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THE REFLECTIVITY OF JUPITER IN THE ULTRAVIOLET*

THEODORE P. STECHER

Four spectral scans of Jupiter were obtained by means of objective grating rocket spectrometers. The geometrical reflectivity is interpreted in terms of Rayleigh scattering by obtaining a numerical relationship between reflectivity and optical depth. This gives an upper limit to the amount of molecular hydrogen above the cloud layer of 10.2 ± 1 km. atm. The effect of Raman scattering by molecular hydrogen increases this to a 10.6 ± 1 km. atm. An absorption feature is found to be consistent with its identification being photodissociation of H_2 .

I. THE OBSERVATIONS

The spectrum of Jupiter in the ultraviolet was obtained from an Aerobee rocket on July 23, 1963 at 06^h02^mU.T. Three additional spectra were obtained in a similar manner on November 14, 1964 at 10^h28^mU.T. The instruments used were objective grating photoelectric stellar spectrometers similar to those described by Stecher and Milligan (1962). Spectral scanning is the consequence of the spin of the rocket. The observations were telemetered to the ground. The exit slit widths were between 50Å and 90Å. The total spectral range covered was from 1050Å to 4000Å. The instruments were calibrated in both a relative and an absolute sense prior to flight in the laboratory. The accuracy of the absolute calibration is believed to be considerably better than the limit set by noise in signal for these observations. A complete description of the instrumental techniques will be included in a forthcoming paper on stellar energy distributions.

The discussion of planetary photometry by Harris (1961) is now followed. In Figure 1 the geometrical reflectivity, p , as a function of wavelength is given between $\lambda 2000$ and $\lambda 3000$. The mean error for each value of p was determined in the standard manner from the observations, no measurable signal was detected below $\lambda 2000$. The solar flux values used in obtaining p are those given by Tousey (1963) and were obtained by photographic spectrophotometry. The necessary geometry was obtained using the appropriate

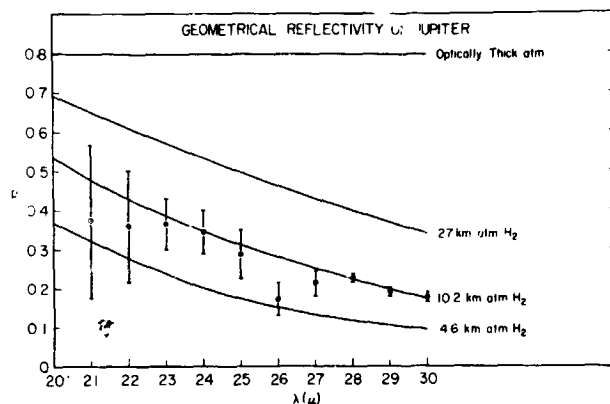


FIGURE 1.—Circles: Observed average geometrical reflectivity of Jupiter as a function of wavelength with mean errors as determined from four spectra. Solid curves: Computed geometrical reflectivities for various amounts of molecular hydrogen.

Ephemeris values. The phase angle of Jupiter was 11.72 degrees on July 23, 1963 and almost zero on November 14, 1964.

II. INTERPRETATION

The literature on Jupiter, in particular recent polarization measurements and molecular hydrogen quadrupole line measurements, indicates the possible presence of a Rayleigh atmosphere at ultraviolet wavelengths above the cloud layer. Upper limits for the number of atoms or molecules above the cloud layer may be derived immediately for each species if the reflectivity is known in terms of optical depth. Tables have been tabulated for the total intensity emerging from the top of a Rayleigh atmosphere by Coulson, Dave and

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Sekera (1960). This tabulation is for optical depths, τ , up to unity as a function of zenith distance of the sun, μ_0 ; zenith distance of the emergent rays, μ , and the azimuthal angle, φ . From these values p may be obtained as a function of τ .

For our purposes, Jupiter is assumed to be at opposition even though one observation was made at quadrature, since the phase integral is almost constant for small phase angles. This approximation makes less than three percent difference for that observation (Talley and Horak, 1956). The plane parallel atmosphere is made tangent to a unit sphere at each point on the illuminated hemisphere by the restraint $\mu_0 = \mu$. The value of the emergent intensity is then projected onto a unit disk. Integration over the surface then gives the geometric reflectivity for a given value of optical depth. The azimuthal angle is 180° . Curves in the $p-\tau$ plane were constructed in this manner in the range $\tau=0$ to $\tau=1$ for ground reflectivities of 0, 0.25, and 0.8. The values of p for the optical thick case are given for Rayleigh scattering and for isotropic scattering by Harris (1961). The extrapolation from $\tau=1$ to $\tau=\infty$ was made with the aid of geometric reflectivities calculated in a similar manner from the available X-Y functions for isotropic scattering given by Mayers (1962) and by Sobouti (1963). Over the range of τ to be used in this paper the extrapolation error is probably negligible.

The total number of atoms or molecules in a column of unit area perpendicular to and above the cloud layer is now obtained from $\tau = n\sigma$ under the assumption of only one constituent. Here n is the number of atoms or molecules and σ is the Rayleigh scattering cross section per atom or molecule. The Rayleigh scattering cross section for molecular hydrogen is given by Dalgarno and Williams (1962)¹. The Rayleigh scattering cross section for helium is given by Dalgarno (1962). The molecular scattering cross section for these gases does not follow the Rayleigh law in the ultraviolet. This is physically due to the increased probability of inducing a dipole moment as a resonance is approached. In the range of interest here the deviation of molecular hydrogen is greater than that of helium. This in principle would allow an abundance ratio determination

but would require more accurate observational material at the shorter wavelengths.

In Figure 1 the observed geometric reflectivities as a function of wavelength (circles) are compared with ones calculated for a given atmosphere. The best fit to the data under the assumption of zero reflectivity in the clouds is a 10.2 km. atm. of H_2 or a 200 km. atm. of He or any combination of the two resulting in the same total reflectivity. If the clouds are assumed to form a Lambert surface with a reflectivity of 0.25 the total number of scattering atoms or molecules is reduced by a factor of ten and the form of the reflectivity curve becomes incorrect for Rayleigh scattering. The possibility that the clouds have a small reflectivity can not be excluded. The derived atmosphere is therefore an upper limit.

The above analysis has been carried out under the assumption that the scattering is coherent. In the case of most molecular gases including molecular hydrogen this is known not to be the case. Raman scattering from H_2 in the lowest vibrational state is five percent of the Rayleigh scattering at $\lambda 1216$ (Dalgarno and Williams, 1962). Isotropic scattering may be used to approximate the effect by setting the particle albedo equal to 0.95 and comparing it with the result for a particle albedo of unity. In the case of an optically thick atmosphere one concludes that 43 percent of the incident photons emerge in the Raman lines. Brant (1963) found 34 percent of the incident Lyman- α photons in the Raman lines by means of an approximation to the Rayleigh phase function.

There is a half electron volt difference between the incident photon and the Raman scattered photon. This energy difference means that the Raman photon has a wavelength several hundred angstroms longer than the incident photon at the wavelengths under consideration here. This would appear as a second order effect except on the longer wavelength side of an absorption feature in the planet or when there is a strong wavelength variation in the source function. The absorption bands of ammonia begin at 2100A and result in an almost continuous absorption at shorter wavelengths reaching an optical depth of more than 10^6 at $\lambda 1216$ (Kuiper 1952) (Watanabe, et al. 1953). This is apparently indicated by the data although the solar continuum becomes so

¹ The ordinate in Fig. 1, Ap. J. 136, 691, 1962 should read $\lambda^4\sigma(\lambda) \times 10^{14} \text{ cm}^2$.

weak here that the determination is unreliable. The effect here is that only the Rayleigh component and not the Rayleigh plus Raman appears up to $\lambda 2200$. Similarly, the absorption feature between $\lambda 2400$ and $\lambda 2700$ reduces the Raman scattered component between $\lambda 2700$ and $\lambda 3000$. Using isotropic scattering as an approximation and assuming that the ratio of the Raman scattering cross section to the Rayleigh cross section is a constant independent of wavelength the total scattering atmosphere would be considerably more.

Dalgarno and Williams (1964) have kindly communicated to me in advance of publication the Raman scattering cross section for H_2 between $\lambda 2000$ and $\lambda 3000$. They give $Q = 2.75 \times 10^{-46} / \lambda'^4$ where λ' is the wavelength of the scattered radiation in centimeters. This is a smaller cross section than was anticipated and leads to only 0.4 km. atm. increase of H_2 . Thus, we have an upper limit of a 10.6 km. atm. of molecular hydrogen. The total mean error is estimated to be \pm one km. atm.

There are several possible causes of the absorption feature between $\lambda 2700$ and $\lambda 2400$ which appears to be real. If for the sake of conjecture, this absorption is assumed to be the forbidden photodissociation of molecular hydrogen, an empirical absorption coefficient may be derived. This may be done by following the path of the photon by using isotropic scattering for which X - Y functions are available (Sobouti, 1963). A particle albedo of unity is equated numerically to the Rayleigh scattering cross section and the particle albedo giving the observed mean absorption depth is determined. If the Rayleigh scattering is considered to be due entirely to H_2 a cross section of $1 \times 10^{-27} \text{ cm}^2$ is obtained for photodissociation of H_2 . Dalgarno (1964) considers 10^{-27} to be a good estimate. Herzberg (1964) points out that H_2S would also absorb in this wavelength region so the identification is by no means certain.

SUMMARY AND DISCUSSION

Zabriskie (1962) determined at 4.6 km. atm. of H_2 from their quadrupole bands. Spinrad and Trafton (1963) empirically derived a 27 km. atm. from these bands. Foltz and Rank (1963) concluded from laboratory measurements and theoretical calculations on the quadrupole bands that

both of these determinations are much too small and it should be on the order of a 270 km. atm. The latter value would give an optical depth of nine at $\lambda 3000$ and correspond to a conservative atmosphere throughout the ultraviolet. This is not observed. Casual inspection of photographs of Jupiter taken on blue plates also indicate this not to be the case since the surface markings would be obscured near the edge of the disk. This large optical depth would also require U and B color intensities several times what is observed (Harris, 1961). Öpik (1962) derives an optical depth by inspection of published photographs which is in remarkably good agreement with that obtained in this paper. Öpik then proceeds to derive an atmosphere that is consistent with the molecular weight he obtained from a rediscussion of the occultation measurement of Baum and Code (1953). His resulting atmosphere consists mostly of helium giving a pressure of 11 atmospheres at the top of the cloud layer. Spinrad and Trafton (1963) find from the widths of methane lines a pressure equal to or less than 2.8 atmospheres at the top of the clouds. If we adopt 2.8 atmospheres at the top of the clouds. If we adopt 2.8 atmospheres as the upper limit then we are limited to less than 50 km. atm. of helium. The cross section for Rayleigh scattering in helium is five percent that of molecular hydrogen. A 50 km. atm. of helium is insufficient to give the observed reflectivity. The amount of molecular hydrogen then becomes at least 8 km. atm. for zero reflectivity clouds.

The conclusion of this paper is that Jupiter has less than 10.6 ± 1 km. atm. of molecular hydrogen above the clouds. If the reflectivity of the clouds is zero in this part of the ultraviolet and the upper limit to the pressure is 2.8 atmospheres at the cloud tops then Jupiter has at least a 8 km. atm. of molecular hydrogen. Inherent throughout this paper is the assumption that the atmosphere has the same physical depth at all wavelengths longer than 2000 Angstroms.

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