Equatorial clouds and haze before, during, and after Jupiter's global upheaval

Michael H. Wong

Astronomy Department
University of California
Berkeley CA 94720-3411

mikewong@astro.berkeley.edu

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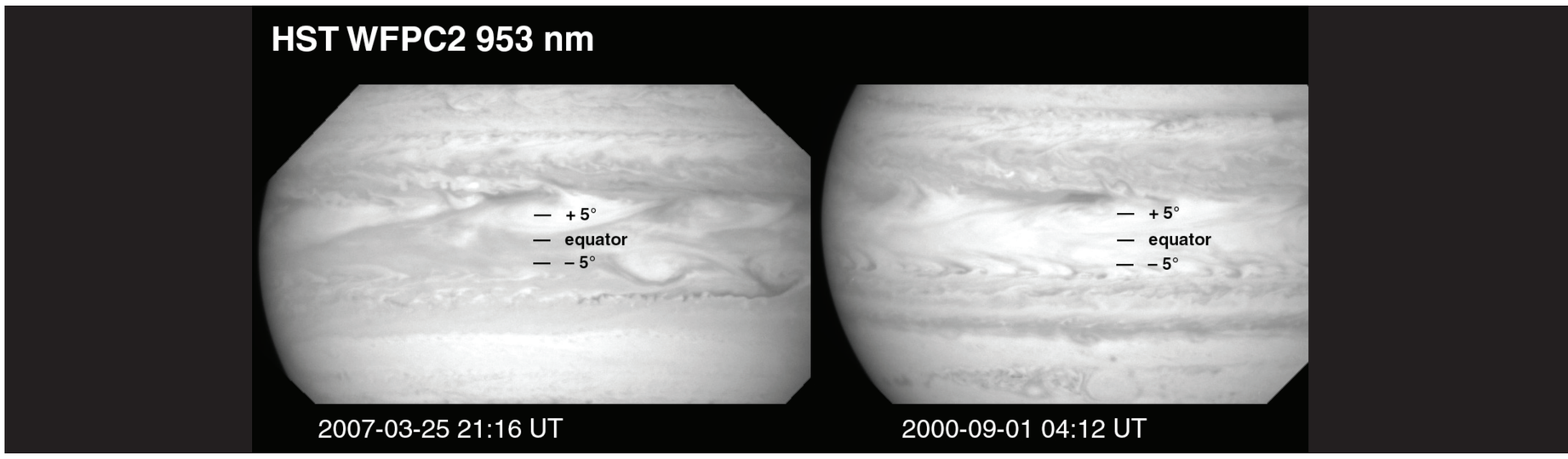

Summary

Jupiter's tropospheric haze is denser and more vertically extended over the equator. One previously suggested source of this haze is vertical transport of fine aerosol particles from below. HST images from before and during Jupiter's global upheaval show changes in the albedos of the equatorial cloud and the equatorial haze. Comparison of the changes to a simple model of haze vertical transport rules out vertical transport of 1-μm cloud particles as a source of the haze, but uplift of smaller particles or in situ photochemical hydrazine production both remain as viable haze sources.

Cloud changes

HST/WFPC2 images of Jupiter from 1998–2000, before the current upheaval, showed thick and nearly complete cloud coverage in the equatorial zone. Images during the upheaval in 2007 show a decrease in cloud cover; most remaining clouds are associated with plumes extending from the northern and southern boundaries of the equatorial zone. The decreased cloudiness corresponds to a 20% decrease in the 953-nm continuum I/F within ±5° of the equator, between 1998–2000 and 2007 (Figure 1).

Jupiter's tropospheric haze has a higher concentration and a greater vertical extent near the equator (Banfield et al. 1998). Twenty-percent level variations in haze albedo are also apparent in the 1998–2007 HST/WFPC2 data studied here (Figure 2), but the variability is not as obvious under cursory visual inspection of the images, because the equatorial haze has, at all times, a greater extinction than the haze at other latitudes.

The tropospheric haze variability is not simply correlated with the equatorial cloud cover variability. Figure 2 shows that the haze albedo increased by about 20% between observations in 1998–1999 and observations in 2000. But in 2007, despite the drop in tropospheric cloud opacity, haze albedos were similar to those in 1998–1999. The lack of correlation between the haze and cloud temporal variabilities offers an opportunity to distinguish between possible sources of the tropospheric haze.

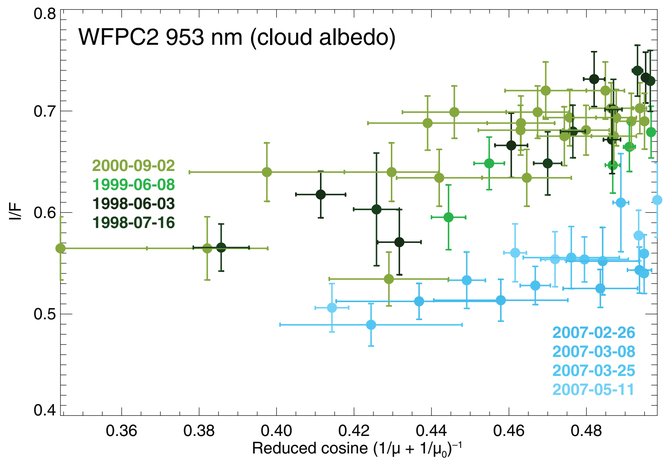

Figure 1. Blue data demonstrate the suppressed cloud opacity in 2007 during Jupiter's upheaval (as compared to 1998–2000). Albedo is plotted as I/F as a function of reduced cosine (0.5 is near disk center and 0 is near the limb).

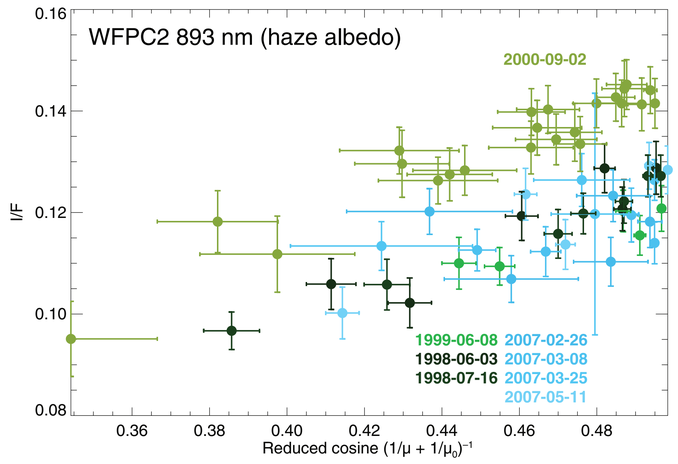

Figure 2. Haze albedo is about 20% higher during 2000, compared to all other times. During the upheaval in 2007, haze extinction is observed to be roughly identical to 1998–1999 values.

Transport model: predicted haze response to cloud changes

The next section discusses possible sources of the tropospheric haze, but this section investigates one option: turbulent diffusion of fine cloud particles from the deeper atmosphere. I apply a simple one-dimensional model to derive order-of-magnitude constraints on haze transport. We start with a modified version of Fick's law for diffusion (Butkov 1968) including a term for sedimentation of aerosols (Equation 1). Combining this with the continuity equation (Equation 2), we get a modified diffusion equation, which describes the variation of haze density as a function of time and altitude (including sedimentation; Equation 3).

$$j = -K \frac{d\rho}{dz} - v_{fall}\,\rho \qquad [1]$$

$$\frac{d\rho}{dt} = -\frac{dj}{dz} \qquad [2]$$

$$\frac{d\rho}{dt} = K \frac{d^2\rho}{dz^2} + v_{fall} \frac{d\rho}{dz} \qquad [3]$$

The behavior of the system was tested in three steps. First a very low-density haze layer was placed above a constant-density slab of tropospheric cloud, and the model was allowed to converge to a vertical density profile (Figure 3, black curve). This "filled-up" profile represents a steady-state balance between aerosol sedimentation and upward turbulent transport. The blue curve in Figure 3 shows the new steady-state balance achieved after a decrease in the cloud source by 20% (similar to the observed cloud decrease during Jupiter's upheaval).

Figure 4 shows the decay of the total haze column abundance as a function of time, in response to an instantaneous decrease in the cloud source. Although not purely exponential in form, the response has an approximate time constant of 72 days (the 2007 HST data in Figures 2 and 3 span 74 days). Assuming a smaller particle size would lead to smaller sedimentation rates and therefore a longer decay. A factor of two decrease in particle size corresponds to a two order of magnitude slower sedimentation velocity (Rossow 1978), with a longer system response time-constant of about 1100 days (3 years).

Model details. Eddy diffusion constant K ranged from 20,000 $cm^2\ s^{-1}$ at depth to 600 $cm^2\ s^{-1}$ at 50 km, following the equatorial K-profile retrieved by Edgington et al. (1999) using HST/STIS spectra. These values are lower than and inconsistent with the minimum K of $10^5\ cm^2\ s^{-1}$ used in the study by Ackerman and Marley (2001). Haze particle sizes of 1 μm and 0.5 μm were assumed, following West et al. (1986, 2004). Corresponding sedimentation times for ammonia ice particles of these sizes are 5×10^7 s and 5×10^9 s, respectively, according to microphysical calculations by Rossow (1978). Numerical values of Δz = 100 m and Δt = 1000 s were used such that the stability criterion for diffusive initial value problems was satisfied (Press et al. 1992).

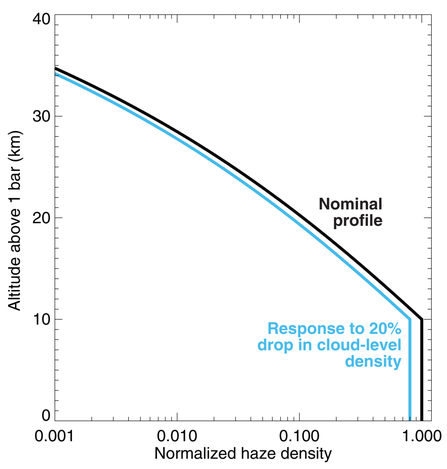

Figure 3. Haze density profiles. Black: equilibrium between sedimentation and diffusion for 1-μm particles. Blue: new equilibrium after 20% drop in cloud-layer haze density.

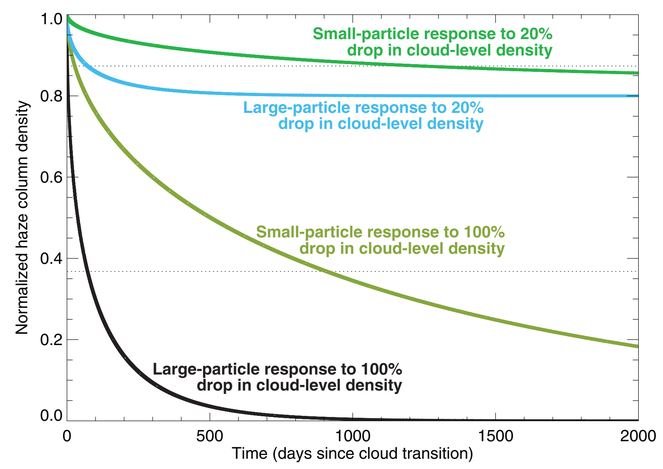

Figure 4. Evolution of tropospheric haze-layer total column density. Large particles are 1 μm, small particles are 0.5 μm. Dotted lines show e-folding levels for 20% and 100% drops in cloud-level haze density.

The source of the haze

The fine aerosols composing the tropospheric haze may be composed of condensed hydrazine (a product of ammonia photolysis at the altitude of the haze layer) mixed with smaller amounts of hydrocarbon and other photochemical products drifting down from the stratosphere (Atreya et al. 1977, 2005). Cloud particles from deeper in the troposphere may also be lofted into the haze region (West et al. 1986), where particles with radii of 0.5–1.0 μm precipitate on a timescale of 1.6 to 160 years (Rossow 1978). Due to the large energies needed to penetrate into the stably stratified haze region, particle compositions may include NH_4HS and H_2O as well as NH_3 (Sugiyama et al. 2007).

If we consider the 1998–1999 haze albedo level to be normal, then the 2007 haze albedo rules out turbulent diffusion of micron-sized particles from the cloud tops as a haze source mechanism. If this were the source of the tropospheric haze, then an observable decrease in haze albedo at least the 10–15% level should have already taken place. Could lofting of smaller particles be the main source of tropospheric haze? According to Figure 4, a drop in haze albedo following a decrease in the source of sub-micron particles lofted from below would not measurable until almost 3 years after the cloud source change.

The range in haze layer response as a function of particle size makes it challenging to determine whether lofting of sub-micron cloud particles or precipitation of photochemical products is the dominant source of the haze. Future observations of Jupiter's equatorial haze and cloud albedos may detect a late response (favoring lofting of sub-micron particles) or no response (favoring photochemical production). However, interpretation of data after about 2010 will be complicated by a further consideration. The reduced equatorial cloud opacity will lead to warming in the haze layer, with changes apparent in about five years (according to estimates of the radiative timescale by Conrath et al. 1990). A haze decrease in 2010 could thus be attributed to sedimentation of small particles or to decreased condensed hydrazine.

The enhanced haze albedo in 2000 is a mystery. A change in the tropospheric cloud particle source seems unlikely, given the stable cloud albedo levels in 1998–1999 (Figure 2). Simon-Miller et al. (2007) noted that temperatures at 250 mbar (~30 km above 1 bar) decreased by several degrees between 1998 to 2000. If the tropospheric haze is dominated by condensation of photochemically produced hydrazine, then the intensification of the haze could be explained as a result of increased hydrazine condensation, as controlled by the strong temperature dependence of the hydrazine saturation vapor pressure.

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