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Radiative forcing of the stratosphere of Jupiter, Part I: Atmospheric cooling rates from Voyager to Cassini

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ABSTRACT

We developed a line-by-line heating and cooling rate model for the stratosphere of Jupiter, based on two complete sets of global maps of temperature, C_2H_2 and C_2H_6, retrieved from the Cassini and Voyager observations in the latitude and vertical plane, with a careful error analysis. The non-LTE effect is found unimportant on the thermal cooling rate below the 0.01 mbar pressure level. The most important coolants are molecular hydrogen between 10 and 100 mbar, and hydrocarbons, including ethane (C_2H_6), acetylene (C_2H_2) and methane (CH_4), in the region above. The two-dimensional cooling rate maps are influenced primarily by the temperature structure, and also by the meridional distributions of C_2H_2 and C_2H_6. The temperature anomalies at the 1 mbar pressure level in the Cassini data and the strong C_2H_6 latitudinal contrast in the Voyager epoch are the two most prominent features influencing the cooling rate patterns, with the effect from the 'quasi-quadrennial oscillation (QQO)' thermal structures at ~20 mbar. The globally averaged CH_4 heating and cooling rates are not balanced, clearly in the lower stratosphere under 10 mbar, and possibly in the upper stratosphere above the 1 mbar pressure level. Possible heating sources from the gravity wave breaking and aerosols are discussed. The radiative relaxation timescale in the lower stratosphere implies that the temperature profile might not be purely radiatively controlled.

1. Introduction

The stratosphere of Jupiter is expected to be in radiative equilibrium due to the inhibition of strong vertical motion by the stratospheric temperature inversion above the tropopause ($\sim$100 mbar) and the approximate isotherm above $\sim$5 mbar pressure level (Moses et al., 2004). Although the major constituents in the atmosphere are hydrogen and helium, the stratospheric radiative budget is mainly controlled by trace amounts of hydrocarbons, including $\sim$0.2% methane (CH_4) and its photochemical products, acetylene (C_2H_2) and ethane (C_2H_6), and aerosols. Previous studies (e.g., Wallace et al., 1974; Appleby, 1990) showed that the stratosphere is primarily heated by the absorption of solar flux via the near-infrared (NIR) bands of CH_4 between 1 and 5 μm. The heating effect of aerosols is less certain. West et al. (1992) found this process to be important around 10 mbar or below, especially in the polar region. But other studies (Moreno and Sedano, 1997; Yelle et al., 2001) claimed that aerosol heating is negligible. The heating from the gravity wave breaking could be also important in the upper stratosphere (Young et al., 2005). On the other hand, the detailed analysis by Yelle et al. (2001) revealed that the most important coolants in the stratosphere of Jupiter are the secondary hydrocarbons, C_2H_2 and C_2H_6, with less important but not negligible contributions from CH_4 and the H_2–H_2 and H_2–He collisional induced transitions, through their thermal emissions at the mid-infrared (MIR) wavelengths.

The thermal emission from those MIR bands, and the absorption from the NIR CH_4 bands, can be directly observed from ground-based and space-based instruments. Therefore, provided enough information can be obtained from the observations, the solar heating and thermal cooling rates can be determined precisely to test the radiative equilibrium hypothesis. However, previous radiative equilibrium models (Cess and Khetan, 1973; Wallace et al., 1974; Cess and Chen, 1975; Appleby and Hogan, 1984; Appleby, 1990; Conrath et al., 1990; West et al., 1992; Moreno and Sedano, 1997), as described in Yelle et al. (2001), are all subject to large uncertainties of the temperature and gas abundance profiles, and aerosol distributions. Yelle et al. (2001) estimated the globally averaged temperature profile based on the Galileo probe data in the hot spot ($\sim$7°N) and hydrocarbon profiles based on the available ground-based and space-based observations at that time. They concluded that radiative

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equilibrium could be achieved from the gas heating and cooling rate balance, although their model tests showed a large uncertainty range for the secondary hydrocarbon profiles, especially for C_2H_2.

The observations and related analysis of the stratosphere of Jupiter prior to 2000 are summarized in Moses et al. (2004). Those results, although successfully revealing the main features for certain latitudes, did not provide spatially resolved information for the full planet. Until the analysis of the Voyager and Cassini flyby data by Simon-Miller et al. (2006), the detailed two-dimensional temperature maps in the latitude–altitude plane have been lacking. Later, Nixon et al. (2007, 2010) retrieved the distributions of the temperature, C_2H_2 and C_2H_6 together, based on the Voyager and Cassini infrared spectra. Those maps with detailed latitudinal and vertical information of the temperature and major coolants in the stratosphere of Jupiter provide us the opportunity to analyze the radiative heating and cooling budgets in detail. This is the first motivation of this study.

The second motivation might be more important. Although the stable stratification prohibits strong vertical and lateral convection, the stratosphere is not stagnant. In fact, observations have shown that the temperature change is much larger than can be explained by the instantaneous radiative equilibrium model (Simon-Miller et al., 2006), possibly owing to the effect of the stratospheric dynamics. The latitudinal distributions of HCN and CO_2 after SL-9 impact suggest the existence of both horizontal eddy diffusion and advection (Lellouch et al., 2006). The distributions of C_2H_2 and C_2H_6 from Nixon et al. (2010) also imply a possible meridional circulation in the stratosphere of Jupiter because the two species also serve as the tracers for transport. The opposite latitudinal trends of the short-lived species (C_2H_2) and the long-lived species (C_2H_6) are a strong evidence of the horizontal advection, as also suggested by the simulations using a chemistry-transport model (Zhang et al., 2013a). On the other hand, the SL-9 debris transport model by Friedson et al. (1999) and the two-dimensional chemical-transport model by Liang et al. (2005) suggested that the horizontal eddy mixing might be more important. Therefore, whether the stratospheric transport is governed by horizontal diffusion or advection is unsolved. Furthermore, whether the stratospheric circulation is driven by the top-down radiative differential heating or by the bottom-up mechanical forcing from the troposphere is not well determined either. Previous studies (e.g. Gierasch et al., 1986; Conrath et al., 1990; West et al., 1992) led to different conclusions based on different assumptions of the radiative forcing or wave drag parameterization. In order to answer both questions, i.e., mixing versus advection, and radiative forcing versus mechanical forcing, the spatially resolved stratospheric radiative forcing needs to be precisely calculated.

This study aims to understand the radiative budget and the related uncertainties based on the state-of-art global datasets in the stratosphere of Jupiter. We will investigate the details of the heating rate and cooling rate in both spectral and spatial domains. Our investigation will be divided in two parts, corresponding to two publications. In this paper (Part I), we will analyze the Cassini and Voyager infrared spectra to quantify the information of the temperature, gas abundances and their uncertainties, and calculate the thermal cooling rate maps for the two eras using a high-resolution line-by-line radiative transfer model, and revisit the globally averaged solar heating and thermal cooling balance. In a complementary paper (Part II), we will discuss the aerosol heating effect and obtain the latitudinal aerosol heating rate map based on the recently retrieved global map of stratospheric aerosols and their optical properties (Zhang et al., 2013b). Combining the aerosol heating rate with the gas heating and cooling rates, we complete the picture of radiative forcing in the stratosphere of Jupiter.

This paper is structured as follows. Section 2 describes how to obtain the best-estimate distributions of the atmospheric temperature and gas abundances, and their associated uncertainties from the Cassini and Voyager spectra. Section 3 introduces the line-by-line cooling rate model and discusses the cooling rate results. Section 4 focuses on the globally averaged heating and cooling balance, followed by a summary and implications for the stratospheric dynamics in Section 5.

2. Jovian stratospheric maps

2.1. Retrieval and error analysis method

In order to characterize the uncertainties of the retrieval results from Cassini Composite Infrared Spectrometer (CIRS) and Voyager Infrared Spectrometer (IRIS), we revisit the same observational data in Nixon et al. (2010). The CIRS data and IRIS data are both mid-IR spectra from 600 to 1400 cm^{-1}. The spectral features in this region are dominated by emissions from the acetylene ν_5 band centered at 729 cm^{-1}, ethane ν_9 band at 822 cm^{-1}, and methane ν_4 band at 1304 cm^{-1}. All the emission features are sitting on top of the H_2–H_2 and H_2–He collisional induced absorption (CIA) continua. The two Michelson-type instruments, i.e., IRIS and CIRS, are similar to each other in the Mid-IR region, but the spectral resolution and spatial resolution from the CIRS interferometer are much higher than the single bolometer of IRIS. For instance, the full-width-to-half-maximum (FWHM) of CIRS is 0.48 cm^{-1} versus 4.3 cm^{-1} of IRIS. The field of view (FOV) of CIRS is 0.29 mrad versus 4.36 mrad of IRIS (see Nixon et al. (2010) for more details). Due to the different data quality, we choose two different retrieval methods for CIRS and IRIS data respectively. But the methods share the same theoretical basis.

In principle, the retrieval problem as an inversion problem is ill-posed because multiple solutions exist, and the solutions may not depend continuously on the measurements and the associated uncertainties (e.g., highly unrealistic vertical oscillations in the retrieved profiles). Regularization approaches are needed. Rodgers (2000) introduces a method based on the Bayesian statistics, in which an additional *a priori* state and the uncertainty covariance are incorporated along with the information from the measurements. The optimal atmospheric states can be solved through a non-linear minimization algorithm. In this study, we adopt NEMESIS, a retrieval algorithm based on the iterative Levenberg (1944), Marquardt (1963) scheme, developed by Irwin et al. (2004; 2008) and first used for retrieving the Jovian hydrocarbon abundances from CIRS spectra by Nixon et al. (2007). The *correlated-k* approximation and *k*-coefficients tables computed from high-resolution spectral line databases (Nixon et al., 2010) make the radiative-transfer forward model in NEMESIS efficient as well as accurate. In order to avoid large oscillations in the retrieved vertical profiles, we adopt the smoothing criteria suggested by Irwin et al. (2008). A good retrieval profile should be able to match the observations weighted by the measurement covariance matrix S_e and also has sufficient smoothing supplied by diagonal elements of the quantity $K_n S_x K_n^T$, where S_x is the error covariance matrix of the *a priori* state vector and K_n is the Jacobian matrix or the matrix of functional derivatives which measures the sensitivity of the forward model with respect to the change of state vector. The measurement covariance matrix S_e includes the measurement errors (see Nixon et al., 2007 for details) and forward model errors. The latter were estimated to be on the same order of magnitude as the measurement errors in this study. We prefer the solutions that are constrained quasi-equally by the measurements and by the *a priori* profile, i.e., when S_e and $K_n S_x K_n^T$ are of the same order of magnitude. See Irwin et al. (2008) for more discussions.

Given an *a priori* profile and the assumption that *a priori* and *posteriori* follow the Gaussian statistics, Rodgers (2000) method