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# A new, fast and flexible radiative transfer method for Venus general circulation models

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ABSTRACT

We present a new radiation scheme for the Oxford Planetary Unified Model System for Venus, suitable for the solar and thermal bands. This new and fast radiative parameterization uses a different approach in the two main radiative wavelength bands: solar radiation (0.1–5.5 μm) and thermal radiation (1.7–260 μm). The solar radiation calculation is based on the $\delta$-Eddington approximation (two-stream-type) with an adding layer method. For the thermal radiation case, a code based on an absorptivity/emissivity formulation is used.

The new radiative transfer formulation implemented is intended to be computationally light, to allow its incorporation in 3D global circulation models, but still allowing for the calculation of the effect of atmospheric conditions on radiative fluxes. This will allow us to investigate the dynamical-radiative-microphysical feedbacks. The model flexibility can be also used to explore the uncertainties in the Venus atmosphere such as the optical properties in the deep atmosphere or cloud amount.

The results of radiative cooling and heating rates and the global-mean radiative–convective equilibrium temperature profiles for different atmospheric conditions are presented and discussed. This new scheme works in an atmospheric column and can be easily implemented in 3D Venus global circulation models.



## 1. Introduction

Venus has a dense atmosphere mainly composed of carbon dioxide (~96%) and a small amount of nitrogen (~3.5%). Despite being closer to the Sun than the Earth, the net absorption of solar radiation by the atmosphere is less than on the Earth due to the high albedo of the cloud deck that covers the planet almost entirely. The main cloud deck is composed mostly of aqueous sulphuric acid droplets. In the UV, visible and most of the infrared wavelength ranges, the clouds are optically thick, hiding completely the surface of the planet.

There has been an important effort in the last 30 years to simulate and understand the atmospheric dynamics and climate of this planet using simplified General Circulation Models (GCMs). These models are usually adaptations of Earth GCMs and use simplified physical parameterizations, including a radiation scheme. The Venus GCM from Lebonnois et al. (2010) using a radiative scheme from Eymet et al. (2009) is the only work published in the peer reviewed literature so far that has been implemented with relative success, a consistent radiative transfer calculation for the thermal radiation only. However, their radiative parameterization has some limitations, such as the need to re-compute new exchange matrices for variations in the atmospheric composition or variations in surface pressure. They also typically maintain a cloud structure constant with latitude and with time in the model, via the use of a pre-computed table of solar fluxes from Crisp (1986) to calculate the solar heating rates.

The radiation plays a very important role in the atmospheric dynamics and climate, and to simulate a realistic self-consistent dynamical state in a GCM, it is important to use a radiative transfer model. It is with this purpose that a suitable fast radiative transfer formulation for the Oxford Venus GCM called Oxford Planetary Unified Model System for Venus (OPUS-V) was developed. The code was planned to enable us to take into account temporal variations of the atmospheric constituents, such as clouds in GCM simulations. A parameterization of radiation-cloud variability interactions in a Venus GCM is important to study more accurately the cloud distribution and its influence on the atmospheric dynamics.

In Sections 2 and 3, the methods used to prepare the input data and compute the heating/cooling rates of the solar and thermal

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radiation are described. In Section 4 the new radiation code is implemented in a 1D radiative–convective model (1D R-CM). The convection scheme used was developed and adapted to take into account the dependence of the atmosphere's specific heat capacity with temperature at constant pressure. In Section 5 the final radiative–convective equilibrium state profiles of temperature are obtained and discussed, and the conclusions are presented in Section 6.

## 2. Solar radiation

The portion of the atmosphere explored in the OPUS-V covers the region between the surface and 100 km altitude with 37 layers (with a maximum vertical grid spacing of ~3.5 km). Above roughly 100 km altitude the assumption of local thermodynamic equilibrium breaks down (e.g., Roldán et al., 2000). Much of the solar radiation is extinct in the Venus' mesosphere (between 55 and 100 km altitude) which accounts for the important contribution of the cloud deck that reflects ~75% of the incident sunlight (Fig. 1). A large amount of solar energy is also absorbed within the cloud region, where an unidentified substance is responsible for the absorption of UV radiation in the upper clouds (e.g., Crisp, 1986), causing prominent contrasting features in UV images of Venus (e.g., del Genio and Rossow, 1990; Titov et al., 2012). Above the cloud tops $CO_2$ is the dominant absorber of solar flux. In the deepest atmosphere, absorption due to gases such as $CO_2$, $H_2O$ and $SO_2$ (the mass mixing ratio of $H_2O$ and $SO_2$ increases) and the Rayleigh scattering, become important, but produce very weak heating rates in comparison with the rest of the atmosphere. The solar energy absorbed at the surface, averaged over the planet, is estimated to be around 2.5% of the total incident solar energy (Tomasko et al., 1980).

The momentum transport by migrating, global scale atmospheric waves forced by the diurnally periodic absorption of solar radiation in the atmosphere (thermal tides) is thought to be an important mechanism to maintain the equatorial super-rotation of the atmosphere (Pechmann and Ingersoll, 1984; Newman and Leovy, 1992; Lebonnois et al., 2010; Mendonça, 2013), which increases the importance of having a self-consistent physically based parameterization for interactions with solar radiation in a Venus GCM.

The method developed here to compute the solar radiation fluxes is a combination of the $\delta$-Eddington method (two-stream-type) and an adding-layer technique. The most important active components that interact with the solar radiation were taken into account. The model includes the absorption and scattering due to three different gases ($CO_2$, $SO_2$ and $H_2O$), four size categories of $H_2SO_4/H_2O$ aerosols, an unidentified UV absorber and the Rayleigh scattering due to $CO_2$ and $N_2$ molecules. This selection of components in the atmosphere was also chosen to be consistent with Crisp (1986) model, which is used in this section to validate our results. However, any extra component can be easily added to the scheme.

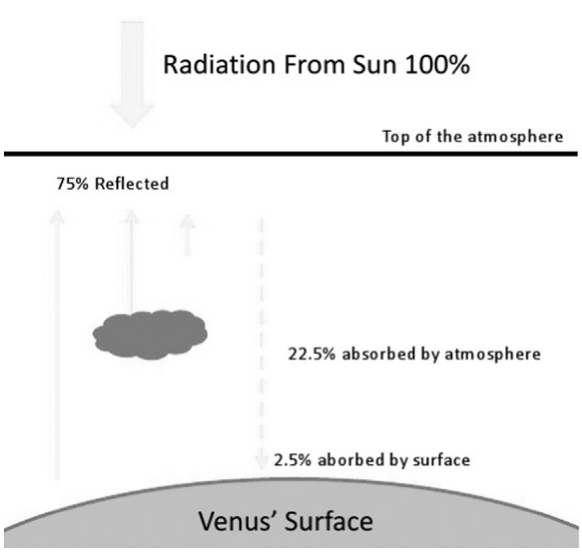


**Fig. 1.** The different components of the solar radiative fluxes in Venus.

### 2.1. Optical properties

#### 2.1.1. Gases

The optical properties of the three main gases that interact with solar radiation in the Venus atmosphere, carbon dioxide ($CO_2$), water ($H_2O$) and sulphur dioxide ($SO_2$), were computed. Fig. 2 shows the volume mixing ratios assumed for these three gases as a function of pressure/altitude. The three profiles were taken from the VIRA model (Venus International Reference Atmosphere, Kliore et al., 1985). The Venus atmosphere is composed mainly of $CO_2$ (assumed to be well mixed in the atmosphere at 0.96 vmr). The independent wavelength-dependent coefficients of absorption used in this section for $CO_2$, $H_2O$ and $SO_2$, were compiled in Lee and Richardson (2011). These coefficients were computed using parameters from the HITRAN 2004 database (Rothman et al., 2005) and the HITEMP $CO_2$ (Rothman et al., 1995) and stored using a $k$-distribution method (Lacis and Oinas, 1991). They were calculated on a 0.1 μm resolution grid between 0.1 and 5.5 μm (i.e., 55 bands), for 20 reference pressures between $10^{-3}$ hPa and $14 \times 10^4$ hPa (equally spaced on a logarithmic scale), 20 reference temperatures from 150 K to 1100 K (equally separated intervals) and 20 Gaussian ordinates (spectral fractions).

Self-broadening was assumed when calculating the $CO_2$ opacity and, due to the limited foreign broadening data available in HITRAN/HITEMP, air-broadening was assumed for $H_2O$ and $SO_2$ (Lee and Richardson, 2011). The absorption line shape of $CO_2$ was assumed to be a sub-Lorentzian as suggested in Meadows and Crisp (1996) and Takagi et al. (2010). The coefficient of absorption for each model layer was obtained by interpolating the $k$-table linearly (in log pressure) for the required temperature and pressure. For more details see Lee and Richardson (2011).

#### 2.1.2. Aerosols

Venus is covered by a cloud deck which hides completely the lower atmosphere and surface over the UV, visible and most of the infrared wavelength ranges, despite the observed existence of some near-IR spectral windows (e.g., Allen and Crawford, 1984). Fig. 3 shows schematically how the clouds in Venus are distributed vertically. For simplicity, a latitudinally uniform cloud distribution

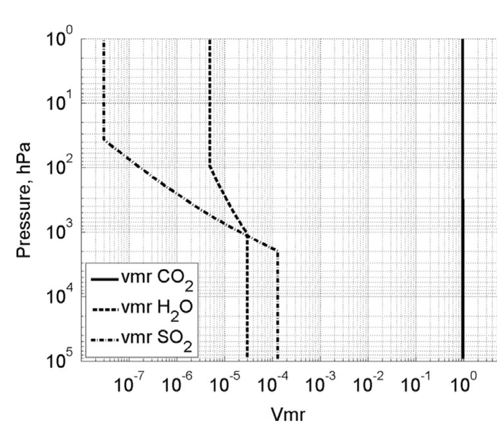


**Fig. 2.** Volume mixing ratios of $CO_2$, $H_2O$ and $SO_2$. The values were obtained from VIRA model (von Zahn and Moroz, 1985).