WATER VAPOR IN JUPITER'S ATMOSPHERE

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High spectral resolution observations of Jupiter at 2.7 and 5 microns acquired from the Kuiper Airborne Observatory were used to infer the vertical distribution of H_2O between 0.7 and 6 bars. The H_2O mole fraction, qH_2O, is saturated for $P<2$ bars, $qH_2O = 4 \times 10^{-6}$ in the 2 to 4 bar range and it increases to 3×10^{-5} at 6 bars where $T = 288$ K. The base of the 5 μm line formation region is determined by pressure-induced H_2 opacity. At this deepest accessible level, the O/H ratio in Jupiter is depleted by a factor of 50 with respect to the solar atmosphere.

High spatial resolution Voyager IRIS spectra of Jupiter's North Tropical Zone, Equatorial Zone, and Hot Spots in the North and South Equatorial Belt were analyzed to determine the spatial variation of H_2O across the planet. The column abundance of H_2O above the 4 bar level is the same in the zones as in the SEB Hot Spots, about 20 cm-amgt. The NEB Hot Spots are desiccated by a factor of 2 or 3 with respect to the global average. The massive H_2O cloud at 5 bars, $T = 273$ K, proposed in solar composition models, is inconsistent with the IRIS data. Instead, a thin H_2O ice cloud would form at 2 bars, $T = 200$ K.

A cloud model for Jupiter's belts and zones was developed in order to fit the IRIS 5 μm spectra. An absorbing cloud located at 2 bars whose 5 μm optical thickness varies between 1 in the Hot Spots and 4 in the coldest zones satisfactorily matches the IRIS data. In contrast, the layered model of Owen and Terrile (1981, J. Geophys. Res. <u>86</u>, *8797-8814) does not reproduce the continuum level at both the long and short end of the 5 μm window, nor does it fit the observed line to continuum ratios.*

No talk about Jupiter at 5 microns is complete without the infrared photograph taken by Rich Terrile using the Palomar 200-inch telescope. There is a wealth of structure in this 5 μm image: one can clearly identify the North Equatorial Belt Hot Spots, the Great Red Spot, and the very cold North Tropical Zone. This high spatial resolution image was acquired using a filter centered at 5 μm with $\lambda/\Delta\lambda = 10$. The next step in exploring Jupiter at 5 μm is to analyze high spectral resolution observations as well. I have used two sets of 5 μm spectra of Jupiter. One set was obtained by Hal Larson using the Kuiper Airborne (KAO) Observatory covering the 40 deg S to 40 deg N latitude range on Jupiter at a resolution of 0.5 cm^{-1}. A complementary set of observations comes from the Voyager IRIS experiment. The spectral resolution is 4.3 cm^{-1}, and large portions of the planet were observed at spatial resolutions between 1 and 10 degrees of latitude.

The most obvious regions of Jupiter to study initially at 5 μm are the Hot Spots, where the signal to noise ratio is best. Kunde *et al.* (1982) used the IRIS data between 5 and 50 μm to derive the gas composition for the North Equatorial Belt Hot Spots. In addition, Drossart and Encrenaz (1982) and Drossart *et al.* (1982) studied the IRIS 5 μm spectra of Hot Spots in both the North and South Equatorial belts as well as a central disk average. They did not analyze the IRIS zone spectra at 5 μm. However, by averaging enough IRIS spectra together we have been able to use the zone data as well as the belt observations in order to measure the spatial variation of the gas composition. Today I am reporting the results of our water vapor analysis.

Water on Jupiter is of interest to many of us in this room. Measurements of H_2O in Jupiter's troposphere allow us to infer the global oxygen to hydrogen ratio (relevant to models of Jupiter's origin), and the location and mass of the H_2O ice cloud. Since this is a clouds and chemistry session, I will focus on this last point. The spatial variation of H_2O on Jupiter is important in studies of dynamics, and the overall oxidation state of the atmosphere determines the stability of disequilibrium species such as PH_3 and CO that have been observed.

Where do we start? We used three observational datasets to study H_2O on Jupiter. We used the airborne and Voyager IRIS spectra at 5 μm that I described previously as well as a recent spectrum of Jupiter at 2.7 μm acquired from the Kuiper Airborne Observatory by Larson *et al.* (1984). This latter spectrum probes a different portion of the atmosphere because near infrared radiation is dominated by reflected solar flux. Thermal radiation at 5 μm originates near 5 bars, while at 2.7 μm the line formation region is around 0.5 bar. By combining measurements from all of these datasets, we have derived a vertical distribution for H_2O in Jupiter's troposphere.

We used a radiative transfer program to synthesize the infrared spectrum of Jupiter at 5 μm. First, the temperature-pressure profile is specified. The Voyager radio occultation team reported a temperature at 1 bar of 165 K. We used a dry adiabat to extrapolate the temperature down to 7 bars. Next, spectroscopic data for 9 molecules, including H_2O, was fed in. The abundance of each molecule was adjusted to fit the entire 5 μm window. An important source of continuum opacity is due to pressure-induced absorption by H_2. Barney Conrath and Peter Gierasch have discussed the importance of H_2 absorption at 17 and 28 μm. The wings of these lines extend out so far from line center that even at 5 μm, H_2 remains an important opacity source. Unit optical depth occurs at the 5 to 7 bar level, where temperatures are between 270 and 300 K. So, if you have a Jovian model atmosphere with only H_2 and He and no clouds, then pressure induced opacity limits how deep you can see at 5 μm to 7 bars.

Once a cloud is introduced the modeling is more complicated. Bob West, Marty Tomasko, Bob Samuelson and others have calculated the Jovian infrared radiance at a few frequencies using a variety of scattering parameters. Our approach is to estimate the contribution of gases to the total 5 µm opacity. The remaining opacity is attributed to clouds. In our model we first calculate the spectrum that would be observed from a cloud-free atmosphere. Then a simple purely absorbing cloud is added. This acts as a neutral density filter to the thermal IR radiation. Our model cloud has only two parameters: 5 µm optical thickness and base temperature. These parameters are adjusted in order to fit the continuum radiance at two selected frequencies at each end of Jupiter's 5 µm transmission window.

The calculated synthetic spectrum is convolved with the instrument function for comparison with either the Voyager or KAO observations of Jupiter. A detailed analysis of these observations is given in Bjoraker (1985) and Bjoraker, Larson, and Kunde (1985, 1986). Here I will briefly summarize our results. We have derived a vertical distribution for H_2O in Jupiter's troposphere by fitting strong and weak H_2O lines simultaneously. The H_2O mole fraction on Jupiter changes by about 3 orders of magnitude between 1 and 6 bars. Our upper limit to H_2O from the 2.7 µm airborne data is 3×10^{-8} (Larson *et al.*, 1984). This applies to a pressure level near the base of the NH_3 cloud around 0.7 bars. The simplest distribution which reconciles the near IR upper limit with the 5 µm detection of H_2O is a saturated distribution. Between 2 and 4 bars the H_2O mole fraction is 4×10^{-6}, and it increases to 3×10^{-5} at 6 bars.

One consequence of this height dependent H_2O distribution derived from the airborne data is that at 4 to 5 bars the measured abundance is sub-saturated by a factor of 100. This, in turn, implies that Jupiter does not have a massive H_2O cloud near 5 bars. Instead, a thin H_2O ice cloud would form near 2 bars. Is this represenative of the whole planet? One possible explanation is that the airborne data sample primarily the belt regions where most of the 5 µm flux originates. If belts are dynamically dried out with respect to the planet as a whole, then perhaps Jupiter may retain a solar O/H ratio. To test this hypothesis it is necessary to examine the Voyager IRIS 5 µm spectra of Jupiter's zones as well as the belts.

We compared the IRIS spectrum of the North Equatorial Belt Hot Spots to synthetic spectra calculated using various H_2O distributions. A height dependent profile is required to fit strong and weak lines simultaneously. The mole fraction of H_2O in our model of the NEB Hot Spots increases from about 10^{-7} at 2 bars to 10^{-6} at 3.5 bars to 3×10^{-5} at 6 bars.

Next, we investigated IRIS 5 µm spectra of cloudy regions in the Equatorial Zone as well as an ensemble of spectra with the coldest 5 µm brightness temperatures, less than 210 K. These latter spectra sample the North and South Tropical Zones as well as the cloudiest portions of the Equatorial Zone. Despite the lower signal to noise ratio compared with belt spectra, the IRIS <u>zone</u> spectra clearly show absorption by H_2O vapor. This represents the first detection of H_2O in spatially resolved spectra of Jupiter's zones. Significantly, the abundance of H_2O in our model which is required to match the zone observations is within a factor of 2 of that derived from the airborne observations of Jupiter's central disk, which included belts and zones. The H_2O mole fraction between 2 and 4 bars in the zones is 2×10^{-6}, and it increases to 3×10^{-5} at 6 bars.

We have assumed that the line formation region for H_2O is the same in Jupiter's belts and zones. Thus, H_2O absorption features in the IRIS spectra of a zone may be compared directly to features in belt spectra to infer relative abundances. Clearly, the degree of cloud cover differs substantially between belts and zones. What if zones have totally opaque clouds at $P<4$ bars? The absorption features in the IRIS zone spectra might pertain to a completely different altitude than the belt spectra. To test this hypothesis we must investigate several cloud models.

In one class of models the brightness temperature at 5 μm is attributed to a completely opaque cloud at the same physical temperature in Jupiter's atmosphere. To see if the IRIS data are consistent with this idea, we measured the continuum radiance in the IRIS data in various "mini-windows" across Jupiter's 5 μm transmission window. The radiance depends on both the cloud optical thickness at 5 μm and its temperature. In addition, if zones have a totally opaque cloud at some pressure level, then the line formation region for all absorbing gases must be above the cloud. We calculated the line to continuum ratios in the IRIS zone spectra as a function of cloud location. The results of this study are reported in Bjoraker (1985) and Bjoraker, Kunde and Larson (1986). We conclude that an opaque cloud is inconsistent with the IRIS zone spectra. Instead, we find that an absorbing cloud with a 5 μm transmittance ranging from 1 to 4 percent provides a good fit to the IRIS zone observations. The base of the main absorbing cloud deck is near 2 bars, where the temperature is 200 K. Absorption lines in both belt and zone spectra are formed very deep at 5 μm ($P=4-5$ bars). The main difference is that 5 μm radiation is attenuated to a greater degree in the zones than in the belts.

To summarize, we exclude a massive H_2O cloud in Jupiter's atmosphere at 5 bars for two reasons. First, the H_2O abundance we have derived for the 5 bar level in both belts and zones is about 10^{-5}. This is a factor of 100 below the mole fraction at 5 bars predicted by Weidenschilling and Lewis (1973) assuming a saturated H_2O distribution and a solar O/H ratio. Second, if there were an optically thick cloud in the same temperature region, 250 to 270 K, there would be a prominent signature of black body emission at the long wavelength end of the 5 μm window. This is not observed in any of the IRIS belt or zone spectra. Instead of a massive H_2O cloud, it appears that H_2 pressure induced absorption limits how deep we can see at 5 μm. We do see evidence for a cloud of some kind near 2 bars based on its thermal emission signature at 5 μm. This is, coincidentally, where H_2O ice and condensed NH_4SH are expected to form. Currently, we do not have a spectroscopic signature for either of these condensates. We have only circumstantial evidence for its composition based on measurements of NH_3 and H_2O in the gas phase. Thank you.

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DR. OWEN: I'm sorry but we really are on a tight time schedule. Time for one question.

DR. LEOVY: Since the water cloud would likely be convective, one might want to look at broken cloud models for a lower cloud. Have you looked at any fractional coverage models (30-50%) for a lower cloud?

DR. BJORAKER: I haven't done that, but clearly the 5 µm images indicate that a heterogeneous cloud model is necessary. A simple gray, absorbing slab is not going to do the trick. An analysis of the center to limb variation of 5 µm continuum radiation should allow you to distinguish between heterogeneous patchy clouds with thick slabs.