NEW TECHNIQUE FOR CALCULATING THE NON-LTE INFRA-RED RADIATIVE COOLING/HEATING RATES IN THE MARTIAN GCM.

A.G. Feofilov, A.A. Kutepov, *NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA (artf@usm.lmu.de)*, **A.S. Medvedev, P. Hartogh,** *Max-Planck-Institute for Solar System Research, Katlenburg-Lindau, 37191, Germany*.

Abstract

We developed a new efficient and accurate routine for calculating the non-LTE radiative cooling/heating (C/H) rates in CO_2 bands in the Martian atmosphere. This routine: a) relies on the exact accelerated lambda iteration (ALI) solution of the vibrational non-LTE problem in CO_2; b) utilizes opacity distribution function (ODF) technique; c) allows varying all input collisional rate and spectroscopic parameters; d) calculates C/H with a prescribed accuracy.

New routine is about 10^4 times faster than the line by line (LBL) approach when reproducing C/H data with ~15–20% accuracy. This allowed implementing the routine to the general circulation and climate model of the Martian atmosphere developed in the Max-Planck Institute for Solar System Research, and running the model at the computers of moderate performance.

The difference between the "standard cooling to space" approximation and the new radiative transfer routine are discussed.

Formulation of the problem

In the middle and upper atmosphere where the frequency of molecular collisions is low, the local thermodynamic equilibrium is broken and the population of ro-vibrational levels of molecules deviates from the Boltzmann law (non-LTE). Accurate calculations of the non-LTE cooling/heating rates require a self-consistent solution of the ro-vibrational relaxation problem and the radiative transfer equation for a large number of ro-vibrational lines. This so-called line-by-line (LBL) approach [*López-Puertas and López-Valverde*, 1995], [*Gusev and Kutepov*, 2003]) is very time consuming. On the other hand, schemes based on the "cooling-to-space" radiative transfer approximation, although fast, do not provide the desired accuracy [*López-Valverde and López-Puertas*, 2001].

Calculation approach

The new routine represents an optimized version of the exact non-LTE ALI–ARMS (Accelerated Lambda Iteration for Atmospheric Radiation and Molecular Spectra) code described by *Kutepov et al*. [1998] and *Gusev and Kutepov* [2003]. This scheme: a) utilizes a differential equation approach to solve the radiative transfer equation, and relies on the exact accelerated lambda iteration (ALI) solution [*Rybicki and Hummer*, 1992, and references therein] of the vibrational non-LTE problem; b) applies the opacity distribution function (ODF) technique [*Mihalas*, 1978] that treats each ro-vibrational band as a single line of a special shape with the detailed accounting for both the Doppler and pressure broadening effects; c) allows for variable input of all collisional rates and spectroscopic parameters, volume mixing ratios (VMRs), including that for O(3P) atoms; and d) calculates cooling/heating with a prescribed accuracy by utilizing the optimized sets of vibrational levels and bands. The accuracy of the scheme implemented in the model is compared with that provided by the ALI–ARMS line-by-line reference model which included 60 vibrational levels of five CO_2 isotopes and 150 ro-vibrational bands. The scheme is about 10^4 times faster than the line-by-line reference model. This acceleration has been achieved a) by applying the ODF (the acceleration factor is approximately equal to the mean number of lines in the band branches), and b) by utilizing the reduced number of the CO_2 vibrational levels and bands (only fundamental bands of isotopes 626, 636 and 628, and first hot bands of isotope 626 were included).

Figure 1 demonstrates the accuracy of the scheme for the three typical temperature profiles in the Martian atmosphere (left panel) for the night time conditions (only 15 μm CO_2 band is operational). Two of these profiles correspond to the measurements during the Pathfinder (1) and the Viking-1 (2) entries. The third one is taken from the model calculations of *Bougher and Roble* [1991]. The thick lines in the Figure 1 denote the reference calculations. The O(3P) VMR for these calculations was taken from [*Nair et al*., 1994]. The absolute error seen in the figure reaches 85 K day^{-1} for the profile No. 3 with the warm mesosphere. It is mostly caused by the reduced set of levels and bands compared to the complete reference model. This error can be decreased by employing a more detailed set. This is demonstrated in Figure 1 for the profile No. 3 where we included additionally the second hot bands of the main isotope 626 and the first hot bands of the isotopes 636 and 628. The corresponding error in cooling rates is reduced by a factor 2, however, at the expense of the computing time (which increased by a factor of about 2 as well).

We use the same scheme for estimating the cooling/heating rates at all altitudes down to the surface. The ODF approach in the LTE region works, in gen-

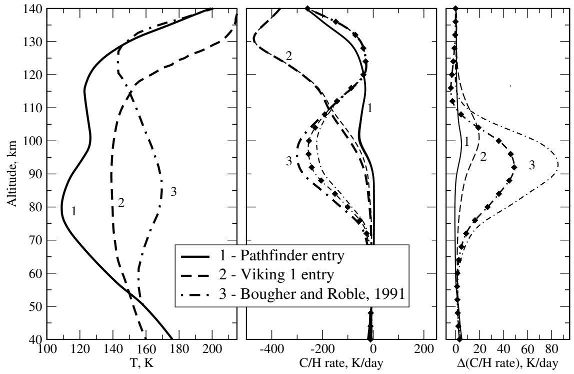

Figure 1: Comparison of the exact cooling rates due to the 15 μm CO_2 band with those computed with the optimized scheme. Left panel: temperature profiles used for the comparison (see text). Central panel: total cooling/heating rates. Thick lines denote the exact calculations for the corresponding temperature profiles. Thin lines correspond to the calculations with the optimized scheme. The thin line with filled diamonds represents calculations with the extended set of levels (see text). Right panel: errors of the estimation of the cooling/heating rates by the optimized (thin lines) and by the extended (thin line with filled diamonds) schemes.

eral, similar to the narrow band technique. This allows for a direct accounting of the radiative properties of the ground, because the differential radiative transfer equation solved by the scheme uses the radiation from the surface as a lower boundary condition. Compared to the line-by-line calculations, the ODFs overestimate cooling near the ground. We minimized this error to 1-2 K day^{-1} by modifying the shape of ODFs in the lower atmosphere.

CO_2 Near-Infrared Absorption

The routine described above allows to calculate the heating effect due to the absorption of the solar near-infrared radiation. This, however, decelerates the total CO_2 radiation calculations due to the increased number of the bands which have to be accounted for. To accelerate calculations one may use the advantage of the fact that the solar add-on to non-LTE cooling/heating rates depends mainly on the pressure and solar zenith angle [*Forget et al.*, 1999], and in the lesser extent, on temperature. This approach is also implemented to the code. In the central panel of Figure 2, we plotted the exact solar add-ons due to the absorption in the near-infrared bands for the overhead solar conditions computed with our reference line-by-line model for the three typical temperature profiles described above. These heating rates are compared with the estimate from the parametric formula suggested by *Forget et al.* [1999]. The left panel of Figure 2 compares the total (day time) cooling/heating rates

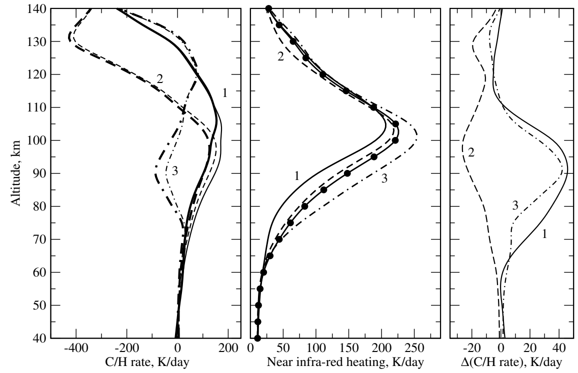

Figure 2: Same is in Fig. 1 but for the daytime solar overhead conditions. Left panel: total cooling/heating rates. Thick lines denote the exact calculations for the temperature profiles from the left panel in Fig. 1, thin lines are for the calculations with the optimized scheme. Central panel: heating rates caused by the absorption of the solar near infra-red radiation. The solid line with filled circles corresponds to the parameterization of *Forget et al* [1999]. Right panel: errors of estimation of the total cooling/heating rates.

computed by the optimized CO_2 radiation scheme with those calculated in the line-by-line reference model. The corresponding errors are given in the right-hand panel of the same figure. They vary from -25 to +40 K day^{-1}. The error in Solar heating rate calculation can be eliminated at the expense of decelerating the calculations by a factor of 3.

Application

The described above routine has been implemented into the Martian GCM developed in Katlenburg-Lindau [*Hartogh et al.,* 2005]. We present the results of the two runs – with the “cooling to space" module [*Cess and Ramanathan, 1972*], and with our routine. After the initial spinup, the model was run for a full Martian year, and the fields were averaged between Ls=85° and Ls=95° such that the figures show a zonal mean for the Southern winter solstice. The resulting temperature maps for the “cooling to space" and for our routine are shown on Figure 3 and Figure 4, respectively.

Although the non-LTE effects appear above ~80 km, the changes are seen much lower through the “downward control" effect and the corresponding changes in the circulation patterns, and due to the more precise radiative calculations at the lower boundary. The major changes are the stronger cooling in the lowermost atmosphere, and weaker cooling in the upper part. Both changes provide more similarity with the temperature fields measured by TES. Note the temperature gradient reversal over the winter pole and the related “polar warming". It appears as a result of the Hadley circula-

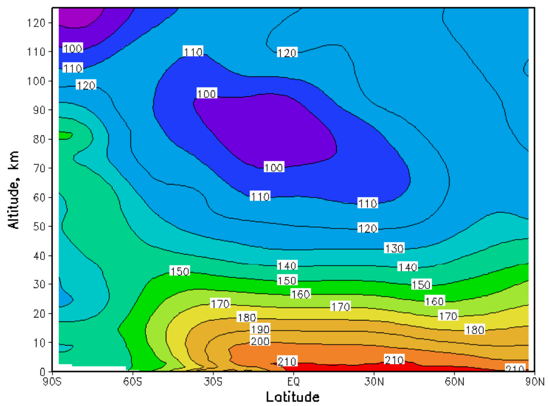

Figure 3: Temperature map obtained in GCM using cooling-to-space approximation

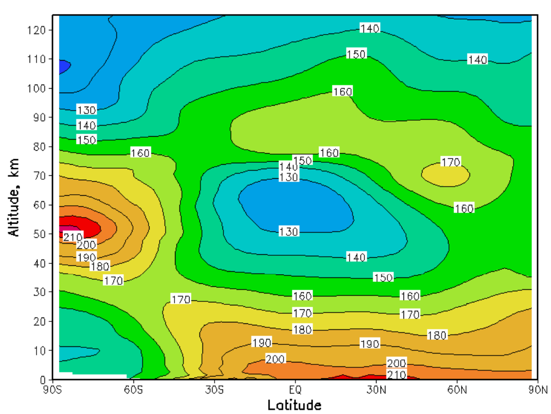

Figure 4: Temperature map obtained in GCM with the optimized non-LTE code

tion cell and strong interactions between the zonal mean state and longitudinal disturbances (planetary waves and tides). Similar sudden stratospheric warmings occur on the Earth during Northern hemisphere winters and last for about a week. However, on the Mars, they are persistent due to the stronger topographically induced waves. Further discussion is provided in [*Hartogh et al.,* 2005].

Conclusions

We present a new efficient technique for calculating the non-LTE infra-red radiative C/H rates in the Martian GCM.
The runs of Martian GCM with the new radiative C/H rates calculation have demonstrated the importance of correct non-LTE calculations for middle and upper atmosphere.
The inputs of the routine are the pressure, temperature, VMR profiles set in arbitrary altitude grid. It outputs the C/H rate in the original grid. The developed routine is a standalone code that can be linked to any GCM.

References

[1] Bougher, S.W., and R.G. Roble (1991), Comparative terrestrial planet thermospheres. 1. Solar-cycle variation of global mean temperatures, *JGR*, *96*, 11,045–11,055.

[2] Cess, R. D. and V. Ramanathan (1972), Radiative Transfer in the Atmosphere of Mars and that of Venus Above the Cloud Deck. J. Quant. Spect. Rad. Trans., *12*, 933

[3] Forget, F., F. Hourdin, R. Fournier, C. Hourdin, O. Talagrand, M. Collins, S.R. Lewis., P.L. Read., and J.-P. Huot (1999), Improved general circulation models of the Martian atmosphere from the surface to above 80 km, *JGR*, *104*, 24,155–24,175.

[4] Gusev, O.A., and A.A. Kutepov (2003), Non-LTE gas in planetary atmospheres, in *Stellar Atmosphere Modeling*, edited by I. Hubeny, D. Mihalas, and K. Werner, *ASP Conference Series*, *288*, 318–330.

[5] Hartogh,P., A.S. Medvedev, T. Kuroda, R. Saito, G. Villanueva, A.G. Feofilov, A.A. Kutepov, and U. Berger (2005), Description and climatology of a new general circulation model of the Martian atmosphere, *JGR*, *110*, E111008

[6] Kutepov, A.A., O.A. Gusev, and V.P. Ogibalov (1998), Solution of the non-LTE problem for molecular gas in planetary atmospheres: Superiority of accelerated lambda iteration, *J. Quant. Spectrosc. Radiat. Transf.*, *60*, 199–220.

[7] López-Puertas, M., and López-Valverde (1995), M., Radiative energy balance of $CO_2$2 non-LTE infrared emissions in the Martian atmosphere, *Icarus*, *114*, 113–129.

[8] López-Valverde, M., and M. López-Puertas (2001), Technical report: CO_2 non-LTE cooling rate at 15-μm and its parameterization for the Mars atmosphere, ESA Contract, ESA 11369/95/NL/JG CCN2.

[9] Mihalas, D. (1978), *Stellar Atmospheres*, Second Edition, Freeman, San Francisco.

[10] Nair, H., M. Allen, A.D. Anbar, Y.L. Yung, R.T. Clancy (1994), A photochemical model of the Martian atmosphere, *Icarus*, *111*, 124–150.

[11] Rybicki, G.B., and D.G. Hummer (1991), An accelerated lambda iteration method for multilevel radiative transfer, 2. Overlapping transitions with full continuum, *Astronomy and Astrophysics*, *262*, 209–215.