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Jupiter

Jupiter is the largest planet and is the prototype of the giant planets, the others of which are Saturn, Uranus and Neptune. It possesses four large, icy moons, a huge and intense magnetosphere, and a unique plasma torus surrounding the orbit of the satellite Io. It has therefore been a prime target for exploration, and in addition, its huge mass has made it a valuable target for gravity assists. The Pioneers and Voyagers used Jupiter in this way to reach Saturn, Uranus and Neptune, and Ulysses used it to obtain a solar orbit of high inclination. The announcement of the Pioneer opportunities in 1968 led to the establishment of the first real Jupiter community, and the measurements by these spacecraft taught us a great deal about the environment of the asteroid belt and Jupiter's magnetosphere, as well as the planet itself. Once they had been launched, studies were initiated for an ambitious, highly reliable spacecraft called Grand Tour but they were never implemented; instead they were replaced by the less-expensive Voyagers. These two spacecraft made history as they visited all four giant planets and also made important measurements of Jupiter's Galilean satellites, as well as Titan and Triton. Galileo included an entry Probe to explore Jupiter's atmosphere and an Orbiter to define the magnetosphere and the satellites. In spite of a delay of many years before it could be launched, and a loss of the reflector of the high-gain antenna, it has been a spectacular success. Ulysses made some measurements of the environment, and Cassini will do the same, as well as providing remote sensing of the planet and satellites.

THE PIONEERS

In 1968, NASA issued an Announcement of Opportunity to solicit experiment proposals for the two spacecraft that would eventually be named Pioneers 10 and 11. At that time there was no real Jupiter 'community'; our body of knowledge was expressed in occasional papers but there was little or no discussion at scientific meetings. Jeffreys had shown that the temperature of the surface [or cloud tops] must be close to the solar-equilibrium value, and Menzel had confirmed this by analysis of thermal-infrared observations (see Wildt 1969). Jupiter's small mean density had led to the inference that hydrogen and helium were major constituents, and models of the interior structure had been worked out (DeMarcus 1958). Öpik (1962) had published a detailed analysis of the composition, leaning heavily on results of a pioneering observation of a stellar occultation by Baum and Code (1953). Unfortunately, the scale height obtained from these data was much too small, and Öpik obtained a helium abundance that was correspondingly much too large. Münch had pointed out the important role of pressure-induced absorption by H_2 in controlling the thermal opacity, and models of the thermal structure involving this opacity had been worked out (Trafton and Münch 1969).

Radio emission from the planet and its magnetosphere were early discoveries as radio astronomy underwent its rapid development after the Second World War. Convenient summaries appear in Berge and Gulkis (1969) and Carr and Desch (1969). Analysis of the synchrotron emission by electrons in the radiation belt allowed an estimate of the strength and orientation of Jupiter's magnetic field. Intense pulses at decametric wavelengths were eventually found to be linked to the position of the satellite Io, and Goldreich and Lynden-Bell (1969) proposed that the mechanism involves a unipolar generator as Jupiter's rapid rotation sweeps the magnetic field past the satellite. The thermal emission by Jupiter's atmosphere appears in the wavelength region from a few mm to tens of cm. The principal opacity source is ammonia in the pressure region of a few bars, and

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allows estimates of the ammonia abundance and the temperature profile (Berge and Gulkis 1969, de Pater and Massie 1985). Measurement of the thermal radiation of the planet had shown that it radiates roughly twice as much energy as it absorbs from the Sun (Low 1976).

The principal objectives of the Pioneers would be to measure the zodiacal light, and therefore the density of interplanetary dust; to diagnose the potential hazard to spacecraft of the asteroid belt; and to make an initial reconnaissance of Jupiter and its radiation belts. One result of the announcement of opportunity was the formation of a Jupiter community, much of which was represented at the Third Arizona Conference on Planetary Atmospheres (1969); several of the papers presented there have been quoted in the preceding paragraph. By the time of the Pioneer encounters (December 1973, December 1974) a large body of Jupiter science had accumulated. This science and the Pioneer results are represented in the book 'Jupiter' (Gehrels 1976).

While Pioneers 1 and 2 were being built and on their way to Jupiter, a number of valuable results were obtained from Earth-based studies. First came the 1971 occultation of the star β Sco by Jupiter. It was successfully observed by three groups: Combes *et al*. (1971), Hubbard *et al*. (1972) and Veverka *et al*. (1974). A critical review by Hunten and Veverka (1976) concludes that the temperature is 170–200 K in the mesosphere (number density $5 \times 10^{14}\,\mathrm{cm}^{-3}$ or pressure near 3 μbar). Two years later (1973) Brown discovered strong emission of the yellow *D* lines of Na in the vicinity of Io (Brown and Yung 1976), and this was followed by the even more remarkable discovery of the Io Plasma Torus (Kupo *et al*. 1976). This object and its physics are described in several chapters of the book by Dessler (1993). One of the first discoveries of the Kuiper Airborne Observatory was that of Jovian water vapor (Larson *et al*. 1975). The absorptions are strong, but they can only be observed from high altitudes because those of the Earth's lower atmosphere are even stronger.

Returning to the Pioneers, the Jupiter-oriented instruments included an Imaging PhotoPolarimeter, a two-channel UltraViolet Photometer, a Magnetometer, and a 2-channel InfraRed Radiometer. Occultation by the ionosphere and atmosphere was observed by means of the telemetry carrier, and tracking of the spacecraft gave information on the mass and gravity field. Charged particles from plasma to cosmic rays were measured by four instruments, and dust particles by two. Although Pioneer 10 passed right through the Io Plasma Torus, its plasma instrument was oriented in the wrong direction to readily detect it, and a detection was not reported until several years after the encounter (Intriligator and Miller 1981). The principal discoveries concerning the planet were:

- The images showed that the well-known cloud structure of belts and zones is supplanted at latitudes above 45° by structures resembling large-scale convection.
- The IR Radiometer confirmed that the planet radiates approximately twice as much energy as it absorbs from the Sun, and showed that this total radiation is essentially independent of latitude (Ingersoll *et al*. 1976). Because the solar heat is deposited primarily at low latitudes, the internal heat must therefore come out preferentially at the higher latitudes, probably as a consequence of the special properties of convective heat transport (Ingersoll and Porco 1985).
- The radio occultation experiment measured the electron densities in the ionospheres of Io and Jupiter. Initial results for the density of Jupiter's neutral atmosphere were very strange; the anomaly was eventually traced to neglect of the planet's oblateness, and corrected temperature profiles are given by Kliore and Woiceshyn (1976). The exospheric temperature was found to be an astonishingly hot $\sim$1000 K, instead of the $<$200 K expected for heating by solar UV. Primary candidates or the additional heat source are absorption of wave energy that has propagated up from the lower atmosphere (Yelle *et al*. 1996), and precipitation of ions and electrons from the magnetosphere (Hunten and Dessler 1977).

THE VOYAGERS

During 1976 studies were under way at the Jet Propulsion Laboratory for the 'Grand Tour'. These two spacecraft were designed for the long life and extreme reliability needed to take advantage of a forthcoming opportunity to visit all four of the Jovian planets by use of gravity assists. Accompanying the spacecraft studies were studies of potential instruments. Right at the end of 1976, the U.S. Congress withdrew support for these ambitious missions, and gave it instead to a pair of missions that would be based on the Mariner line that had successfully explored Venus, Mars and Mercury. Initially called 'MJS' (Mariner Jupiter-Saturn), these spacecraft were later re-named 'Voyagers 1 and 2'. Fortunately the planetary alignment did not go away and the Voyagers kept working, so both missions were eventually extended to carry out the exploration of the Uranus and Neptune systems.

The Voyagers arrived at Jupiter in March and July 1979. With 3-axis stabilization each spacecraft was able to carry a pair of cameras, much more powerful than the spin-scan instrument on the Pioneers. Figure 1 shows two false-color mosaics, one each for Voyagers 1 and 2, showing one complete rotation (actual colors are various shades of yellow). An UltraViolet Spectrometer (UVS) was used in a novel mode, in which it observed occultation of the Sun by the upper atmosphere. It was therefore possible to obtain height profiles of the major gases, especially H_2, H and CH_4. The Pioneer occultation experiments of the telemetry carrier

Figure 1 Comparison of two cylindrical projections of Jupiter, made from images taken by Voyagers 1 and 2. Longitudes are 400 to 0 degrees in the top image, and the bottom one is aligned with it. Colours have been enhanced in the processing. Relative motions of features can be seen; for example, the Great Red Spot has moved westward and the white ovals eastward. Regular plume patterns are equidistant around the northern edge of the equator, while a train of small spots at approximately 80 degrees south latitude has moved eastward. Significant changes are evident in the recirculating flow east of the Great Red Spot, in the disturbed region west of the Great Red Spot, and in the brightening of material spreading into the equatorial region from the more southerly latitudes. (P-21772 C.)

were repeated. Both measurements confirmed the very high exospheric temperatures, ~1000 K, found by the Pioneers, but the height of the ionosphere was much greater than expected (McConnell *et al*. 1982). Presumably the ionospheric plasma is raised by vertical drifts.

The UVS also observed the airglow from the same atmospheric region. Its most striking discovery was of intense far-ultraviolet emissions from the Io Plasma Torus, making it clear that this body is the seat of enormous energies, much greater than had been expected from the ground-based studies mentioned above. The principal constituents are ions of O and S, each in several charge states. The source is Io's atmosphere, of which SO_2 was found by IRIS, the InfraRed Interference Spectrometer to be a (or the) major constituent (Pearl *et al*. 1979). When this gas escapes from the satellite, it is dissociated and ionized by torus electrons, and the ions are then accelerated to co-rotation with Jupiter by the latter's magnetic field. This acceleration is a major source of energy, which probably powers the entire medium. The plasma temperature is typically several eV or several hundreds of thousands of degrees K, with a component of electrons at several hundred eV (Brown *et al*. 1983). After the ions are neutralized, their velocity is high enough to carry them to distances of ~100 Jovian radii, where they can again become ionized and join the magnetospheric population. As they work their way back inward, they are accelerated to energies in the millions of eV and contribute a major part of the magnetospheric population.

A detailed analysis of the infrared spectra has been presented by Carlson *et al*. (1993). Confirming earlier Earth-based work, they found the abundances of the ice-forming vapors CH_4, NH_3 and H_2O to be somewhat greater than 'solar', the values they would have if all the C, N and O were converted to these molecules. The NH_3 and H_2O were depleted at the higher altitudes and lower temperatures roughly as expected for condensation into the cloud particles that are inferred to be present. The excess is generally thought to be accounted for by late accretion of icy planetesimals which would be vaporized in the atmosphere. A careful analysis of the energy balance confirmed that Jupiter radiates 1.668 times as much as it receives from the Sun (Hanel *et al*. 1981). The excess heat from the interior is believed to arise from a combination of residual primordial heat and release of gravitational energy by a slight shrinkage of the planet.

Some of the images of the night side showed bright spots attributed to lightning flashes. Close analysis (Borucki and Williams 1986) showed that they had the size and elliptical shape expected if the flashes had occurred at the 3–5 bar level of the water clouds and the light was diffused by the ammonia clouds at ~0.6 bar.

GALILEO

The idea of a Jupiter Orbiter-Probe (JOP) mission received a great deal of study even before the launch of the Voyagers. The Jet Propulsion Laboratory had organized a Science Advisory Group as early as 1971 and JOP was recommended by the U.S. National Academy's Space Science Board (SSB) after consideration by its Committee on Planetary and Lunar Exploration (COMPLEX). It was proposed in the U.S. President's budget for consideration late in 1977, but was omitted from the version of the budget prepared by the Budget Committee of the House of Representatives. A major stated reason, which turned out to be all too valid, was that the Space Shuttle and the necessary Centaur upper stage would not be ready in time to launch the mission. In response, the U.S. planetary community staged a supporting campaign, which was successful in that the House rejected the recommendation of its own committee and appropriated the funds necessary to start the mission, which was soon re-named 'Galileo'. As the date of availability of the Shuttle slipped again and again, the same thing happened to Galileo. Development of the Shuttle version of the Centaur upper stage caused further delays, but in 1985 the launch system was declared ready and the spacecraft was shipped to Cape Canaveral for launch preparations. The JPL crew took time off from these preparations to watch the launch of Challenger and its disastrous breakup. Investigation of the reasons imposed a delay in the launch date of Galileo. Next, NASA cancelled the adaptation of the Centaur stage to the shuttle, on the grounds that it would be too dangerous to launch with a payload containing such large quantities of liquid hydrogen and oxygen. It appeared that there would be no way to get Galileo to Jupiter by means of the available solid-fueled upper stages, until it was realized that the necessary velocity could be gained by means of gravity assists, a flyby of Venus followed by two of the Earth. Such a trajectory required the addition of a system of sun shades to Galileo, which had not been designed to withstand the additional heating that it would encounter so close to the Sun. After a further delay of three years, the mission was finally launched in October 1989. Because of the three extra orbits, Galileo did not arrive at Jupiter until December 1995. During its transit, Ulysses obtained its Jupiter gravity assist in February 1992. It made some measurements of the plasma environment, but was not equipped with any instruments that could sense the planet itself.

Shortly after the first Earth encounter a command was sent to Galileo to unfurl the reflector of the High-Gain Antenna, which was a duplicate of one that had been used on several Earth satellites operating in geosynchronous orbit. Although the motor responded, something in the system stuck and the reflector only partially opened. In spite of many attempts to complete the deployment, none was successful and the mission had to be carried out with a low-gain antenna with a bit rate of only a few tens of bits per second. A massive re-programming of the spacecraft's central computer was successfully undertaken, providing the ability to compress the data to the greatest possible extent. There was no loss of the relayed Probe data, but considerable restriction in the amount of data that could be taken by and transmitted from the remote-sensing and magnetospheric instruments on the Orbiter.

The Jupiter objectives of Galileo, and the corresponding instruments, were reviewed by Hunten *et al*. (1986). Many of the instruments were carried into the atmosphere by the Probe; they comprised

- the Atmospheric Structure Instrument, measuring temperature, pressure and acceleration;
- the Mass Spectrometer, measuring composition throughout the descent;
- the Helium Abundance Interferometer, dedicated to an accurate measurement of this one gas;
- the Net Flux Radiometer, to measure this quantity in several IR and visible wavelength bands;
- the Lightning and Radio Detector, also including a detector for very energetic electrons and ions in the innermost magnetosphere;
- equipment to measure the Doppler shift of the Probe-Orbiter relay signal and therefore obtain information on the descent rate and winds.

The Orbiter carried a magnetometer and a suite of instruments to measure the fluxes of ions and electrons as a function of energy in the torus and magnetosphere. More closely related to the planet and the satellites were an imaging system, the Near Infrared Mapping Spectrometer (NIMS), and the Photo-Polarimeter Radiometer (PPR), with many channels from the visible to the far infrared.

These three instruments had an unexpected workout in 1994 when the fragments of Comet Shoemaker-Levy 9 entered Jupiter's atmosphere at locations visible from Galileo but not from the Earth (Carlson *et al*. 1997). Many other measurements of the impact sites were obtained from Earth after they had rotated into view. Here only three will be mentioned: detection of cometary water vapor from the KAO (Bjoraker *et al*. 1996, Sprague *et al*. 1996) and non-detection of seismic waves propagating away from the impacts, which would have given a probe of Jupiter's interior (Walter *et al*. 1996). Generally speaking, this event taught us far more about the comet and the nature of the impact phenomena than about Jupiter.

The entry site of the Probe was constrained to a very low latitude for various reasons, including the need to take advantage of Jupiter's rapid rotation to minimize the entry velocity relative to the atmosphere. This velocity, of order $50\,\mathrm{km\,s^{-1}}$, was much greater than the $11\,\mathrm{km\,s^{-1}}$ experienced by Apollo capsules returning from the Moon, and the energy per unit mass greater by a factor of 20. The challenge of designing a successful entry system was therefore a major one. Unfortunately, the equatorial region is the site of extensive areas with much less cloud than exists elsewhere. These areas are called 'hot spots' not because they are any warmer than other areas, but because they appear

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