New Studies of Jupiter's Atmosphere

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ABSTRACT

Assuming that the shapes of weak methane lines are determined by hydrogen and helium collisional broadening, the value of H/He in the Jovian atmosphere is found to be much greater than unity. A preliminary interpretation of differences in the amount of absorption by a strong methane band over the disk of the planet leads to an estimation of height differences of 18 km over the Great Red Spot and 12 km over the equatorial zone. The yellow coloration observed on Jupiter and Saturn is compared with the properties of ammonium sulfide (\(\text{NH}_3\))\(\text{S}\), a compound that may occur in the atmospheres of these planets.

1. Introduction

In this paper, we will describe the current status of several different investigations whose purpose is the elucidation of certain characteristics of the structure and composition of the Jovian atmosphere. In each case, we will indicate the direction of future research in addition to summarizing the results obtained so far. We discuss in turn the abundance of helium and the half-widths of methane lines, an attempt to investigate the vertical structure of cloud features, and a new source for the coloration of the cloud deck.

2. The abundance of helium and line half-widths

We have reviewed our best records of the 6190 Å CH\(_4\) band in the spectrum of Jupiter. All of these spectrograms were obtained at a reciprocal dispersion of 1.25 Å mm\(^{-1}\) at the McDonald Observatory. The instrumental profile, as determined from an analysis of the very narrow lines in the 6300 Å oxygen band, has a half-width of 0.21±0.03 cm\(^{-1}\). [In this discussion, we are accepting the definition of Rank et al. (1966) for the half-width; \(\pi\), the full width at half-intensity.]

The half-widths of the methane lines are 0.28±0.05 cm\(^{-1}\). Thus, since the resolution achieved by the instrument is not adequate to determine the methane line widths directly, a rather large correction for the slit function must be made. Using the correction factor developed by Adel (1947), and taking the uncertainty in the half-widths into account, we estimate that the true half-width lies in the range 0.09≤\(\alpha\)≤0.20 cm\(^{-1}\).

The lower limit is obtained by adopting the maximum value for the instrumental profile and the minimum value for the methane half-widths.

The importance of these calculations lies in their bearing on the Jovian helium abundance. Adopting 85 km atm for the amount of hydrogen above the lower cloud deck on Jupiter (Owen and Mason, 1968), and using the H\(_2)/\text{CH}_4\) broadening coefficient determined by Rank et al. (1966), we can predict a half-width of 0.19 cm\(^{-1}\) for the CH\(_4\) lines from hydrogen broadening alone. Since this value is very close to our upper limit for \(\alpha\), it appears that the atmosphere cannot contain large amounts of He, i.e., H/He≥1. Even if we simply adopt the measured half-width of 0.28 cm\(^{-1}\) without making any corrections, we find H/He≥5 (Owen, 1969). However, the exact value of this ratio remains elusive because: 1) if scattering is important in the formation of the absorption lines, we may have overestimated the hydrogen abundance; 2) scattering in the atmosphere will also affect the line profiles, and would lead to an overestimate of the line widths; and 3) we don't know that the methane lines we are examining are singlets. If they are unresolved multiplets, we have again overestimated the line widths.

In considering these uncertainties, we may draw on our experience in the case of the Venus atmosphere. In the derivation of a relative CO\(_2\) abundance from line widths in the spectrum of Venus, it appears that ignoring effects of scattering does not lead to gross errors, provided one chooses the proper value for the effective air mass (Gray, 1968). Furthermore, a correction for the third effect cited above will tend to increase the derived value of H/He, since the true line widths would be even narrower than the results given here.

This suggests that our original estimate of the value of H/He is probably valid to within a factor of 2 (Owen and Mason, 1968). In that derivation, we used an upper limit of 0.16 cm\(^{-1}\) for the half-widths of CH\(_4\) lines as measured by Spinrad and Trafton (1963)\(^2\) and set the

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\(^1\) Contribution No. 447 from the McDonald Observatory, The University of Texas, Fort Davis.

\(^2\) These authors actually quoted a value of 0.08 cm\(^{-1}\) for the half half-width. Note that their upper limit of 0.16 cm\(^{-1}\) falls well within the range of 0.09–0.20 cm\(^{-1}\) set by our observations.
air mass \( \eta \geq 3.12 \). This led to \( \text{H}/\text{He} \geq 9 \), within the range of values determined for the solar photosphere.

Further progress on this difficult but important problem will be most rapid if the spectrum can be recorded at still higher resolution.

3. The vertical structure of the clouds

Photographs of Jupiter taken with an interference filter centered on a strong methane band have revealed that there are considerable variations in the absorption over the disk of the planet (Owen, 1969). It is not yet clear whether this structure is the result of towers of cloud extending upward from a lower deck, or whether it is caused by an overlying haze concentrated over certain regions of the planet, or perhaps a combination of the two. It is also possible that one is simply dealing with a change in the density or single scattering albedo of the cloud particles. However, the lack of correlation with the visual or infrared appearance of the planet suggests that the second of these last two alternatives is unlikely. We cannot unequivocally rule out the first possibility, but we note that the very slight limb darkening observed on the photographs is not a strong support for this alternative either, since either cloud towers or a haze layer would cause the same effect (Squires, 1957; Kuiper, 1952). As there are other reasons supporting the presence of a haze layer (e.g., the polarization observations of Gehrels et al., 1969), we are inclined to think that this must at least play an important role in the production of the phenomenon.

In any case, the observations show bright regions over the equatorial and temperate zones of the planet, with bright hoods or caps at one or both poles. Results obtained to date indicate that the south pole is more likely to exhibit this effect than the north. The Great Red Spot (GRS) also appears as a bright area. A series of photographs showing these effects has been reproduced elsewhere (Owen, 1969); a more recent picture obtained with slightly better resolution is shown in Fig. 1.

If we assume that the light areas on these photographs are indeed elevated areas, we may crudely estimate the height to which they extend above the lower cloud layer by adopting a simple Beer's law extinction for the incident radiation, i.e.,

\[
I_s = I_0 e^{-x}\text{km}.
\]

To evaluate the parameters in this expression, a spectrogram was taken with the slit running across the GRS and the equatorial zone and extending in wavelength from 8800 to 9500 Å. Using the conventional spot sensitometry calibration, we could find \( I_0 \) in the continuum adjacent to the 8900 Å CH\(_4\) absorption and then solve for the absorption coefficient \( \kappa \) over the north polar region of the disk, assuming \( x = 60 \pm 30 \text{ m atm} \). We then measure \( I_s \) over the GRS and the equatorial zone and solve for \( x \), the amount of gas above these regions. The result is

<table>
<thead>
<tr>
<th>Region</th>
<th>( x ) (m atm)</th>
<th>( h ) (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Great Red Spot</td>
<td>34</td>
<td>18</td>
</tr>
<tr>
<td>Equatorial zone</td>
<td>40</td>
<td>12</td>
</tr>
</tbody>
</table>

The height data are obtained by assuming a constant lapse rate of 2.1K km\(^{-1}\) (Owen, 1969).

In other words, with this simplified interpretation, it appears that the top of the cloud layer that forms
the reflecting layer at 8900 Å was 18 km above the lower cloud deck over the GRS and 12 km above the deck over the equatorial zone, at the time this spectrogram was obtained. These elevations are still well below the tropopause, estimated to be at 52 km (Owen). We must bear in mind, however, that even outside the bright areas on these photographs, we may not be seeing down to the lower cloud deck, i.e., our reference level remains poorly defined.

We may now ask how these results compare with observations made at other wavelengths. It has already been pointed out that the absence of large NH₃ absorption at 2200 Å indicates that at this wavelength penetration into the atmosphere is relatively slight (Greenberg and Owen, 1967). It now seems that the lower boundary there may be the tropopause, or at least very near it (Owen). We thus anticipate that as one moves toward longer wavelengths, one will be looking progressively deeper into the atmosphere. The proposed model on which the conclusions given above are based rests on the assumption that weak absorption lines observed in the near infrared correspond to an optical path that reaches the lower cloud deck. At these wavelengths, we find no increase or decrease in the intensity of the CH₄, NH₃, and H₂ absorptions over the GRS as compared with their values over the adjacent parts of the disk, within the uncertainty of the measurement (±15%).

At intermediate wavelengths, one does not have molecular absorptions to study. Photographs taken with filters to isolate certain wavelength regions are also informative, but this approach has not yet been pursued with sufficient rigor to lead to unequivocal conclusions. Inspecting a typical series of such photographs, one gets the impression that the amount of detail apparent on the planet decreases with decreasing wavelength. Features that are reddish or yellowish are more prominent because of their color contrast in green light than in yellow or red, but in blue light, these differences are diminished somewhat, at least on some occasions. On one photograph obtained by B. Smith⁶ at the shortest wavelengths used so far in this work (3250 Å), the appearance of the planet is quite uniform, with the exception of the GRS, which is still dark. We also note that on this photograph, the poles appear dark, although at other times a very small bright polar cap has been reported on photographs obtained at 3750 Å (Smith⁶). More observations at these wavelengths would be very useful, particularly if obtained in conjunction with the 8900 Å pictures.

With the help of the preceding discussion, the following interpretation may be offered: As one examines the planet at progressively shorter wavelengths, one is looking to levels that are less and less deep in the atmosphere. Above the lower cloud deck, the atmosphere is charged with scattering particles (presumably ammonia cirrus), whose concentration varies with time, altitude and position on the disk. The effect of the pure molecular atmosphere above the tropopause also becomes more important as the wavelength of observation diminishes, but evidently remains subsidiary to the particle scattering at least to 3250 Å. This conclusion follows from the fact that the polar regions of the planet remain darker than the equatorial and temperate regions even at this wavelength, although we know from polarization observations (as well as from the interference filter photography) that there is a deep, clear atmosphere over the poles, with the exception of the hoods already mentioned. The fact that the GRS is still dark (i.e., red) at 3250 Å offers evidence in addition to that provided by the 8900 Å photographs that the disturbance associated with the GRS propagates to relatively high altitudes in the Jovian atmosphere.

It would be very interesting to have photographs at even shorter wavelengths. Does the GRS still appear as a unique entity at 2200 Å? i.e., does it reach the tropopause? Are other details visible on the disk? Judging from the available data, we would guess that the answer to this last question is negative, since color differences (except for the GRS) are beginning to be dominated by particle scattering even at 3750 Å on some of these photographs. We also want to examine the appearance of the planet at 8900 Å in more detail. At a larger scale, with slightly better resolution, it should be possible to distinguish the various features on the disk with better precision, and to search more carefully for possible correlations with the visual appearance of the planet. A laboratory study of the 8900 Å band, to be conducted in the near future, should permit some refinement of the assumptions implicit in the Beer's law formulation used for this first-order height analysis.

4. The colors in the cloud deck

There have been three primary hypotheses to explain the colors observed in the Jovian cloud deck: 1) solutions of metallic sodium in ammonia (Wildt, 1939), 2) trapped free radicals (Rice, 1956), and 3) complex organic molecules (Urey, 1952). The last of these has come to seem the most reasonable as the composition and structure of the atmosphere have become more certain. Laboratory experiments with synthetic atmospheric mixtures have also lent credence to this interpretation (Ponnampерuma, 1969). However, there is at least one alternative that should be explored.

Lewis (1969) has proposed that if the elements are present in solar relative abundances in the Jovian atmosphere, sulfur should be present as H₂S which in turn will combine with ammonia to form NH₄HS. It occurred to us that if this were the case, one might also expect (NH₄)₂S to form. The significance of this possibility is that (NH₄)₂S is yellow, and both Jupiter and Saturn exhibit distinctly yellow colored equatorial zones from time to time. This yellow coloration is not

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⁶ Private communication.
just a visual contrast effect; these regions appear very dark in the UV (Marin, 1968).

We have obtained some UV spectra of a solution of \((\text{NH}_4)_2\text{S}\) in water with a Cary spectrophotometer. The UV absorption of this compound is extremely strong, showing a characteristic dip at 2300 Å that is only visible in a 1/2000 dilution of a 33% solution. Following a suggestion made by J. Lewis, we have tested the identification of this dip by bubbling \(\text{H}_2\text{S}\) through an NaOH solution. A spectral scan of the resulting mixture again showed the 2300 Å absorption, strongly suggesting that it is produced by the \(\text{HS}^-\) ion, and hence not characteristic of \((\text{NH}_4)_2\text{S}\).

The yellow coloration and UV absorption exhibited by this compound are intriguing but by no means constitute proof for its existence in the atmospheres of Jupiter and Saturn. Accurate photometric colorimetry of regions on both planets, reduced properly to allow for the effect of overlying particles and gas, will provide a firmer basis for comparison with the laboratory data. In addition, an intensive search for the presence of \(\text{H}_2\text{S}\) should be made spectroscopically. The best band to look for occurs at 1.58 μ, and observations available so far give marginal evidence that some small amount of this gas may be present (Cruikshank and Binder, 1969). A more comprehensive discussion of the chemical equilibrium existing among \(\text{H}_2\text{S}, \text{NH}_3\) and the two sulfides would also be helpful.

It is perhaps worthwhile to stress that we do not propose that sulfur compounds produce all the observed colors, but simply that they may be responsible in part for some of them. We still favor the idea that organic polymers are the causative agents of most of the coloration. One significant aspect of this problem is the fact that the GRS remains visible on the photographs obtained at the shortest wavelengths studied thus far, since not only has the disturbance propagated to very high levels, but it has preserved its color at these levels as well. One could also interpret this high contrast at short wavelengths as the result of a transparent region of atmosphere above the red matter characterizing the GRS. However, the brightness of the GRS on the 8900 Å photographs is a strong argument against this interpretation. Clearly, much remains to be done before we can hope to understand this enigmatic phenomenon.

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