THE SOLAR SYSTEM BEYOND MARS: AN EXOBIOLOGICAL SURVEY

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1. Introduction

Beyond Mars lie the asteroids, the Jovian planets and their moons, Pluto and the comets. This is where the vast bulk of the angular momentum of the solar system resides, as well as most of the non-solar mass. Past the region of the inner or terrestrial planets with which we are most familiar, lie a range of very different objects, of major significance not only to studies of planetary atmospheres and surfaces, and to solar system cosmogony, but also of the very greatest importance for exobiology.

The asteroids are the presumed parent bodies of most meteorites which fall on the Earth, including the carbonaceous chondrites, which are rich in (probably prebiological) organic matter, and about which various evanescent claims have been made for fossil forms of living organisms. There are dozens of large asteroids, more than, say, 10 km in diameter; and there are a variety of theories of their origin. The earliest classical view that the asteroids are the remnants of an exploded planet runs into serious problems because no plausible mechanism for such an explosion can be envisioned. The classical alternative theory has been that the asteroids are the remains of a planet whose formation was impeded by the tidal gravitational field of nearby Jupiter. There is, however, a third possible explanation, implicit in the recent solar system model dynamics calculations of Hill (1969). Hill shows that the nonlinear terms in the gravitational interaction of planets of roughly Jovian mass with planets of much smaller mass will sweep the Jovian part of model solar systems free from low-mass objects in times much shorter than the age of the solar system. It is possible that all small objects not captured as satellites of the Jovian planets were ejected – many of them into the asteroid belt – billions of years ago.

There are some 30 natural satellites in the solar system beyond Mars, ranging from some with the mass and gravitational acceleration of Mercury to others which would only be visible from the surface of their primary with a 6-in. telescope. These satellites are marvellously diverse and, as we shall see, it is not out of the question that some are of exobiological interest. Some of the satellites of the Jovian planets are regular, in the sense that their orbits have low eccentricity and inclination to the equatorial plane of their primaries; others are irregular in the sense of large eccentricity and inclination (cf. Table I). Of the irregular Jovian satellites something like half are in direct orbits and half in retrograde orbits, suggesting (Kuiper, 1956) that the irregular satellites have been captured after the formation of their primaries.

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TABLE I
Physical properties of the Jovian planets

Property	Jupiter	Saturn	Uranus	Neptune
Mass	317.9 $M_\oplus$	95.1 $M_\oplus$	14.5 $M_\oplus$	17.3 $M_\oplus$
Equatorial Diameter	142700 km	120800 km	48000: km	44000: km
Mean density	1.33 gm/cm^3	0.69 gm/cm^3	1.68: gm/cm^3	1.59: gm/cm^3
Period of Rotation	About 9^h55^m See text	10^h2^m equator 10^h30^m temperate	-10^h8:	15^h8:
Oblateness	0.062	0.096	0.06:	0.02:
Moment of inertia, *C*	0.25	0.22	0.23	0.29
Surface gravity	2.7 $g_\oplus$	1.2 $g_\oplus$	1.1: $g_\oplus$	1.1: $g_\oplus$
Escape velocity	61 km/sec	36 km/sec	23: km/sec	24: km/sec
Optical frequency Bond albedo	0.73:	0.76:	0.93:	0.84:
Bolometric Bond albedo	0.45:	0.6:	0.4:	0.4:
Mean distance from Sun	5.20 a.u.	9.54 a.u.	19.18 a.u.	30.06 a.u.
Equilibrium radiation temperature	105 K	70 K	50 K:	40 K:
Equatorial inclination to orbital plane	30.07°	26.74°	97.93°	28.80z

Masses and accelerations due to gravity are given in terms of the corresponding Earth values. A colon indicates considerable uncertainty.

The Jovian planets themselves are of major cosmogonic and exobiological significance. They are far from the Sun; even though there are few molecules in their upper atmospheres which are efficient infrared emitters, their exosphere temperatures tend to be rather cold by terrestrial standards – probably less than 1000K. Their gravitational accelerations are larger than on Earth. In the usual equations for gravitational escape [see, for example, Sagan (1968)] the ratio of gravitational acceleration to exosphere temperature appears as an exponent in the escape flux. Accordingly even the atom of lowest mass, hydrogen, has not been significantly depleted from the upper atmospheres of the Jovian planets in geological time. Indeed the mean *e*-folding time for hydrogen escape from the Jovian exosphere is some 10^{100} years! If the Jovian planets retain hydrogen, they must retain all heavier elements. Since hydrogen has a greater cosmic abundance than any other chemically reactive element, we expect the atmospheres of the Jovian planets to contain the fully saturated hydrides of the most abundant reactive atoms – namely carbon, nitrogen, and oxygen. The resulting expectation, that the atmospheres of the Jovian planets are composed of hydrogen, helium, methane, ammonia, water, and perhaps neon as primarily constituents, tends to be borne out by the observations (see below), although direct detection of He, H_2O and Ne remain to be accomplished.

By precisely the same cosmic abundance arguments, the early atmosphere of the earth, in which the origin of life occurred, is expected to have had just such a composition. In the case of the Earth the expected exospheric temperatures are sufficiently high and the acceleration due to the gravity sufficiently low for the escape of large quantities of hydrogen to have occurred during geological time. Before the hydrogen was lost at least the major steps leading to the origin of life on the earth must have occurred. In the case of the Jovian planets such hydrogen-rich reducing atmospheres must have been retained for much longer periods of time. By this very simple argument it does not seem quixotic to expect that the Jovian planets will, at the very least, be of exobiological interest because of the presence of large quantities of prebiological organic matter. Laboratory and computer experiments leading to the same conclusion are discussed below.

The outer solar system also contains comets: the short-period comets which have their aphelia roughly in the vicinity of Jupiter, and the long-period comets which have aphelia far beyond Pluto, in the outer reaches of the solar system. Some comet theories invoke a vast cloud of comets orbiting the sun at tens of thousands of astronomical units, and propose that when a member of this cometary cloud is accidentally perturbed into the inner solar system its gravitational interaction with planets such as Jupiter converts it into a short-period comet. In many theories of cometary origin, the comets are either typical denizens of interstellar space or debris left over from the very first stages of the origin of the solar system. It is difficult to determine which of these two possibilities is of more fundamental interest. The spectra of comets clearly show molecular fragments suggestive of organic molecules and reminiscent of the interstellar molecules now being discovered by microwave spectroscopy; accordingly the study of comets is of major importance either for interstellar organic matter or for organic matter in the early solar nebula from which the planets were formed.

In a review of this sort some selection of topics must be made. Because there are separate discussions of meteorites elsewhere, and because (apart from the meteorites) the greatest information available pertains to the Jovian planets, we will concentrate on Jupiter – with less attention paid to Saturn, Uranus, and Neptune and to the satellites of the Jovian planets. The review closes with short discussions of the asteroids and the comets. In the treatment of the Jovian planets primary emphasis will be placed on their exobiological significance; as a result such topics as the radiation belts and models of the deep interiors of Jupiter will be touched on, generally, only when they bear on exobiological questions.

2. The Jovian Planets

A. PHYSICAL PROPERTIES

The physical properties of the Jovian planets are given in the accompanying Table I. Due to the small angular size of Uranus and Neptune, the equatorial radius, mean density, oblateness and period of rotation of these objects is rather poorly known. Since Uranus rotates around an axis which is inclined some 97° to the normal to its orbital plane, its atmospheric circulation is likely to be quite different from that of other planets. The phase angle is defined as the angle between the Sun and the Earth as viewed from the planet in question. Because of the orbital geometry of the Earth with respect to the Jovian planets, observations are never made very far from 0° phase angle. As a result the determination of the photometric quantity, the phase integral,

q, must be made from analogy with, e.g., Venus, or from theory – both of which are inadequately known at the present time. As a consequence there are significant uncertainties in the determination of the Russell-Bond albedo of the Jovian planets, a quantity which measures the total amount of sunlight reflected from a planet in all directions, and which is proportional to q. The phase angle excursion limitation also limits the utility of studies based on the variation of brightness with phase angle – which gives some indication of the roughness of the scattering material; and of the polarization phase curve – which should give some indication of the real and imaginary parts of the index of refraction and of the size distribution of scattering particles. In addition, of course, nighttime phenomena on these planets have never been observed. These are a few of many reasons that space vehicle observations of the Jovian planets, even from fairly distant flybys, are of importance: large phase angles could then be viewed.

The rotation of Jupiter is complex and three distinct rotation periods are usually recognized: System I refers to the rotation of features in the Jovian clouds within about 10° of the equator, and has been measured as 9 h 50 min 30.03 sec. The rotation of cloud features more distant than 10° from the equator in both the northern and southern hemisphere is given as 9 h 55 min 40.632 sec, and is known as System II. These high accuracies are of limited value because individual features are known to move with respect to others, and because the 10° lat. transition is not a very sharp one. The decameter radio emission from Jupiter has a period of rotation usually quoted as 9 h 55 min 29.37 sec, known as System III. But since 1961 the mean period of decameter sources is thought, at least by some radioastronomers to be somewhat longer (for a contrary view, see Duncan, 1967).

These rapid rotations immediately suggest a large oblateness, an expectation which is confirmed by observations (cf. Table I). The very low mean densities of the Jovian planets (Saturn is so under-dense it would float in water if there were enough water) set severe constraints on models of their interiors. For Jupiter and Saturn only solid hydrogen and helium have adequately low densities for plausible interiors. The densities of Uranus and Neptune are large enough that some considerable admixture of carbon, nitrogen, and oxygen compounds, and perhaps silicates and other geochemically abundant materials are possible. Order of magnitude values of the central pressures of the Jovian planets can be obtained immediately from Newtonian gravitational theory with no assumptions about the structure of the planets. These interior pressures are so high that metallic hydrogen is expected there. Metallic hydrogen is produced by pressure ionization; that is, when the energy density due to the hydrostatic pressure load exceeds the ionization potential per unit volume. As a result the interiors of Jupiter and Saturn, and probably of Uranus and Neptune, are highly conductive both electrically and thermally. Pressure ionization should occur at approximately 10^6 bar. Typical values of the central pressures on Jupiter are of the order of 10^8 bar; central densities are only a few grams per cubic centimeter and central temperatures are a few thousands of degrees Kelvin. Since these pressures are much higher than can be achieved conveniently in contemporary laboratories, detailed questions of interior temperatures, pressures and composition of the Jovian planets remain uncertain.

B. COLORATION AND METEOROLOGY

A color photograph of Jupiter appears in Figure 1; drawings of Uranus and Neptune, in Figures 3 and 4. These planets, or at least the inner Jovian planets, are marked by a striking set of zones and belts, parallel to their equators. Some observers report that a transient spot will appear, perhaps rising as a bubble from the interior of the atmosphere, and then be torn apart by differential shear forces into a zone or belt. The distribution of these parallel zones and belts, however, is so fixed in time, at least in a statistical sense, that this cannot be an explanation for the most apparent low-latitude features. The zones and belts, known for more than a century, have attached to them the nomenclature indicated in Figure 5. The dark parallel markings are called belts, the bright ones zones or bands. The level which is observed in visible light is almost certainly a Jovian cloud layer (perhaps one of many). Good agreement is obtained between the observed velocities in the zones and belts and the predictions of the thermal wind equation (Ingersoll and Cuzzi, 1969), provided that systematic temperature differences between belts and zones is assumed; but the bright zones must be warmer than the dark belts. Important direct infrared radiometric observations of Jupiter in the 5 μ region (Westphal, 1969), however, indicate that the bright zones are colder than the dark belts. The implication is clearly that bright zones are clouds and that the dark belts are clearer regions between the clouds where perhaps we are looking down to an underlying and deeper cloud. Indeed the visual impression given by color photographs (see Figure 1) is that small white clouds frequently obscure, with convex geometry, darker clouds, suggesting that the white clouds are higher. The possibility that we are looking deeply into the Jovian atmosphere near the poles has been stressed by Gehrels (1969).

The belts and zones are colored, as inspection of Figure 1 clearly shows. The zones have a yellowish or yellow-brown cast although they are sometimes white. The belts are generally of a neutral color but the literature abounds with reports of faint pastel colorings, including pinks and blues. As in the case of Mars, there is a danger that when a neutral color is juxtaposed to a vivid color, the neutral color will take on, due to psycho-physiological phenomena alone, a color complementary to that of the bright hue. Photographs of the planet with narrow band filters and the continuous spectrum of the planet confirm the overall color impressions. The major requirement in search of a molecule to explain the colors is one which is strongly absorbing in the blue, although the diversity and time-variability of colors on Jupiter is striking. Visual observations of Jupiter give that impression of roiling convective turmoil, on which is superimposed the steadying hand of zonal motion. There are many cloud details not indicated in Figure 5, including dark streaks, evanescent or oscillating spots, and circulating currents. By far the most famous of the Jovian features other than the zones and belts is the Great Red Spot (see Figures 1 and 5), a feature probably first viewed by Hooke and Cassini in 1664–1665. It is an elliptical marking some 40000 km in length, and about 13000 km in breadth; it is larger than half a dozen Earths. Its dimensions, shape, color and, indeed, existence, however, are time-variable.

Fig. 1. A typical color photograph of Jupiter (Catalina Observatory photograph taken 25 Jan., 1968 by J. W. Fountain), The Great Red Spot is seen towards upper left; the black circle near the center of the planet is the shadow of a satellite.

Fig. 2. Polymeric material produced by ultraviolet irradiation of simulated Jovian atmospheres in the author's laboratory (C. Sagan and B. N. Khare, 1971, in press). This material, as yet of unknown composition, may be connected with the brownish coloring material on Jupiter. The necktie is for color comparison.

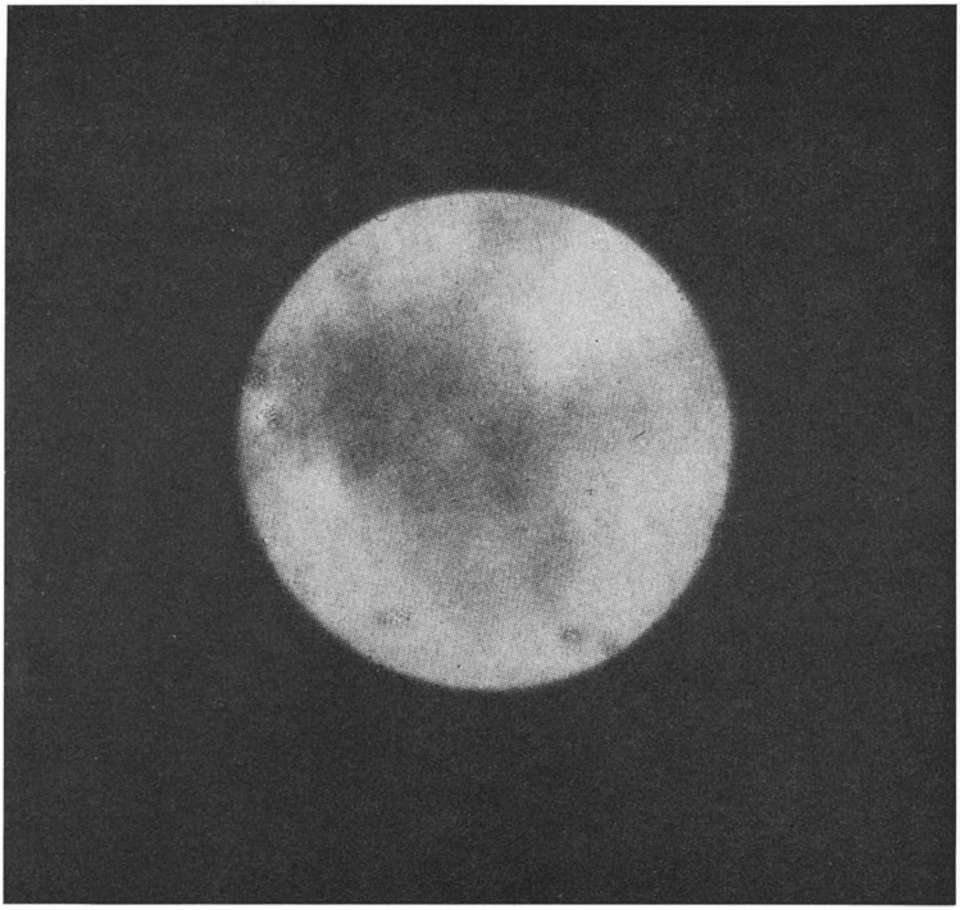

Fig. 3. The planet Uranus as drawn by A. Dollfus, 8 April 1962 at Pic du Midi Observatory.

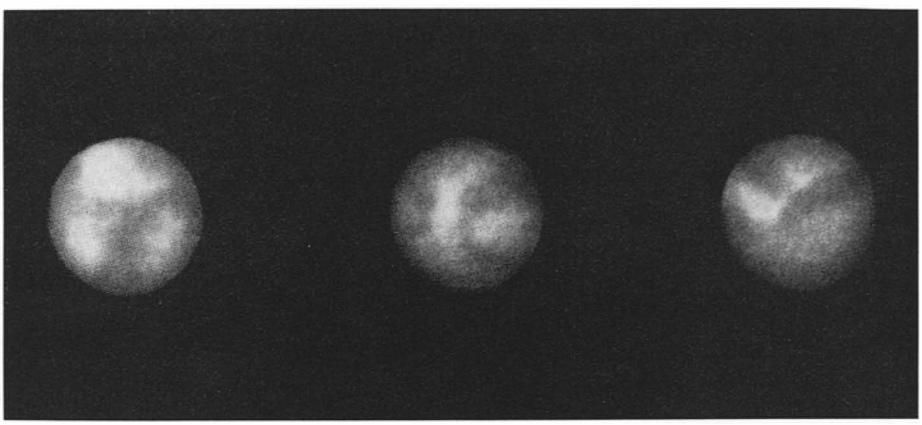

Fig. 4. Three drawings of Neptune executed by A. Dollfus at Pic du Midi Observatory. After 'Atlas des planètes', by de Callatay and A. Dollfus, Gauthier-Villars, Paris (1968).

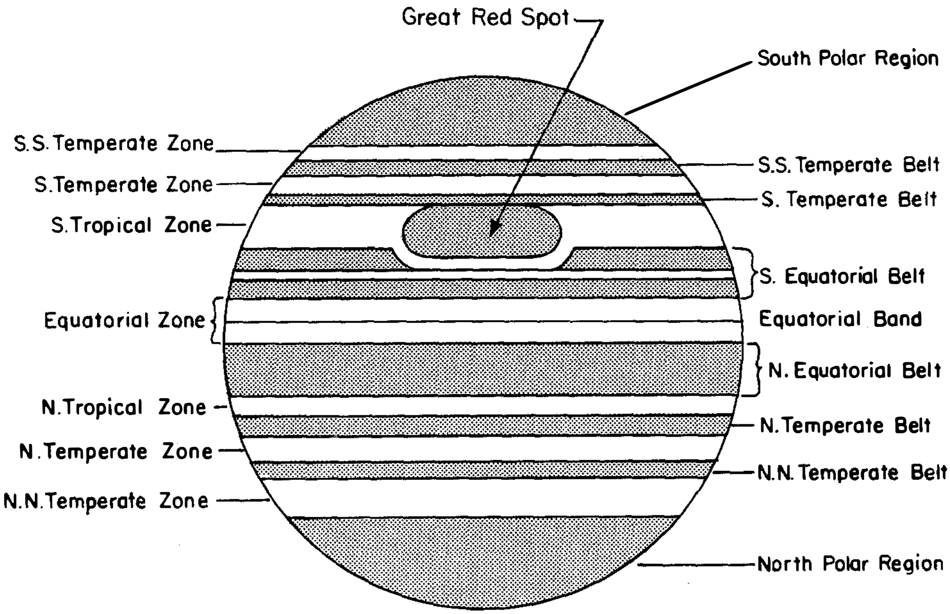

Fig. 5. Nomenclature of the 'permanent' features in the Jupiter clouds.

In 1920, for example, it was nearly invisible. Even when the spot itself is not present, however, the Red Spot Hollow in the South Tropical Zone in which it resides can be seen (Figure 5). We discuss the nature and coloration of the Red Spot and the problem of the general coloration of Jupiter below.

The color and contrast of the Great Red Spot, the latitudes of belts and zones, and a number of other cloud phenomena on Jupiter exhibit various periodicities with periods of some years. Nonperiodic changes occur with much shorter time constants: spots many thousands of kilometers across can appear in some 15 minutes. Spots approaching the Great Red Spot at a larger angular velocity are sometimes observed to accelerate around it, following the contours of the Red Spot Hollow, and to reappear at the other side. On the other hand, there appear to be well-substantiated reports of the exchange of material from within to without the Red Spot (Focas, 1962). More details on visual observations of Jupiter and their time-variability can be found, e.g., in Peek (1957), and Chapman (1969); important observations of Great Red Spot motions made at New Mexico State University can be found in Reese (1970), Reese and Smith (1968) and references cited in these papers. Older general references, mainly to observational material for Saturn and Uranus, respectively, are by Alexander (1962) and Alexander (1965). A recent discussion of the Jupiter atmosphere in Russian is by Teifel (1970); see also Teifel (1971) and Bobrov (1971).

C. TEMPERATURES

The equilibrium temperature of Jupiter is probably about 100 ± 20K based upon contemporary values of the bolometric albedo, that is the Russell-Bond albedo integrated over the Planck distribution. The value of the bolometric albedo is uncertain (1) to a small extent because the reflectivity of Jupiter at all wavelengths in the near infrared has not been completely studied, but (2) to a larger extent because q for Jupiter is not well-established, and a scattering phase function with a strong forward lobe could lead to slightly higher temperatures. The anticipated equilibrium temperatures can be compared with the temperatures deduced by various observational methods (Table II).

TABLE II

Observed temperatures of Jupiter

Wavelength, λ	Measurement technique	T	Reference
1 μ	Methane rotational temperature	170 ± 30K	Owen and Woodman (1968)
2.25 μ	Width of pressure induced dipole (1,0) band of H_2	210 ± 15K	Danielson (1966)
4.6–5.2 μ	Infrared radiometry	230K	Gillett *et al.* (1969)
8–14 μ	Infrared radiometry	130K	Murray *et al.* (1964)
18–25 μ	Infrared radiometry	150K	Low (1966)
2 cm	Microwave radiometry of the ammonia inversion doubling band	110–160K	Law and Staelin (1968)

Since the infrared temperatures are uniformly and significantly larger than the theoretical equilibrium temperature, even making generous allowances for the uncertainty in the bolometric albedo, one is almost forced to conclude, as was first suggest by Opik (1962), that Jupiter is emitting significantly more radiation to space than it is receiving per unit area from the Sun. This view has been championed by Low [see Low and Davidson (1969)], although some authors [e.g., Trafton and Münch (1969)] urge caution in this regard. The calibration of Low's infrared radiometer is difficult and has been incompletely documented. However a completely independent argument for the infrared excess, obtained from Jupiter infrared limb darkening, has been presented by Trafton and Wildey (1970). Low also reports large time variation in the infrared magnitude of Jupiter; variations of as much as half a magnitude in a decade have been reported at optical frequencies (see, for example, DeMarcus, 1970) but the much shorter period infrared fluctuations are quite novel.

It is clear that the existence of a high brightness temperature at some infrared wavelengths is not a clear demonstration of an inequality between energy input and output: at some wavelengths we may be in regions of low opacity and therefore be viewing to great depths and to high temperatures. However, Low stresses that the radiation observed by him at long wavelengths probably itself constitutes more emission than Jupiter is receiving from the Sun: he [Low and Davidson (1969)] also reports such an inbalance for Saturn. The required additional energy source is commonly thought to be gravitational potential energy of contraction. Had Jupiter begun its career some tens of times more massive than it is today, its central temperatures would probably have reached a few million degrees K, adequate for some thermonuclear reactions; our solar system would then be graced by a double star instead of our solitary Sun. Jupiter has avoided this evolutionary sequence, but it may still be in the pre-main sequence Kelvin-Helmholtz or Hayashi (depending on the extent of interior convection) contraction stages. A contraction rate of 1 mm a year is adequate to produce the observed energy surfeit. Such a contraction rate is of course too small

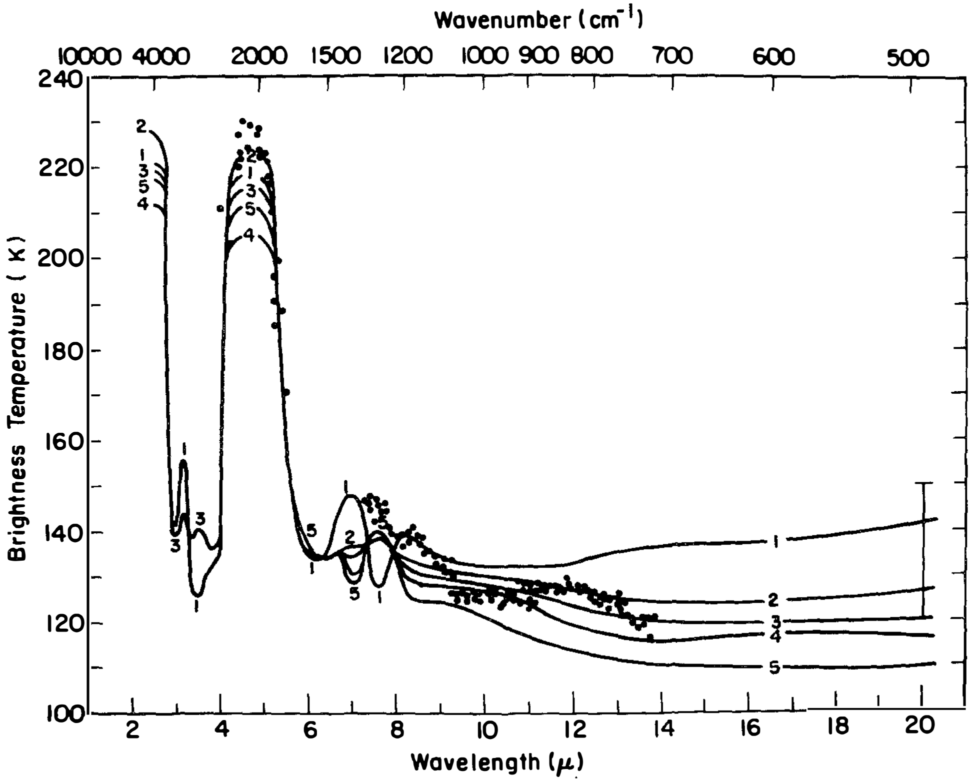

Fig. 6. Comparison of observed infrared spectrum of Jupiter (dots and error bar at 20 μ) with theory for five numbered models of the temperature structure of the Jovian atmosphere. After Hogan *et al.* (1969).

to be directly detectable over the time scale of modern astronomical observations of Jupiter.

The infrared and microwave brightness temperatures of Jupiter have been computed by Hogan *et al.* (1969), using plausible abundances of the major atmospheric constituents of Jupiter, discussed below. Their results are displayed and compared with observations in Figures 6 and 7. The agreement is seen to be good. The high 5 μ brightness temperature is correctly reproduced, and is due to the fact that the constituents of the Jovian atmosphere are quite transparent at this wavelength.

D. RADIO SPECTRUM

As we go to longer and longer microwave wavelengths, away from the center of the inversion doubling band of ammonia at 1.25 cm, we go to regions of smaller microwave

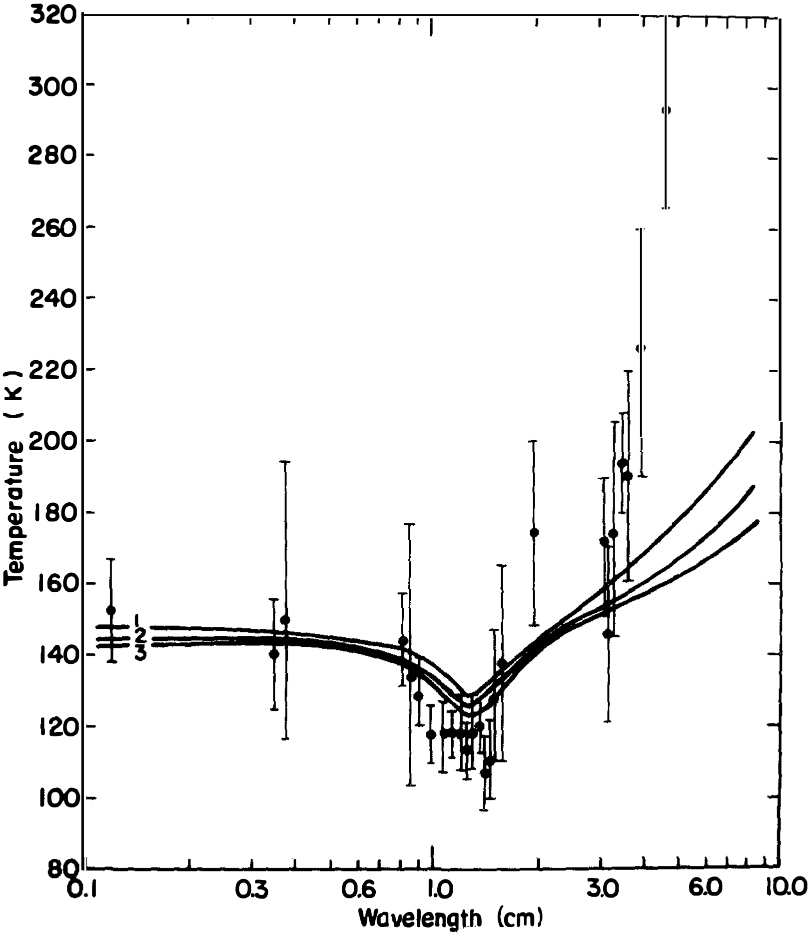

Fig. 7. Comparison of observed microwave observations of Jupiter with 3 theoretical models for thermal emission. The poor fit longward of 3 cm is due to Jovian non-thermal emission. After Hogan *et al.* (1969).

opacity; therefore, to regions of greater vertical depth in the atmosphere; and therefore, assuming convective equilibrium, to regions of higher temperature. In the case of Jupiter, this expectation is confirmed, but at wavelengths of many centimeters we begin to observe the non-thermal emission of the Jovian van Allen belts. The non-thermal emission can be separated from the termal component, for example by taking account of the fact that the non-thermal emission is polarized and the thermal emission is not. In the case of Saturn no non-thermal emission has been detected, and the increase of temperature with wavelength is in good accord with expectations from model atmospheres in convective equilibrium [Gulkis *et al.* (1969); Wrixon and Welch (1970)]. Observations of Uranus and Neptune at 1.9 cm give brightness temperatures quite comparable to those observed for Jupiter and Saturn, despite the much greater heliocentric distance of these planets [Kellermann and Pauliny-Toth (1966)]. This similarity has been explained by Sagan and Pollack [quoted in Kellermann and Pauliny-Toth (1966)] as follows: In the vicinity of its condensation level and above, the distribution of ammonia will be determined by its vapor pressure curve, avoiding the tendency towards uniform mixing; this then establishes a relation, constant for all four Jovian planets in this region of ammonia condensation, between temperature and ammonia partial pressure, and therefore between temperature and optical depth. Hence, at a given wavelength we are seeing to the same optical depth, thus to the same pressure, and accordingly to the same brightness temperature on all 4 Jovian planets. The argument provides some evidence for ammonia in the outer Jovian planets. While suspected there on cosmic abundance grounds (see below) this molecule has not yet been detected directly, nor is it expected to be detectable in the infrared, because of the low equilibrium temperatures of Saturn, Uranus and Neptune.

The microwave emission of Jupiter increases with increasing wavelength, at first at a rate consistent with expectation for an atmosphere in which the temperature is increasing adiabatically with depth; but very soon the temperature increases much too fast to be explained on such grounds, reaching tens of thousands of degrees at wavelengths longer than about 40 cm [see, e.g., Moroz (1967), page 347]. The shape of this long wavelength spectrum and the polarization of the emission suggested to Drake and Hvatum (1959) that the emission is synchrotron radiation from a van Allen radiation belt about Jupiter. This expectation was directly confirmed by the

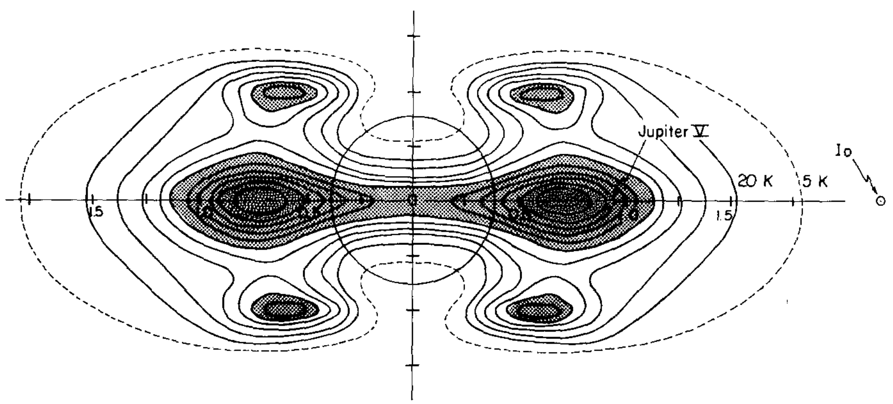

Fig. 8. Intensity contours of Jupiter's radiation belts, determined by radio interferometry of its synchrotron emission. After Berge (1966). The position of the planet itself, and of its innermost 2 satellites, lying in its equatorial plane, are also indicated.

interferometric observations of Berge (1966) who observed brightness temperature contours, corresponding roughly to those of a dipole magnetic field, extending in the equatorial plane of Jupiter several Jovian radii from the center of the planet (Figure 8).

The origin of the Jovian magnetic field is not entirely clear. It may be due to fluid motions in a conducting inner core, even though by most mechanical criteria the core would be considered solid. Alternatively, it is possible that the field is a primordial one, partially retained from the early contraction history of Jupiter. Such a field would not decay because of the high electrical conductivity of the Jovian interior, which is in turn due to pressure ionization.

It is important to ask why only Jupiter, of the four outer planets, has a detectable radiation belt. There are a variety of possibilities. Smoluchowski (1970b) has suggested that the Jovian magnetic field arises from motions not in the deep interior but rather at the level of onset of the transition leading to an alloy of metallic H and He, which is about half the Jovian radius. By coincidence this is just the relative depth at which the Earth's fluid core begins. Such high pressures (~ 10 Mb) do not occur for the other 3 Jovian planets, with the possible exception of Saturn. The Saturnian situation might be a special one because charged particles trapped in a Saturnian magnetic field will intersect the particles in the rings of Saturn once in each reflection between mirror points. The rings of Saturn would very efficiently sweep out any Saturnian radiation belts. It would be interesting to check this suggestion by flying a magnetometer close to Saturn.

One additional possibility bears mentioning; namely that the heliopause, the theoretically predicted region of transition between the solar magnetosphere and the interstellar medium, occurs somewhere in the region of the Jovian planets. In this case there would be no trapped radiation belts in the outer Jovian planets because the charged particle source – the solar wind – to supply these radiation belts does not reach the planets in question.

In addition to the centimeter wavelength emission which is largely of thermal origin, and the decimeter emission (10–100 cm) which is of synchrotron origin, Jupiter also exhibits sporadic decameter emission (10–100 m), which was in fact the first planetary radio emission to be discovered. The decameter emission sources appear to be localized in specific locales on Jupiter which rotate approximately with System III. The 4 or so clearly identified decameter sources are apparently correlated with none of the identifiable optical features on Jupiter, including the Great Red Spot. The decameter radiation is remarkably correlated with the position of Io, the innermost Galilean satellite of Jupiter; control by any of the other satellites is not well established [Dulk (1968); Lebo (1968)]. The method by which decametric bursts are triggered by Io is not well-understood, but it is worthy of note that Io and the innermost satellite Jupiter V are the satellites which are most within the Jovian radiation belts (Figure 8). An interesting theoretical attack on the problem has been made by Goldreich and Lynden-Bell (1969), but this has recently been criticized by Dermott (1970).

While there is general agreement on the synchrotron nature of the decimetric emission, there are still major problems in understanding the decametric emission. There is disagreement in the literature on the inclination of the Jovian magnetic field axis, whether it has significant quadrupole components, whether it passes through the geometric center of Jupiter, and on the surface magnetic field strength implied by the strong circular polarization of the bursts. Field strengths of the order of tens of gauss are often quoted. Recent reviews of the Jovian radio emission have been written by Warwick (1967), by Carr and Gulkis (1969), by Kellermann (1970), and by Dickel, Degioanni, and Goodman (1970).

E. MOLECULAR CONSTITUENTS

Chemical abundances in planetary atmospheres are determined generally by infrared spectroscopy, usually in the reflection rather than the emission spectrum. In the regions of the spectrum conveniently accessible from the Earth, it is usually high overtones and combination bands of the molecular rotation-vibration spectrum which are observed. Many molecules, particularly complex ones, also absorb in the visible and near ultraviolet, but their spectral signatures are not as unique. Spectra in the middle and far ultraviolet are potentially of very great usefulness, but, because they must be obtained from above the Earth's atmosphere, this technique has been incompletely exploited to date. An incident photon, at, say, near infrared frequencies arrives from the Sun, passes through the upper Jovian atmosphere which has a rather small optical depth for Rayleigh scattering, and then is multiply scattered by interaction with cloud particles and aerosols. After a random walk through the cloud particles, the photon emerges from the aerosol or cloud layer, passes through the overlying atmosphere and, if it is to be observed by the groundbased astronomer, travels across intervening space towards the Earth. After many such events an infrared absorption line can be detected on the Earth. The depth or equivalent width of this line should provide a clue to the abundance of the gaseous absorber. But if the incident photons have undergone extensive multiple scattering they will exhibit an apparent absorption greater than if they emerged after a single scattering event. Thus the determination of absolute abundances is a function of whether Jupiter has a diffuse haze layer giving rise to multiple scattering, or a sharp cloud layer giving rise to single scattering. In principle it should be possible to distinguish between these possibilities by observing the variation of absorption line intensities from the center to the limb of the planet, by comparing absorptions by different constituent gases, etc. Unfortunately, in the case of Jupiter and other planets with dense cloud layers, neither of these 2 models is without difficulties [see, e.g., McElroy (1969)]. The situation is further complicated by such quite plausible possibilities as billowy clouds varying in height from place to place (Squires, 1957), or a high optically thin haze and a lower optically thick cloud with a clear space in between [Danielson and Tomasko (1969)]. However, we will probably not be far off if in determining *relative* abundances we consistently use the same model. This procedure requires the assumption that the single scattering albedo of individual particles is approximately the same in the spectral regions being compared. Because of its simplicity, the simple reflecting model is usually used for this purpose.

The abundances of such gases as hydrogen and ammonia, as determined from rocket ultraviolet observations, are known to be considerably less than the values obtained from infrared observations (see, for example, Owen and Greenspan, 1968). The discrepancies are evidentally due to a greater penetration through particulate matter in the Jovian atmosphere by infrared than by ultraviolet photons. Teifel (1971) believes, from this discrepancy, that there is a high-altitude dust layer on Jupiter, perhaps arising from micrometeoritic debris.

Consistent with the expectations from cosmic abundances and the theory of gravitational escape, hydrogen is the most abundant gas detected on Jupiter. Its abundance is determined from the very weak quadrupole lines in its vibration-rotation spectrum. Recent estimates of the hydrogen abundance using the simple reflecting layer formalism are 85 ± 15 km-atmospheres (Owen, 1969) or 67 ± 17 km-atmospheres (Fink and Belton, 1969). For relative abundance purposes we adopt in this paper a hydrogen abundance of 80 km-atmospheres; in the simple reflecting layer formalism this is the hydrogen abundance above some 'effective reflecting layer', usually identified as the cloud 'tops'. The mixing ratio of helium, the second most abundant gas cosmically, is difficult to determine directly because it has no permitted spectrum of its own except in the ultraviolet; the best present estimates of upper limits on its abundance are derived from the line widths of methane. Ammonia and methane are observed directly throughout the infrared. Since the highest temperatures observed from the distribution of rotational energy levels in the near infrared are only a little above 200 K, we would not expect water vapor to be detected down to the levels which are observed, nor is it. The neon mixing ratio is rather the same sort of problem as the helium mixing ratio but even more difficult to determine.

A variety of unsuccessfull search for other gases have been performed. Upper limits

TABLE III

Molecular abundances in the atmosphere of Jupiter (Relative to H_2)

Molecule	Mixing Ratio
He	<0.4
CH_4	6×10^{-4}
NH_3	1.2×10^{-4}
H_2O	$<6 \times 10^{-7}$
H_2S	$<3 \times 10^{-6}$
C_2H_2	$<5 \times 10^{-7}$
C_2H_4	$<2 \times 10^{-5}$
C_2H_6	$<3 \times 10^{-5}$
HCN	$<6 \times 10^{-7}$
CH_3NH_2	$<2 \times 10^{-7}$
SiH_4	$<2 \times 10^{-4}$
CH_3D	$<2 \times 10^{-4}$
HD	$<6 \times 10^{-3}$
CO_2	$<1.2 \times 10^{-4}$

on their abundances in the simple reflecting layer formalism relative to 80 km-atmospheres of H_2 is given in the accompanying Table III. Shown in the table are volume mixing ratios – that is the ratio of the abundance of the molecule in question (by number) to the abundance of molecular hydrogen. The values are taken from a variety of sources (e.g., Owen, 1969; McElroy, 1969; Cruikshank and Binder, 1969). All but the last entry in the table are plausible constituents of the Jovian atmosphere. As in the case of H_2O, however, many of them have such low vapor pressures, at the low temperatures of the spectroscopically accessible Jovian atmosphere, that they would be undetectable by these techniques even if present in great abundance in the lower atmosphere. It is just possible that microwave spectroscopy might be used to search for such molecules, although the ammonia inversion doubling line tends to dominate the microwave spectrum.

The situation is rather similar for the other three Jovian planets. The observable abundance of hydrogen and methane generally increases as we go outward in the solar system, probably because the ambient temperatures are progressively lower and therefore the clouds, of whatever composition, form at a greater depth in an atmosphere where the temperature increases with depth. Detection of ammonia in the near infrared reflection spectrum of Saturn has been claimed and disputed, but the evidence from the microwave spectrum quoted above suggests that it is in fact present in very roughly the abundance for Jupiter. Weaker microwave evidence for ammonia on Uranus and Neptune have also been mentioned.

It is of interest to consider what chemical composition should be expected in the lower atmosphere, where condensation of NH_3 and even of H_2O at low temperatures is not a problem. There are two general approaches to this question, both of them inadequate for different reasons, and a range of intermediate possibilities. First one might assume thermodynamic equilibrium of the atomic precursors at some temperature. This temperature might either be the ambient temperature or some higher temperature corresponding for example to the temperature in lightning leaders, if these are the primary energy sources for the production of more complex molecules. The difficulty with this approach, particularly at lower temperatures, is that we have no assurance that thermodynamic equilibrium is attained in times short compared with the history of the solar system. A second approach is to use absolute reaction rate kinetics. Here it is possible to make estimates of the abundances even of materials which should be absent after thermodynamic equilibrium is attained. However, unlike the thermodynamic equilibrium approach, one must here be quite sure that all significant reaction pathways have been considered, and the neglect of even one such pathway can lead to the apparent piling up of some material which should not in fact be present. In a complete treatment not only must absolute reaction rate kinetics be considered but the detailed photochemistry must be brought in, as well as the question of convective and diffusive transport of precursor gases and products between various pressure and temperature levels in the atmosphere. Since we are not even close to being able to perform such calculations, the work which has been done heretofore, while in many cases stimulating and provocative, cannot in all cases be said to be conclusive.

The first such approach to the chemical composition of the Jovian atmosphere was performed by Wildt (1934, 1937). He deduced that the only chemically reactive species which should be present in significant abundances are hydrogen, methane, ammonia, and water, a conclusion confirmed by more elaborate calculations (Sagan *et al.*, 1967; Lewis, 1969a), as well as, for all but H_2O, by the observations. Lewis (1969a) argues that if equilibrium at ambient temperatures is attained such otherwise plausible materials as SiH_4, H_2S, PH_3 and C_2H_6 should not be present in spectroscopically determinable quantities. On the other hand, Sagan *et al.* (1967) argue that non-equilibrium processes dominate; they have performed calculations involving high local temperatures and subsequent quenching. Two sample systems are displayed in Table IV. The first, at a pressure of 1 bar and a temperature of 1500K is intended to represent electrical discharges in the vicinity of the visible clouds; the second, at 10^{-6} bar and 1000K, is intended to represent a hypothetical Jovian thermosphere from

TABLE IV

Predicted equilibrium in the Jovian atmosphere at high temperatures and moderate to low pressures

Pressure	~ 1 atm	$\sim 10^{-6}$ atm
Temperature	1500K	1000K
Noble gases	0.4	0.4
Hydrogen	0.6	0.6
Methane	4×10^{-3}	6×10^{-5}
Acetylene	2×10^{-4}	2×10^{3}
Ethylene	3×10^{-5}	7×10^{-7}
Ethane	2×10^{-7}	1×10^{-2}
Benzene	2×10^{-9}	1×10^{-7}
Napthalene	1×10^{-12}	4×10^{-9}
Asphalt (yellow)	6×10^{-25}	1×10^{-8}
Nitrogen	7×10^{-5}	6×10^{-5}
Hydrogen cyanide	6×10^{-5}	9×10^{-5}
Ammonia	2×10^{-7}	2×10^{-13}
Methyl cyanide	6×10^{-8}	2×10^{-10}
Azulene (blue)	5×10^{-14}	2×10^{-9}
Aniline	3×10^{-19}	2×10^{-23}
Azobenzene (red)	3×10^{-28}	3×10^{-33}

The formation of graphite was excluded. High temperatures produced by lightning could permit approach to such equilibria, followed by rapid quenching. Polynuclear aromatics and coloured compounds such as azulene tend to form.

which molecules may diffuse to lower altitudes. Among the most abundant molecules produced in these computer simulation experiments were hydrogen cyanide, acetylene, ethylene, and ethane. These are just the most abundant molecules preferentially produced in the laboratory by corona discharge in the Jovian simulation experiments of Sagan and Miller (1960).

In these calculations the high abundance of ethane predicted for the upper atmosphere at quenched equilibrium is noteworthy (Table IV, Column 3). In a recent detailed discussion of the photochemistry of methane on Jupiter, ethane has again been pinpointed as the most abundant expected product molecule (Strobel, 1969); the mixing ratio in these calculations is $\sim 10^{-7}$. The fact that higher hydrocarbons are readily produced after methane photolysis has been known for many years (see, e.g., Noyes and Leighton, 1941). There are a number of other hints, some of them very faint, that simple higher hydrocarbons may be present on Jupiter and Saturn. And Gillett and Stein (1969) suggest that ethylene may be responsible for the absorption they find in the 8–14 μ spectrum of Saturn, a conclusion which McElroy (1969) treats with some skepticism.

F. COLORATION AND ORGANIC MOLECULES

We have already mentioned the diversity and the space- and time-dependence of the Jupiter coloration. Saturn exhibits such colors to a lesser extent and Uranus and Neptune only marginally. The existence of such colors strongly suggests a non-uniform distribution, both in space and in time, of molecular species which absorb visible light. The identification of these molecular absorbers is obviously an important and unsolved Jovian enigma. Since some not implausible materials have very large absorption coefficients in the visible, the molecules responsible for the coloration need not be very abundant – which complicates the investigation of their identities. Since there are many colors observed there must be many molecules. Since the coloration is in the clouds, their identification is connected with the chemical identification of the clouds of Jupiter. Because the observed abundances of ammonia are consistent with the vapor pressure above condensed ammonia at observed infrared temperatures, it has traditionally been assumed (Kuiper, 1952) that 'the' clouds of Jupiter are ammonia cirrus. However, since the vapor pressure depends exponentially on the reciprocal of the temperature, and since there is now such a variety of infrared temperatures (see Table II), this conclusion is not so firm as it once was. An estimate of the temperature

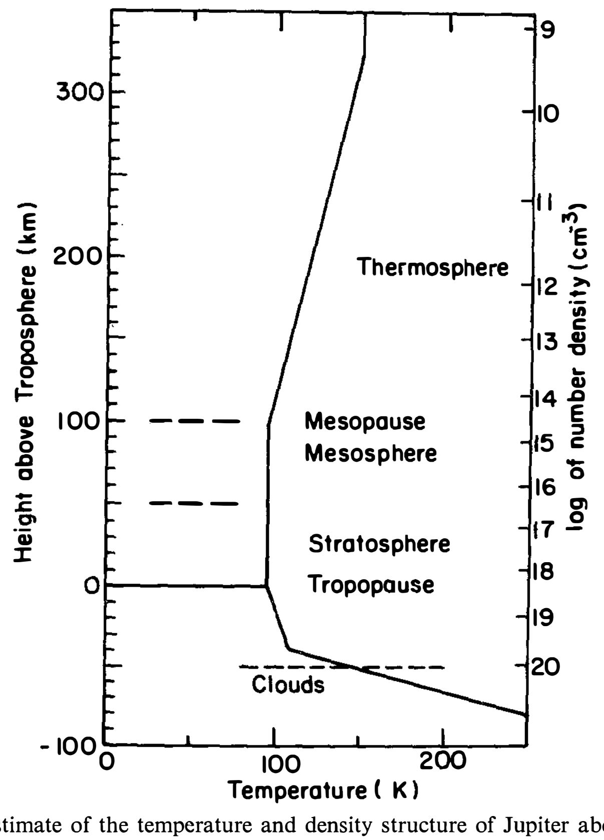

Fig. 9. One estimate of the temperature and density structure of Jupiter above the clouds. After Hunten (1969).

of the upper atmosphere of Jupiter is shown in Figure 9 (after Hunten, 1969). These temperatures are nowhere low enough to permit methane condensation. The clouds at the 200 + K level may well be condensed water clouds, as was suggested by R. Gallet (quoted in Wildt *et al.* 1963) and by Sagan (1964) on different grounds. The cloud temperatures on Uranus and Neptune are so low that condensed methane is a likely constituent. Methane clouds at the Saturnian polar regions are also reasonable.

Some additional possibilities for Jupiter have recently been suggested by Lewis (1969b). Lewis shows from thermodynamic arguments that clouds of ammonium hydrosulfide (NH_4SH) are expected at about the 225 K level with the peak above the peak of the ice clouds; and an extensive cloud below the ice clouds composed of an aqueous solution of ammonia (see Figure 10). The argument on ammonium hydrosulfide of course assumes some roughly cosmic abundance of sulfur on Jupiter. Now

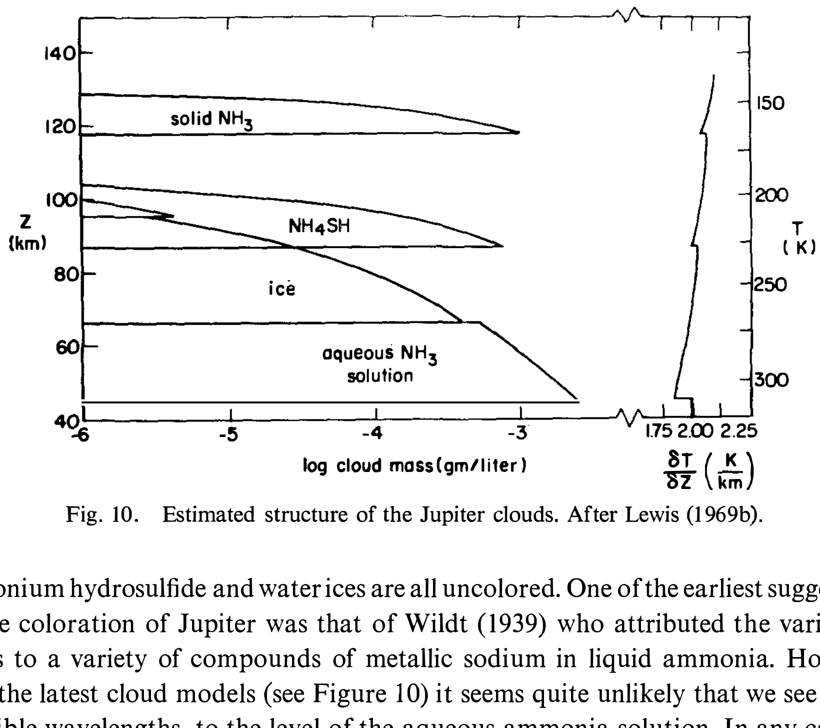

Fig. 10. Estimated structure of the Jupiter clouds. After Lewis (1969b).

ammonium hydrosulfide and water ices are all uncolored. One of the earliest suggestions on the coloration of Jupiter was that of Wildt (1939) who attributed the variegated colors to a variety of compounds of metallic sodium in liquid ammonia. However, from the latest cloud models (see Figure 10) it seems quite unlikely that we see down, at visible wavelengths, to the level of the aqueous ammonia solution. In any case the temperatures there are much hotter than required for the sodium-ammonia chemistry. Alternatively, it has been suggested that the coloration is due to free radicals, produced by charged particle irradiation of ammonia or other ices (cf. Rice, 1956; Papazian, 1954). Such free radicals are routinely prepared by matrix isolation techniques in contemporary chemistry laboratories by the high energy particle bombardment of ices. Leakage of protons or electrons from the Jovian van Allen belts is in fact to be expected as discussed below. However, the colors are in the clouds and the ranges of such particles (even with 10 MeV energies) are too small by many orders of magnitude to reach the clouds.

Another possibility has recently been suggested by Owen and Mason (1969). They suggest that in addition to ammonium hydrosulfide, ammonium sulfide, $(NH_4)_2S$, might be expected; and, it is claimed, ammonium sulfide is yellow. Their first conjecture can be confirmed; in experiments in prebiological organic chemistry in which H_2S is introduced into a mixture of gases containing ammonia, ammonium sulfide was observed to form in stoichiometric quantities; however, the compound is very indistinctly yellowish, if at all, from room temperature to 77 K (Sagan and Khare, 1970). In any case, the ammonium sulfide suggestion does not explain the time- and space-variability of the Jovian coloration.

This then brings us to the question of possible organic molecules on Jupiter. Probably the most natural hypothesis is that the coloring material of the Jovian clouds is made from the most abundant reactive materials available on Jupiter, namely hydrogen, methane, ammonia and probably water. Such interaction products, if containing carbon, are called organic compounds. The word 'organic' carries no implication of biological origin. The first suggestion that organic molecules might be responsible for the Jovian coloration was made by Urey (1952, page 152), who proposed that the principle blue-absorbing coloring material was cuprene, a polymer of acetylene. Acetylene has in fact been made in Jovian laboratory simulation experiments (Sagan and Miller, 1960), and is predicted in computer simulation experiments (Sagan, *et al.*, 1968). However, the thrust of recent work on possible organic chromophores on Jupiter has been to implicate other molecules. Most molecules which absorb in the blue do so because of an unbound electron, as NO_2, or because the molecules are heterocyclic, displaying alternating single and double bonds which results in pi electrons bound to the molecules but not to any individual atom. Nitrogen dioxide and its dimer, nitrogen tetroxide, N_2O_4, have in fact been proposed as a coloring material on Jupiter (Heyden *et al.*, 1959); but the presence of even small quantities of so highly oxidized a molecule in such a highly reducing environment as Jupiter is extremely untenable. In the latter case, the physics is close to the quantum mechanical solution of the one-dimensional Schroedinger equation with infinite potential walls. The energy levels are so closely spaced that the visible absorption is a broad continuum. There are a range of such compounds: polycylic aromatic hydrocarbons – derivatives of benzene; polypyrroles, especially the porphyrins – for example, chlorophyll and hemoglobin; and purines and pyrimidines and their derivatives – the basic building blocks of nucleic acids. In addition to absorbing at short visible and near-ultraviolet wavelengths, these heterocyclic ring compounds exhibit considerable stability to high temperatures and to high-ultraviolet fluxes. Thus, even were their production unlikely, their stability in the face of continuing irradiation may make them numerically preponderant after a time. This remark applies as well to the moon and the asteroids, and to the interstellar medium.

Sagan (1962) pointed out that many of the interaction products of HCN, C_2H_2, C_2H_4, C_2H_6, and CH_3CN – expected to be produced on Jupiter from the interaction of methane and ammonia – are colored, and in subsequent computer experiments Sagan *et al.* (1967) found that a range of polycyclic aromatic hydrocarbons are produced under possible Jovian conditions; and that some of these (Table IV) are vividly colored – including asphalt (yellow), pyrene (yellow), coronene (yellow), azulene (blue), azobenzene (red), and chrysene (which exhibits a red-blue fluorescence). The conditions for the formation of such compounds seem to be merely that high temperatures occur locally and intermittently under Jovian conditions. Woeller and Ponnamperuma (1969) have examined the products of an electrical discharge through an anhydrous mixture of methane and ammonia, both at room temperature and at liquid air temperatures. A deep red polymeric material was produced and is attributed both to the polymerization of HCN and to the polymerization of cyanogen. Woeller and Ponnamperuma attribure the lack of spectroscopically identifiable HCN and C_2N_2 to the polymerization reactions themselves: if these molecules are very reactive their steady state abundance should be quite low. The vapor pressure curves of these materials will also work to reduce their abundances. In attempting to separate the colored product on a Dowex column, several bands of various colors were produced including 'brownish yellow, intense orange, bright yellow, and deep orange'. Woeller and Ponnamperuma propose that these colored polymers of hydrogen cyanide and cyanogen may contribute to the red and orange colors of Jupiter, but that other reported colors may be due to the polycyclic aromatic hydrocarbons proposed by Sagan *et al.* (1967).

In a recent series of experiments methane, ethane, ammonia, water and hydrogen sulfide have been mixed together at room temperature and approximately one atmosphere total pressure, and ultraviolet irradiated (Sagan and Khare, 1970). Because hydrogen sulfide is absorbing at long ultraviolet wavelengths, simulated sunlight can for the first time be used effectively in experiments dealing with reducing planetary atmospheres. A wide range of amino acids and other organic compounds are produced in these circumstances, as is a brownish yellow polymeric material. Analysis of this material is not yet complete, but polymers of elemental sulfur up to S_8 have been detected mass spectrometrically. This material is displayed in Fig. 2.

The question of which are the most important energy sources for the production of organic molecules on Jupiter is of some interest. The rate of electrical discharge in the Jovian clouds is unknown. If we scale from the Earth, which is about half cloud-covered, to Jupiter, which is entirely cloud covered, and on which the clouds are of significantly greater depth, we might guess at an energy source of some tens of calories cm^{-2} yr^{-1}. The leakage flux from the Jovian van Allen belts is likewise uncertain (Brice, 1968), but it is several orders of magnitude below our estimate for electrical discharges. At wavelengths shorter than about 3000 Å, where some organic photochemistry can be expected, the ultraviolet flux at Jupiter is roughly 100 cal cm^{-2} yr^{-1}. For all these energy sources the specific efficiency for the production of amino acids and other organic molecules is quite low. On the other hand in experiments in which pressure shocks have been utilized in simulated reducing environments, the efficiencies for the production of organic molecules appears to be considerably larger (Bar-Nun *et al.*, 1970). Sources of shock waves on Jupiter include thunder (that is, the bulk of the energy in electrical discharge not available in the lightning leader) and from the hypervelocity impact of micrometeorites and cometary meteors. Although the energy available from shocks on Jupiter is low (perhaps several calories cm^{-2} yr^{-1}) the efficiencies are so high that it probably corresponds to the most efficient energy source for the product of organic molecules; if the mean molecular weight of synthesized molecules were of the order of 100, the resulting shock production flux is $\sim 10^{-12}$ g cm^{-2} sec^{-1} (Bar-Nun *et al.*, 1970). Over 5×10^9 yr a total production of several hundreds of kilograms per square centimeter column of organic matter is implied. (And shock production can occur at depths where uv energy cannot penetrate.)

This is of course not the steady state abundance of organic molecules because there should be significant loss mechanisms, including ultraviolet irradiation of synthesized molecules and the convective transport of synthesized molecules down to great depths where they are thermally dissociated. Indeed this latter mechanism has been invoked in order to resupply methane to the Jovian upper atmosphere after its photodissociation (Strobel, 1969). However, these loss mechanisms may not be of very great efficiency. The ultraviolet flux is surely principally attenuated at the depth of coloration of the Jovian clouds; at the estimated pressures at that level of a bar or more, Rayleigh scattering alone would provide a significant attenuation source. The efficiency of downward convective transport depends on the depth of the convective cells in the outer Jovian atmosphere, a meteorological problem which is unsolved. However the rates of convective circulation for Jupiter calculated by Golitsyn (1970) and Smoluchowski (1970a) are so slow as to indicate that thermal degradation is not the dominating process. The existence of an isothermal region in the deep Jovian atmosphere is relevant to the question of thermal degradation. It also is in dispute and is connected with the internal heat source problem (see, e.g., Trafton and Münch, 1969). With an adiabatic lapse rate of 2°/km, the distance below the colored Jovian clouds that we must go to reach temperatures of say 1000 K is only some 400 km. But since the estimated central temperature of Jupiter are only a few thousands of degrees Kelvin, it is clear that the adiabatic lapse rate does not extend indefinitely. Some of the organic compounds in question, for example asphalt, are very stable at high temperatures and may very well survive convective circulation.

A reason for exercising some caution in the application of laboratory simulation results to the Jovian environment is that such experiments are usually performed without an excess of hydrogen, while Jupiter, of course, contains such an excess. The point is relevant because many of the organic compounds in question are relatively hydrogen-poor; producing their fully saturated hydrides would reduce them to methane, ammonia and water. Yet there is a large body of experience with such experiments (for reviews see, e.g., Fox, 1965; Ponnamperuma and Gabel, 1968; Kenyon and Steinman, 1969). In such experiments excess hydrogen is generally built up as a result of the synthetic processes while the rate of production of organic molecules generally continuous unabated until the supply of precursors is entirely gone. In any case it seems rather clear that very large quantities of organic molecules must exist on Jupiter today, that quite complex organic reaction chains are operating, and that organic molecules are an important presumptive source of the Jovian coloration.

G. ULTRAVIOLET SPECTRA

The question of Jovian organic matter has entered considerations of the near ultraviolet reflection spectrum of Jupiter. Since ultraviolet radiation short of about 2900 Å is absorbed by ozone, oxygen and other telluric molecular constituents, to perform observations at these wavelengths it is necessary to move the observatory above the Earth's atmosphere. This has been done by sounding rockets, which perform observations for a short period of time at the peak of their trajectories, and, most recently, from Earth orbit by the Orbiting Astronomical Observatory A–2 spacecraft of the United States. The sounding rockets generally are unable to obtain usable signals below about 2000 Å, because the reflected solar flux is very weak at such wavelengths and the rockets spend too short a period of time above the ozonosphere to have any useful time-integration. In the first such rocket observation by Stecher (1965) a resolution of about 50 Å was employed between 2100 and 3000 Å. Stecher found a reflectivity depression roughly 200 Å in width centered at 2600 Å. The same rocket which obtained Stecher's photoelectric spectra also obtained photographic spectra (Evans *et al.*, 1965), which confirmed this feature, as did a subsequent rocket flight by Evans (1966; see also Evans, 1967). Subsequently spectra of Jupiter were taken at one Ångstrom resolution between 2400 and 3000 Å in a 1967 rocket flight (Jenkins, 1969).

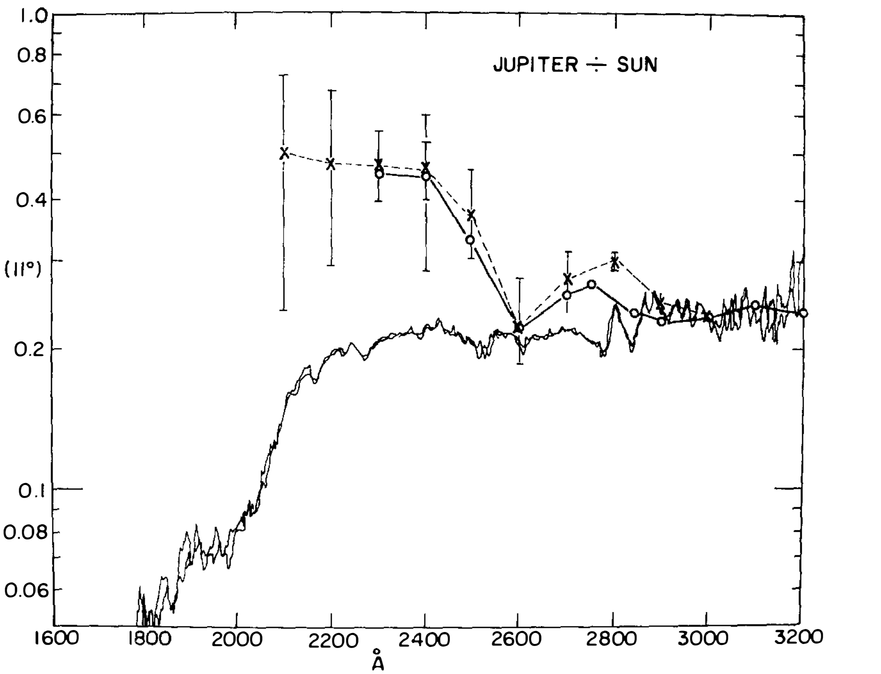

Fig. 11a. Ultraviolet geometric albedos of Jupiter at phase angle 11°. The crosses represent the results of Stecher (1965) and the open circles the results of Evans (1962). The solid curves show the more recent results of Anderson *et al.* (1969).

A slight reflectivity minimum was observed in this flight at 2600 Å, but it did not match well either in wavelength or in strength with the features reported previously by Stecher and by Evans.

In a December 1967 rocket flight, 2 groups using spectrometers with poorer resolution than that of Jenkins obtained no trace of a 2600 Å feature (Anderson *et al.*, 1969; Kondo, 1969). Preliminary examination of OAO UV spectra of Jupiter taken subsequently also shows no sign of the 2600 Å feature.

Since some features in the visible – notably the Great Red Spot – are seen only upon the presentation of the appropriate central meridian, it is also possible that an ultraviolet feature such as the reported 2600 Å feature resides at a particular longitude on Jupiter, and may therefore sometimes be present and sometimes not. Remarkably enough, all 11 available ultraviolet spectra of Jupiter, including as-yet-unpublished OAO spectra, were taken with the Great Red Spot in the averted hemisphere. If all observations were independent in time, the probability of having this occur by chance would be less than 5×10^{-4}; in fact, however, since several of the observations were performed on the same flight or orbit, the improbability is somewhat less. In any case it does not seem likely that a feature with as small a projected area as the Great Red Spot would be able to produce as prominent a feature as that reported at 2600 Å. But the observations reporting the 2600 Å feature seem to be reliable (Figure 11a). Secular variability of coloration occurs in the visible. We will therefore consider as a working hypothesis that secular variability of coloration also occurs in the ultraviolet. However the change implied for the integrated ultraviolet light over the disc of Jupiter is very large. Note that Low, in work referred to above, reports large secular variability in the infrared brightness of Jupiter. If then the 2600 Å feature can be considered tentatively as real, we may inquire what molecule may be responsible for it.

Greenspan and Owen (1967) proposed that benzene, which absorbs in this region, may be responsible. Benzene is the simpliest aromatic hydrocarbon. However the envelope of benzene absorption does not well-match the reported 2600 Å feature (Greenspan and Owen, 1967; Sagan, 1968). In addition, the high resolution spectrum of benzene should show the B-band fine structure, as stressed by Sagan (1968) – such fine structure was not found in the high resolution spectra (Jenkins, 1969). As alternatives, Sagan (1968) proposed that the absorption may be due to purines and pyrimidines, or their derivatives. Their fit to the reported spectrum is good; a very small amount $\sim 1\ \mu g\ cm^{-2}$ is required [cf. Figure 11b], and the molecules should be easily produced on Jupiter – adenine is in fact the pentamer of hydrogen cyanide. While it is true that a wide range of organic compounds absorb at 2600 Å (Greenspan and Owen, 1968), almost all of these molecules are derivatives of benzene or polycyclic aromatic hydrocarbons, on the one hand, or derivatives of purines and pyrimidines on the other. Such absorptions are likely to be caused by condensed phase molecules in the Jovian clouds rather than by molecules in the gas phase (Sagan, 1968). Regardless of the reality of the 2600 Å feature, it appears that very small quantities of condensed phase organic molecules can give rise to major ultraviolet and visible absorption features.

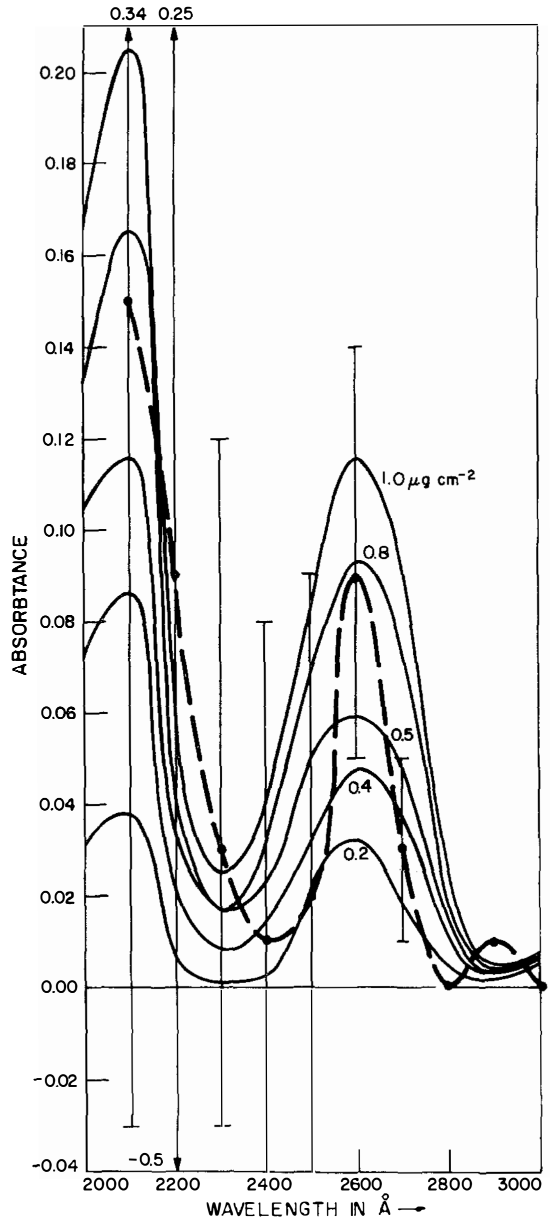

Fig. 11b. Comparison of Stecher's results, expressed as residual absorption, with the absorption of various quantities of adenine, measured in dilute aqueous solution in the laboratory. After Sagan (1968).

H. THE GREAT RED SPOT

Related questions of colorations and time variability apply to the Great Red Spot. The coloration varies from deep red to pinkish to indetectable. There is moderately good evidence for high correlation between the visibility of the Red Spot and solar activity (Basu, 1969), although the correlation is quite poor after 1947. The motion of the Red Spot is quite remarkable; since 1879 it has drifted erratically in latitude only some 2 or 3° from its mean latitude of $-22°$; but it has drifted in longitude since 1831, losing more than 3500° with respect to System II. This corresponds very roughly to a drift loss of 10^{-4} sec/sec. High dispersion spectra of the Great Red Spot, kindly obtained for us at the Lick Observatory's 120-in. telescope by Herbig, show no sharp line features intrinsic to the Red Spot (Regas and Sagan, 1966): the spectrum merely confirms that the Red Spot is red. The polarization of scattered sunlight from the Red Spot appears to be the same as from its surroundings, indicating that a fine haze surmounts the Red Spot as well as the belts and zones generally (Dollfus, 1961).

The idea that the Red Spot represents an enormous floating object runs into serious dynamical difficulties, and curious problems about what is floating in what (Sagan, 1962; however, see also Streett, 1969). An alternative model has been proposed by Hide (1961, 1969) who suggests that the Red Spot is the top of a stagnant Taylor Column rising to very great altitudes above a surface depression or elevation. If the Red Spot is a stagnant Taylor Column, the existence and variation of its coloration remains very difficult to explain. However, exchange of materials through the boundaries of the Red Spot is observed; in almost any model with any small deviations from the barotropic approximation for the classical Taylor column, we would expect some vertical convection within it. Such convection may be effective in carrying materials characteristic of the deep atmosphere up to our view (Sagan, 1962). To explain the fact that the Great Red Spot moves significantly in longitude with respect to System II, Hide must propose a decoupling between the atmosphere and the hypothetical surface at great depths below the visible cloud. The Taylor Column hypothesis has however not been immune to meteorological criticism (Goody, 1969).

It is tempting to ascribe the existence of the Red Spot to a site of preferential leakage of the trapped particles in Jupiter's radiation belt – perhaps one of the mirror points. If the Jovian magnetic dipole is off-center, as some theories suggest, then one of the principal mirror points may be at much higher altitudes than the other; as a result, the interesting organic chemistry attendant to such passage of charged particles through the reducing Jovian atmosphere would occur preferentially in only one locale on Jupiter. This idea however runs into the probably fatal objection that System III, which characterizes the motion of the radiation belts via the decameter emission, distinctly moves – at least in recent years – with respect to the Great Red Spot. The drift is about 6 sec per revolution.

There are several lines of evidence suggesting that the Red Spot extends to quite great altitudes: (1) the Red Spot remains dark to 3250 Å, where Rayleigh scattering is beginning to become quite important (Owen and Mason, 1969); (2) ammonia absorption over the Red Spot is significantly less than in zones and belts at corresponding latitudes (Moroz and Cruikshank, 1969); and (3) the 10 μ brightness temperature of the Red Spot is slightly lower than its surroundings (Wildey *et al.*, 1965). The van Allen belt precipitation model can explain why the coloration of the Red Spot should be high, but so can some categories of meteorological models. It seems safe to say that there are no entirely successful models of the Great Red Spot at the present time. Any such model must explain why the drift in longitude with respect to Systems II and III is acompanied by very little drift in latitude, the fact that the Great Red Spot is red, and the fact that there is only one Red Spot.

I. LIFE?

If organic molecules are abundant on Jupiter, it is not entirely out of place to ask about the possibility of life on that planet. Traditionally the question of life on Jupiter has been dismissed with an appeal to freezing temperatures, crushing gravity and poisonous gases. But we know today that the temperatures in the Jovian clouds are no more representative of temperatures in the lower atmosphere than is the case for the Earth; that the slightly greater Jovian gravity is of no significance whatever with respect to possible life; and that, far from being unambiguously poisonous, the gases in the Jovian atmosphere are precisely those required to understand the origin of life on Earth [these points are not new – cf. Sagan, 1961a]. Direct evidence for biologically interesting temperatures on Jupiter is obtained from the observations of Westphal (1969) who observes at 4.8 μ an average temperature of 240 K in the vicinity of a dark equatorial cloud belt. In localized regions within the cloud belt temperatures of 300 K or more are anticipated. This is in a wavelength region where methane and ammonia do not absorb and where we have a large *a priori* possibility of seeing below the bright visible clouds. We have already referred to uncertainties in the structure of the Jovian atmosphere. In the models of Lewis (1969b), the water and aqueous ammonia solutions occur at temperatures within some tens of degrees of 300 K and at pressures of some tens of atmospheres. This level exists very roughly 50 km below the ammonia cirrus clouds. Organic chemistry in liquid ammonia is quite complex and not describable by simple analogies with organic chemistry in water (for example, by a simple substitution of NH_2 for OH groups); organic chemistry in the aqueous ammonia clouds of Jupiter should be very interesting (cf. Smith, 1953; Franklin, 1935). If we see in the zones down to the water ice clouds of Jupiter, it seems quite likely that some sunlight filters down to the aqueous ammonia clouds. Thus, although heterotrophy seems to be the easiest mode of life on a planet in which large quantities of organic molecules are produced abiologically, photosynthetic autotrophy also seems attainable. In the convective atmosphere of Jupiter, small quantities of minerals can be expected to be circulated from below. Lewis (1969b) predicts a silicate cloud with roughly the composition of pyrex at the 1200 K, 10^4 bar level. He anticipates the biologically important phosphates to be a minor constituent precisely in the aqueous ammonia clouds.

In the deep atmosphere of Jupiter there are regions in which the atmospheric pressure approaches that of a solid; and there are clouds. Thus there seems to be no dearth of effective interaction media for the production of very complex organic chemicals on Jupiter. Similarly the environment seems to be extremely time-variable, providing adequate selection pressure. With life on Earth taking only some hundreds of millions of years to have evolved, it does not seem at all out of the question that

TABLE

Satellites of the

Satellite	Semi-major Axis	Eccentricity	Inclination	Sidereal Period	Mass
Jupiter					
JV	1.81×10^5 km	0.0028	0°27′.3	$11^h57^m22^s7$	–
Io (JI)	4.22×10^5	0.0000	0°1′.6	$1^d18^h27^m33^s5$	0.994 $M_☾$
Europa (JII)	7.71×10^5	0.0003	0°28′.1	$3^d13^h13^m42^s1$	0.646
Ganymede (JIII)	1.07×10^6	0.0015	0°11′.0	$7^d3^h42^m33^s4$	2.101
Callisto (JIV)	1.88×10^6	0.0075	0°15′.2	$16^d16^h32^m11^s2$	1.292
JVI	1.15×10^7	0.158:	27°6′:	250^d57	–
JVII	1.17×10^7	0.207:	24°8′:	259^d65	–
JX	1.10×10^7	0.130:	29°0:	263^d55	–
JXII	2.13×10^7	0.169:	147°:*R*	631^d	–
JXI	2.25×10^7	0.207:	164°:*R*	692^d	–
JVIII	2.35×10^7	0.378:	145z:*R*	739^d	–
JIX	2.37×10^7	0.275:	153°:*R*	758^d	–
Saturn					
Janus	1.6×10^5	0.0:	0:	0^d749	–
Mimas	1.86×10^5	0.0201	1°31′.0	0^d94242	0.00049
Enceladus	2.38×10^5	0.0044	0°01′.4	1^d37022	0.0011
Tethys	2.95×10^5	0	1°05′.6	1^d88780	0.0088
Dione	3.78×10^5	0.00221	0°01′.4	2^d73692	0.014
Rhea	5.28×10^5	0.00098	0°21′	4^d51750	0.031
Titan	1.22×10^6	0.029	0°20	15^d94545	1.9
Hyperion	1.48×10^6	0.104	0° (17′–56′)	21^d27667	0.0013:
Iapetus	3.56×10^6	0.0283	14°72′	79^d3308	0.019
Phoebe	1.30×10^7	0.1633	150°05′ *R*	550^d45	–
Uranus					
Miranda	1.30×10^5	0.01	0°:	1^d4135	0.0012
Ariel	1.91×10^5	0.0028	0°:	2^d5204	0.018
Umbriel	2.66×10^5	0.0035	0°:	4^d1442	0.0073
Titania	4.36×10^5	0.0024	0°:	8^d7058	0.059
Oberon	5.83×10^5	0.0007	0°:	13^d4633	0.034
Neptune					
Triton	3.56×10^5	0:	159°95′ *R*	5^d8768	1.8
Nereid	5.57×10^6	0.749	27°71′	359^d881	0.001:

Masses are given in terms of the Moon's mass. 'R' indicates retrograde revolution. The colon signifies very uncertain data.

V

Jovian Planets

Mean Diameter	Mean Density	Visual Geometric Albedo	Surface Gravity	Escape Velocity	Satellite
160 km	–	–	–	–	JV
3340	3.71 g/cm^3	0.92	0.17 g	2.4 km/sec	Io (JI)
2920	3.6	0.83	0.15	2.1	Europa (JII)
5100	2.2	0.49	0.16	2.8	Ganymede (JIII)
4720	1.7	0.26	0.11	2.3	Callisto (JIV)
120:	–	–	–	–	JVI
40:	–	–	–	–	JVII
20:	–	–	–	–	JX
20:	–	–	–	–	JXII
24:	–	–	–	–	JXI
40:	–	–	–	–	JVIII
22:	–	–	–	–	JIX
–	–		–	–	Janus
510:	0.5	–	–	–	Mimas
640:	0.7	0.54	–	–	Enceladus
1020:	1.2	0.84	–	–	Tethys
890:	2.8:	0.94	–	–	Dione
1300	2.0:	0.82	–	–	Rhea
4800	2.4	0.21	–	–	Titan
400:	3.3:	–	–	–	Hyperion
1300	2:	–	–	–	Iapetus
300:	–	–	–	–	Phoebe
600:	–	–	–	–	Miranda
400:	–	–	–	–	Ariel
1000:	–	–	–	–	Umbriel
800:	–	–	–	–	Titania
200:	–	–	–	–	Oberon
4000:	4:	–	–	–	Triton
200:	3:	–	–	–	Nereid

life has originated on Jupiter after billions of years. It would be of very great interest to perform simple biological simulations of the Jovian environment: for example, the microbial inocculation of a mixture of methane, ammonia, and water at room temperature and 1 bar pressure, in a search for microbial growth. The information accumulated since 1961 seems only to enhance the judgment (Sagan, 1961a) that of all the planets of the solar system Jupiter is the one with the largest *a priori* biological interest.

Similar remarks about organic chemistry and exobiological interest can be made about Saturn, Uranus, and Neptune, although there is some reason to believe that these planets may have very extensive outer envelopes, in radiative rather than convective equilibrium, due to the low value of the solar flux at their distances from the Sun (Sagan, 1969). It may be for this reason that the prominent colors and atmospheric turbulence which characterizes Jupiter are less often observed in the more distant Jovian planets, even after allowance is made for the greater difficulty in observing these planets. Irradiation of the suspected methane clouds of the outer Jovian planets should produce some interesting hydrocarbons – and suggests a range of fruitful laboratory experiments. It is clear that our information about these planets is pityfully small in comparison with Jupiter, about which we also know far too little.

J. FUTURE SPACE MISSIONS

Many important advances must await flybys, orbiters, and entry vehicles for these planets. The United States intends to launch 2 spacecraft through the asteroid belt to the vicinity of Jupiter. One, Pioneer F, is to be launched in February 1972; the other, Pioneer G, is to be launched in March 1973. The anticipated arrival dates at Jupiter are, respectively, between November 1973 and June 1974, and between October 1974 and March 1975. These space vehicles contain 6 detectors for charged particles and magnetic fields, instruments which should make it possible to clarify many enigmas about the Jovian radiation belts. There will be 2 meteoroid detectors primarily designed for the passage through the asteroid belt, and 3 experiments oriented towards Jupiter itself: a visual imaging photometer and polarimeter, an infrared radiometer, and an ultraviolet photometer. There will also be *S*-band occultation and celestial mechanics experiments. Pioneers *F* and *G* are the precursors of a wide variety of planetary swingby and 'Grand Tour' missions, which become possible in the middle to late 1970's. One method of obtaining information on atmospheric structure and composition from flybys is via *S* and *X*-band occultation experiments. This has been discussed for Jupiter, for example, by Sodex (1968). On a grand tour mission occultation measurements could be made for a least one satellite per planet flown by. A recent discussion of possible future space vehicle missions to the outer planets has been published as 'The Outer Solar System', by the Space Science Board, National Academy of Sciences (1969).

K. SATELLITES OF THE JOVIAN PLANETS

Table V summarizes most of the relevant facts about the satellites of the Jovian planets.

The four largest satellites of Jupiter were discovered by Galileo and are known as the Galilean Satellites. They are of lunar dimensions or larger. The same remark applies to Titan, the seventh satellite of Saturn, to Triton, the first satellite of Neptune, and to Pluto. At the low exospheric temperatures which may be anticipated for these seven objects, the ratio of mass to radius is probably large enough for them to retain some atmosphere. If their environments are reducing, as the Jovian planets themselves are, the only abundant stable gas which is plausible and unlikely to escape seems to be methane, with some possibility of ammonia for the Galilean satellites. Direct spectroscopic searches for atmospheres of these satellites have been successful only in the case of Titan for which two methane bands have been found (Kuiper, 1944). The total pressure of methane corresponds to a few tens of millibars. Rather weak evidence for a trace of a methane atmosphere on Triton was also found by Kuiper (1944). Photometric investigations of Io (Binder and Cruikshank, 1964) show that, after a solar eclipse by Jupiter, it is approximately 0.09 magnitudes brighter than before; after about a quarter of an hour, its brightness fades to its usual value. The effect is observed only upon eclipse egress, and not on ingress. If the effect is real, Binder and Cruikshank propose to explain it in terms of an atmosphere which condenses out to give a bright precipitate during an eclipse but which rapidly revaporizes in sunlight. However, Veverka (1969 and 1970, to be published) shows that it is very difficult to devise a material which provides sufficient ground coverage to account for the post-eclipse brightening and which at the same time can be vaporized in 15 min. The observations are in any case quite difficult.

The visual albedos of Io and Europa are very high (Harris, 1961), comparable to that of freshly fallen snow. Their mean densities are somewhat greater than the Moon's. On the other hand many of the Saturnian satellites, which have comparably high visual albedos, have mean densities of the order of 1 g cm^{-3} and must be giant snowballs. Characteristic theoretical surface temperatures for the Jovian satellites are, very roughly, about 150 K, values confirmed by 8–13 μ infrared radiometry (Low, 1965); for the Saturnian satellites, on the other hand, the temperatures are about 80 K All 4 Galilean satellites show an increase in albedo from blue to red and can therefore be described as reddish; however, Io and Callisto show approximately flat spectra from red light to about 2.5 μ while Europa and Ganymede show a precipitous decline (Moroz, 1967). This decline for Europa and Ganymede is rather similar to that observed for the Martian polar caps, and Moroz takes this as evidence for a water frost covered Europa and Ganymede. However, he correctly points out that temperatures of 130 K or less are required to prevent the complete evaporation of initially very thick ice layers on these satellites during the history of the solar system; while the theoretical and observed values are significantly above this value. The infrared spectra of ammonia and methane ices are not yet well-established, but it seems much more likely that such materials are responsible both for the high albedos and for the occasional time-variability reported for satellites of the Jovian planets. Figures 12–14 show drawings of the surface features of the Galilean satellites and of Titan. It is apparent that (1) there are clear surface features to be seen on these objects, and (2)

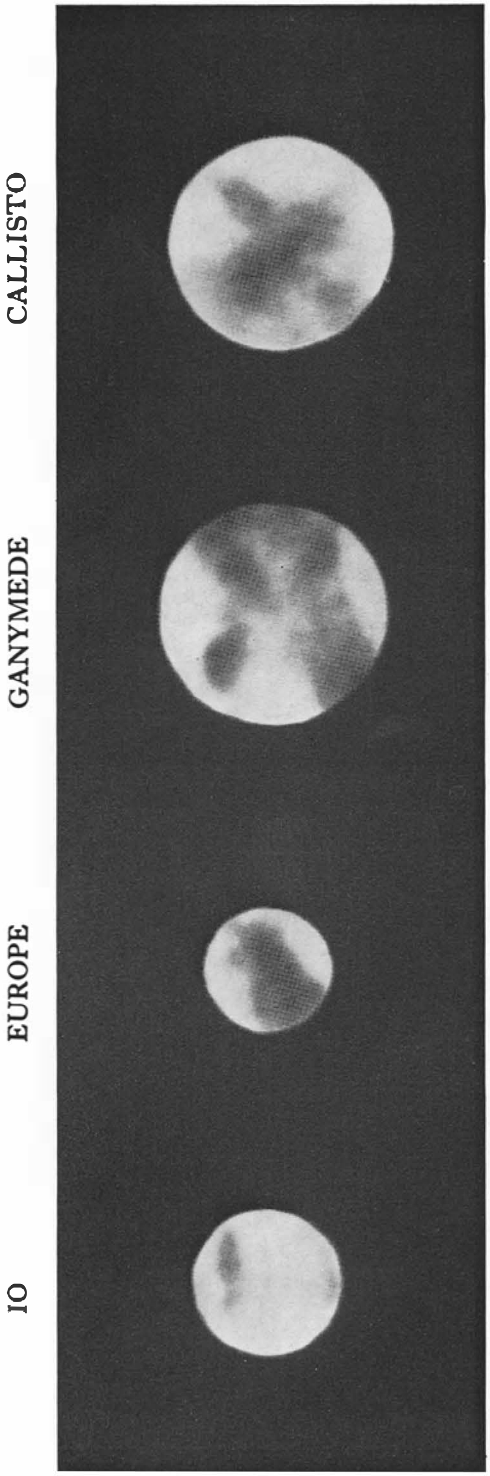

Fig. 12a

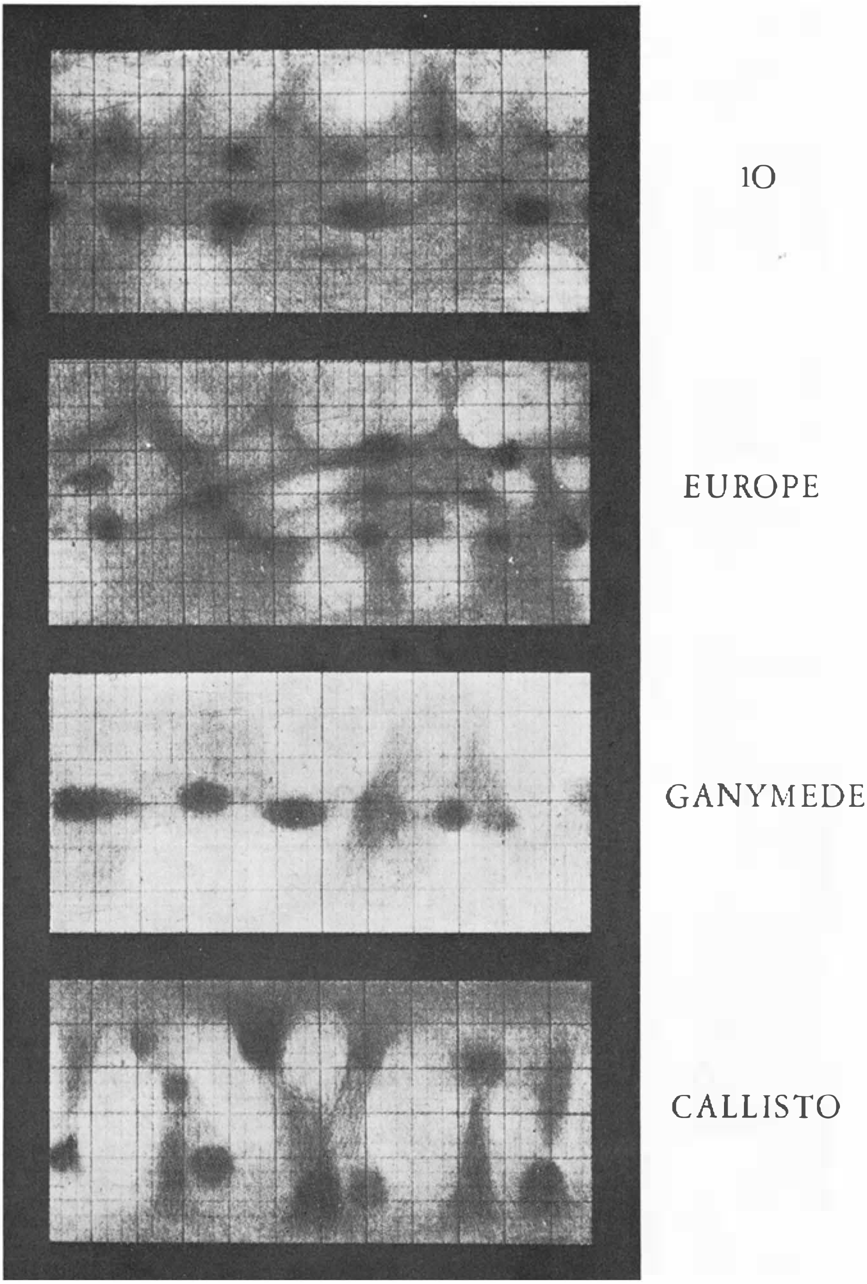

Fig. 12a–b. Drawings of the 4 Galilean satellites of Jupiter, Io, Europa, Ganymede and Callisto, executed by A. Dollfus at Pic du Midi Observatory. Shown are both representative disc images and Dollfus' efforts at presenting maps in mercator projection. After de Callatay and Dollfus, *op. cit.*

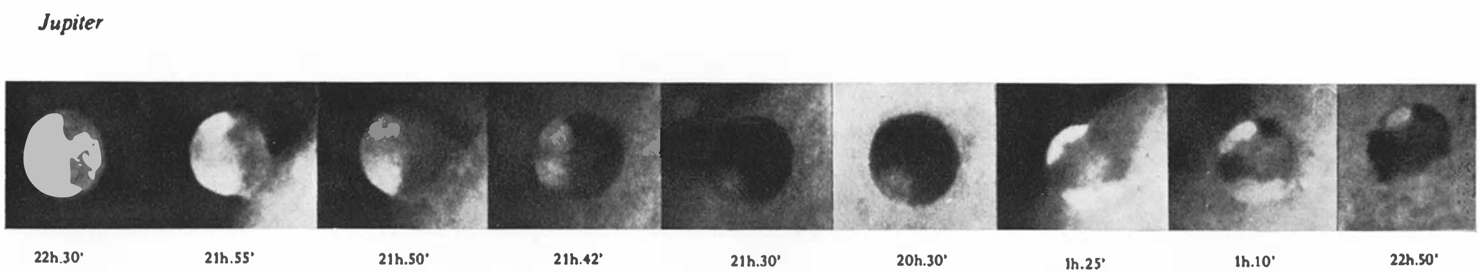

Fig. 13. Passage of Ganymede in front of Jupiter as observed at Pic du Midi on 13 and 14 September 1962 by Dollfus.

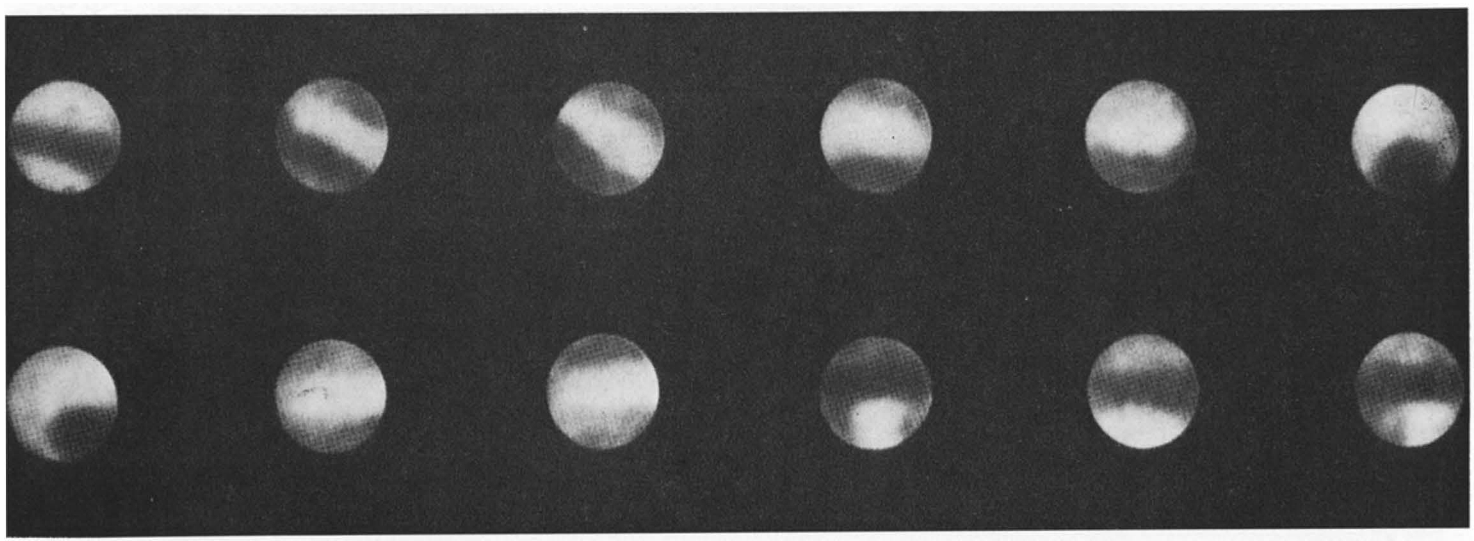

Fig. 14. Various representations of the Saturnian satellite Titan drawn between 1948 and 1950 at Pic du Midi Observatory by Dollfus. The apparent variability of bright and dark markings suggests to Dollfus the presence of clouds.

the extent of dark markings varies from satellite to satellite and therefore the ratio of bare ground to frost probably varies as well. The dark markings are non-uniformily distributed in longitude for these satellites and the rotational phase curves for these satellites show a marked harmonic variation (Harris, 1961). The visual reflectivity of Iapetus varies with rotational phase angle by more than a factor 6, while its color varies only slowly with rotation (Harris, 1961); why the albedo of Iapetus should be distributed so non-uniformily in longitude is a very intriguing question.

While proved only conclusively for Titan, it seems possible that the Galilean satellites, Titan, Triton, and Pluto all have atmospheres of methane and other gases. The continued application of energy sources to these atmospheres should produce simple hydrocarbons, polycyclic aromatics, and other organic chemicals of exobiological interest. In addition, Io, residing within the Jovian van Allen belts, should receive a very major flux of charged particles which probably is the dominant energy source for organic molecular synthesis on that satellite. For this reason Io is of particular exobiological interest. It is conceivable that the mechanism by which Io precipitates Jovian decametric bursts – now very poorly understood – is relevant to this problem. Were Io to have no atmosphere of any significance, charged particles from the Jovian van Allen belt might directly reach the surface and generate trapped free radicals there. A related point is that Mimas and Enceladus move approximately in the plane of the Saturnian rings, and within the D ring. The orbit of Mimas also intersects the ring plane, but at an angle of 1.5°. Thus the three innermost satellites of Saturn should experience considerable accretion of D ring particles. The velocity of infall, particularly for Janus and Enceladus, will be small, but it should be large enough to vaporize the condensates in the D ring and contribute to a transient atmosphere on these satellites. Since there is rapidly increasing evidence for at least some volcanism on the Moon, it would be surprising if there were none such on the 6 major satellites and Pluto. In what can only be described as an extreme hypothesis, it has even been suggested that short period comets arise by volcanic ejection from the satellites of the major planets (Vsekhsviatsky, 1966).

While life at low temperature is customarily dismissed with reference to the low rate of biochemical reactions at such temperatures, it is usually forgotten that these low reaction rates are in organisms and biochemical systems which are, through long evolutionary process, optimized for 300 K. It is by no means out of the question that there is a quite complex organic chemistry which proceeds at respectable rates at the temperatures of the satellites of the Jovian planets (Sagan, 1970; Pimentel *et al.*, 1966). With a possibility of atmospheres, volcanic activity, and organic chemical reaction schemes which proceed at reasonable rates, there appear to be some interesting exobiological opportunities on Io, Europa, Ganymede, Callisto, Titan, Triton, and Pluto.

3. The Asteroids

The asteroids are the presumed parent bodies of most of the meteorites recovered on Earth. Since the preliminary examination of Apollo returned lunar samples shows material quite different from that of the carbonaceous chondrites, it is also plausible that carbonaceous chondrites are of asteroidal origin, perhaps arising from the Apollo objects, now thought to be dead comets. These meteorites are discussed more fully elsewhere. I wish here only to mention a very few points of possible exobiological relevance to the asteroids.

Since the surface of these bodies are almost certainly airless and waterless and have been so for long periods of time, the chance of them being of biological interest appears at first to be exceedingly remote. However, it is very interesting that, because of the carbonaceous chondrites, something like 10^{-4} by mass of all the meteorites that fall on the Earth are composed of quite complex organic compounds – clearly suggesting the presence of organic matter in the asteroids. Moreover, the mineralogy of the carbonaceous chondrites seems to require the action of liquid water on the parent body; the mineralogy implies that this exposure to liquid water occurred at temperatures of about 300K, a pH of 6 to 10, and for times of at least a thousand years (DuFresne and Anders, 1963). The exposure to liquid water almost certainly occurred subsurface, in a region heated by extinct radioactivity or some other internal energy source. It seems quite unlikely that sunlight would reach this region, but it is not entirely out of the question that the origin of life could have occurred in such an environment, either hetrotrophs living off the abiological chemicals to be found there (Sagan, 1961b), or chemoautotrophs living off the free energy conversion of mineral assemblages (Anders, 1963). These possibilities are, needless to say, highly speculative.

4. Comets

There is a diversity of views on the origin of comets, ranging from accretions from the interstellar medium by solar gravitational focusing (Lyttleton, 1953) to the more generally accepted view that the bulk of the comets reside at a distance greater than 20000 astronomical units from the Sun, are driven to the inner solar system by stellar perturbations, and probably represent remnants from the early history of the solar system (Oort, 1963). Of principal interest for the present discussion are the spectra of comets. Among molecules found in emission in the heads of comets are CN, C_2, C_3, NH, OH, NH_2, CH, O, and various metals; in addition such ionized species as CO^+, N_2^+, CO_2^+, CH^+, and perhaps OH^+ are characteristically found in comet tails, but also appear in the heads (see, e.g., Wurm, 1963). Some of these emission features have long been taken as evidence for methane, ammonia and water ices in comets; and indeed one of the most successful models of the structure of the cometary nucleus invokes an ‘icy conglomerate’ as the primary constituent (Whipple, 1963). However, the presence of such molecular fragments as C_2 and C_3 clearly indicates the presence of more complex molecules – by definition, organic molecules. Comets are being irradiated not only by solar ultraviolet and X-rays, but also by solar protons; in fact the first evidence for the existence of the solar wind was obtained from the fact that the radiation pressure of sunlight was inadequate to explain the observed accelerations of knots in comet tails (Biermann and Lust, 1963). While a very few experiments have been carried out in the UV or proton irradiation of a mixture of methane, ammonia and water ices, it seems quite likely that a variety of organic compounds would be produced under these conditions. In addition the comets may contain organic compounds of interstellar or perhaps primordial solar system origin, depending on the origin of the comets. To explain the sublimation rates *in vacuo* of ammonia, methane and water, it has been proposed that clathrate hydrates such as $CH_4 \cdot 6H_2O$, rather than the pure ices, are present (Delsemne and Swings, 1952). Cometary bursts, sporadic increases in brightness, are often observed to occur within periods of hours and at distances of many astronomical units. The energy for these bursts has been attributed to free radicals, or to organic molecules of high free energy such as acetylene [Donn and Urey, quoted in Whipple (1963)]. Both free radicals and such organic molecules can be expected in comets. The ultraviolet and proton irradiation of cometary ices at low temperatures seems to be a promising area of laboratory investigation.

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