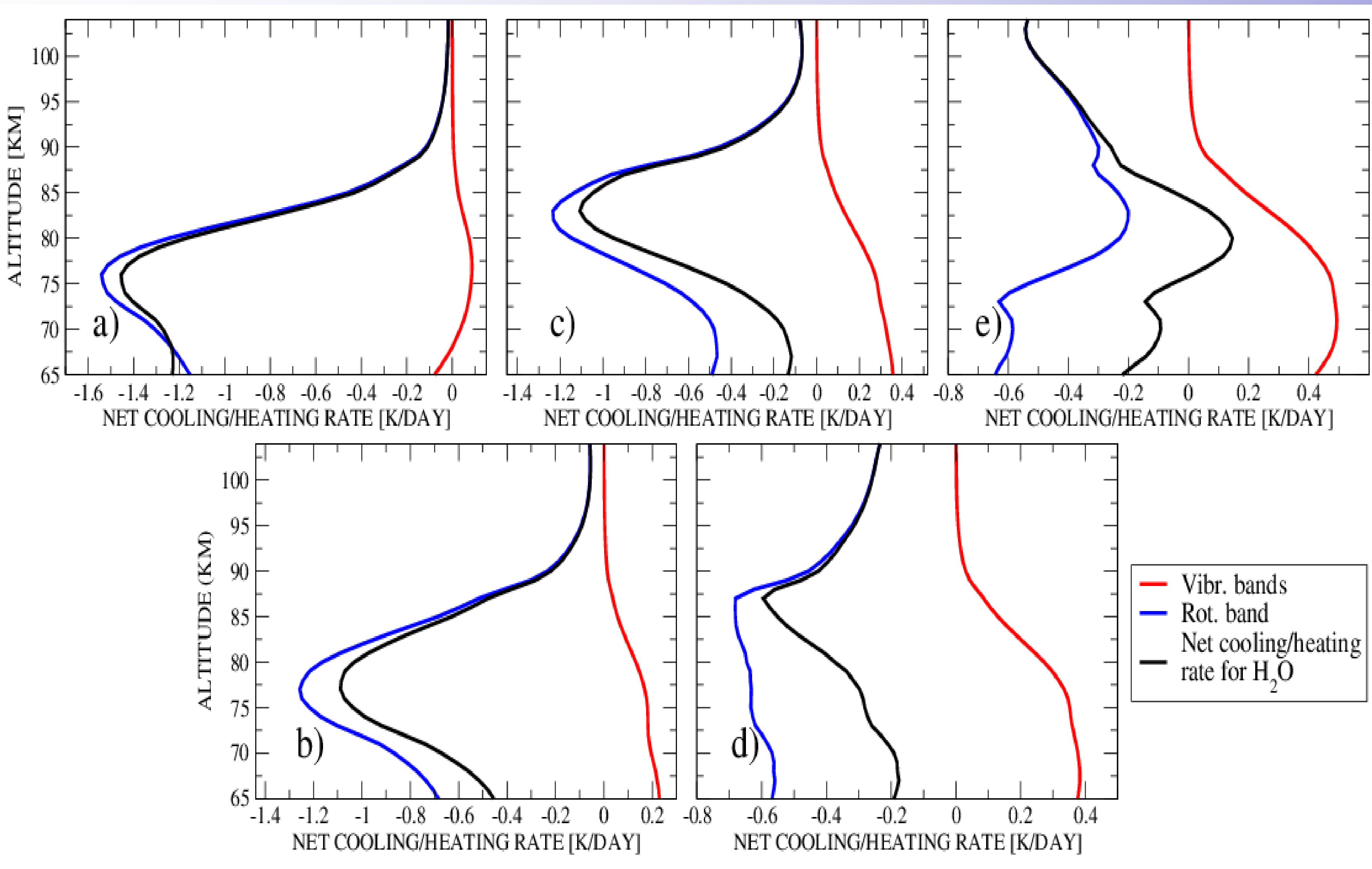


H_2O levels and transitions

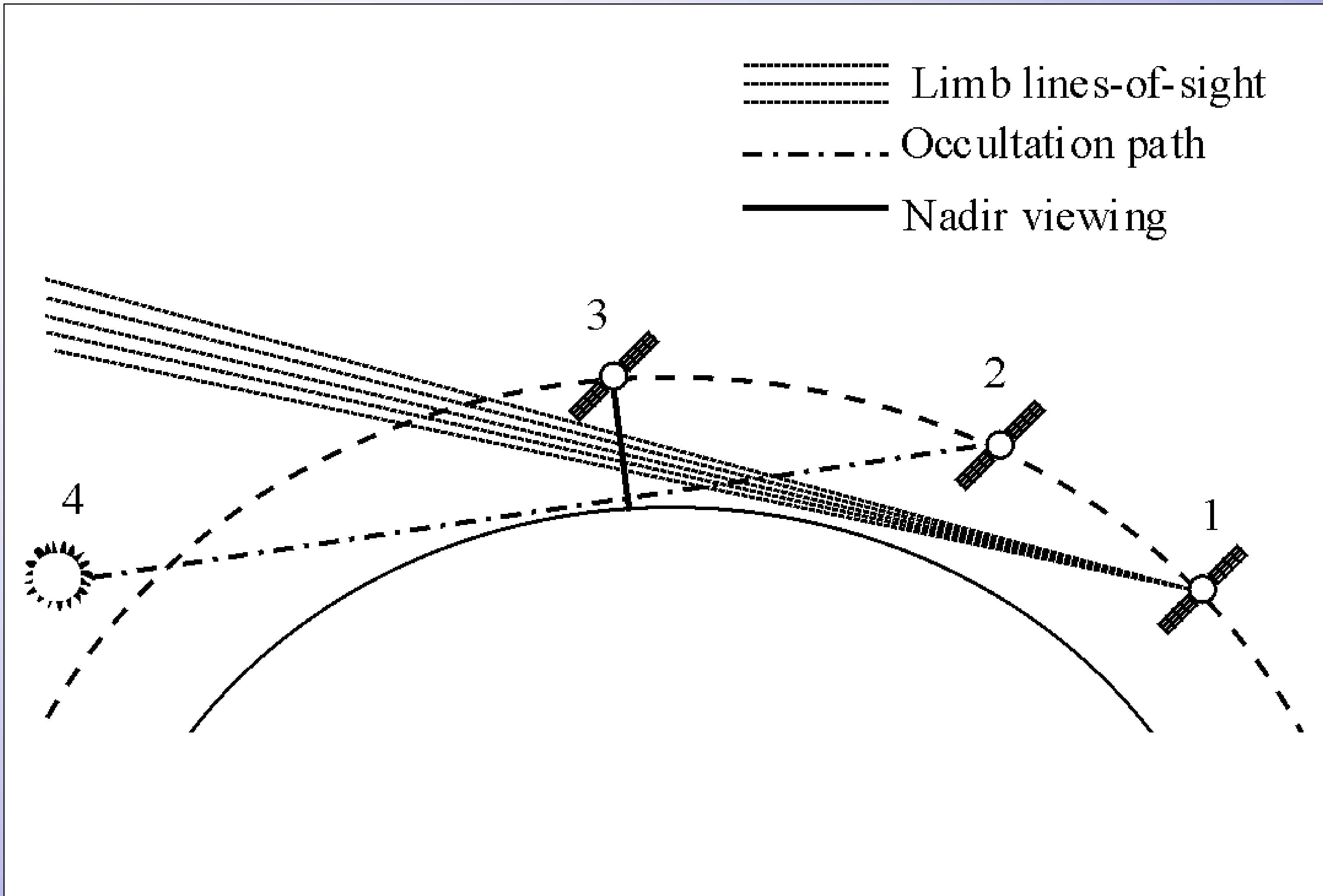
Feofilov et al., 2009



H_2O cooling/heating rates in rotational and vibrational bands



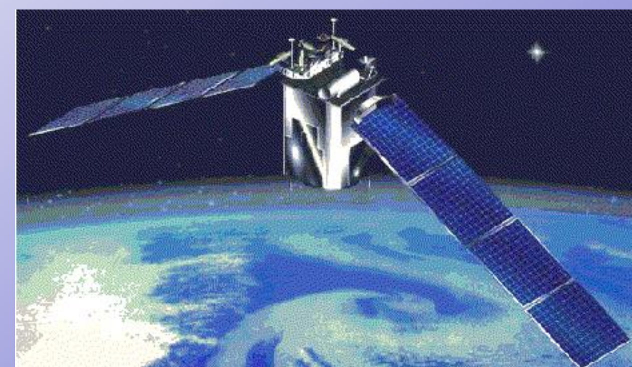
MLT observations from space



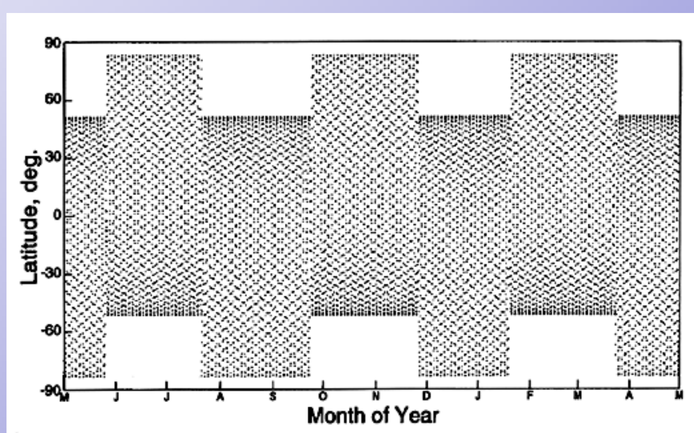
The SABER Instrument Aboard the TIMED Satellite

TIMED: Thermosphere, Ionosphere, Mesosphere Energetics & Dynamics

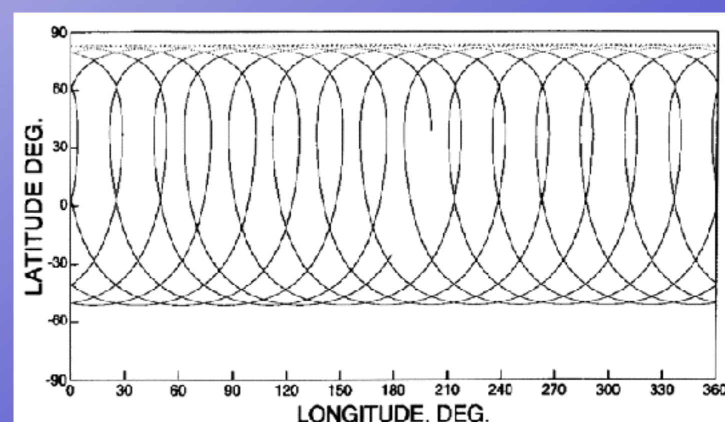
Mission launched on December 7, 2001
Data available since January 25, 2002
4 instruments:
GUVI, SEE, TIDI, **SABER**



Latitudinal coverage



Example of an orbit

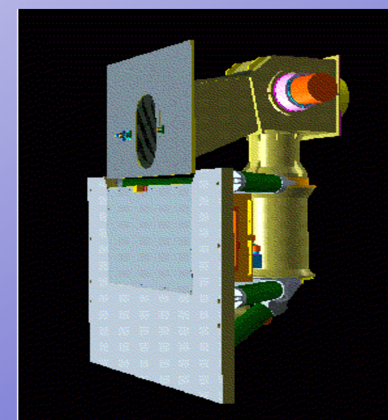


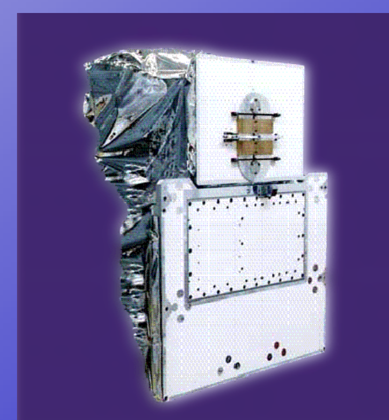
The SABER Instrument Aboard the TIMED Satellite

SABER: Sounding of the Atmosphere Using Broadband Emission Radiometry

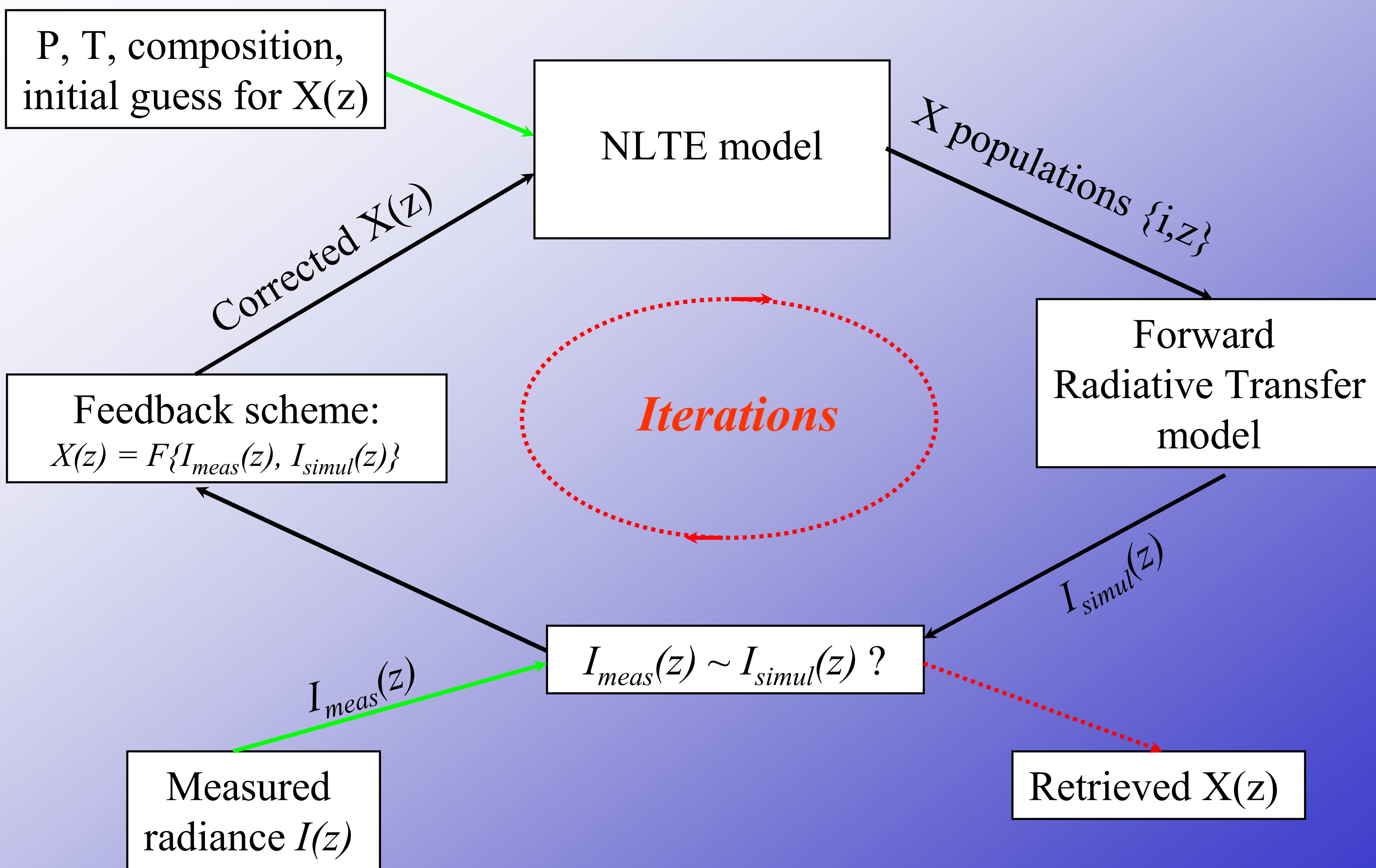
SABER instrument:

- Designed to study the Mesosphere and Lower Thermosphere (MLT)
- Limb scanning infrared radiometer (~10-100 km, ~2 km footprint)
- 10 broadband channels (1.27-17 µm)
- Products: kinetic temperature, CO_2, O_3, H_2O, NO, O_2, OH, O, H

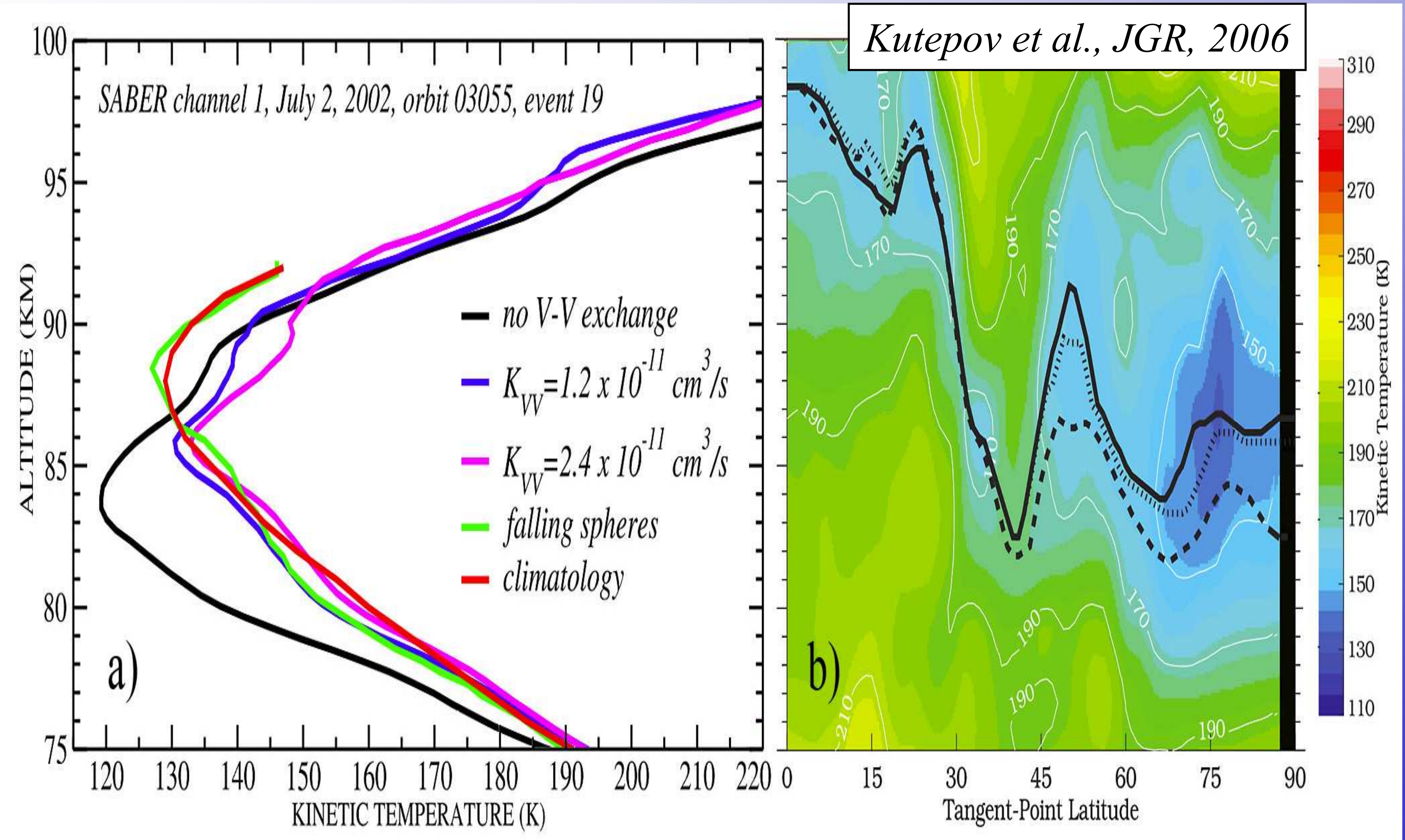




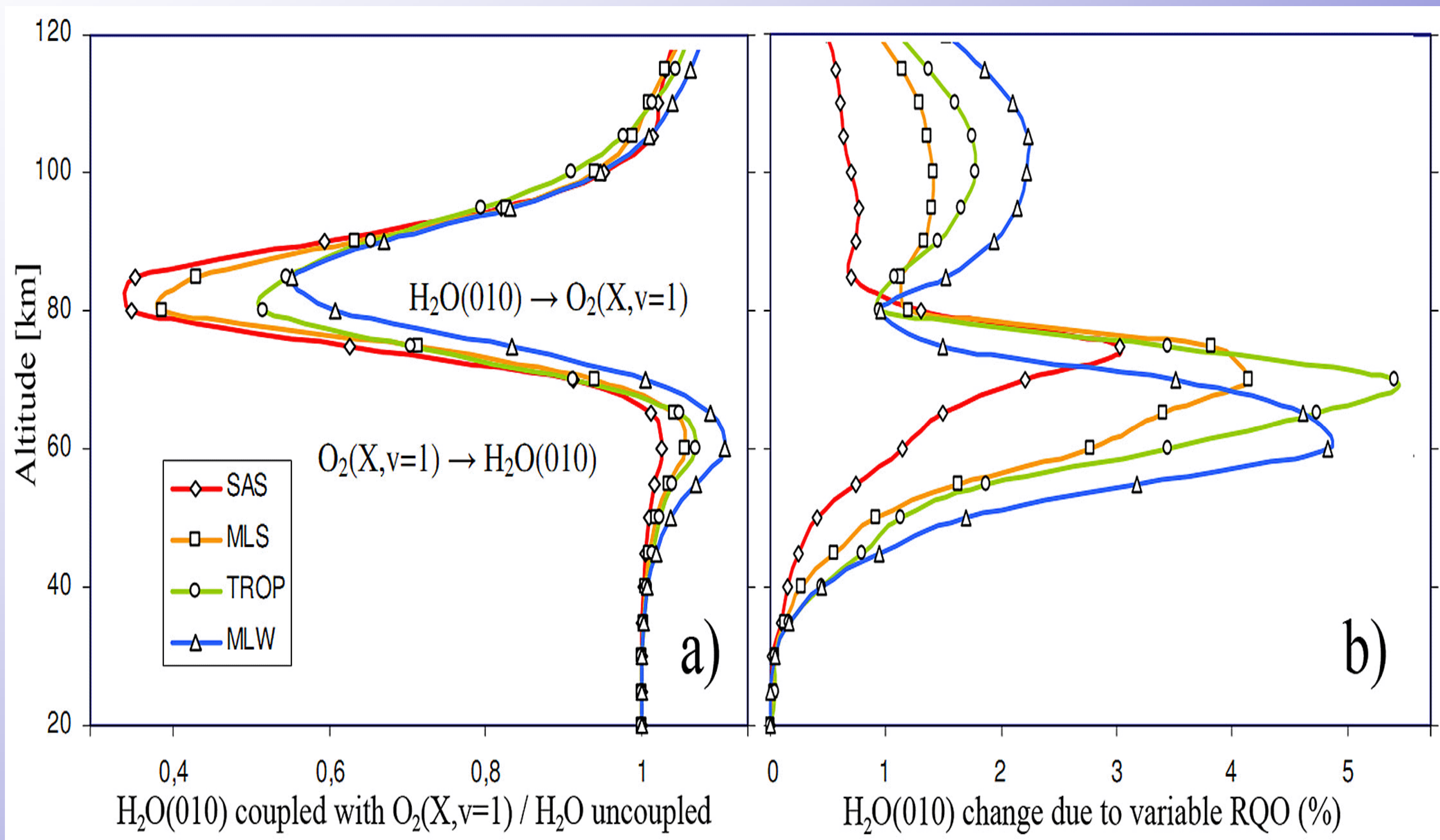
General approach to X(z) retrieval: forward fitting



Peculiarities of the non-LTE temperature retrievals: V-V exchange between isotopes



Peculiarities of the non-LTE H_2O retrievals: proper taking into account pumping from $O_2(X,v=1)$



Polar mesospheric clouds and P, T, H_2O

Picture taken by Martin Koitmäe on the 26.07.09, at 58°N, 25°E, Soomaa National Park, Estonia

A simplified model of PMC formation

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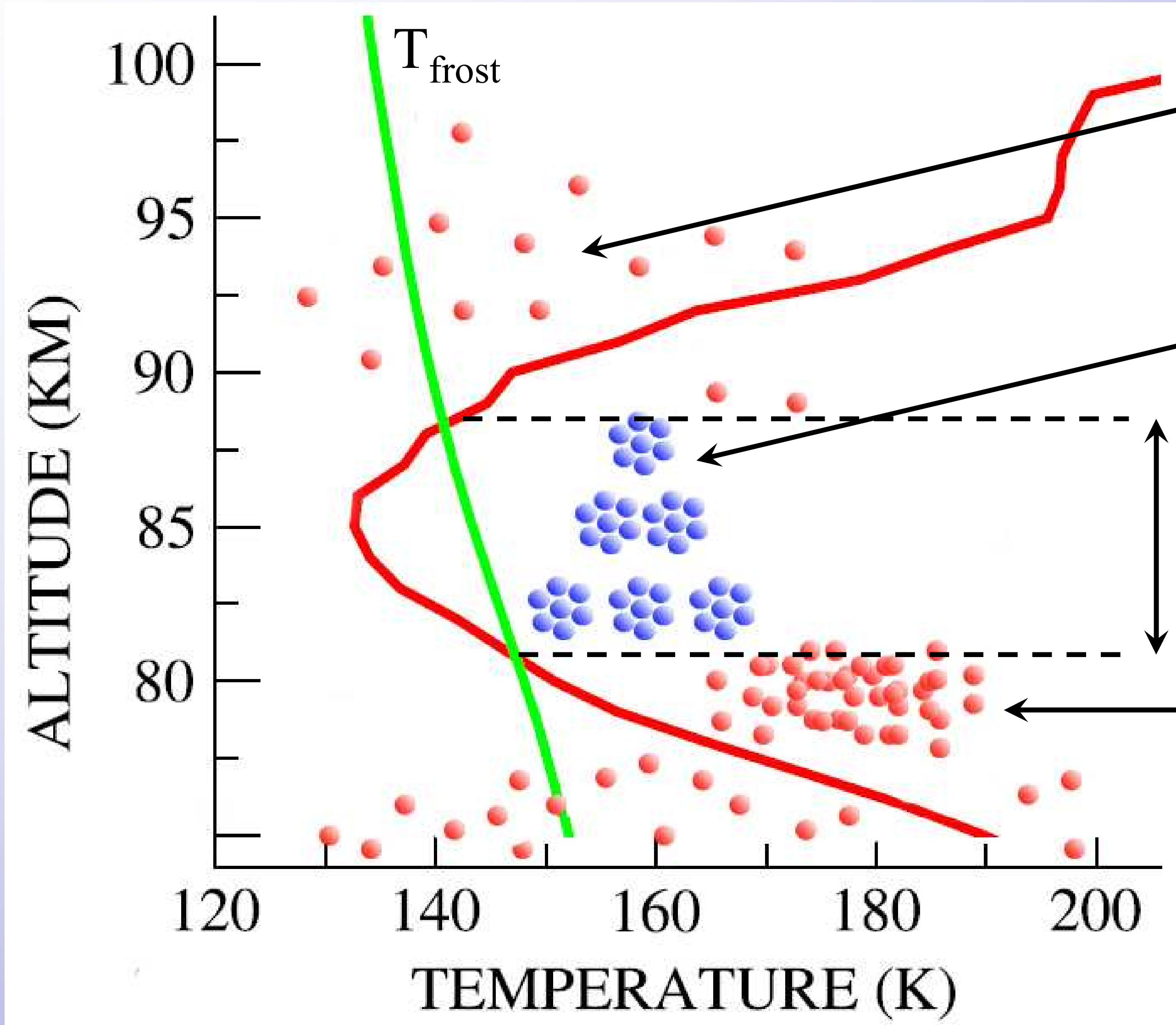


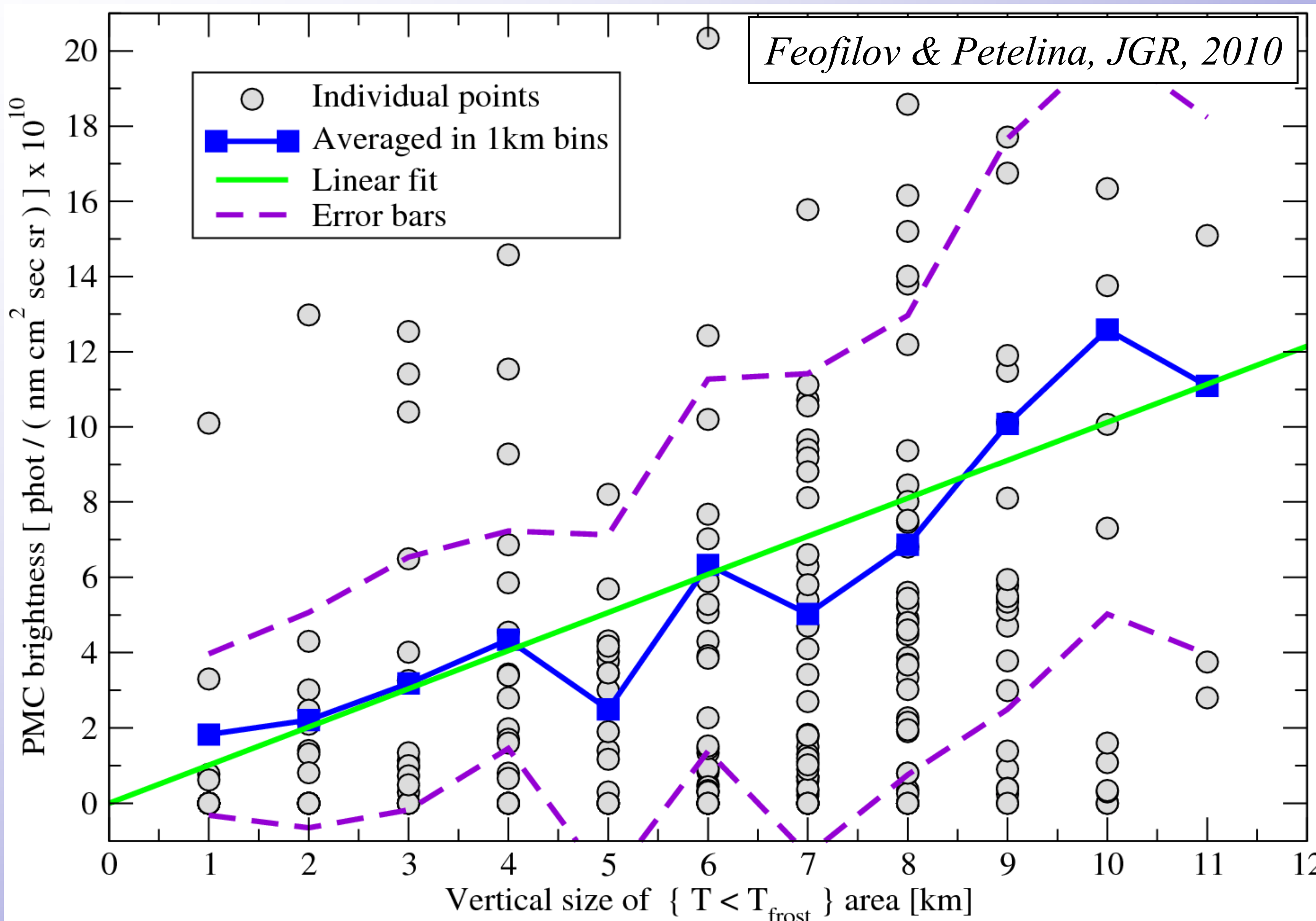
Water vapor

Precipitating ice particles

L_{frost}: the vertical size of the area where PMCs can form

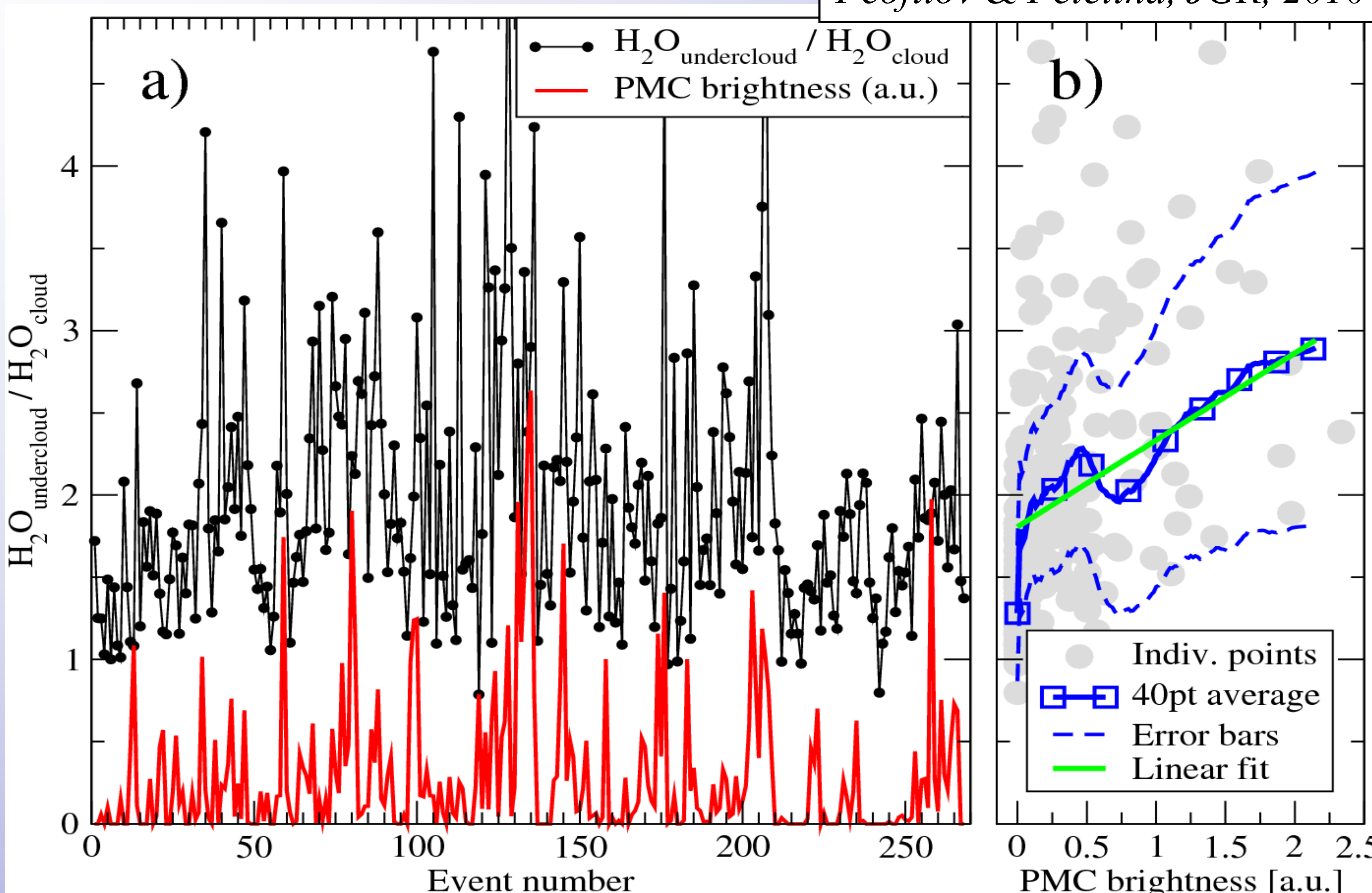
Sublimated ice = enhanced H_2O

OSIRIS PMC brightness vs integrated L_{frost}

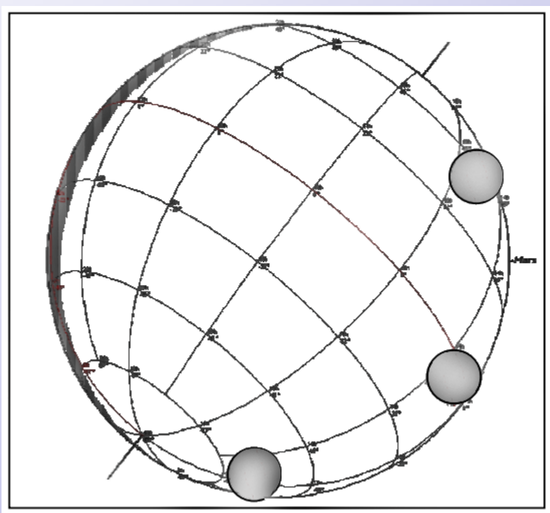


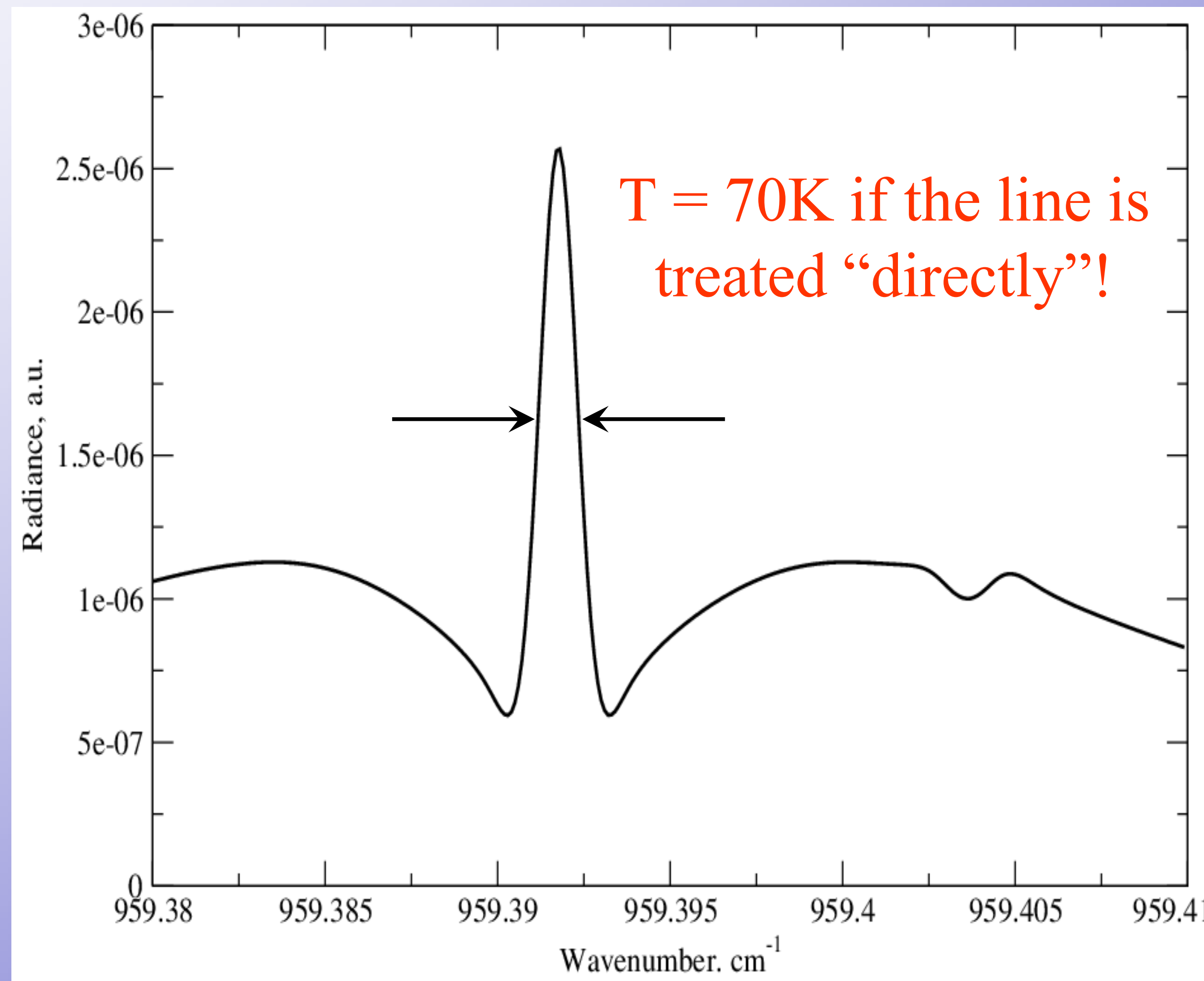
PMC brightness correlated with H_2O VMR in and below the cloud

Feofilov & Petelina, JGR, 2010



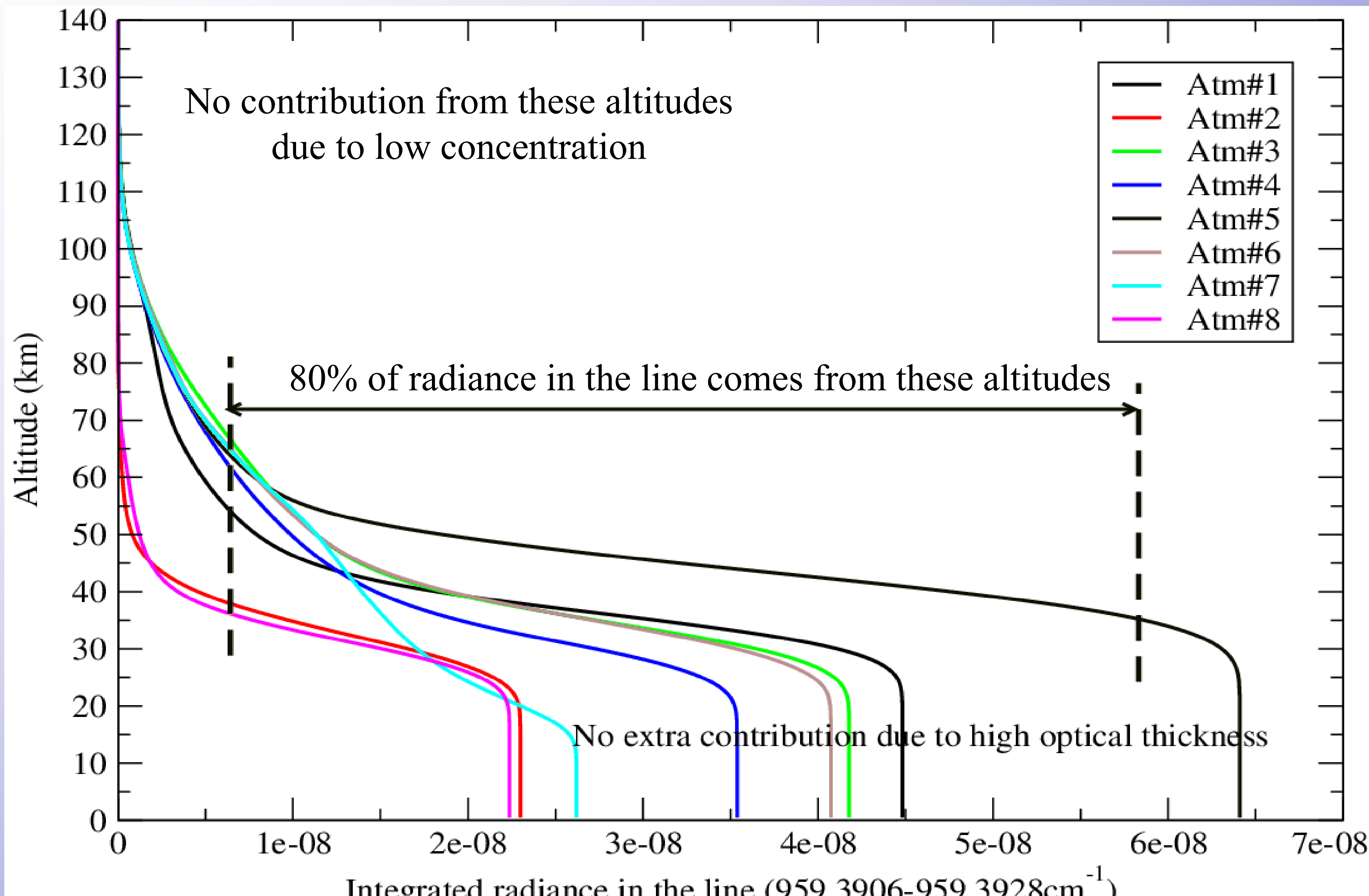
Upper atmosphere affecting lower atmosphere measurements





HIPWAC measurements of Martian atmosphere in nadir mode (ground observations of Mars)

Contribution of various atmospheric layers to the 959cm^{-1} emission line



Conclusions

- MLT is the area sensitive both to solar variability and the influence of the lower atmosphere.
- Three main contributors to MLT radiative balance are CO_2, O_3, and H_2O.
- Infrared emissions can provide the information about P,T, and a number of gaseous components in MLT.
- Estimating the infrared emissions in the MLT requires accounting for non-LTE effects.
- The calculated non-LTE populations of the vibrational levels are sensitive to numerous sources and sinks of energy some of which are poorly known.
- Non-LTE emissions are to be taken into account when the line-of-sight of a given instrument passes through the corresponding atmospheric layers.