Atmospheres of Jupiter and Saturn [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1981 **303**, 225-245
doi: 10.1098/rsta.1981.0198

Phil. Trans. R. Soc. Lond. A **303**, 225–245 (1981)
Printed in Great Britain

Atmospheres of Jupiter and Saturn

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In this paper I review current knowledge of the atmospheres of Jupiter and Saturn, making use of the extensive telescopic studies, International Ultraviolet Explorer Satellite observations and the measurements made during the recent Pioneer and Voyager flybys which have been supported by detailed theoretical studies. A detailed discussion is given of the composition of these atmospheres and the abundance ratios which provide insight into their original state and their evolution.

The Voyager observations indicate a surprisingly close similarity between the weather systems of the Earth and the giant planets. Although both Jupiter and Saturn have internal heat sources, and are therefore star-like in their interiors, they appear to produce terrestrial-style weather systems. A detailed discussion is given of this work, which forms a major study of the Laboratory for Planetary Atmospheres at University College London.

1. Introduction

One of the fundamental goals for the research programme of the exploration of the Solar System is to provide a quantitative explanation of the extreme differences between the terrestrial planets and the major planets, Jupiter, Saturn, Uranus and Neptune. The latter are huge, rapidly rotating, low density objects with optically reducing atmospheres. They contain more than 99% of the planetary mass of the Solar System. The low density of these objects suggests that, like the stars, they are entirely composed of light elements, hydrogen, helium, carbon and nitrogen, whereas silicates, iron and nickel chiefly constitute the cores of the inner planets. Since hydrogen and helium are thought to be the principal constituents of the solar nebulae, understanding the origin and evolution of these giant planets may hold important clues to the formation of the Solar System.

There has been a tremendous advance in knowledge and understanding of Jupiter and Saturn in the past 7 years, through the observations made by instruments on the Pioneer and Voyager space probes, from the I.U.E.† Earth orbiting observatory and from Earth-based telescope observations supported by detailed theoretical studies (Kondratyev & Hunt 1981).

In this paper I review current understanding of these planets. I first discuss the composition of these planetary atmospheres (§2) and analyse observations for both cosmogonical and cosmological investigations (§4). I discuss the visible and thermal structures of these planetary atmospheres which relate closely to their compositions (§3). For centuries both amateur and professional astronomers have made telescopic observations of these planets, tracking cloud features and providing catalogues of planetary weather systems. Now, for the first time, with Voyager observations, and using image processing techniques such as the I.P.I.P.S.† facilities at U.C.L. (Hunt *et al.* 1981*d*), I am able to discuss the meteorologies of Jupiter and Saturn in a

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† I.U.E., International Ultraviolet Explorer Satellite; I.P.I.P.S., Interactive Planetary Image Processing System.

quantitative manner. In the final sections (§§5 and 6) I discuss the motions of these atmospheres and the relationship of their driving mechanisms to characteristics of the terrestrial atmosphere.

This paper therefore provides a discussion of the major atmospheric processes in the troposphere and stratosphere, and includes the initial results from the Voyager 1 encounter with Saturn in 12 November 1980.

2. ATMOSPHERIC COMPOSITION

The advances in infrared astronomy during the past few years are primarily responsible for the rapid increase in our knowledge of the composition of the atmospheres of the distant, giant planets. For Jupiter, infrared spectroscopy is responsible for the discovery of most of the minor molecules. As recently as 1970, only H_2, CH_4 and NH_3 had been positively identified as constituents in the Jovian atmosphere. Since then, more than a dozen minor constituents

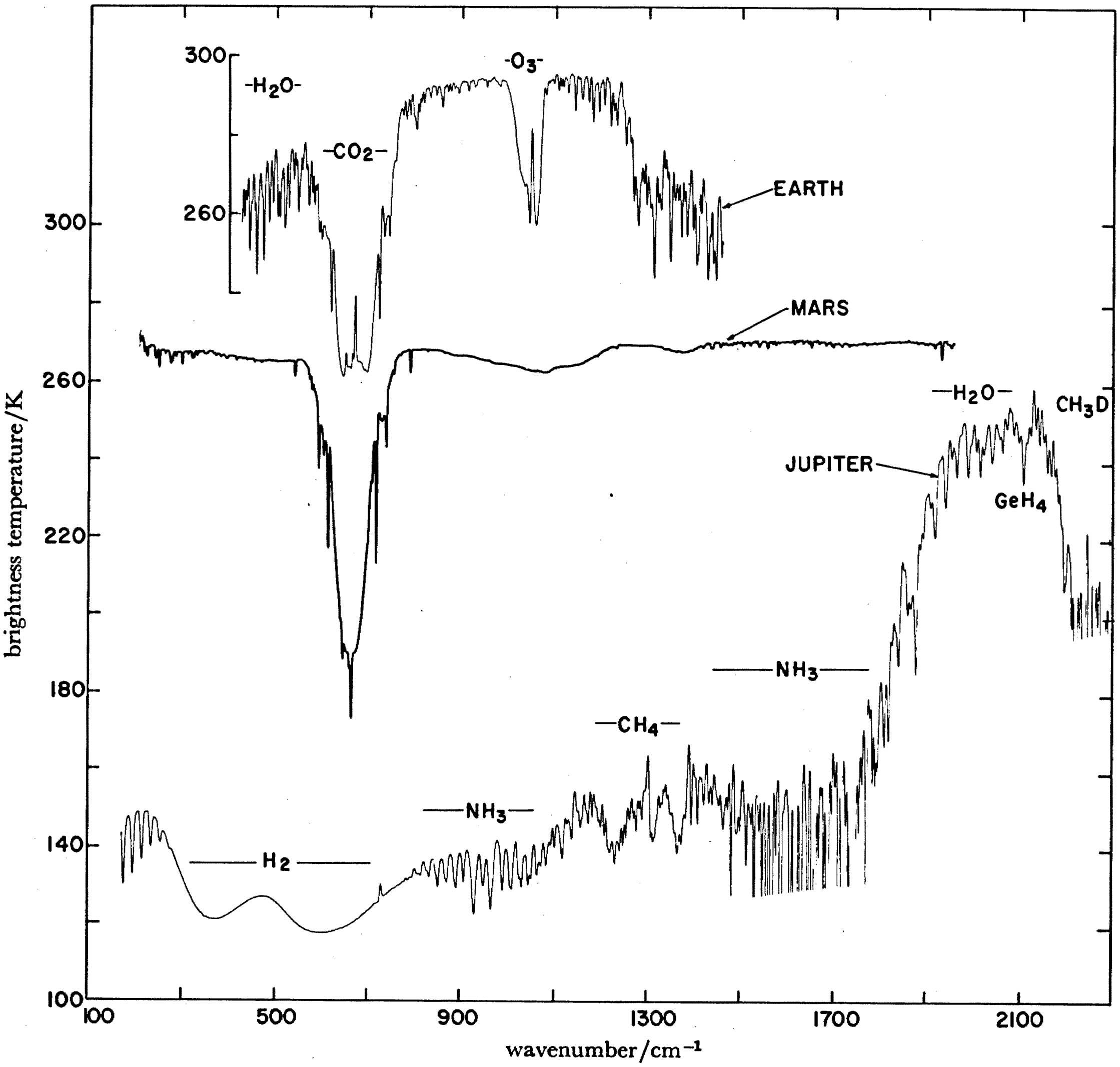

FIGURE 1. The brightness temperatures of the Earth, Mars and Jupiter, obtained by IRIS instruments mounted on Nimbus 4, Mariner 9 and Voyager 1 spacecraft respectively (after R. Hanel, private communication).

have been detected. Most of these molecules have been observed in the wavelength range 1–3 μm or in the far infrared range of $\lambda > 5$ μm. Observations made from Earth-based telescopes utilize the terrestrial atmospheric windows which occur at wavelengths centred on 5, 10 and 20 μm. Then, by means of very sensitive detectors, it is possible to obtain high signal to noise ratios to produce extremely high spectral resolution on the brighter planets. With Fourier transform spectrometers, the resolving power can reach 10^5 in the near infrared (Maillard *et al.* 1973; Lecacheux *et al.* 1976) and 10^4 at 5 μm (Larson 1980) and at 10 μm (Tokunaga *et al.* 1979). This type of instrument has also been flown on the Voyager spacecraft to obtain observations of the entire infrared spectrum at a resolution of 4.2 cm^{-1} (Hanel *et al.* 1979).

In figure 1 I compare the infrared spectrum of Jupiter with those of the Earth and Mars for the region 100–2300 cm^{-1}. In this region of the spectrum many molecules exhibit strong vibration–rotation bands, whose structure is relatively simple, and in many cases they have been extensively studied in the laboratory, which greatly assists in their identification and interpretation.

Molecular hydrogen is symmetric, and therefore does not have a permanent dipole moment. However, a weak collision-induced dipole spectrum exists which creates significant absorption for the very long path lengths encountered in the Jovian and Saturnian atmospheres, of about 40 km above the 1 bar level. The presence of hydrogen in the Jovian spectrum in the region 100–750 cm^{-1} is clearly seen in figure 1.

The determination of the abundance of atmospheric helium in the atmospheres of Jupiter and Saturn is of fundamental importance for understanding the evolution of these atmospheres. Although the first positive detection of helium was made by Carlson & Judge (1974) from the observation of the He I line at 58.4 nm, there are many uncertainties in interpreting this observation owing to the lack of any neighbouring spectral observations of hydrogen. A more precise result can be determined through the influence of helium on the far infrared thermal emission spectrum. Trafton (1967) demonstrated that the pressure-induced absorption due to collision between hydrogen molecules and hydrogen and helium is responsible for a large fraction of the far infrared opacity of Jupiter. Gautier & Grossman (1972) developed a method for inferring the helium abundance from spectral measurements in the 300–700 cm^{-1} region, which uses the different spectral characteristics of the H_2–H_2 and H_2–He absorption coefficients. Using the Voyager Jupiter observations, Hanel *et al.* (1981*a*) and Gautier *et al.* (1981) have ed values using two methods. The first scheme uses only the IRIS spectra from selected ons on the planet, while the second method uses a thermal profile independently derived from radio occultation measurements and infrared spectra recorded near the occultation point. A hydrogen mole fraction of 0.897 ± 0.03 is obtained by Gautier *et al.* (1981) by the first method, and 0.880 ± 0.036 by the second. These correspond to helium mass fractions of 0.19 ± 0.05 and 0.21 ± 0.06 respectively. These values are the most accurate for Jupiter since high spectral resolution data (4.2 cm^{-1}) have been used to calibrate the method.

A similar method has been applied to the Saturn observations, and Hanel *et al.* (1981*b*) find values for H_2 of *ca.* 0.94 and for He of *ca.* 0.11. I discuss the significance of these results, and in particular the depletion of helium on Saturn, in §4.

In table 1 I list the molecules that have been detected in the atmospheres of Jupiter and Saturn. The region of the spectrum where these molecules are detected is extremely significant since there is considerable variation in the level of line formation with wavelength.

Clearly, in the troposphere, the interpretation of the measurement will be affected by clouds. Their basic microphysical properties and spatial variations are not accurately known, which puts some uncertainty into the derived abundances (Hunt 1978).

All the molecular identifications, apart from those of He and HD, are the results of infrared observations made with resolving power better than 10^3. On Jupiter, H_2, $^{13}CH_4$, CH_3D, C_2H_2, C_2H_6, CO, PH_3 and $^{15}NH_3$ have been detected from the ground while H_2 and GeH_4 were observed from the Kuiper Airborne Observatory. On Saturn, Hanel *et al.* (1981*b*) detected C_3H_4 and C_3H_8 for the first time, and these species have also been found in the atmosphere of Titan.

TABLE 1. OBSERVED MOLECULES IN ATMOSPHERES OF JUPITER AND SATURN

	spectral range/μm	
molecule	(Jupiter)	(Saturn)
He	0.0584	—
HD	0.746	0.6064
H_2	0.8, 2.5, 1.25	0.8, 1.25
CH_4	0.8, 1.1	0.8, 1.1
$^{13}CH_4$	1.1	1.1
CH_3D	5	5
NH_3	1–2, 10, 50–200	0.645
$^{15}NH_3$	10	—
H_2O	5	—
CO	5	—
GeH_4	5	—
PH_3	2, 5, 10	3, 5, 10
C_2H_2	*ca.* 0.17, 13	*ca.* 0.17
C_2H_6	12	12
C_3H_4	—	*ca.* 15
C_3H_8	—	*ca.* 13

The detection of C_2H_2 and C_2H_6 in the infrared spectrum of Jupiter by Ridgeway (1974) was the first observational evidence for CH_4 photodissociation by the solar ultraviolet radiation in the upper Jovian atmosphere. Hanel *et al.* (1981*a*) estimate mixing ratios of 3×10^{-8} for C_2H_2 and 5×10^{-6} for C_2H_6 (see also table 1). However, these values, which refer to stratospheric levels, do show some latitudinal and hemispheric variations. The abundance of ethane relative to acetylene in Jupiter's atmosphere appears to be about three times larger in the polar regions than at lower latitudes. Furthermore there is an overall increase in the abundance ratio by a factor of 1.7 between the Voyager encounters. Obviously it is not possible to account for this large variation through photodissociation processes. Hunt *et al.* (1981*a*) believe that this observation is more consistent with the suggestion by Bar-Nun (1979) that some C_2H_2 is generated by lightning discharges. Cook *et al.* (1979*a*) have shown that the Jovian lightning coincides with areas of convective activity. Hunt *et al.* (1981*a*) suggest that cloud structures are consistent with more convective cloud systems in the equatorial region than at the poles, which is consistent with this hypothesis.

Acetylene is visible in the Jovian ultraviolet spectra too (figure 3), where a strong absorption feature is seen at *ca.* 170 nm. The corresponding spectrum for Saturn shows a very strong absorption at this wavelength, indicating the presence of C_2H_2 in the upper atmosphere. Previously, C_2H_2 had been noticeably absent from the infrared spectra (Encrenaz & Combes 1981), since it was thought that it could be associated with the formation of photochemical haze layers in the upper atmosphere. Such effects will have a marked hemispheric effect on Saturn, where the planet's rotation axis is inclined at 26°. Indeed, at the time of the Voyager encounter the southern hemisphere of the planet was partially obscured by haze layers, with a correspondingly marked difference in the observed atmospheric constituents between the hemispheres (Hanel *et al.* 1981*b*).

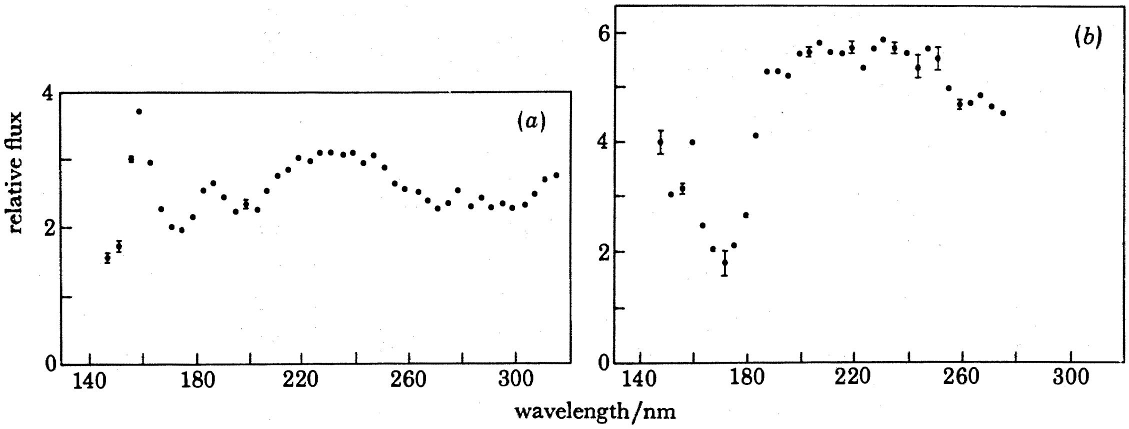

FIGURE 2. I.U.E. observations of the ultraviolet spectra of (*a*) Jupiter and (*b*) Saturn in the range 140–200 nm.

The observations of PH_3, GeH_4 and CO in the atmosphere of Jupiter and PH_3 on Saturn are not in agreement with models of thermochemical equilibrium (Prinn & Owen 1976). For example, one would expect phosphorus to be in the form of PH_3 only in regions where the temperature is greater than 800 K, in the deep, unobservable portions of the atmosphere. Barshay & Lewis (1978) suggest that PH_3 should not be observed since it is expected to react with H_2O below a temperature of 2000 K. Its discovery on Jupiter and Saturn at 2, 5 and 10 μm (Ridgeway 1974; Larson *et al.* 1977; Ridgeway *et al.* 1976; Tokunaga *et al.* 1981) was entirely unexpected. Prinn & Lewis (1975) suggested that PH_3 was probably carried from deep atmospheric levels, where it has been observed. For Jupiter this corresponds to the 200–230 K level at 5 μm and the 130–145 K level at 9–10 μm. The time needed for the transportation would have to be short enough for the PH_3 to be observed at the top of the current before it has been completely oxidized with the available H_2O. Similar mechanisms could then account for GeH_4 and CO. As a consequence, the observations of these non-equilibrium species is further evidence of the dynamic, and particularly the convective, activity in the atmospheres of Jupiter and Saturn (table 1).

The abundance of H_2O in these atmospheres is affected by condensation processes. With the higher spatial resolution, Hanel *et al.* (1979) find concentrations of 5×10^{-6}, which is about five times higher than the previous estimates made from aeroplane measurements.

The abundance of sulphur and its vertical profile are also important for understanding the evolution and present state of these atmospheres. At depth H_2S is expected to be the predominant sulphur compound, and the detection of its presence will require the direct measurements to be made by the Galileo probe later this decade.

3. Atmospheric structure

Both Jupiter and Saturn have internal heat sources and emit more energy than they receive from the Sun. The initial Earth-based observations of Aumann *et al.* (1969) have now been refined by Hanel *et al.* (1981 *a*). With a global geometric albedo of 0.266 ± 0.013 and a phase integral of 1.25, derived from the Pioneer observations of Tomasko *et al.* (1978), they estimate a Bond albedo of 0.333 ± 0.026. These values yield an effective lightness temperature of 124.9 ± 0.3 K and an energy balance of 1.67 ± 0.13. For Jupiter it is possible to account for this additional energy in terms of the gravitational contraction of the planet at a rate of about 1 mm per year (Hubbard, this symposium).

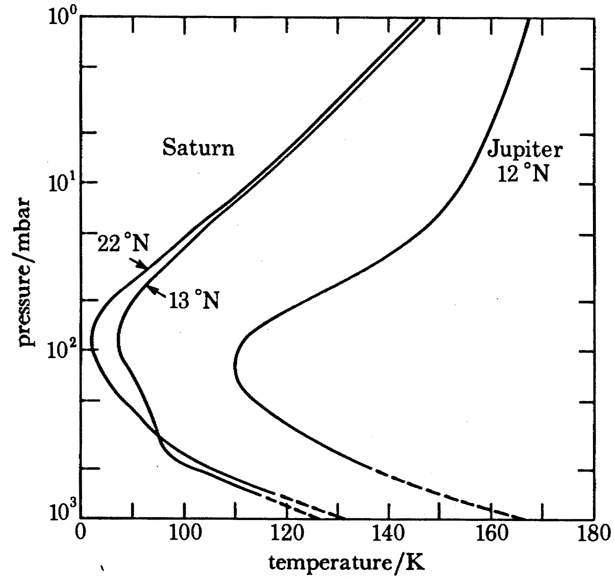

Figure 3. A Saturn atmospheric profile for latitude 3.1° to 11.1° S centred on the region sounded by the Pioneer 11 egress radio occultation. The radio occultation profile is used for $p < 126$ mbar and the retrieved temperature profile at larger pressures (after Orton & Ingersoll 1980).

For Saturn, the situation may be slightly more complicated. Tomasko *et al.* (1980) indicate that the phase integral is 1.50, which corresponds to a Bond albedo of 0.54 ± 0.15. Orton & Ingersoll (1981) then estimate an effective planetary temperature of 96.5 ± 2.5 K. This then suggests that Saturn emits 2.8 ± 0.9 times the energy received from the Sun. It is possible that this value is an overestimate since the Pioneer observations refer only to the southern hemisphere and therefore one season. Also, Hanel *et al.* (1981 *b*) suggest that the albedo may be less than 0.36, which would then reduce the estimate of internal heating. Certainly this value of Saturn's internal heat flux, quoted by Orton & Ingersoll (1981), is thought to be too large to be explained by simple cooling and contraction. An additional energy source, namely precipitation of helium at the top of a metallic hydrogen liquid interior, could supply some of the additional energy (Hubbard, this symposium). However, from the point of view of the atmospheric physics issues, both planets have internal heating which will be an additional energy source for their weather systems.

This heating will have some effect upon the temperature structure of the atmospheres at the tropospheric levels. Representative atmospheric profiles for Jupiter and for Saturn are shown in figure 3. For both planets the tropospheric temperature structures are close to the adiabatic profile. Remote sensing observations from Earth (see, for example, Orton 1981) and from spacecraft (Hanel *et al.* 1979; Orton & Ingersoll 1981), penetrate to pressure levels of about 1 bar. The lapse rate for the Jovian atmosphere is about 1.9 K km^{-1}, while for Saturn it is about 0.9 K km^{-1}. As a result we can expect more extensive cloud layers in the Saturn atmosphere in comparison with Jupiter.

The major differences between these atmospheres occur above the tropopause, in the less dense regions which are more sensitive to the changes in the solar radiation. We are primarily concerned with the stratospheric levels where the photolysis of CH_4 to produce C_2H_2 is the major reaction (Atreya 1981). For Jupiter, the volume mixing ratios of C_2H_2 and C_2H_6 are found to be 6×10^{-8} and 2×10^{-8} respectively at an altitude of 160 ± 15 km above the ammonia cloud tops. This corresponds to the values of 3×10^{-8} for C_2H_2 and 5×10^{-6} for C_2H_6 deeper in the stratosphere obtained by Hanel *et al.* (1981*a*). On Saturn, Hanel *et al.* (1981*b*) find mole fractions of 5×10^{-6} for C_2H_6 and 2×10^{-8} for C_2H_2, and have also detected the presence of C_3H_4 and C_3H_8.

The acetylene absorption band at *ca.* 160 nm is clearly evident in the ultraviolet spectrum of Moore & Hunt (1981). However, the feature is considerably stronger in the corresponding spectrum for Saturn (figure 3), emphasizing a basic difference between the two upper atmospheres. It is generally thought that temperature structure in the stratospheres of the atmospheres is due to the heating created by the absorbed sunlight in the strong methane bands that are situated in the infrared portion of the spectrum. However, there may be additional contributions due to upper atmosphere haze layers. Strobel (1973) suggested that hydrazine particles could form at these levels and act as nucleation agents. Prinn (1974) found that such particles of radius $\leqslant 1$ μm could form an absorbing layer of optical depth in the range of 0.2–0.25, with a tropopause temperature between 110 and 120 K. While this result is certainly consistent with the high altitude haze provided by Axel (1972), Prinn's study is critically dependent upon the ammonia concentration at these levels. Certainly there is an extensive haze throughout the Jovian stratosphere and atmosphere as the Voyager studies of Cook *et al.* (1979*b*) have shown. Its composition is not known, but there is every reason to believe that the inward diffusion of the ring particles could be a familiar contribution to the opacity. With a variety of particle sizes, and different setting times, this may then create distinct layers in the stratosphere, which is suggested in the occultation data of Eshelmann *et al.* (1979). The stratosphere of Saturn shows similar structure (figure 4). The haze over the southern hemisphere during the time of the Voyager encounter appears to extend throughout the stratosphere (Smith *et al.* 1981). However, unlike for Jupiter there is a marked seasonal effect of this haze which Trafton (1978) noted affected the spectroscopic observations of Saturn.

4. ABUNDANCE RATIOS

In table 2 are summarized the abundance ratios of the constituents of the atmosphere of Jupiter and Saturn. Considerable care has been taken to use observations made at similar times and regions of the spectrum to minimize the uncertainties in the derived values.

Without doubt, the most important ratios for understanding the variation of these planets is H_2/He. We see from table 1 that this value differs between the two planets which must relate to differences in their evolution and internal structure.

The present helium abundances may differ from the planets' bulk composition, as a result of helium differentiation during its evolution. Differentiation is possible since helium and hydrogen are immiscible over the range of temperature and pressures relevant to Jupiter's interior. Also the metallic molecular hydrogen transition near 3 Mbar implies a discontinuity in helium abundance across the phase boundary. As Gautier *et al.* (1981) indicate, on the basis of the decay in the variation of the internal luminosity to its current value over the past 4.6×10^9 years, the helium differentiation has at most only recently begun on Jupiter.

TABLE 2. ABUNDANCE RATIOS OF JUPITER AND SATURN

ratio	spectral range	Jupiter	Saturn	primordial nebula	Sun
$\frac{H_2}{H_2+He}$	thermal radiation	0.897 ± 0.03	0.94 ± 0.03	0.871 ± 0.02	0.89
C/H	scattering model	$(2\text{–}3) \times 10^{-3}$	—	—	—
	1–2 μm	8×10^{-4}	1.15×10^{-3}	—	$4.7^{+1.2}_{-1.0} \times 10^{-4}$
	thermal radiation	7×10^{-4}	—	—	—
D/H	HD/H_2 (visible)	$(5.1 \pm 0.7) \times 10^{-5}$	$(5.5 \pm 2.9) \times 10^{-5}$	2.5×10^{-5}	—
CH_3D/H_2	5 μm	$(2.5\text{–}5) \times 10^{-7}$	—	—	—
	10 μm	$(2\text{–}5) \times 10^{-7}$	—	—	—
$^{12}C/^{13}C$	1.1 μm	89^{+12}_{-10}	89^{+25}_{-18}	—	89 ± 5
$^{15}N/^{14}N$	10 μm	$(3.7 \pm 1.5) \times 10^{-3}$	—	—	(Earth 3.7×10^{-3})

The Jovian H_2/He ratio (table 2; Gautier *et al.* 1981) is equal to the solar value and, more significantly, it is slightly smaller than the primordial estimate of Lequeux *et al.* (1979). If the possible uncertainties in the estimates are taken into account, it would seem that the results are consistent with a present uniform mixture of hydrogen and helium within the Jovian interior. The observation by Hanel *et al.* (1981 *b*) that the helium mass fraction on Saturn is only 1%, compared with 19% on Jupiter, is very significant. An atmospheric depletion implies significant gravitational separation of hydrogen and helium within Saturn's interior. This is consistent with energy balance considerations.

Information on the stable isotopes $^{12}C/^{13}C$ and $^{14}N/^{15}N$ provides information on the chemical evolution of the Galaxy. Combes & Encrenaz (1979) estimate the $^{12}C/^{13}C$ ratios for Jupiter and Saturn to be 89^{+12}_{-10} and 89^{+25}_{-18} respectively, which are in good agreement with the solar value. Encrenaz *et al.* (1980) identified the presence of $^{15}NH_3$ in the Jovian atmosphere and estimate a value of 0.0037 ± 0.0016 for the $^{14}N/^{15}N$ ratio. This is in good agreement with the terrestrial value.

It is possible to estimate the C/H ratio from measurements in both the near and the far infrared portions of the spectrum (tables 1 and 2). A detailed discussion is given by Wallace & Hunten (1978) on the possible sources of error associated with the various line formation methods used to correct for the scattering effects that contaminate the spectral lines. Encrenaz & Combes (1981) show that there are basically two classes of results. The Jovian C/H value, derived from visible and near infrared data, which use scattering models, predict values of 2 to 5 times the solar ratio. Also, estimates of an enrichment by less than a factor of 2 are obtained by methods using the thermal spectrum without scattering models. There is some uncertainty in the Jovian values; there is also some variation in the solar values. Encrenaz & Combes (1981) suggest that the most accurate value is that of Pagel (1977) and Lambert (1978), of 4.7×10^{-4}. From this estimate, it would seem that the C/H ratio is greater for Jupiter than for the Sun (table 2). Using the values of Fink & Larson (1979) for Saturn, one finds that there is a carbon enrichment for this major planet too (table 2).

The D/H ratio of these major planets is also important because of the astrophysical implications. Reeves *et al.* (1973) argue that 'big bang' nucleosynthesis is the only viable production mechanism and that nuclear burning to produce ^{3}He is an efficient loss mechanism. It is therefore thought that the Jovian D/H ratio is indicative of the primordial value, but, as for the C/H value, the measurements are still controversial. There are two methods available. The HD molecule can be used in the visible and associated with the H_2 or CH_4 measurements in the same spectral range. Alternatively the CH_3D molecule can be observed in the thermal infrared, and the ratio computed from the CH_3D/H_2 values from model studies. Combes & Encrenaz (1979) derive a value of $D/H < 2.3 \times 10^{-5}$, which implies no deuterium enrichment on Jupiter. Their method is more accurate than that used by Trauger *et al.* (1973) since it avoids the use of the H_2 quadrupole lines which are difficult to measure.

In the thermal infrared, estimates of the CH_3D/H_2 ratio have been obtained in the 5 and 10 μm regions. However, Encrenaz & Combes (1981) have shown that there are significant problems in interpreting these data due to the possible variations in cloud structure, spectral properties of the clouds and a precise knowledge of the fractionation properties of CH_3D into its components which is strongly dependent upon the temperature. For example Kunde *et al.* (1981) derive a value for the CH_3D/H_2 ratio of 2.5×10^{-7} at 5 μm, but a value of 5×10^{-7} in the 8–9 μm region. This emphasizes the care that must be taken in choosing the spectral region for the determination of these abundance ratios. At the present time the D/H ratios of Jupiter and Saturn remain unsolved.

The presence of PH_3 is direct evidence of convective activity in these planetary atmospheres (§2). Encrenaz *et al.* (1980), Fink & Larson (1979), and Beer & Taylor (1979) estimate that the P/H value is depleted by a factor of 4 relative to the solar value. On Saturn, this ratio would appear to be enriched relative to the solar value. Tokunaga *et al.* (1980) suggest the enrichment value of at least a factor of 3, while Larson *et al.* (1981) suggest a factor of 2 from their 5 μm observations.

As Larson *et al.* (1981) suggest, the reaction of PH_3 with H_2O may be slower than previously thought (Sill 1976). Furthermore, according to Strobel (1977), photodissociation of PH_3 is expected to be inhibited by the presence of gaseous NH_3. This situation could occur for Saturn and account for the differences between the PH_3 abundances of the two planets (tables 1 and 2).

Without doubt NH_3 is one of the most important molecules in these atmospheres. It follows the saturation law below the level of minimum temperature on these major planets. Above this level, ammonia would follow a hydrostatic law in absence of photodissociation. For Jupiter, NH_3 is strongly depleted in the upper atmosphere. This information is found in the rotational band of NH_3 (40–110 μm) and in the 10 μm NH_3 band, where no thermal emission appears in the centre of the NH_3 emission multiplets (see, for example: Goorvitch *et al.* 1979; Gautier *et al.* 1979; Martin *et al.* 1980). Below the NH_3 cloud level at 145 K, the differing estimates of the NH_3/H_2 ratio from observations and various parts of the spectrum suggest the presence of nitrogen compound in this region. Combes & Encrenaz (1979) and Martin *et al.* (1980) derive a N/H value depleted by a factor of 2 in the region. This would suggest that nitrogen may be trapped as NH_4SH or NH_4OH cloud layers.

Information on the NH_3 distribution on Saturn is much more restricted. It has been observed in the visible region by Encrenaz *et al.* (1974), but not in the near infrared, where the bands are stronger (Owen *et al.* 1977). Recent I.U.E. observations in the 200 nm region do not show any pronounced features. These spectroscopic observations refer to the cloud-top region, so that the effects of scattering particles may simply be complicating the spectral structure.

The current knowledge of the composition of Jupiter and Saturn is still rather too uncertain to specify any precise information on the internal structure of these planets. For Jupiter, it is believed that the enrichment in helium, deuterium and carbon is moderate, and not sufficient to imply an inhomogeneous interior to the planet. More precise values are still required for the Saturn atmosphere.

However, the measurements of atmospheric composition may not necessarily determine the bulk composition of the planet. There are several possible separation processes that could give the interior a composition different from that of the atmosphere. For example, the planet could retain an original rocky core, while processes to separate helium in the interior have also been suggested. However, a knowledge of the atmospheric composition is a constraint on the bulk properties.

In connection with this basic problem of the development of these planetary atmospheres is the origin of the colours. This matter is still strongly debated and will not be resolved until more precise compositional measurements are available. The observations of lightning (Cook *et al.* 1979*a*) provide a further energy source in the photochemical cycles that may involve CH_4, NH_3, H_2S and the hydrocarbons that result from reactions of these. The importance of lightning is that it is localized and penetrates beneath the cloud that would otherwise absorb the incident solar ultraviolet energy. The study by Prinn (1970) and Sill (1976) indicates the importance of H_2S as a colouring agent. On the other hand Sagan (1971) maintains that organic molecules are involved. However, an important constraint on this issue is the apparent lack of spectral contrast between red regions and neighbouring white cloud areas.

5. METEOROLOGY

For more than 300 years, observations of large-scale cloud features have provided the basic information on the gross characteristics of the atmospheres of Jupiter and Saturn (see, for example: Peek 1958; Smith & Hunt 1976; Alexander 1962). The visible appearance of Jupiter is one of alternating cloud bands of differing colours, separated by jet streams. Superimposed upon these cloud systems are large scale features, such as the Great Red Spot and the three white ovals, which appear to have lifetimes varying from decades to centuries. Saturn is in many ways similar to Jupiter. Although the banded structure is clearly seen, the presence of haze layers above the main clouds seems to obscure the evidence of the larger scale spots, which have now been observed at high resolution during the recent Voyager flyby (Smith *et al.* 1981).

Unlike the meteorological systems of the terrestrial atmospheres, the weather systems of these planets are not solely driven by differential solar heating. We have seen in §3 that both planets have strong internal heat sources. Consequently, the meteorologies of these planets are influenced by two energy sources and by strong rotation. All the cloud velocities on Jupiter are referenced to the System III period of 9 h 55 min 29.711 s, and on Saturn to the System III period of 10 h 39.9 min ± 0.5 min.

On a large scale, there is little, if any, pole to equator energy transfer at the level of the visible clouds, which is the major difference between the Earth and the giant planets. The Pioneer 11 measurements of Ingersoll *et al.* (1976) have shown that the difference between the equator and polar temperature is not more than 3 K. At a latitude of ± 45° the belt zone structure breaks down in the Jovian atmosphere.

The temperature contrasts between the belts and zones are also small (see Hanel *et al.* 1979), with contrasts of only 1–3 K, at both cloud-top and tropopause levels. However, the location of the maximum contrast does vary significantly, and between the Pioneer 10/11 flybys of 1973/1974 (Gehrels 1976) and the Voyager encounters of 1979 (Smith *et al.* 1979) it has shifted hemispheres. The bright white zone initially at 12–24° S has become narrower by a factor of 2, while the zone at 18–30° N has increased in width by a similar amount during this time. Even between the Voyager encounters, considerable changes were noticeable around the Great Red Spot (Smith *et al.* 1979).

TABLE 3. LATITUDES OF ZONAL JET MAXIMA

	latitude/deg†				
name of current	I	II	III	IV	$\bar{u}$/(m s^{-1})‡
N. Polar Region	—	—	—	56.5	10
	—	—	—	51.0	−13
	—	—	—	47.5	20
N.N.N. Temp. Ct.	43	44.46	42.8–45.9	43.0	−4
N.N. Temp. Ct. A	36–40	35–41	37.3–40.6	39.0	19
N.N. Temp. Ct. B	35	§	35.1–35.8	35.0	−19
N. Temp. Ct. A	29–33	28–32	30.2–31.4	31.5	−31
N. Temp. Ct. C	23	§	23.8–24.2	23.0	138
N. Trop. Ct. A	14–22	14–21	15.5–19.6	17.5	−26
N. Equat. Ct.	3–10	4–8	6.6–9.6	7.0	102
Central Equat. Ct.	—	—	—	0.0	95
S. Equat. Ct.	3–10	6–8	5.8–7.6	7.0	137
S. Edge $\mathrm{SEB_s}$	19	18–22	20.3–21.7	19.5	−61
N. Edge STB	27	26	25.2–26.2	26.5	47
S. Temp. Ct.	29	32–35	33.6–33.7	32.0	−25
	—	—	—	36.5	34
S.S. Temp. Ct.	38–45	39–45	38.8–41.3	39.5	1
S. Polar Region	—	—	—	49.0	−3
	—	—	—	52.5	33
	—	—	—	56.5	−6

† Columns I, II, III are from Smith & Hunt (1976) and cover the years 1898–1948, 1946–1964, 1962–1970, respectively. Column IV is from Voyager (Ingersoll *et al.* 1981), and covers the first half of 1979.

‡ Magnitude of the zonal velocity $\bar{u}$ is from Voyager (Ingersoll *et al.* 1981).

§ The current was not observed during the time interval.

By image-processing techniques, such as the I.P.I.P.S. facility at University College London, it has been possible for the first time to quantitatively analyse the Voyager images. Measurements on cloud winds have been obtained by tracking individual cloud elements between specific frames. The estimated errors in the zonal velocity are ± 2 m s^{-1}, and in the meridional velocity ± 1 m s^{-1} (Ingersoll *et al.* 1981). The analyses of the Jovian data described here are for observations for the period around 26–27 February 1979 for Voyager 1, and the period around 1–2 July 1979 for Voyager 2. This is a fraction of a data set extending from January to August 1979.

In table 3, we have compared the zonal profiles obtained from the Voyager data by Ingersoll *et al.* (1981) with 80 years of Earth-based observations summarized by Smith & Hunt (1976). From comparison of these tabulations, it is apparent that the latitudes of the zonal jet maxima have changed very little during this period of 80 years. This is in marked contrast to the visible appearance of the planet. Also, there is a marked north–south symmetry in the zonal jet structure which clearly shows seven jet maxima in the latitude range of 0 to 45°. Once more, this is in complete contrast to the visible appearance of the planet.

Indeed, we find that the temperature structure of the troposphere measured by Hanel *et al.* (1979) has a close resemblance to the visible cloud markings. Consequently these albedo features are more associated with the radiative budget of the Jovian atmosphere than with the jet structures.

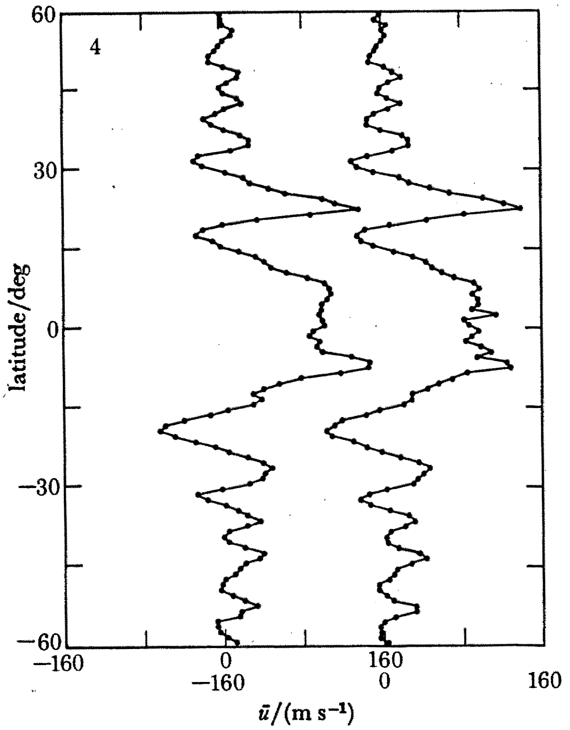

FIGURE 4. Comparison of zonal velocity $\bar{u}$ in late February 1979 (Voyager 1, left) with that in early July 1979 (Voyager 2, right).

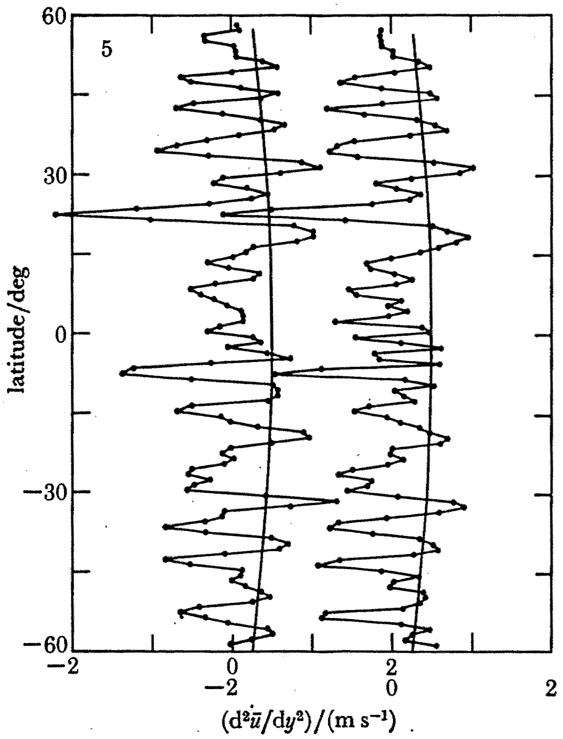

FIGURE 5. Same as figure 5, except that $\mathrm{d}^2\bar{u}/\mathrm{d}y^2$ is plotted. The smooth curves give β, the planetary vorticity gradient, in the same units. (After Ingersoll *et al.* 1981.)

In figure 4 the zonal profiles of the Jovian cloud system at the time of the encounters are shown. These data may be used to assess the stability of the jets by computing the latitudinal gradient $\mathrm{d}\zeta/\mathrm{d}y$ of the absolute vorticity associated with the zonal wind profile. By definition

$$\frac{\mathrm{d}\zeta}{\mathrm{d}y} = \beta - \bar{u}'' = \frac{2\Omega\cos\theta}{r} - \frac{\mathrm{d}^2\bar{u}}{\mathrm{d}y^2}, \tag{1}$$

where y is the northward component, β is the vertical component of vorticity coordinates, Ω is the planetary rotation rate, θ is the latitude and $\bar{u}''$ is the curvature. Ingersoll *et al.* (1981) have demonstrated that the barotropic stability condition $\mathrm{d}^2\bar{u}/\mathrm{d}y^2 < \beta$ is violated at the latitudes of the westward jets (figure 5). It is apparent that $\mathrm{d}^2\bar{u}/\mathrm{d}y^2$ varies between -3 and $+2$ as a function of latitude. Earlier estimates by Ingersoll & Cuzzi (1969), using Earth-based data, underestimated the parameter $\mathrm{d}^2\bar{u}/\mathrm{d}y^2$ by a factor of 2. Numerical experiments (Rhines 1975; Williams 1979) with eddy mean flow interaction show that stratified and unstratified rotating fluids tend to relax to a state in which the flow is mainly zonal and $\mathrm{d}^2u/\mathrm{d}y^2 < \beta$.

The numerical experiments have been run with a variety of forcings and initial conditions, including mechanical forcing and thermal (baroclinic) forcing. The computed flows seem to marginally satisfy the barotropic stability criterion $d^2u/dy^2 < \beta$, but whether a factor of 2 is significant requires further analysis.

At each point i, the velocities (u_i, v_i) may be measured, together with the quantities $\bar{u}' = v_i - \bar{u}$, $\bar{v}' = v_i - \bar{v}$, which are the deviations from the zonal mean quantities. From data sets of several thousand individual measurements Beebe *et al.* (1980) and Ingersoll *et al.* (1981) have found that the eddy momentum flux variation with latitude, $\overline{u'v'}$, is positively correlated with $d\bar{u}/dy$ for both Voyager 1 and 2 data sets (figure 6). This situation occurs for the entire global data set, which indicates that the main motions are being driven by the conversion of eddy kinetic energy into zonal mean kinetic energy, as in the Earth's atmosphere (Holton 1973).

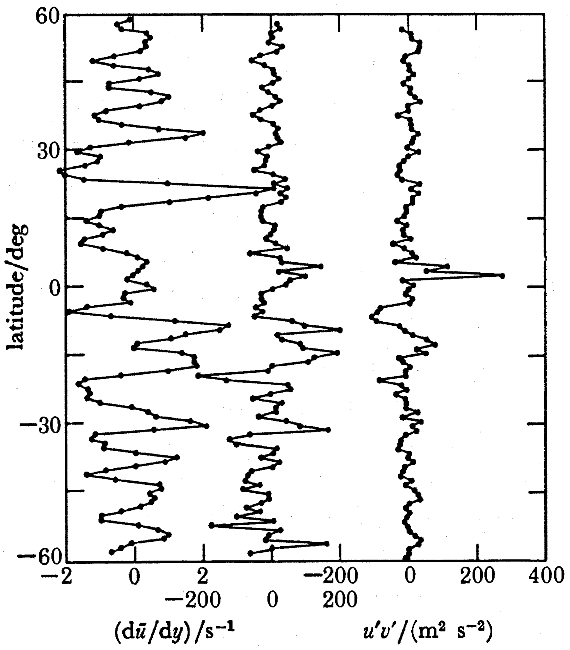

FIGURE 6. The northward eddy transport of eastward momentum $u'v'$ (Voyager 1, centre; Voyager 2, right) compared with $d\bar{u}/dy$ for Voyager 1 (left). A positive correlation indicates that the eddies are transferring energy into the mean zonal flow. The correlation coefficient is 0.986 for the two curves (after Ingersoll *et al.* 1981.)

The rate of conversion $\{k'\bar{k}\}$ of eddy kinetic energy into zonal mean kinetic energy is in the range 1.5 to 3 W m^{-2} for a layer 2.5 bar deep. The time constant for resupply of zonal mean kinetic energy by eddies is in the range of 2–4 months, which is less than the interval between the Voyager encounters. The rate of energy conversions is more than 10 % of the total infrared heat flux for Jupiter, in contrast to the figure of 0.1 % for the Earth. This 100-fold difference suggests that the thermomechanical energy cycles are very different on the two planets. It is certainly possible that the zonal flow $\bar{u}(y)$ extends much deeper than the eddies, and therefore is affected on a time scale much longer than 4 months. Certainly one sees, from table 3, that the jets are remarkably stable compared with the visible features, which implies that the jets are associated with the deeper layers of the atmosphere.

These results from the Voyager analyses are very significant for planetary meteorology (Kondratyev & Hunt 1981). The behaviour of $\{k'\bar{k}\}$ and the stability of the jets is very similar to the results obtained by the numerical model of Williams (1979). It would seem therefore that, like that of the Earth, the meteorology of Jupiter is also quasi-geostrophic. The initial baroclinicity of the flow is developed through the horizontal temperature gradients (Williams 1979; Hanel *et al.* 1979). No large scale vertical motions have been observed in the Jovian atmosphere; so it is unlikely that the zones and belts correspond to large scale rising and descending motions as was previously thought. Instead, these cloud bands may simply be ultra-long baroclinic waves, symmetrically arranged in pairs of alternating high and low pressure systems. Williams (1979) suggests that the blocking effect of the planetary wave propagation on quasi-geostrophic turbulent cascades determines the width and zonality of the bands. It would appear that the degree of zonality is higher in the absence of surface drag. At the polar regions there is no horizontal temperature gradient and correspondingly no available baroclinity. Consequently, the belt/zone structure disappears at a latitude where the internal heating is dominant over the contribution from solar heating.

We have noted earlier the frequent and apparently cyclic changes in the visible appearance of the Jovian cloud features. This may have some relationship with the magnitude and sign of $\{k'\bar{k}\}$, which may not always be positive as Beebe *et al.* (1980) and Ingersoll *et al.* (1981) find from the analysis of this portion of the Voyager observations. Williams (1979) finds the value of this term to oscillate with a period of 100–300 Earth days. The complete analysis of the Voyager data, and subsequent investigations with space-telescope observations, as is planned at University College London, will be extremely important in trying to resolve this matter.

An important test of the theories are the observations of Saturn obtained by Voyager in November 1980 (Smith *et al.* 1981). In contrast with Jupiter, only a small number of spots have ever been observed in the atmosphere of Saturn (Alexander 1962). The high resolution images have shown that the equatorial clouds are moving at speeds of 500 m s^{-1}. This is five times the speed of the features at an equivalent latitude in the Jovian atmosphere, and an equatorial prograde jet considerably broader on Saturn (figure 7). As Williams (1979) indicates, the broader bands and stronger jets are connected by the relation

$$L_\beta = \pi(2u/\beta)^{\frac{1}{2}}. \qquad (2)$$

He also suggests that, from the quasi-geostrophic view, the Saturnian jets may be explained by a larger static stability on a weaker dissipation that results in the stronger flow.

It is interesting to note that PH_3 observed in the atmosphere of Saturn is much stronger than in Jupiter. This is further evidence of stronger vertical motions on Saturn, which may then result from the increased buoyancy and therefore the potential energy of the atmospheric energy cycle which results in the stronger winds.

However, this numerical study of Williams (1979) assumes that the flow principally takes place in a thin layer. Certainly, all the terrestrial weather takes place in a region no more than 10–12 km deep. One of the most fundamental problems to resolve is the depth of the meteorologically active regions of Jupiter and Saturn. There are considerable differences in their interiors and the sizes of their metallic cores (Hubbard, this symposium). Indeed Busse (1976) suggested that the inner motions on these planets could take the form of concentric cylinders, spinning around each planet's rotational axis at different speeds. Then Saturn's faster winds could result from its small core and therefore a deeper atmosphere. But it has been seen that the hemispherical symmetry of the Jovian winds frequently breaks down, which suggests that such a motion is not possible. However, there must be an important interaction between the internal processes and the atmosphere that makes the star-like interior of the planet assist in the production of Earth-like weather systems.

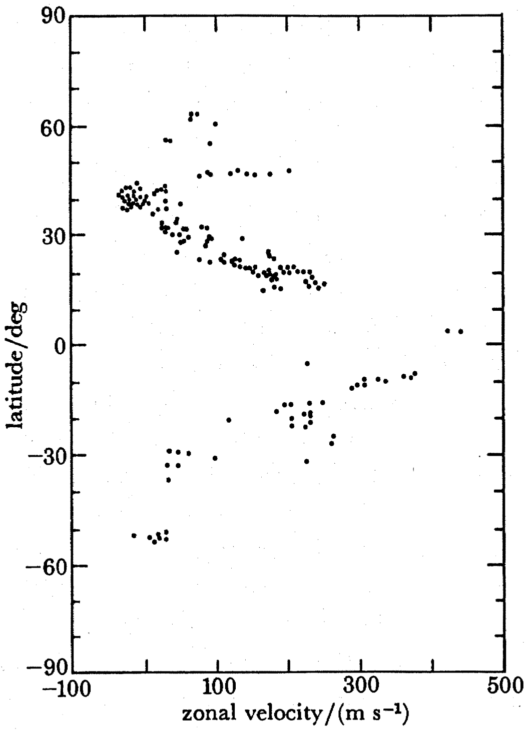

FIGURE 7. Zonal velocity profile of the Saturn atmosphere obtained from Voyager 1 observations, by analyses using the I.P.I.P.S. at University College London.

6. LARGE SCALE CLOUD FEATURES

6.1. *Great Red Spot; white ovals*

The Great Red Spot (G.R.S.) has been the centre of debates for many centuries and the Voyager observations have provided some important observations that may assist in resolving its origin. This feature is not fixed but moves in an easterly direction relative to the main zonal flow at about 0.5° per day. At the time of the first encounter, small cloud vortices can be seen rotating in an anticlockwise manner around the G.R.S. in a period of 6 days. However, a few months later, the growth of a large white cloud system to the east of the G.R.S. forms a barrier to these cloud vortices.

The Voyager observations have shown that the G.R.S., the white ovals and the small scale spots at 41° S all possess similar meteorological features (Smith *et al.* 1979; Hanel *et al.* 1979). Wind speeds of 110–120 $\mathrm{m\,s^{-1}}$ are observed near the edges of both features along their minor axes. Relative vorticity profiles reach a maximum of $6 \times 10^{-5}\ \mathrm{s^{-1}}$. This is several times greater than the ambient $5 \times 10^{-5}\ \mathrm{s^{-1}}$ of the meridional shear winds at the latitudes of these features. Their vorticities are in the range $(2–3) \times 10^{-5}\ \mathrm{s^{-1}}$ with corresponding Rossby numbers for the flows within the G.R.S. and Oval BC of 0.36. Generally the Rossby numbers within these features are much lower, indicating the geostrophy of the flow (Mitchell *et al.* 1981). All these features rotate anticyclonically and are elevated relative to their surroundings (Conrath *et al.* 1981). However, in contrast to the white ovals, the G.R.S. possesses a large quiescent interior region. These similarities strengthen the idea that all the features are of the same type, with the only difference being their individual size. The infrared observations of Hanel *et al.* (1979) indicate that the G.R.S. and the ovals have a cold region above the feature extending throughout the troposphere. This is consistent with a divergence at cloud-top level, although there is little evidence of organized flow in the G.R.S. Flasar *et al.* (1981) suggest that this upward motion may be driven by latent heat release in the water vapour cloud region.

However, to understand their origin, it is necessary to examine the behaviour of the white ovals that have been observed since their formation in 1939. Peek (1958) and Hunt & Beebe (1981) have shown that these features originally formed from a cloud system (zone) that stretched around the planet. In the past 40 years, the ovals have been contracting to their current size of 11000 km × 5000 km. It is very likely therefore that the G.R.S. behaved in a similar way. Smith *et al.* (1979) have found that it is only 24000 km in length now compared with 46000 km a century ago. The G.R.S. is also contracting.

These observational characteristics are consistent with the numerical model of Williams (1979) which, as seen in §5, closely resembles the large scale features of the Jovian atmosphere. His model predicts a large scale circulation gyre in the position of the G.R.S., which corresponds to the warm anticyclonic core of a neutral baroclinic wave. Features of this type seem to appear naturally from the general circulation and may therefore account for all the large scale features observed. However, their existence and the Voyager measurements are consistent with this type of driving mechanism. The solitary wave theory suggested by Maxworthy *et al.* (1978) may only apply to those special situations where the flow becomes primarily barotropic and account for the local interactions between cloud systems that are sometimes seen.

The lifetime of the vortices in the Jovian atmosphere is a further important problem, since, unlike the terrestrial atmosphere, there are no solid surface features to constrain the flow. The radiative relaxation time is several years, so that with a cooling rate of about 10 K a^{-1} features will radiatively dissipate very slowly. However, Ingersoll & Cuong (1981) also suggest that the long-lived vortices maintain themselves against dissipation by absorbing small vortices which are produced by convection.

The colour of the G.R.S. remains a major unresolved problem. The direct evidence is that there is upward motion in the spot. This assists in supporting the prediction of Prinn & Lewis (1975) who suggested that the colour is due to the conversion of PH_3 into P_4, which condenses to form triclinic red phosphorus crystals. As a consequence, this explanation requires the G.R.S. to extend more deeply into the atmosphere than the outer large scale spots, such as the ovals.

6.2. *Equatorial plumes*

Observations by the Voyager spacecraft imaging and IRIS instruments show an organized train of features moving in a westerly current at 9° N with a zonal speed of 100–120 m s^{-1} (Hunt *et al.* 1981*b*). The region is characterized by a wavenumber 11–13 pattern which was observed to fluctuate in its precise characteristics between the two encounters (Smith *et al.* 1979). Only a small number of plumes have active convective centres. Hunt *et al.* (1981*b*) show that these cloud systems cause a perturbation to the temperature of the upper troposphere (figure 8). The thermal structure of an individual plume supports the concept that the head is a region of strong upwelling while subsidence is occurring in the surrounding areas. Hunt *et al.* (1981*c*) have measured the time variation of the change in the areas of the active plumes and estimated the divergence and vertical velocities associated with these features. The divergences are in the range of $(0.5–1.5) \times 10^{-5}\ \mathrm{s}^{-1}$ and vertical velocities of $10–40\ \mathrm{cm\ s}^{-1}$ for the more active features.

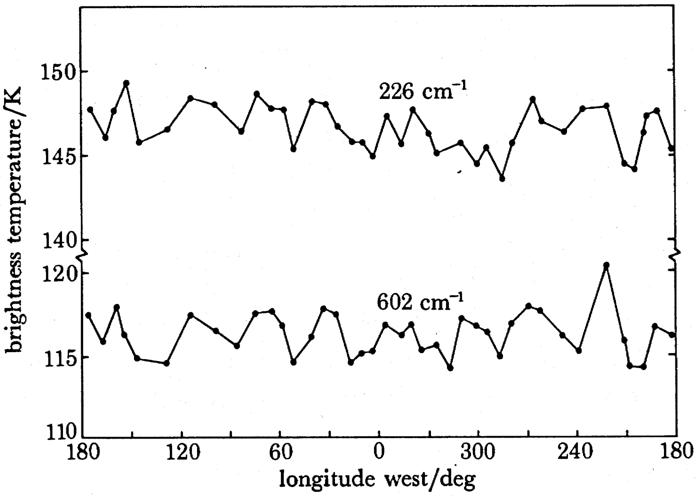

FIGURE 8. The brightness temperature at 226 cm^{-1} (cloud tops) and 602 cm^{-1} (tropopause) for the latitude range 5–11° obtained by IRIS during the Voyager 1 encounter (after Hunt *et al.* 1981 *b*).

The rapid development of convective activity is suggestive of an instability mechanism while the global coherence implies that the same role is played by a planetary scale wave system. A possible mechanism is wave c.i.s.k.† (Lindzen 1974), which is operative in the i.t.c.z.† of the tropical region of the Earth's atmosphere. This mechanism requires the presence of a finite amplitude wave field with alternating lower level regions of convergence and divergence along a moisture field capable of providing an energy power through latent heat release in the regions of upwelling that accompany convergence. The water vapour beneath the visible clouds may play an important role in developing the Jovian plumes. Furthermore, their presence on the northern edge of the equatorial region may be due to the presence in the southern hemisphere of large scale features such as the Great Red Spot and white ovals that perturb the low level convergence.

Plume features do not seem to be present in the equatorial region of Saturn during the time of the Voyager encounter. This may be due to greater vertical extent of the Saturn cloud systems since it is thought that c.i.s.k. operates in a relatively thin layer.

7. CONCLUSIONS

The emerging picture of the atmospheres of Jupiter and Saturn shows some large scale similarities in the bulk properties of these planets, but superimposed upon them some intriguing differences. Their compositions do have a close similarity with that of the Sun, but in some aspects of the Jovian composition there is the indication of enrichment in helium, carbon and possibly deuterium. The real surprise has come in terms of the meteorologies of these

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† Abbreviations: c.i.s.k., convective instability of the second kind; i.t.c.z., intertropical convergence zone.

planets. The detailed analysis of some of the Voyager observations has provided the unexpected result that both Jupiter and the Earth are quasi-geostrophic, with the eddies transferring energy into the mean zonal flow. Saturn may behave in a similar way. However, the winds in this atmosphere are much stronger. Here we seem to have the paradox of two planets with a star-like interior whose weather systems behave in an Earth-like manner.

The Great Red Spot has been reduced to being no more than the largest in a family of features seen in these atmospheres. Indeed there are also red spots in the atmosphere of Saturn. It would seem that they are simply the natural result of the planetary circulations.

The studies using ground-based telescopes, the observations from I.U.E., and the Pioneer and Voyager space missions have provided the material to answer the first order problems that have concerned us for several years, decades, and even centuries. A considerable amount of time will be required to fully analyse all of them. At University College London extensive use will be made of the I.P.I.P.S. image processing system in continued studies of the meteorologies.

However, direct measurements of the atmospheric composition are urgently needed to answer some of the basic questions related to origin and evolution of these atmospheres. This will be possible with the Galileo mission. A more detailed knowledge of the meteorology requires more extensive temporal observations than were possible from the myopic view obtained by the Voyagers. This will be possible with Space Telescope. During the next decade we can expect many more fundamental geophysical problems related to the outer Solar System to be resolved.

The work described in this paper results from my detailed involvement as an experimenter in the Voyager mission to the outer planets during the past 8 years. I wish to thank many of my colleagues for the helpful comments that have led to the improvements in the earlier drafts. My research and participation in the Voyager project is supported by the Science Research Council. This paper is contribution 74 of the Laboratory for Planetary Atmospheres, University College London.

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Discussion

R. Hide, F.R.S. (*Geophysical Fluid Dynamics Laboratory, Meteorological Office, Bracknell*). Dr Hunt has given an excellent summary of important work by a number of research groups concerned with the meteorology of Jupiter. He has outlined various ideas about the dynamical processes underlying the general banded appearance of the planet and the nature of irregular markings. This part of the subject is now particularly lively and deserving of a conference in its own right. Perhaps I might be permitted to mention some recent work of my own laboratory which was partly stimulated by the magnificent Voyager pictures (see N.A.S.A. 1979).

The regular flow régime of thermal convection in a rotating fluid annulus subject to differential heating in the horizontal is characterized by the presence of upper level jet streams, where intense concentrations of vorticity and high concomitant horizontal temperature gradients are found. The main features of the upper-level flow pattern can be interpreted by straightforward arguments (Hide 1958) based on general thermodynamic considerations and the requirement that the flow should be quasi-geostrophic (i.e. with the horizontal pressure gradients in approximate balance with Coriolis forces). Thus, when the distribution of applied heating and cooling is such that the corresponding gradient of the impressed radial temperature field has the same sign at all radii, the most conspicuous feature of the upper-level flow pattern is a single jet stream meandering in a wave-like pattern between the bounding cylinders. When, however, the impressed radial temperature gradient changes sign near mid-radius (as occurs when heat is introduced throughout the body of the fluid and withdrawn at both side walls), the corresponding upper-level flow consists of a number of separate closed eddies, each circulating anticyclonically with the horizontal flow largely confined to a narrow jet stream at the periphery of the eddy (Hide & Mason 1970). In some respects these stable closed eddies are dynamically similar to long-lived anticyclonic eddies found in Jupiter's atmosphere in the southern hemisphere (Hide 1980), notably the Great Red Spot in the South Tropical Zone, the three somewhat smaller irregularly spaced white ovals that formed in 1939, at the boundary between the South Temperate Belt and the South Temperate Zone, apparently as the residue of the highly variable South Tropical Disturbance first seen in 1901 (see: Peek 1958; Smith & Hunt 1976), and the dozen (approximately) even smaller irregularly spaced oval markings seen at still higher latitudes. The occurrence of transient False Red Spots in Jupiter's South Tropical Zone and the apparent absence of large stable oval eddies in the Equatorial Zone are consistent with this tentative interpretation. Previous work on stable baroclinic eddies in the laboratory is now being extended in various directions and supporting numerical work is also being carried out. Dr P. L. Read and I will report on progress with these investigations in due course.

A basic difficulty in all applications of dynamical ideas to the interpretation of the structure and motions of Jovian markings is the lack of temperature and velocity measurements at well determined levels well below the upper cloud deck. Indeed, a fascinating challenge to the dynamicist is to exploit his skills to infer the vertical structure of the outer layers of the planet from observations of surface markings. How well, one wonders, could the terrestrial meteorologist or oceanographer infer the vertical structure of the atmospheric troposphere or the oceans from observations comparable with these available to observers of Jupiter?

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P. R. PISHAROTY (*Physical Research Laboratory*, *Navrangpura*, *Ahmedabad*, 380009, *India*). With the help of observed cloud movements Dr Hunt has neatly shown the kinematics of the Jovian Great Red Spot (G.R.S.). At the periphery of the spot the movements are very rapid, more than 100 m/s, and the movements are in a clockwise direction. The winds near the centre are weak.

Dr Hunt mentioned that the movements represent an anticyclonic motion with divergence. Since the Red Spot is in the southern hemisphere of Jupiter, the movements are cyclonic and should be associated with *convergence*. On the other hand the pattern of the Spot is suggestive of rising motion at the centre with an appearance of outflow. Therefore, the observed motions apparently refer to different levels of the Jovian atmosphere. The motion at the peripheral parts of the G.R.S. apparently refers to the lower levels where cyclonic and convergent motion prevails, while the motion observed near the centre apparently refers to much higher levels, near the top of the cyclone, where there should be divergence to permit a continued rise of the material from below.