large residuals; and the variations in b and T_1 vary more from spectrum to spectrum than one might expect when looking at the displacements in the corresponding images. A more sophisticated model with several areas of different temperatures might be preferred; with such a model it may be possible to determine whether any areas with temperatures as high as the melting point of sulfur (~ 385 K) are present. Such refinements will also benefit both from better pointing information than is yet available and from recovery of the rejected IRIS frame indicated in Fig. 6. On a larger scale, the degree of correlation between volcanic landforms and hot areas remains to be determined.

The region just discussed represents the warmest area observed by the infrared experiment. Another type of thermal anomaly, in which temperature differentials on the order of 50 K exist over the instrument footprint, is very common, however. Arbitrarily considering these differentials to represent 50 K enhanced warm spots, such spots would often cover as much as 5 percent of the field. These areas might represent numerous local sources for expulsion of material, cooling extrusive material, or regions of subsurface activity. This type of anomaly is common over the portion of the planet on which the data are concentrated; based on preliminary pointing information, this is the region $-40° < \lambda < 30°$, $240° < \phi < 360°$. Very limited sampling in other regions, however, indicates that this is not planetwide; between latitudes −20° and −50°, near longitudes 110° and 200°, such anomalies seem to be absent. It is apparent, however, that the IRIS observations on Io are consistent with observational (*18*) and theoretical (*19*) evidence for a thermally unusual and geologically active planet.

R. HANEL
B. CONRATH, M. FLASAR
V. KUNDE, P. LOWMAN
W. MAGUIRE, J. PEARL
J. PIRRAGLIA, R. SAMUELSON
Goddard Space Flight Center, Greenbelt, Maryland 20771
D. GAUTIER
Paris Observatory, Meudon, France
P. GIERASCH
Cornell University, Ithaca, New York 14853
S. KUMAR
Jet Propulsion Laboratory, Pasadena, California 91103
C. PONNAMPERUMA
University of Maryland, College Park 20742

References and Notes

1. R. Hanel *et al.*, *Space Sci. Rev.* **21**, 103 (1977).
2. R. G. Prinn and T. Owen, in *Jupiter*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1976), p. 319; S. T. Ridgway, H. P. Larson, U. Fink, in *ibid.*, p. 384. The CH_4 volume mixing ratio adopted was 8.14×10^{-4}, based on the assumption of a solar C : H ratio.
3. D. Goorvitch and C. Chackerian, Jr., *Icarus* **32**, 348 (1977).
4. J. D. Poll, J. L. Hunt, J. W. Mactaggart, *Can. J. Phys.* **53**, 954 (1975).
5. R. J. Terrile and J. A. Westphal, *Icarus* **30**, 274 (1977): R. J. Terrile, thesis, California Institute of Technology, Pasadena (1978).
6. U. Fink, H. P. Larson, R. R. Treffers, *Icarus* **34**, 344 (1978); R. Beer and F. W. Taylor, *Astrophys. J.* **219**, 763 (1978); H. P. Larson, R. R. Treffers, U. Fink, *ibid.* **211**, 972 (1977); R. Beer and F. W. Taylor, *ibid.* **179**, 309 (1973); H. P. Larson, U. Fink, R. Treffers, T. N. Gautier III, *Astrophys. J. Lett.* **197**, L137 (1975).
7. D. Gautier and K. Grossman, *J. Atmos. Sci.* **29**, 788 (1972).
8. G. Birnbaum, *J. Quant. Spectrosc. Radiat. Transfer* **19**, 51 (1978); G. Birnbaum and E. R. Cohen, *Can. J. Phys.* **54**, 593 (1976).
9. G. S. Orton and A. P. Ingersoll, in *Jupiter*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1976), p. 197.
10. W. Sinton, W. Macy, G. S. Orton, *Bull. Am. Astron. Soc.* **10**, 563 (Abstr.) (1978).
11. J. G. Charney and P. G. Drazin, *J. Geophys. Res.* **66**, 83 (1961).
12. G. H. Rieke, *Icarus* **25**, 333 (1975).
13. J. R. Thomas, *Eos* **53**, 1090 (1972).
14. N. F. Ness, M. H. Acuna, R. P. Lepping, L. F. Burlaga, K. W. Behannon, F. M. Neubauer, *Science* **204**, 982 (1979).
15. D. B. Nash and F. P. Fanale, *Icarus* **31**, 40 (1977); R. M. Nelson and B. W. Hapke, *ibid.* **36**, 304 (1978).
16. J. B. Pollack, F. C. Witteborn, E. F. Erickson, D. W. Strecker, B. J. Baldwin, T. E. Bunch, *ibid.* **36**, 271 (1978); D. P. Cruikshank, T. T. Jones, C. B. Pilcher, *Astrophys. J.* **225**, L89 (1978).
17. B. A. Smith *et al.*, *Science* **204**, 951 (1979).
18. O. L. Hansen, *Icarus* **18**, 237 (1973); F. C. Witteborn, J. D. Bregman, J. B. Pollack, *Science* **203**, 643 (1979).
19. S. J. Peale, P. Cassen, R. T. Reynolds, *Science* **203**, 892 (1979).
20. We thank D. Vanous, D. Crosby, and J. Taylor and their colleagues at Texas Instruments, Goddard Space Flight Center (GSFC), and Jet Propulsion Laboratory (JPL) for preparation of the instrumentation. L. Herath (GSFC), F. Rockwell, C. Otis, and R. Thompson (Astro Data Systems Inc.) contributed substantially to the data reduction. K. Fox provided molecular constants for methane. T. Burke, E. Miner, D. Collins, and L. Horn (JPL) made substantial contributions. We also thank the imaging team, especially B. Smith, G. Hunt, H. Masursky, and R. Terrile for many discussions, for permission to use Fig. 7, and for help in the selection of 5-μm hot spots for IRIS observations. The support of the Voyager Project Staff is also gratefully acknowledged. Portions of the research described in this report were supported by the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract NAS 7-100.

20 April 1979

Radio Science with Voyager 1 at Jupiter: Preliminary Profiles of the Atmosphere and Ionosphere

Abstract. *A preliminary profile of the atmosphere of Jupiter in the South Equatorial Belt shows (i) the tropopause occurring at a pressure level of 100 millibars and temperature of about 113 K, (ii) a higher warm inversion layer at about the 35-millibar level, and (iii) a lower-altitude constant lapse rate matching the adiabatic value of about 2 K per kilometer, with the temperature reaching 150 K at the 600-millibar level. Preliminary afternoon and predawn ionospheric profiles at 12° south latitude and near the equator, respectively, have topside plasma scale heights of 590 kilometers changing to 960 kilometers above an altitude of 3500 kilometers for the dayside, and about 960 kilometers at all measured heights above the peak for the nightside. The higher value of scale height corresponds to a plasma temperature of 1100 K under the assumption of a plasma of protons and electrons in ambipolar diffusive equilibrium. The peak electron concentration in the upper ionosphere is approximately 2×10^5 per cubic centimeter for the dayside and about a factor of 10 less for the nightside. These peaks occur at altitudes of 1600 and 2300 kilometers, respectively. Continuing analyses are expected to extend and refine these results, and to be used to investigate other regions and phenomena.*

The planned radio science investigations with Voyager, the radio equipment parameters, and the mission characteristics of importance in these experiments have been described (*1, 2*); we now present preliminary results on features of the atmosphere and ionosphere of Jupiter based on the occultation of Voyager 1 by the planet. During occultation, the radio rays from the spacecraft to Earth traverse these regions and the radio signal characteristics are affected in measurable ways. Because questions have been raised about the accuracy of such experiments, we also briefly describe several relevant aspects of the Voyager investigation.

Pioneer 10 and 11 were used in the first radio occultation experiments at Jupiter. The errors in early published atmospheric profiles based on these measurements (*3*) have resulted in concern that the occultation technique might never be useful for studying the neutral atmospheres of the giant planets. Although several key error sources were subsequently identified, and modified atmospheric profiles were published (*4, 5*), appreciable uncertainties in these newer results still remain, and the doubts have not been wholly resolved.

The Voyager occultation experiment has several features that are expected to improve the accuracy and reliability of its final results. These include the use of (i) two coherent radio frequencies [wavelengths (λ) of 3.6 and 13 cm] to provide self-calibration of the effects of plasma along the propagation paths; (ii) increased transmitter power and antenna size on the spacecraft to provide greater signal strengths; (iii) a radiation-resistant oscillator of greatly improved stability as the spacecraft frequency reference, which permitted us to use the single ray path from the spacecraft to Earth and thus avoid uncertainties in the frequency of the spacecraft transponder under dynamic propagation conditions when a signal from Earth is used for the frequency reference; (iv) a spacecraft trajectory that produces a path of the spacecraft in the plane of the sky that is nearly perpendicular to the limb of the planet, as compared with the oblique occultations of the two Pioneer spacecraft (and also of Voyager 2) at Jupiter; (v) an orientation maneuver to point the spacecraft antenna in the proper direction to compensate for the bending of the ray path around the limb of the planet; and (vi) computational techniques that use the available information on the detailed gravitational field of the planet, and on the zonal atmospheric winds, for the three-dimensional ray-tracing inversion of the measured data needed to produce the profiles.

This report is preliminary from several points of view. First, there are two data sources from different receiving systems. The results reported here are based on data from automatic signal-tracking receivers at the observing stations. These receivers provide immediate Doppler frequency measurements that are relatively easy to use. However, complete signal characteristics can be determined only from future analyses of the data from the wide-band linear receivers. Consequently, we have no ready results for several of the radio science investigations. Moreover, the profiles given here should be improved upon and extended by later, more complete analyses. Second, the estimate of the spacecraft trajectory during encounter with Jupiter is still being refined, and this will also improve the accuracy of the atmospheric and ionospheric profiles. Third, there has not been an opportunity for a detailed comparison of results obtained for the same regions from several different Voyager experiments. Although it is not expected that the refinements will cause substantial changes in the profiles for the regions reported upon, these results should be considered with due regard to their limitations.

Figure 1 presents the pressure-temperature (*p-T*) profile for the atmospheric region probed by the 3.6-cm radio signal during occultation entry. (The 13-cm signals were not used in this preliminary study since they are more affected by the ionosphere.) The location for this region is in the South Equatorial Belt at about 12°S, 63°W (System III, 1965.0); it was just shortly before sunset at this location when the measurements were made. The results cover a height range of about 80 km, between pressure levels of about 10 and 600 mbar. The two curves result from different assumed boundary-condition temperatures of 130 and 160 K at about the 10-mbar level, where Pioneer and ground-based infrared measurements have been used to derive temperatures in this range (*6*). Of particular interest in Fig. 1 are (i) the tropopause pressure of 100 mbar and temperature of about 113 K; (ii) the temperature lapse

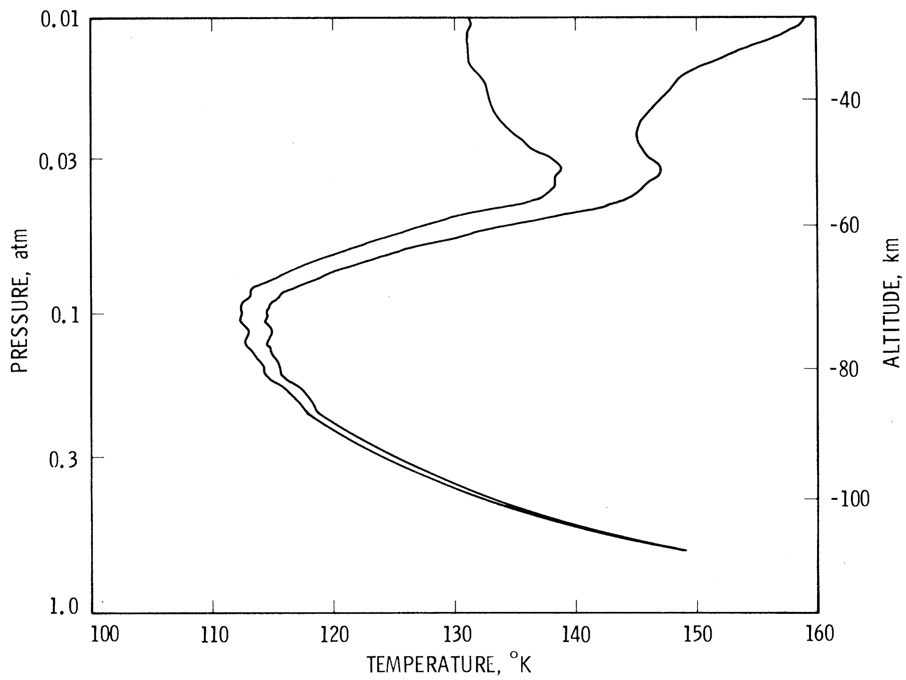

Fig. 1. Preliminary profile of atmospheric temperature as a function of pressure, as computed from the 3.6-cm radio occultation of Voyager 1 at about 12°S, 63°W (System III, 1965.0) on Jupiter. The zero of the (nonlinear) altitude scale is at the height at which the refractive index of the atmosphere is one part in a million greater than unity, which occurs approximately at the 10^{-3} atmosphere pressure level. Different assumed upper boundary conditions on the temperature yield the two separate curves which coalesce at lower altitudes. It is assumed that the atmosphere consists of 88 percent H_2 and 12 percent He by volume and that the zonal westerly wind speed at the occultation point is 20 m/sec.

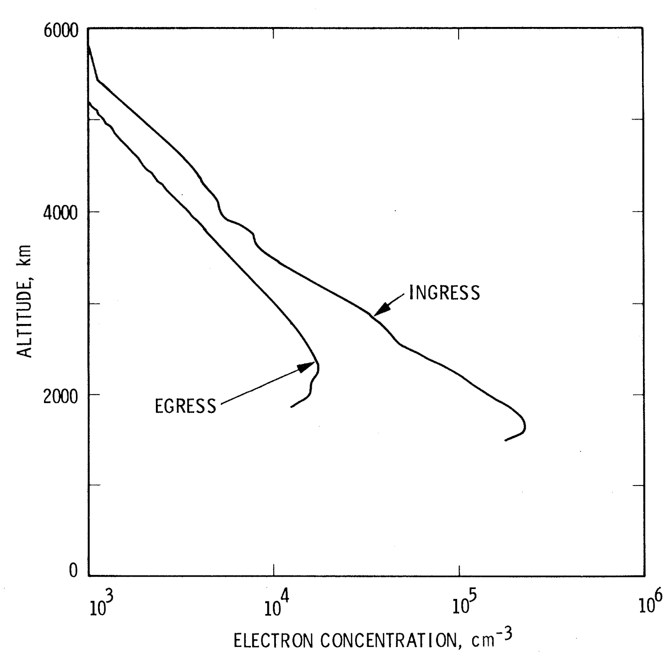

Fig. 2. Preliminary profiles of upper ionospheric electron concentration as a function of altitude (same reference level as in Fig. 1) for the locations of the occultation ingress and egress.

rate at lower altitudes of about 2 K/km, which matches the expected value for adiabatic conditions in Jupiter's atmosphere; and (iii) a relatively warm inversion layer in the stratosphere at the 35-mbar pressure level, which may be due either to absorption of solar radiation by a minor atmospheric constituent at this level or to upward propagating inertia gravity waves (*7*). This latter possibility might also help explain the high plasma temperature discussed below. Although the uncertainty in Fig. 1 for the temperature at the tropopause, for example, is 5 to 10 K, this should decrease with more analysis. However, the relative locations and shapes of the small-scale temperature features are not expected to change. It will also be possible, we believe, to derive occultation entry and exit profiles extending both higher and lower in the atmosphere and, in addition, to determine the location and effects of microwave-absorbing regions in the lower atmosphere. Whereas the preliminary data yield a profile ending at the 600-mbar level, for example, it is known that both the 3.6- and 13-cm signals penetrated more deeply. Because of the incompleteness of the present results, comparison with other sources of information about these atmospheric regions is not attempted at this time.

The basic occulatation measurements yield refractivity profiles, and temperatures and pressures are computed based on assumed atmospheric constituents in hydrostatic equilibrium. For Fig. 1, we used a mixture of 88 percent H_2 and 12 percent He by number density, based on infrared measurements (*6*). If, for example, the mixture were actually 94 percent : 6 percent, a point at 100 mbar and 113 K would be moved to about 99 mbar and 107 K. On a plot of log p versus log T, all points would be moved the same distance and direction so that the shape of the curve would not change.

The profiles of upper ionospheric electron concentration at occultation entry (12°S, 63°W, solar zenith angle 82°, late afternoon) and exit (1°N, 314°W, solar zenith angle 98°, predawn) were derived from the dispersive Doppler frequency determined by comparative measurements of the two coherent radio signals. The signals were propagated from Voyager 1 to Earth through Jupiter's ionosphere. For the entry side, the sunlit ionosphere had a peak electron concentration of about 2.2×10^5 cm^{-3} at an altitude 1600 km above the ~ 1-mbar pressure level in the neutral atmosphere. The topside scale heights are about 590 and 960 km below and above an altitude of 3500 km, respectively. The exit ionospheric region, which had been in darkness for nearly 5 hours, had a peak concentration of about 1.8×10^4 cm^{-3} at an altitude of 2300 km and a very nearly constant topside scale height equal to that of the upper part of the sunlit ionosphere. The larger scale height corresponds to a plasma temperature of 1100 K, under the assumption that ionized atomic hydrogen (protons) and electrons are in ambipolar diffusive equilibrium. The change to the smaller scale height in the lower part of the sunlit ionosphere may represent a transition to chemical equilibrium conditions in this region (*8*). It appears difficult to explain the large difference in peak day and night electron concentrations in terms of proton lifetimes and the time constant for diffusion (*8*). That is, factors other than those related to the response of this region to varying solar illumination appear to shape the upper ionosphere.

For comparison with the above results, an interpretation of the single-frequency Pioneer 10 experiment yields a value of 975 km for the scale height of the late-afternoon topside ionosphere probed near 28°N latitude (*9*). This profile does not show the transition between two values of scale height that is apparent in the corresponding Voyager profile. Pioneer results from higher latitudes also suggest that there may be large changes of ionospheric characteristics with position and time (*9*), although equipment limitations on these missions may restrict the detail to which comparisons should be made.

The ionosphere extends well below the regions shown in Fig. 2, but as with Pioneer, its structure is too complex to be analyzed on the basis of the preliminary data. The wide-band receiver measurements are needed to separate the simultaneously existing propagation modes for this region. This analysis must also be completed in order to refine the results for the upper regions of the neutral atmosphere.

Analyses of the data from the prime source (recordings of the wide-band, dual-frequency receiver output) for the Voyager 1 radio science investigations at Jupiter are just beginning. Particular efforts will be made to (i) extend the results to higher and lower altitudes and improve the accuracy of the profiles of ionospheric plasma density and atmospheric pressure and temperature; (ii) measure characteristics of the absorbing regions in the lower atmosphere; (iii) study atmospheric turbulence and other irregularities from their effects on the radio signals; (iv) search for a limb focusing effect directly behind the planet (*10*); and (v) determine if characteristics of the newly discovered ring of Jupiter (*11*) can be obtained from the radio signals which passed through the ring plane at occultation emersion, using analysis methods similar to those planned for the study of the Saturn ring system (*1*). In addition, more extensive Doppler tracking observations of the coherent dual-frequency signals are being studied to determine whether the plasma in the magnetosphere can be measured, with a particular interest in possible investigations of the Io flux tube and torus.

V. R. ESHLEMAN
G. L. TYLER
Center for Radar Astronomy, Stanford University, Stanford, California 94305
G. E. WOOD
G. F. LINDAL
J. D. ANDERSON
G. S. LEVY
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91103
T. A. CROFT
Radio Physics Laboratory, SRI International, Menlo Park, California 94025

References and Notes

1. V. R. Eshleman, G. L. Tyler, J. D. Anderson, G. Fjeldbo, G. S. Levy, G. E. Wood, T. A. Croft, *Space Sci. Rev.* **21**, 207 (1977).
2. In view of the pre-encounter description of the radio science experiment (*1*), it should be explained that several investigations in the area of celestial mechanics and relativity were not included in the mission plan for Voyager 1 and 2 at Jupiter. The primary reasons are related to the good results from the Pioneer encounters and the expected improved results to be obtained with the Galileo orbiter of Jupiter, plus problems with the Voyager 2 spacecraft receiver and the effects of the larger-than-anticipated, unmodeled, attitude-control forces on both Voyager spacecraft. However, investigations in these areas are planned for the Saturn encounters.
3. A. Kliore, D. L. Cain, G. Fjeldbo, B. L. Seidel, S. I. Rasool, *Science* **183**, 323 (1974); A. Kliore, G. Fjelbo, B. L. Seidel, T. T. Sesplaukis, D. N. Sweetnam, P. M. Woiceshyn, *ibid.* **188**, 474 (1975).
4. W. B. Hubbard, D. M. Hunten, A. Kliore, *Geophys. Res. Lett.* **2**, 265 (1975); V. R. Eshleman, *Science* **189**, 876 (1975); A. J. Kliore and P. M. Woiceshyn, in (*5*), pp. 216–237.
5. T. Gehrels, Ed., *Jupiter* (Univ. of Arizona Press, Tucson, 1976).
6. G. S. Orton and A. P. Ingersoll, in (*5*), pp. 206–215.
7. R. G. French and P. J. Gierasch, *J. Atmos. Sci.* **31**, 1707 (1974).
8. S. K. Atreya and T. M. Donahue, in (*5*), pp. 304-318.
9. G. Fjeldbo, A. Kliore, B. Seidel, D. Sweetnam, D. Cain, *Astron. Astrophys.* **39**, 91 (1975); G. Fjeldbo, A. Kliore, B. Seidel, D. Sweetnam, P. Woiceshyn, in (*5*), pp. 238–246.
10. V. R. Eshleman, G. L. Tyler, W. T. Freeman, *Icarus* **37**, 612 (1979).
11. B. A. Smith *et al.*, *Science* **204**, 951 (1979).
12. We thank the members of the Voyager Flight Team and the Deep Space Network, particularly the operations personnel at the Jet Propulsion Laboratory and in Spain, for their help and many contributions to the observations reported here. We especially thank B. J. Buckles and D. P. Holmes for their efforts in the implementation and execution of this experiment, D. N. Sweetnam and H. B. Hotz for help in the profile computations, and W. T. Freeman for this calculation of the antenna pointing maneuver. This work was supported by the National Aeronautics and Space Administration.

23 April 1979