ments involving particle bombardment of gas mixtures of methane and hydrogen have demonstrated the production of C_2 to C_5 hydrocarbons in which the saturated aliphatic compound predominates, presumably because of free radical scavenging (*8*). The unique characteristic of this kind of hydrocarbon mixture is that it is colorless in visible light and absorbs substantially in the near UV, especially in the 2000- to 2600-Å range. Assuming that the nitrogen and sulfur compounds, principally NH_3 and H_2S, are trapped by cold at lower altitudes and higher pressures, the radiation and photochemically induced processes should be active high in the atmosphere and should mostly involve CH_4 and H_2.

The Voyager 1 and 2 UV spectrometers detected a very intense auroral ring around the Jovian polar regions that is connected to the Io torus (*9*). Particle precipitation along the magnetic field lines into the Jovian atmosphere provides the mechanism for intense radiation bombardment of the polar region with subsequent radiation-induced chemistry and the production of small-particle UV absorbers at high altitudes. It is interesting to note that the Voyager 1 and 2 infrared interferometer spectrometers (IRIS) have detected marked north-south spatial asymmetry in the ratio of ethane to acetylene, with the saturated hydrocarbon more dominant in the polar domains—indicative, perhaps, of change in equilibrium toward a higher percentage of radiation-induced chemistry (*10*). The IRIS-determined latitudinal dependence appears to follow approximately the asymmetry in latitude of the auroral ring, with the north polar ring extending more southerly to lower latitudes than the south polar ring extends northward (*11*). This may account for the characteristics of the photopolarimeter observations and explain the production of absorbing material at high altitudes.

Further modeling of center-to-limb variations and phase angle variations will permit a much better determination of the altitude distribution and physical characteristics of the absorber.

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26 September 1979

Radio Science with Voyager at Jupiter: Initial Voyager 2 Results and a Voyager 1 Measure of the Io Torus

Abstract. *Voyager 2 radio signals were observed essentially continuously during a grazing occultation of the spacecraft by the southern limb of Jupiter. Intensity data show a classic atmospheric occultation profile and the effects of turbulence and ionospheric focusing and defocusing. No reliable profile of the neutral atmosphere has yet been obtained, primarily because of a combination of large trajectory uncertainties and error multiplication effects associated with the grazing geometry of the Voyager 2 occultation. Analysis of the dispersive ionospheric refraction data yields preliminary profiles for the topside ionosphere at 66.7°S (entry in the evening) and 50.1°S (exit in the morning) that are reversed with respect to corresponding Voyager 1 profiles in terms of plasma concentration at a fixed altitude. Plasma scale heights and temperatures of 880 kilometers, 1200 K and 1040 kilometers, 1600 K were obtained for morning and evening conditions, respectively. Preliminary reduction of the pre-encounter occultation of Voyager 1 by the Io torus yields an average plasma density of about 1000 electrons per cubic centimeter.*

About 22 hours after its closest approach to Jupiter, Voyager 2 passed behind the planet as viewed from the earth. Although the spacecraft was geometrically occulted for nearly 2 hours, the radio links between it and the earth were maintained almost continuously because of the refraction of the signals in Jupiter's south polar atmosphere. Figure 1 shows the plane-of-the-sky geometry of this grazing occultation and preliminary data on the intensity of the spacecraft radio signals as received by the tracking station at Goldstone, California.

The conditions for this occultation differ markedly from the nearly central passage of Voyager 1 behind Jupiter (*1, 2*) and, as a result, somewhat different characteristics of the atmosphere can be studied in the two experiments. In this report, we discuss several general features of the Voyager 2 occultation and present preliminary profiles of the plasma density for the topside of the ionosphere at the two occultation locations. Voyager 1 and 2 were also occulted by the Io torus; we have derived a preliminary result from the Voyager 1 experiment for the density and distribution of plasma in this region. Our previous comments in the Voyager 1 report (*1*) concerning (i) the nature and limitations of the initial data and derived preliminary results and (ii) the need for intensive studies of more complete signal characteristics for all of the potential radio science investigations (*1, 2*) apply to the Voyager 2 data and results as well.

Ionospheric occultation entry of Voyager 2 occurred at about 66.7°S, 254.8°W (system III, 1965.0), and occultation exit was at about 50.1°S, 148.1°W (Fig. 1). Jupiter limb-to-spacecraft distances were about 18 and 19 Jupiter radii (R_J) at entry and exit, respectively, and the maximum angle of refraction in the atmosphere at midoccultation was about 0.3°. This bending would be produced at a pressure level of about 200 mbar in a region about 10 km below the tropopause, under the assumption of an atmospheric structure similar to that measured by Voyager 1 near 12°S latitude (*1*). The intensities and frequencies of the two communications signals (at wavelengths of 3.6 and 13 cm) were measured during the occultation period; only intensity data are shown in Fig. 1 (*3*).

Both atmospheric and ionospheric features are illustrated in the intensity data. At occultation entry (Fig. 1), the ionosphere first caused an increase in the sig-

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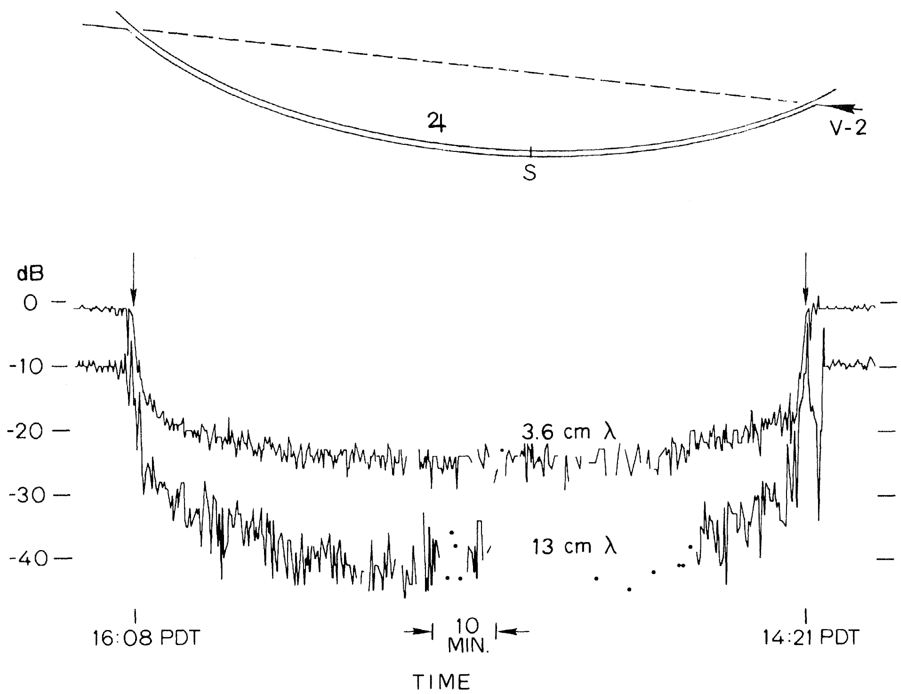

Fig. 1. Occultation of Voyager 2. (Top) View from Earth of the Voyager 2 trajectory (*V-2*) behind the southern limb of Jupiter. (Bottom) Intensity of coherent 3.6- and 13-cm wavelength radio signals during the occultation period. See text for positions on Jupiter. Time increases to the left. Data are preliminary (*3*); for example, 3.6-cm wavelength data are artifically compressed as a result of a calibration error at the station. The maximum bending angle was 0.3°.

nal followed by a decrease over a period of several minutes; for the signal with the longer wavelength, the increase was by a factor of about 4 and the decrease was apparently by more than a factor of 200. Immediately after these ionospheric effects, both signals weakened rapidly because of the strong defocusing effect of the neutral atmosphere. Throughout most of the occultation period, the lowest points on the radio ray paths moved approximately horizontally within the pressure levels between 100 and 200 mbar, sampling certain atmospheric conditions from the entry latitude to the south pole and then to the exit latitude, where an ionospheric effect was seen again.

The signal fluctuations observed during the main part of the occultation are attributable to small-scale structure in the atmosphere, which caused variations in refractivity along the radio ray path with changing geometry. Typical values for the vertical components of the ray velocity during the main portion of the occultation were a few tens of meters per second, while the horizontal velocity component was typically several hundred times larger relative to the limb of the planet.

Although the general shape of the intensity curves near occultation entry and exit is indicative of the average atmospheric pressure-temperature (*p-T*) structure, the measured signal frequencies should provide a better data source for computing *p-T* profiles. Preliminary study of the initial frequency data indicates, however, that these data, when used with the best current information on the spacecraft trajectory, do not yield usefully accurate profiles. Compared with the Voyager 1 observations, this degradation was expected and is due to several causes: (i) the accuracy with which the Voyager 2 trajectory is known has been seriously reduced, compared with that of Voyager 1, primarily because of problems with the Voyager 2 receivers (*4*); (ii) profile errors resulting from errors in trajectory and other sources are proportionately greater at a given pressure level as a result of the greater spacecraft-to-limb distance in the Voyager 2 occultation (*5*); (iii) the effects of certain error sources are multiplied still further by amounts proportional to the tangents of the angles between the occultation entry and exit paths in the plane of the sky and the verticals relative to Jupiter's limb (*5, 6*), which were much larger for Voyager 2 than for Voyager 1; and (iv) even in the absence of error, the oblique geometry of the Voyager 2 occultation samples the atmosphere along a slant path so that computation of accurate vertical profiles depends on the assumption of horizontal uniformity of the atmosphere. It should be emphasized, however, that the trajectory uncertainties are the primary problem.

Despite these difficulties, we believe that further analysis may provide useful atmospheric profiles at the two occultation points, for altitudes above the tropopause. Such an analysis might be based on an iterative approach to improving our knowledge of the trajectory through the use of information derived from the Voyager occultation measurements, including a careful comparison of intensity and frequency data. In any event, one of the most important features of the Voyager 2 occultation is its long horizontal cut through the south polar atmosphere where the results are expected to be nearly ideal for future detailed studies of atmospheric turbulence (*7*), for which the trajectory uncertainties are not serious.

Because of the large vertical extent of the ionosphere as compared with the atmosphere, the problems are not expected to degrade the accuracy of the topside ionospheric profiles derived from the observed dispersion of the two coherent radio signals. Figure 2 shows preliminary results for the plasma density as a function of height at the occultation entry and exit locations, where the solar zenith angles were 87.9° and 92.4°, respectively. The entry profile (66.7°S latitude) is for evening conditions where the ionosphere has been sunlit for hours; the exit profile (50.1°S latitude) is for morning conditions where the lower regions of the ionosphere have just emerged into sunlight after having been in darkness for hours.

For comparison with Voyager 2, we discuss several aspects of the Voyager 1 and Pioneer ionospheric profiles. The two Voyager 1 profiles were for similar evening and morning conditions, but they apply to lower latitudes on Jupiter (*1*). These results show that the evening plasma density in the topside ionosphere was greater than the morning density at all altitudes, and that the peak of the evening topside layer was lower in altitude and a factor of 10 higher in density than the peak of the morning layer. As compared with the ionospheric results obtained from Pioneer 10 and 11 occultations (*8*), the Voyager 1 profiles appear to have a larger vertical extent, a greater diurnal variation, and greater altitudes for the peaks of the topside layers. To explain these differences, Atreya *et al.* (*9, 10*) conclude (i) that the rate of ionization increased by an order of magnitude during the time between the Pioneer and Voyager 1 measurements, because of both increased solar activity and an increase in atomic hydrogen columnar abundance in the upper atmosphere; (ii) that the eddy diffusion coefficient at the homopause decreased significantly; and (iii) that the higher exospheric temperature for the Voyager 1 observations means that a different reaction may be controlling ion loss. These circumstances would seem to explain the principal Voyager 1 profile characteristics, for which the morning ionosphere would be a remnant of the evening one after the evening low-altitude bulge dissolves and the topside density decreases.

Returning to the Voyager 2 profiles of Fig. 2, we find that their most striking feature is that the morning profile has the higher topside density (the reverse of the Voyager 1 situation). Thus, the explanation of the Voyager results does not appear to be directly applicable to the Voyager 2 measurements. We have not extended the evening profile low enough in altitude to show its topside peak, however. As explained in (*1*), the sharp lower-altitude layers require the detailed study of the more complete data sources; the evening topside peak also appears to require such investigation. But the preliminary signal intensity measurements (Fig. 1) indicate that the evening (entry) ionosphere will show greater electron concentration below altitudes of about 1000 km than is the case for the morning profile and that the evening topside peak will be below this altitude. That is, the previous discussion of a dissolving bulge during the night may still pertain, but some other consideration seems to be required to explain the higher density in the upper reaches of the morning ionosphere and the lower altitude of the daytime peak. While it does not appear from the Pioneer 10 and 11 results that there is a strong latitude dependence, explanation of the Voyager 2 profiles may require further consideration of possible latitudinal variations, perhaps as related to the trapped-particle environment in the magnetosphere.

The plasma scale heights for the Voyager 2 profiles of Fig. 2 are about 880 and 1040 km for the morning and evening occultation locations, respectively. This corresponds to plasma temperatures of 1200 and 1600 K for the upper regions, under the assumption of a plasma of protons and electrons in an ambipolar diffusive equilibrium. The neutral gas may be considerably cooler, however (*9, 10*). The evening ionosphere measured at 66.7°S latitude by Voyager 2 has the highest plasma temperature of all of the topside regions sampled in the radio occultation experiments by the four Pioneer and Voyager spacecraft, being 45 percent greater than for the Voyager 1 results at lower latitudes (*11*).

During both Voyager encounters with the Jupiter system, the radio ray paths from the spacecraft to Earth traversed the Io torus (*12*), which made it possible to measure characteristics of the plasma

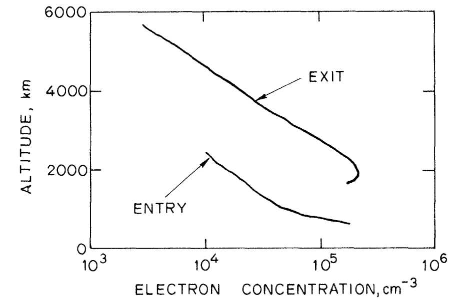

Fig. 2. Preliminary profiles of electron concentration in the upper ionosphere. These profiles are referenced to the level at which the refractivity equals unity, or about the 1-mbar level in the neutral atmosphere. See text for positions on Jupiter and solar zenith angles.

density and distribution in this region. Since the dispersive Doppler measurements of the dual-wavelength signals from the spacecraft provide an accurate indication of the change of plasma density as integrated along the total propagation path, it is particularly important to obtain independent information, to the degree possible, about the separate contributions of the torus, the interplanetary medium, and Earth's ionosphere. For the observation illustrated below, the main contribution of Earth's ionosphere has been determined and subtracted from the total. It is assumed that the interplanetary content did not change during the measurement.

Preliminary results of the 5 March 1979 pre-encounter torus occultation of the Voyager 1 spacecraft, measured simultaneously at the tracking stations in California and Australia, are presented in Fig. 3. Jupiter and the torus are depicted in the plane of the magnetic equator.

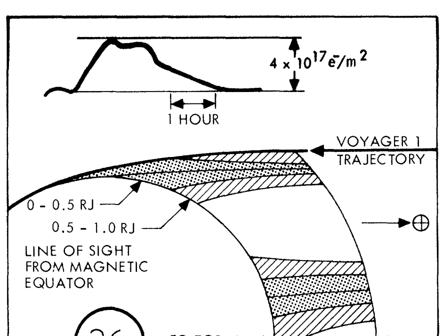

Fig. 3. Geometry and preliminary results of Voyager 1 occultation by Io torus. Figure gives position of the Voyager 1 Earth line relative to the magnetic equatorial plane of Jupiter as a function of position along the pre-encounter trajectory. The curve at the top shows variation in columnar electron content along the ray path for corresponding positions on the trajectory just below the curve. Effects of changes in the earth's ionosphere have been removed.

The Voyager 1 trajectory has been orthographically projected onto this plane; the perpendicular distances of the ray paths from the magnetic equator are shown in three ranges 0 to 0.5 R_J, 0.5 to 1.0 R_J, and > 1.0 R_J. At a given instant, the relationship of the ray path to the torus is obtained by examining the contour intervals along a line connecting the spacecraft position and the earth. The columnar electron content as a function of time, and hence the position along the trajectory, is plotted at the top of the figure. A maximum change of approximately 4.0×10^{17} electrons per square meter is attributable to the torus. This value corresponds to an electron concentration of about 1000 cm^{-3}, assuming a uniform distribution of plasma within a torus having a radius of 1.5 R_J. This compares favorably with other results (*12*). The small dip in the signal near its maximum was seen at two separated tracking stations and is hence believed to be real. A second occultation of the torus occurred after planetary occultation. These data require further analysis.

Continuing study of the Voyager radio science data taken during the two Jupiter encounters will be directed toward the extension and improvement of results, plus a search for other possible signatures in the data, such as might be present due to the occultation of Voyager 1 by the Jupiter ring system. Particularly challenging is the question of whether *p-T* profiles can be obtained for the neutral atmosphere sampled by Voyager 2, and the extent to which atmospheric turbulence can be characterized using the combined results from the two spacecraft. The dispersive observations of the Io torus will be used to test models of the plasma concentration within this feature. It is evident that, in addition to the results reported here, there is much information yet to be derived from the radio science observations of Jupiter.

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3. Data shown in Fig. 1 were obtained from the automatic tracking receivers and the 64-m antenna at Goldstone, California. Values were obtained approximately each 15 seconds during the period when the receivers detected the signals. Con-

sequently, while the figure indicates the correct range of fluctuations, the apparent fluctuation rates are much higher than those shown. During the ionosphere portions of the occultation, the values given may be contaminated by the limited capability of the automatic receivers to discriminate strong multipath signals occurring in the vicinity of ray caustics. More complete reduction and analysis must be based on broadband linear sampling of the received signals. Additionally, the automatic system depends on linearized calibration procedures for accurate intensity results. This procedure was evidently in error and resulted in a compression of the 3.6-cm data by about 5 dB. This effect has been verified by preliminary examination of the broadband data. Use of the broadband data samples will correct this problem.
4. One of the two redundant Voyager 2 radio receivers has failed, and the remaining unit, now in use, has suffered a partial failure. As a result, no coherent radio tracking data were collected for a period of several days surrounding the closest approach of the spacecraft to Jupiter. In addition, a trajectory correction maneuver, executed near perijove, further increased the uncertainties in spacecraft trajectory state during the occultation period. For long-distance occultations the effects of trajectory uncertainties can be multiplied by large factors (*5*, *6*), in this case of the order of 10^2 to 10^3.
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11. S. K. Atreya (personal communication) suggests how the Voyager 2 ionosphere profiles can be interpreted as being consistent with those obtained with Voyager 1. At the higher plasma temperature observed at the Voyager 2 entry point, the population of vibrationally excited H_2 is sufficient to reduce the ionization by the same reaction employed in (*9*) to explain the Voyager 1 day-to-night differences. Also, the Voyager 2 entry latitude is within the range of invariant latitudes for which the plasma torus associated with Io maps onto the southern hemisphere of Jupiter, thus providing a potential source of energy to produce the elevated temperatures.
12. A. L. Broadfoot *et al.*, *Science* **204**, 979 (1979); J. W. Warwick *et al. ibid.*, p. 995.
13. We thank the members of the Voyager flight team and the Deep Space Network, particularly the operations personnel at the Jet Propulsion Laboratory and the Goldstone Tracking Station, for their help and contributions to the observations. We especially thank B. J. Buckles, D. P. Holmes, and P. E. Doms for their efforts in the implementation of this experiment; D. N. Sweetnam and H. B. Hotz for their help in profile computations; D. E. Kline for his help in data production; and H. B. Royden, D. W. Green, and D. L. Nixon for their efforts in reduction of the torus observations. Supported by the National Aeronautics and Space Administration.

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Extreme Ultraviolet Observations from Voyager 2 Encounter with Jupiter

Abstract. *Extreme ultraviolet spectral observations of the Jovian planetary system made during the Voyager 2 encounter have extended our knowledge of many of the phenomena and physical processes discovered by the Voyager 1 ultraviolet spectrometer. In the 4 months between encounters, the radiation from Io's plasma torus has increased in intensity by a factor of about 2. This change was accompanied by a decrease in plasma temperature of about 30 percent. The high-latitude auroral zones have been positively associated with the magnetic projection of the plasma torus onto the planet. Emission in molecular hydrogen bands has been detected from the equatorial regions of Jupiter, indicating planetwide electron precipitation. Hydrogen Lyman α from the dark side of the planet has been measured at an intensity of about 1 kilorayleigh. An observation of the occultation of α Leonis by Jupiter was carried out successfully and the data are being analyzed in detail.*

During the Voyager 1 encounter with Jupiter, the ultraviolet spectrometer (UVS) made a series of significant discoveries, including a hot plasma torus near the orbit of Io and localized auroral zones at high latitudes on the planet (*1*). Now, with the Voyager 2 observation sequences modified to take advantage of our new knowledge of the planet and its environs, many details of the phenomena discovered by Voyager 1 have been elucidated. The measurement sequences recently made have allowed advances of particular interest in the study of the plasma torus and in the morphology and energy budget of particles exciting the atmosphere of Jupiter. Satellite observations by Voyager 2, as by Voyager 1, were somewhat compromised by the intense radiation environment. The question of satellite atmospheres is not emphasized here; more data analysis is required.

A number of the important features of Jupiter and its magnetosphere are displayed in Fig. 1.

Io plasma torus. The extreme ultraviolet (EUV) emission of the Io plasma torus observed by Voyager 2 shows the same major characteristics of spatial distribution and spectral content as the Voyager 1 observations described by Broadfoot *et al.* (*1*). The dominant emitting species are S III, S IV, and O III, as reported earlier, and a number of other persistent unidentified lines remain with roughly the same relative intensities. The spatial distribution of the plasma also remains as a full continuous torus with a radius of symmetry of 5.9 ± 0.3 Jupiter radii (R_J) and a cross-sectional radius of 1 ± 0.3 R_J, both in the magnetic plane and perpendicular to the plane. Figure 1 shows the distribution of emitting species graphically. The sharp peaks at ± 6 R_J are due to the torus emissions at the points at which the path length through the plasma reaches its maximum value of about 9 R_J. The bright emission at 685 Å, composed mostly of three strong multiplets of S III, dominates the spectrum at all times in spite of short-term variations in spectral content.

Although spectral content and spatial distribution did not change systematically between the two encounters, apparent systematic variations in intensity and electron temperature have been recorded with the Voyager 2 spectrometer. Figure 2 shows plots of measured intensity of the S III multiplet at 685 Å and estimated electron temperatures between day 60 and day 192, 1979. The available data indicate an increase in intensity by a factor of approximately 2 after day 158 and a reduced electron temperature as measured by the relative intensities of the S III features at 685 and 1020 Å. The intensities shown in Fig. 2 refer to the location of torus elongation on the sunward side of the planet, and a path length in the plasma of 9 R_J. The Voyager I measurement on day 60, indicated in Fig. 2, is the same datum discussed by Broadfoot *et al.* (*1*) and is on the high side of average brightness during that time. The combined increase in brightness and reduced electron temperature suggests an increase by a factor of 2 in ion density after day 158.

Model calculations in the analysis of the plasma torus emissions have been based on an assumed thin plasma in collisional ionization equilibrium (*1*, *2*). Although the EUV observations are consistent with the model from the point of view that excitation of states within a particular species is reasonably explained by a thermalized electron energy source, the observations show signs of disequilibrium between species such as S III and S IV. An example of this type of disequilibrium is shown in Fig. 3, which compares spectra obtained on days 171 and 192. Spectrum a (day 192) indicates a lower electron temperature (see Fig. 2) than spectrum b, based on the relative intensities of the S III multiplets at 685 and 1020 Å. However, spectrum b—in spite of its higher electron temperature—indicates a barely measurable S IV abundance, as deduced from the intensity of