that the mass of Io is significantly larger than de Sitter's determination by about 20 percent. The masses of the other three satellites are in better agreement. The recent measurement of the radius of Io by means of the occultation of Beta Scorpii (*2*) in combination with the mass determined from the Pioneer data yields a mean density of 3.5 g/cm^3 for the satellite. This high a value for the density of the inner Galilean satellite definitely suggests that it is composed of heavier elements than Ganymede or Callisto. Further analyses of the data will specify the masses of the Galilean satellites more precisely and will also yield a value for Jupiter's mass, a quantity that has not been determined reliably from the Pioneer 10 data at this time.

Perhaps the most interesting results from the analysis of the Pioneer data lie in the determination of the gravity field of the planet to a greater accuracy than has been possible with the natural satellites. Preliminary determinations of the even zonal harmonic coefficients indicate that the dynamical flattening of Jupiter $(a-b)/a$ (where a is the semimajor axis and b is the semiminor axis) is definitely in the neighborhood of 0.065, which agrees with the dynamical value determined from the satellites (*3*).

Future analyses of the Doppler data obtained in the few hours around closest approach will concentrate on achieving better resolution in the gravity field of Jupiter. In particular, attempts will be made to determine or bound the third zonal harmonic coefficient (J_3) and the second-degree sectoral harmonics (C_{22}, S_{22}). Whatever the results of the gravity analysis, it is certain that Pioneer 10 will provide some very good boundary conditions on the interior models of Jupiter and will yield important clues on the distribution of mass in the outer layers of the planet.

J. D. ANDERSON
G. W. NULL, S. K. WONG
Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91103

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21 December 1973

Preliminary Results on the Atmospheres of Io and Jupiter from the Pioneer 10 S-Band Occultation Experiment

Abstract. *The preliminary analysis of data from the Pioneer 10 S-band radio occultation experiment has revealed the presence of an ionosphere on the Jovian satellite Io (JI) having an electron density peak of about* 6×10^4 *electrons per cubic centimeter at an altitude of approximately 60 to 140 kilometers. This suggests the presence of an atmosphere having a surface number density of about* 10^{10} *to* 10^{12} *per cubic centimeter, corresponding to an atmospheric surface pressure of between* 10^{-8} *and* 10^{-10} *bar, at or below the detection threshold of the Beta Scorpii stellar occultation. A measurement of the atmosphere of Jupiter was obtained down to the level of about 80 millibars, indicating a large temperature increase at about the 20 millibar level, which cannot be explained by the absorption of solar radiation by methane alone and can possibly be due to absorption by particulate matter.*

The Pioneer 10 spacecraft flew by Jupiter on 4 December 1973, on a remarkably precise trajectory which took it not only behind the disk of Jupiter but also behind the satellite Io (JI). This trajectory afforded an opportunity to study their atmospheres by the method of radio occultation which has been used in the past to study the atmospheres of Mars and Venus (*1*). The occultation of Io, occurring while the spacecraft was in the plane of Io's orbit, some 550,000 km from the satellite, established the presence of an ionosphere and hence of a neutral atmosphere on Io.

The existence of an atmosphere on Io has been suspected ever since anomalous brightenings of the satellite were discovered after eclipses by Jupiter (*2*). However, since that time many observations have produced conflicting evidence of this phenomenon, which was regarded as inconclusive or sporadic by most investigators (*3*). Some evidence of frost-like deposits on the surface was also obtained by polarization measurements (*4*). The occultation of Beta Scorpii by Io in 1971 provided no positive indication of an atmosphere, although an upper limit for the surface atmospheric pressure was determined to be between 10^{-6} and 10^{-7} bar (*5*).

A preliminary analysis of the "quick-look" closed-loop Doppler data obtained as the Pioneer 10 spacecraft was entering occultation by Io has produced a profile of the electron density as shown in Fig. 1. It shows an ionosphere extending for some 700 km above the surface of Io with an electron density peak of about 6×10^4 electrons per cubic centimeter and a topside plasma scale height of about 220 km. At the time of these observations Io was on the earth's side of Jupiter and the point of entry into occultation was facing away from Jupiter. The solar zenith angle at this point was approximately 81 deg. The planetary surface, as established from a crude estimate of the time of loss of signal, lies between 60 and 140 km below the ionosphere peak. A more accurate determination of the radius of Io is currently under way.

If an analogy with the ionosphere of Mars is permissible, then such an ionosphere should form at a number density level of neutrals of from 10^9 to 10^{11} per cubic centimeter. In that case the density at the surface would lie between about 10^{10} and 10^{12} per cubic centimeter. Again assuming a mean molecular weight lower than that of the Mars atmosphere, one obtains a surface atmospheric pressure ranging from 10^{-8} to 10^{-10} bar, which is below the threshold of detection of the Beta Scorpii stellar occultation observation (*5*).

The discovery of an ionosphere on

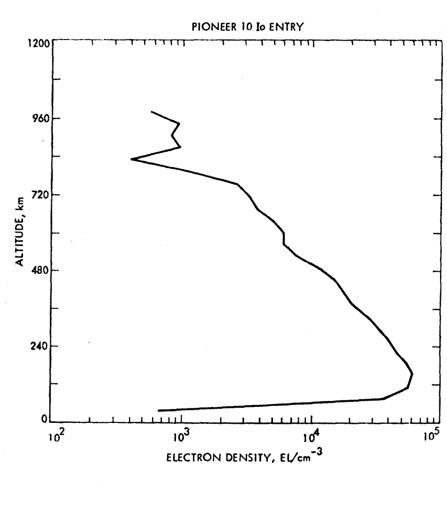
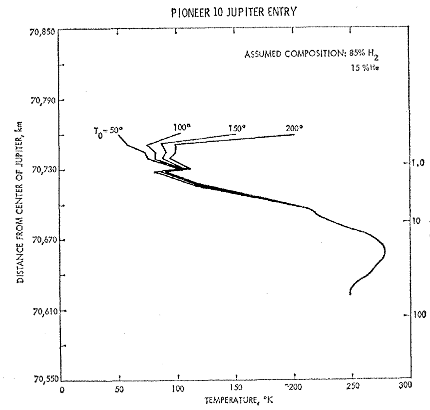


Fig. 1. Electron density in the ionosphere of Io observed at a solar zenith angle of about 81 deg. (The uncertainty in altitude above the surface is about ± 40 km.)

Fig. 2. Temperature profile in the atmosphere of Jupiter to the level of approximately 100 mbar (the assumed composition is 85 percent H_2 and 15 percent He, by volume).



Io is of considerable significance for those interested in the history of planetary atmospheres. The recent determinations of the size and shape of the ionospheres of Mars and Venus have already proved to be the prime source of information on the structure and dynamics of the upper atmospheres of these planets. In the case of Mars, with an escape velocity of the order of 5 km/sec, it has been shown that, although the classical thermal escape of gases is inefficient, the energies involved in the ionospheric processes are sufficient to impart the required escape energy to not only H atoms but even N and O atoms (*6*). The ionosphere of Mars, therefore, seems to have played a major role in the evolution of water at its surface and in its atmosphere, and, therefore, in all probability, in determining the degree of evolution of life on that planet. In the case of a satellite like Io, comparable in size and density to our moon and situated at 5 A.U. from the sun, it is not altogether unexpected that a small amount of atmosphere, and therefore an ionosphere, should exist. However, we are probably dealing with an entirely new type of ionosphere which extends from the surface to more than 700 km above it; despite the fact that the solar radiation intensity is less by more than a factor of 50 than it is at Venus, the peak electron density on Io is within a factor of 2 of that of the Venus ionosphere. One is surely dealing with a different species of gas and an unknown set of mechanisms.

The recent discovery of Na emissions from Io (*7*) and the postulation that N_2 and H_2 may also be present in the atmosphere (*8*) may very well be related to the ionosphere that has been observed. A detailed study of this ionosphere will not only contribute to the understanding of the atmosphere of Io but will also contribute significantly to the entire subject of aeronomy.

During the occultation of the Pioneer 10 probe by Jupiter, the radio beam entered the Jovian atmosphere on the sunlit side at a latitude of about 27.7° and a solar zenith angle of about 81 deg. Preliminary analysis of the closed-loop Doppler data obtained during entry into occultation reveals that, as expected, the defocusing and absorption in the atmosphere of Jupiter caused the receivers to lose the signal when the radio beam was at about the 100-mbar level in the atmosphere. Under the assumption of a composition containing 85 percent H_2 and 15 percent He (by volume), the temperature profile shown in Fig. 2 was obtained. The four different profiles at the top result for different values of the initial temperature T_0. This temperature distribution in the upper levels of the atmosphere of Jupiter is completely different from any published model of the atmosphere. Although the existence of a temperature inversion at about 100 mbar due to the absorption of solar radiation by methane has been predicted by Gillett *et al.* (*9*) and Hogan *et al.* (*10*), the observed temperature increase is extremely large and probably cannot be accounted for by methane absorption alone. However, a large temperature increase at this level in the atmosphere can probably be attained by the absorption of solar visible radiation by particulate matter and dust, as suggested by Axel (*11*). One additional interesting point worth noting in Fig. 2 is the fact that the temperature gradient between the altitude 70,650 km and the altitude 70,730 km is about 2.3°K/km, very close to the adiabatic lapse rate for the assumed composition. Also, 20μm and 40-μm remote sensing measurements indicate a temperature of about 130°K (*12*) at the visible cloud tops, which probably lie much below the region explored here. Thus, the atmospheric temperature probably continues to decrease with depth below the level at which we lost the signal until it reaches a value of about 130°K. This will give credibility to the conjecture that the observed high temperature at the 20-mbar level is an atmospheric inversion caused by the absorption of solar radiation.

The closed-loop Doppler data also show that both the evening and morning sides of Jupiter have ionospheric layers. The detectable portion of the ionosphere appears to extend over an altitude range of at least 1500 km. Discontinuities in the observed Doppler shift indicate the possible occurrence of multipath propagation, in which case the spacecraft signal may have reached the tracking stations via several paths through the Jovian ionosphere, and thereby caused the phase-locked receivers at the Deep Space Net stations to go in and out of lock because of fading. It is hoped that further analysis of the open-loop, wide-bandwidth recordings of the occultation data will provide further information on the ionosphere and the deeper layers of the neutral atmosphere of Jupiter.

ARVYDAS KLIORE
DAN L. CAIN
GUNNAR FJELDBO
BORIS L. SEIDEL

Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91103

S. I. RASOOL

NASA Headquarters, Washington, D.C. 20546

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