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New insights on Jupiter's deep water abundance from disequilibrium species

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ABSTRACT

The bulk water abundance on Jupiter potentially constrains the planet's formation conditions. We improve the chemical constraints on Jupiter's deep water abundance in this paper. The eddy diffusion coefficient is used to model vertical mixing in planetary atmosphere, and based on laboratory studies dedicated to turbulent rotating convection, we propose a new formulation of the eddy diffusion coefficient for the troposphere of giant planets. The new formulation predicts a smooth transition from the slow rotation regime (near the equator) to the rapid rotation regime (near the pole). We estimate an uncertainty for the newly derived coefficient of less than 25%, which is much better than the one order of magnitude uncertainty used in the literature. We then reevaluate the water constraint provided by CO, using the newer eddy diffusion coefficient. We considered two updated CO kinetic models, one model constrains the water enrichment (relative to solar) between 0.1 and 0.75, while the other constrains the water enrichment between 3 and 11.

1. Introduction

The bulk abundances of oxygen in Jupiter and Saturn potentially constrain conditions in the Sun's protoplanetary disk. However, determining these abundances through the direct measurement of water, the dominant carrier of oxygen in the envelopes of these objects, is very difficult. Galileo probe measurements show the effect of dynamical processes on the water abundance down to 22 bars (Wong et al., 2004), while ground-based microwave observations are not sufficiently sensitive to provide a deep water abundance (that is, below the meteorological layer) for either body (de Pater and Massie, 1985). A determination of the deep (>50 bar) water abundance on Jupiter should be obtained by the microwave radiometer aboard the Juno spacecraft set to arrive at Jupiter in 2016 (Janssen et al., 2005; Helled and Lunine, 2014). There is no similar possibility for Saturn in the near future because, even though the Cassini spacecraft will be put in a Juno-like orbit in 2017, it does not carry a microwave radiometer.

An alternative way to determine water abundance, through disequilibrium species observed in Jupiter and Saturn's troposphere, is a long-standing approach that goes back to Prinn and Barshay (1977) (see Visscher and Moses, 2011 for an extensive list of published papers on this subject). The abundance of disequilibrium species depends on the relevant chemical kinetics, which determines the chemical loss rate, and the eddy diffusion coefficient, which determines the efficiency of vertical mixing. Our study is timely, in spite of the long history of published papers, for three reasons. First, we derived a new formulation of the eddy diffusion coefficient based on laboratory studies of turbulent rotating convection. The new formulation systematically describes the transition from slow-rotation convection to rapid-rotation convection with significantly less uncertainty than previously. Secondly, we used the two most updated CO kinetic models to place constraints on Jupiter's deep water abundance. Third, a possible future mission to deploy a descent probe into Saturn's atmosphere, if conducted, will almost certainly be a "New Frontiers" medium-class mission (National Research Council, 2011), or an ESA M-class mission (Mousis et al., 2014). Such a probe will probably not be able to get to the base of the water cloud which is essential to determining directly the deep oxygen abundance on Saturn. Indirect methods including using disequilibrium species as described here may be the only way to determine oxygen abundance even through probe measurements, and therefore a study is warranted using the most recent kinetics to assess whether such an approach provides a well-constrained oxygen value. Our results identify and quantify significant ambiguities inherent in such an approach.

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The paper is organized as follows. In Section 2, we analyze the results from rotating tank experiments and propose a new formulation of eddy diffusion coefficient. In Section 3, we derive constraints on the deep water abundance from CO measurements with the kinetic information from two different models. In Section 4, we discuss the implication on Jupiter's formation and potential improvements relative to the current model.

2. A new formulation for the deep eddy diffusion coefficient

In the atmosphere of Jupiter, heat is assumed to be transported by vertical eddy diffusion. The eddy diffusion coefficient K_{eddy} is introduced to measure the efficiency of vertical diffusion. In the convective part of the atmosphere, the heat flux and superadiabatic temperature gradient can be related to K_{eddy} by the following equation:

$$F = -\rho c_p K_{\mathrm{eddy}} \left(\frac{dT}{dr} - \frac{dT}{dr}|_{ad} \right), \tag{1}$$

where F is the internal heat flux, ρ is the mass density, c_p is the specific heat per unit mass, and $dT/dr - dT/dr|_{ad}$ is the superadiabatic temperature gradient. Formulations of K_{eddy} in terms of heat flux F, rotation rate Ω and fluid thermal properties are derived based on mixing length theory or perturbation of linearized equations (Stone, 1976; Flasar and Gierasch, 1978; Stevenson, 1979), predicting K_{eddy} near CO quench level ($\sim$ 1000 K, 300 bars) for Jupiter to be between $1 \times 10^7\ \mathrm{cm^2\ s^{-1}}$ and $1 \times 10^9\ \mathrm{cm^2\ s^{-1}}$ (e.g. Bézard et al., 2002; Visscher et al., 2010), and this value is widely used in theoretical modeling of disequilibrium chemistry. One difficulty in improving the estimation is the lack of observation. No natural convective system under rapid rotation, like the interior of giant planets or the Earth core, can be easily observed. However, the estimation of K_{eddy} could be improved by utilizing results from laboratory studies on turbulent rotating convection. Laboratory studies on turbulent rotating convection have been done since 1980s, however, application to giant planet convection has hitherto been limited. Here, we summarize relevant results of these laboratory studies, and propose a new formulation of K_{eddy}.

In Section 2.1, we review theoretical investigations on K_{eddy}. In Section 2.2, we summarize results from rotating tank experiments, and present the new formulation for K_{eddy}. In Section 2.3, we apply the new formulations to Jupiter and Saturn, and predict K_{eddy} profiles for these two planets.

2.1. Theory on eddy diffusion coefficient

By analogy to molecular diffusion coefficient, K_{eddy} can be approximated as the product of vertical convective velocity w and a mixing length l, representing a typical distance a parcel could travel before it lost its identity. Therefore, Eq. (1) can be rearranged as

$$F \sim -\rho c_p w \delta T, \tag{2}$$

where $\delta T = (dT/dr - dT/dr|_{ad})l$ is the temperature fluctuation. A parcel's kinetic energy is obtained from the work done by buoyancy force over a mixing length l, thus

$$w^2 \sim -\alpha g \delta T l, \tag{3}$$

where α is the thermal expansion coefficient and g is the acceleration of gravity. With Eqs. (2) and (3), we find the convective velocity

$$w \sim \left(\frac{\alpha g F}{\rho c_p} l \right)^{1/3}. \tag{4}$$

The mixing length is usually assumed to be a pressure scale height H, thus eddy diffusion coefficient can be estimated as (Stone, 1976)

$$K_{\mathrm{eddy}} \sim wl \sim \left(\frac{\alpha g F}{\rho c_p} H \right)^{1/3} H, \tag{5}$$

Stone's (1976) estimation ignored the effect of rotation on K_{eddy}, however, rotation could have an important effect on convection in suppressing vertical mixing (Guillot et al., 2004). The importance of rotation can be measured by a Rossby number

$$Ro = \frac{v}{fl}, \tag{6}$$

where $f = 2\Omega sin\phi$ is the Coriolis parameter, and ϕ is the latitude. The Rossby number is defined as the ratio of inertial to Coriolis force, therefore, lower Ro means Coriolis acceleration is more important. Near the CO quench level, we find $Ro \approx 0.01/(sin\phi)$. Therefore, near the equator, rotation has little effect, while at extra-equatorial latitudes, rotation is important in suppressing turbulent convection.

The trend is consistent with Flasar and Gierasch's (1978) results. In the limit of rapid rotation, Flasar and Gierasch (1978) analyzed the linear modes generated by the perturbation of a superadiabatic and inviscid fluid in plane geometry, and identified the most unstable modes that transport the most heat. Assuming shear instability limits the growth rate, they found

$$K_{\mathrm{eddy}} \sim \left(\frac{\alpha g F}{\rho c_p} \right)^{3/5} \left(\frac{H}{2\Omega sin\phi} \right)^{4/5}, \tag{7}$$

and

$$w \sim \left(\frac{\alpha g F}{\rho c_p} \right)^{2/5} \left(\frac{H}{2\Omega sin\phi} \right)^{1/5} \tag{8}$$

at extra-equatorial regions, while near the equator, the formulation is the same as Eqs. (4) and (5). Eqs. (7) and (8) are rearranged from Eq. (5.3) in Flasar and Gierasch (1978).

Eqs. (5) and (7) are widely used in estimating K_{eddy} (e.g. Bézard et al., 2002; Visscher et al., 2010). In comparison to Eqs. (5) and (7), laboratory experiments on turbulent rotating convection indicate the same scaling as Eq. (5) for slow rotation, but a different scaling from Eq. (7) for rapid rotation. We will discuss the new scalings from rotating tank experiments in Section 2.2, but here we will show that the new scalings can be easily derived based on the assumption that overturning timescale is limited by the rotational timescale Ω^{-1}, instead of H/w. With this assumption, the relevant length scale would be $l = w/\Omega$, and the velocity scale would be

$$w \sim \left(\frac{\alpha g F}{\rho c_p \Omega} \right)^{1/2}, \tag{9}$$

according to Eqs. (2) and (3). This velocity scale was found to be consistent with the convective velocity data from a three dimensional anelastic simulation of the convective envelope of Jupiter (Showman et al., 2011). The relevant length scale would be

$$l \sim w/\Omega \sim \left(\frac{\alpha g F}{\rho c_p \Omega^3} \right)^{1/2} \tag{10}$$

instead of a pressure scale height. Therefore, we can formulate a new scaling for the eddy diffusion coefficient using the velocity and length scale described here. The eddy diffusion coefficient would be

$$K_{\mathrm{eddy}} \sim wl \sim \frac{\alpha g F}{\rho c_p \Omega^2}. \tag{11}$$

Here we neglected all the prefactors in the scalings, however, these prefactors can be determined from laboratory measurements.