THE PLANET JUPITER

by

S. I. Rasool*

Institut d'Astrophysique, Paris
Observatoire de Nice, Nice

* On leave from NASA, Goddard Institute for Space Studies, New York, New York

These last few years have witnessed space probes systematically unravelling the mysteries of Mars and Venus with methodic precision. Close range television pictures of the surface of Mars, and radio wave exploration of its atmosphere by Mariner IV have given us an entirely new concept of the Martian evironments--a crater-ridden surface overladen with only a trace of an atmosphere almost entirely composed of carbon dioxide. On the other hand, Venus which had so far guarded its mysteries by a thick veil of white clouds has recently been the object of in situ exploration by Venera IV and a close look by Mariner V. The results are most astounding. It was not only confirmed that the surface of Venus is actually very hot ($\sim 600^{o}K$), but it appears that the atmosphere is 20 to 100 times more massive than that of the earth, essentially composed of carbon dioxide and almost completely devoid of water vapor.

These findings on Mars and Venus mark the beginning of the accumulation of basic data for the understanding of the history of the terrestrial planets. But to resolve the age-old problem of the origin and evolution of the solar system as a whole, it is exploration of Jupiter which will eventually provide information of prime significance. This is so, not only because Jupiter is the largest planet, several times more massive than the other eight planets combined, but because it presents such puzzling aspects of far reaching importance that their eventual solution will have direct bearing on our understanding of the primitive environments from which the planets were formed and the life on earth originated.

For example, it has recently been found that Jupiter may have a source of heat in the interior, almost four times more intense than the sun is at that distance. What is the source of this energy? Is it that Jupiter is still contracting towards its final size and thereby releasing gravitational energy? If so, what about the other giant planets? Are they all, 4.5 billion years after their birth, still in the process of accumulation and do not yet have a solid surface? Why then are the terrestrial planets formed so quickly?

Another puzzle on Jupiter seems to be that despite the fact that it is extremely massive, 318 times heavier than the earth and, therefore, possesses a strong gravitational field, it appears that its atmosphere is deficient in hydrogen, with respect to helium, by a large factor. Is it that the primitive material out of which Jupiter was formed was itself deficient in hydrogen, or that most of the hydrogen was later "blown" away? It may also be that the bulk of the hydrogen is locked up in the interior of the planet and, therefore, not visible.

Third, and perhaps the most interesting aspect of Jupiter is that its present atmosphere seems to be composed of the same gases, hydrogen, methane and ammonia, out of which the first living organisms are believed to have been synthesized on the earth about four billion years ago. Is it possible that similar initial steps along the path of life are occurring now on Jupiter? Such questions make Jupiter the "Rosetta stone" of the solar system and the most potential candidate for future planetary exploration.

Excess Thermal Energy

Situated at 5.2 A.U. from the sun, Jupiter receives 27 times less solar energy than the earth; only 12,500 ergs $/cm^2/sec$ distributed over the planetary globe. In addition, the albedo of Jupiter is 0.45 and, therefore, only 55% of this energy or 7,000 ergs $/cm^2/sec$ actually enters the planet, which should eventually be returned back to the space in the form of thermal radiation. The recent measurements of this energy, however, suggest that the flux emitted by Jupiter is of the order of 30,000 ergs $/cm^2/sec$, about four times higher than the expected value. How accurate are these measurements and what could be the source of this excess energy?

If it is assumed that Jupiter behaves as a blackbody then the effective radiating temperature for the amount of solar energy reaching the planet will be $105^{\circ}K$. At this low temperature the radiation will be mainly at wavelengths between 10 and 100μ with a maximum at 30μ. Measurement of this radiation is difficult to make from the ground because of the absorbing properties of the earth's atmosphere. The earth's atmosphere contains molecules of CO_2 and H_2O which absorb the far infrared with great efficiency. There are, however, "windows" where the atmospheric absorption is small, which allows ground based astronomers to measure energy from different celestial sources. The window between 8 and 12μ has been extensively used to measure temperatures of the planets. The first attempts to measure the thermal radiation from Jupiter were made as early as in the 1920's, which indicated that the emission temperature of the planetary disc at these wavelengths is $130 \pm 10^{\circ}K$. More recently, Murray and Wildey of CalTech, using the 200" Mt. Palomar telescope and highly sensitive detectors, not only confirmed the earlier value, but, in addition, measured the disbribution of the 8 - 12μ brightness temperature over the Jovian disc (Fig. 1). What does this measurement mean and where in the atmosphere of the planet does the 130°K temperature exist?

To answer this question one has to consider the absorbing properties of the Jovian atmosphere. It is known that the atmosphere of Jupiter, above the visible clouds, contains substantial quantities of methane and ammonia. Though the concentration of these gases relative to the total amount of the atmosphere is quite small (< 1%), their absolute amounts by terrestrial standards is quite large. These gases have strong absorption bands in the far infrared and, therefore, the emission spectrum of Jupiter should be considerably modified from a simple Planck Curve of 105°K. For example, ammonia has a strong vibration-rotation band centered at 10.5μ which for large amounts and higher pressures may extend from 8 to 15μ. Radiation at these wavelengths emitted from the cloud level of Jupiter will, therefore, be immediately absorbed by the atmosphere above. The radiation in 8 - 12μ region which will eventually emanate from the planet will not be that which originated at the cloud level but from higher above, where the concentration of ammonia has decreased so much that no more absorption is possible. From this principle of radiative transfer, one can calculate a temperature profile of the atmosphere provided the temperature at the base is known. Both Kuiper and Öpik have argued that if the clouds are made of ammonia crystals the temperature at the cloud tops of Jupiter must be in the neighborhood of 150°K. (Also, the radio-wave temperature measurement at 8 mm. suggest the same value). Fig. 1 shows temperature distribution for a model jovian atmosphere with cloud-top pressure of 3 bars and $T = 150^{\circ}K$. The bulk of the atmosphere is composed of hydrogen and helium (60% and 40% respectively by volume, as discussed in the next section) but contains 0.1% CH_4 and 0.005% NH_3 which is the main absorbing gas. As the density of CH_4 and NH_3 decreases with altitude the optical thickness of the atmosphere decreases as well and eventually becomes zero at $\sim$ 50 km resulting in an isothermal temperature profile.

If Jupiter is observed in the wavelengths where the absorption by NH_3 and CH_4 is strong, the energy received will be emanating from the altitudes of 20 to 50 km above the clouds ($T = 130 - 120^{\circ}K$), while in the "windows" one could detect the emission originating near the cloudtops and, therefore, would measure temperatures of the order of $140 - 150^{\circ}K$. This is demonstrated in(Fig. 3) which has been drawn combining the temperature profile of Fig. 2 with the known absorption properties of methane and ammonia.

It is important to note that because of the presence of ammonia and relatively low temperatures of the Jovian atmosphere, the bulk of the emission takes place at $\lambda > 20\mu$. Radiation of these wavelengths is practically undetectable from the earth's surface because of extremely strong absorption by the terrestrial water vapor in this region of the the spectrum. F. Low of the University of Texas has, however, recently succeeded in measuring the emission temperature of Jupiter at $\lambda = 18 - 22\mu$ where the water vapor absorption is weak. The measured temperature was actually found to be surprisingly high, $T = 140^{\circ}K$. The emission curve of Jupiter seems to follow the trend shown in (Fig. 3). Urgently needed, of course, are the measurements at $\lambda > 25\mu$ to confirm this highly significant finding. Such observations can only be made by carrying instruments to high altitudes by means of aircraft, balloons, rockets and earth orbiting satellites. Attempts in this direction are already being made in France and in the U.S. The next few years will provide the answer to this important question.

Fragmentary though the evidence so far is, both the thermal measurements and theoretical arguments seem to suggest quite strongly that Jupiter may be radiating at an effective temperature of $140^{\circ}K$, rather than $105^{\circ}K$. This is a factor of 3 to 4 in energy, and would, therefore, imply a strong source of heat in the interior. One immediately asks himself, is it possible that there could be a dimly glowing nuclear fire at the center of this giant planet? To answer this question it is necessary to make an estimate of the temperature at the center of the planet. Such studies have been considerably hampered by the fact that no reliable information is so far available on the manner in which the density and pressure are related in a medium of hydrogen and helium which has been compressed to pressures of the order of 10^6 to 10^8 bars. Nonetheless, several authors, notably de Marcus and Peebles have extrapolated the available laboratory data and attempted detailed investigation of the interior of Jupiter. The most optimistic estimate of central temperature is $500,000^{\circ}C$. This is much smaller than 20 million degrees which is the threshold temperature for the commencement of nuclear reactions. In fact, Jupiter falls short by at least a factor of 30 in mass to become a sun-like star!

In a giant planet like Jupiter, there could be another source of heat in the interior which is produced by the gravitational contraction. If Jupiter is still contracting under the pressure of its own weight and has not yet reached its final size then the modest rate of contraction of only 1 mm per year will release almost as much as 20,000 ergs $/cm^2/sec$, thereby accounting for the excess of energy which has been observed to be emanating from Jupiter. How this energy is transported from the interior to the surface is a problem of great complexity. A combination of change in phase, convection, radiation and conduction has been suggested. A proper evaluation of the problem awaits a better knowledge of the equation of state of hydrogen and helium at high pressures and temperatures.

<u>Deficiency of Hydrogen in the Atmosphere</u>

Jupiter and the other giant planets differ markedly from the terrestrial planets in regards to their composition, both in the interior and in the atmosphere. Though they are much larger and hundreds of times more massive than the earth they have surprisingly low density. In general, the density is about that of water. For Jupiter it is $1.33\ g/cm^3$ and for Saturn only $0.71 g/cm^3$. This should be compared with the density of the earth which is $5.5g/cm^3$. The low density of the giant planets is puzzling because the pressure of their great mass should compact them to a higher density than that of the earth. The explanation of this apparent paradox is connected with the composition of the giant planets; in contrast to the terrestrial planets which are made up of Fe, Ni and silicates, the major planet seems to be composed mainly of hydrogen and helium, the lightest of all the elements. In fact, the density of Jupiter is almost exactly the same as that of the sun, indicating that the ratio of hydrogen and helium to other heavier elements may be about the same on Jupiter as on the sun. This is what one would expect if Jupiter condensed out of a contracting solar nebula which had the same composition as the sun has today. Jupiter, being so massive did not lose any of the gases during its long history, and should, therefore, reflect the composition of the material out of which it was formed.

Based on the table of cosmic abundances of elements compiled by Aller, Suess, Urey and others, Cameron has recently tabulated the elemental composition of the primitive solar nebula. Hydrogen and helium make up 99.5% of the material, of which molecular hydrogen is 86% and helium 13.5% by volume. The remaining 0.5% is made up of heavier atoms like C, N, O, Ne, Si, Fe, etc. Greenspan and Owen have recently made thermodynamic calculations to determine what molecules would be formed out of these elements at temperatures existing in the middle atmosphere of Jupiter. They found that carbon, nitrogen and oxygen could combine readily with the excesses of hydrogen available and should form methane, ammonia and water with a percentage composition of 9×10^{-2}, 2×10^{-2} and 14×10^{-2} respectively.

Spectroscopic observations of Jupiter have already discovered the presence of methane, ammonia and hydrogen above the clouds of Jupiter and it is believed that substantial amounts of water are present below. Methane and ammonia are easy to detect because of their strong absorption bands in the near infrared and careful analysis of the band structure can also give the concentration of these gases in the atmosphere. As early as 25 years ago, Kuiper successfully measured the amounts of methane and ammonia on Jupiter and their concentration appears to be roughly the same as mentioned above.

Hydrogen and helium, however, pose special problems. Neither of them produce absorption bands in the far infrared, as do methane and ammonia. Helium being a rare gas is completely inert and under ordinary conditions cannot be detected by spectroscopic techniques employed in optical astronomy. It does, however, produce emission lines in the ultra-violet which can only be observed from the earth if the measurements are made from above the atmosphere. Hydrogen, however, under special conditions produces absorption lines in the visible part of the spectrum. Molecular hydrogen has a quadrupole moment and could produce a vibration-rotation spectrum which could be detected from the earth if sufficiently large amounts were present on Jupiter. Kiess, Corliss and Kiess were first to detect four such lines of hydrogen at around 8,200 A. A comparison of their strengths with the theoretical values of their intensities can give an estimate of the amount of hydrogen on Jupiter above the reflecting level of 8,200 A photons. Because of several inherent problems in this technique of measurement the estimate of hydrogen on Jupiter cannot be made with greater precision than more than a factor of three. A critical review of this problem has led George Field of the University of California in Berkeley to conclude that the partial pressure of hydrogen at the reference level on Jupiter may lie between 0.36 and 1 bar, with the lower value quite probable. An independent measurement of the total pressure at the cloudtop was made by Spinrad who deduced a value of about 3 bars. Öpik had earlier suggested 8 bars. The indication seems to be that the total pressure at the cloudtop is several times higher than the partial pressure of hydrogen. What then is the other gas which makes up the rest of the atmosphere? Helium, most probably. If this is so, then it would appear that the Jovian atmosphere is deficient in hydrogen by a factor of at least two to three relative to helium.

How could hydrogen have disappeared from a giant planet like Jupiter? Because of Jupiter's large mass the escape velocity from the planet $\left(\sqrt{\frac{2MG}{R}}\right)$ is 61 km/sec. This should be compared with 11.3 km/sec for the earth and 2.4 km/sec for the moon. Hydrogen, the lightest of all elements and which should be the easiest to escape, should be heated to a temperature of $\sim 100{,}000^{\circ}K$ in the upper atmosphere of Jupiter, in order to acquire thermal velocities in excess of the escape velocity. This seems highly unlikely, especially because Jupiter is so far away from the sun. As a matter of fact, recent calculations of the upper atmospheric temperature of Jupiter, give a value of only $130^{\circ}K$. How then did hydrogen escape from Jupiter?

Several suggestions have been made to explain this apparent deficiency of hydrogen. According to Öpik the temperature in the primitive solar nebula, at the distance of Jupiter, was so low, about $4^{\circ}K$, that all hydrogen solidified and today makes up the bulk of the solid planet. The other alternative is that in the very first million years in the history of the solar system when the sun was much more luminous and the solar wind was about 10^7 times more intense, most of the hydrogen of the solar nebula was blown away to the outer regions of the solar system. Which of these hypotheses is closest to reality is a question which can only be discussed when the composition of the Jovian atmosphere and of the other giant planets is determined with a greater precision. The exact amount of hydrogen, deuterium, helium, neon, in the outer planets are the basic data which are necessary, not only for the understanding of evolution of the Jovian atmosphere, but for the early history of the solar system.

None of these measurements can be carried out with great accuracy from the surface of the earth. Orbiting earth satellites looking at Jupiter, deep space probes,fly-bys and landers will eventually resolve this problem.

Radio Source

There are several other aspects of Jupiter which have been discovered during the last decade and have never ceased perplexing the scientific mind. In 1954, Burke and Franklin discovered that Jupiter emits bursts of radio waves at frequencies of about 20 mc/s (λ = 15 meters). Repeated measurements since have not only confirmed but unravelled many mysterious properties of these bursts. The one puzzling aspect is that they are not continuous, but sporadic, and occur in short series of milliseconds to tens of seconds in the form of an intense storm which may last for a few minutes to several hours. The energy contained in these bursts could be as high as 10^{21}ergs, equivalent to that of megaton hydrogen bombs exploding at the rate of one per second. In fact, Jupiter is the most intense radio source in the sky after the sun. Another remarkable property of these emissions is that they seem to be modulated by the position of one of its 12 satellites, Io. The intensity of these bursts appears to be five times higher when Io is about 90^{o} away from superior conjunction.

In addition to these mysterious sporadic bursts there is, also, a sustained and steady emission of radio waves from Jupiter at wavelengths between 3 and 100 cm. The energy at these wavelengths is also high and corresponds to thermal emission at several tens of thousands of degrees.

The currently preferred explanation of these two types of radio emissions from Jupiter goes back to one of the first important scientific results of the space programs, the discovery of Van Allen belts around the earth. Immediately after this discovery, it was hypothesized, as an explanation of the radio emission from Jupiter, that intense Van Allen belts also exist around that planet. The circling motion of the electrons in these belts would result in the emission of waves in the decimeter region of the spectrum; the occasional dumping of particles out of the belts into the ionosphere would account for the sporadic bursts of radiation at the longer decameter wavelengths. If this hypothesis is correct, a study of the properties of the radio emission should enable one to deduce the strength of the magnetic field on Jupiter as well as the density of the trapped particles in the Jovian magnetosphere. Such analysis indicates that Jupiter's magnetic field may have strength of between 10 to 50 gauss at the surface of the planet, 20 - 100 times stronger than the magnetic field of the earth.

In this picture of the magnetic environment of Jupiter, how can one fit the recently observed effect of the satellite Io? One interesting fact is that the orbit of this first Galilean satellite is such (R = 6 Jovian radii) that it travels around the planet within the magnetosphere of Jupiter. But why should Io effect the decametric radiation and especially at particular positions is an intricate problem of interaction of fast moving plasma with a body of unknown conductivity. This problem, therefore, is the object of extreme controversy in the current literature.

What space experiments can help clarify the situation? In situ measurements of the density of trapped particles in the Jovian Van Allen belts, a measure of magnetic field strengths in the vicinity of the planet and a search for Jovian auroras which the dumping of the charged particles in the atmosphere may produce, could be mentioned as high priority experiments to understand the radio physics of Jupiter.

Color and Life

The orange and blue coloration of the cloud bands of Jupiter and the presence of a giant red spot has long fascinated the optical astronomers. A recent new interpretation of these features has made the problem all the more exciting. It has been proposed that the visible colorful "surface" of Jupiter is the seat of intense pre-biological activity, where the first living organisms are being synthesized.

Three arguments have been advanced in favor of this hypothesis. First, the atmosphere of Jupiter is composed precisely of these gases, hydrogen, methane, ammonia and water vapor which have supposedly played a critical role in the events which have led to the development of life on the earth.

Second, Cyril Ponnamperuma has demonstrated that when a simulated Jovian atmosphere, at temperatures as low as $150^{O}K$, is exposed to ultraviolet radiation, it not only produces the complex organic molecules like amino-acids and nucleotides but the color of the resulting products is very similar to the yellowish-orange red of the Jovian clouds and of the famous "red spot."

Third, an ultraviolet spectrum of Jupiter first taken by T.P. Stecher from a rocket had indicated a significant absorption centered at $\lambda = 2600$ A. This has been recently confirmed by D.C. Evans of Goddard Space Flight Center. None of the known major atmospheric constituents of Jupiter can account for this feature. However, C. Sagan of Harvard University has pointed out that the absorption features observed on Jupiter match closely with those of Adenine, which is a basic constituent of both RNA and DNA and, therefore, one of the most important chemicals in biological systems. In fact, laboratory experiments of Cyril Ponnamperuma have convincingly shown that in electron irradiation of methane, ammonia and water, the largest single non-volatile compound formed is Adenine. In addition, the production of Adenine is enhanced when hydrogen is deficient, as it seems to be the case at the cloudtops of Jupiter!

How can one test this extremely interesting hypothesis? First and foremost in this respect, is of course the ultraviolet spectroscopy of Jupiter from rockets and earth orbiting satellites.

High resolution spectra of Jupiter in the 1800 to 3000 A interval when matched with laboratory spectra of organic molecules, as suggested by C. Sagan, should provide highly significant information on this problem. Subsequent experimentations in the infrared and a search for HCN by close-range fly-by missions should further clarify the question. The actual resolution of the problem will probably have to await _in situ_ exploration of the Jovian atmosphere or return of the samples to the earth. It is difficult to predict the time-table involved for such experimentations. Because of the long travel to Jupiter and the crushing force of gravity of the planet, the _in situ_ exploration and return of samples is perhaps another 20 years away. But numerous experiments of great value can certainly be performed from high altitude aircraft, balloons, rockets and earth-orbiting satellites starting as early as next year!

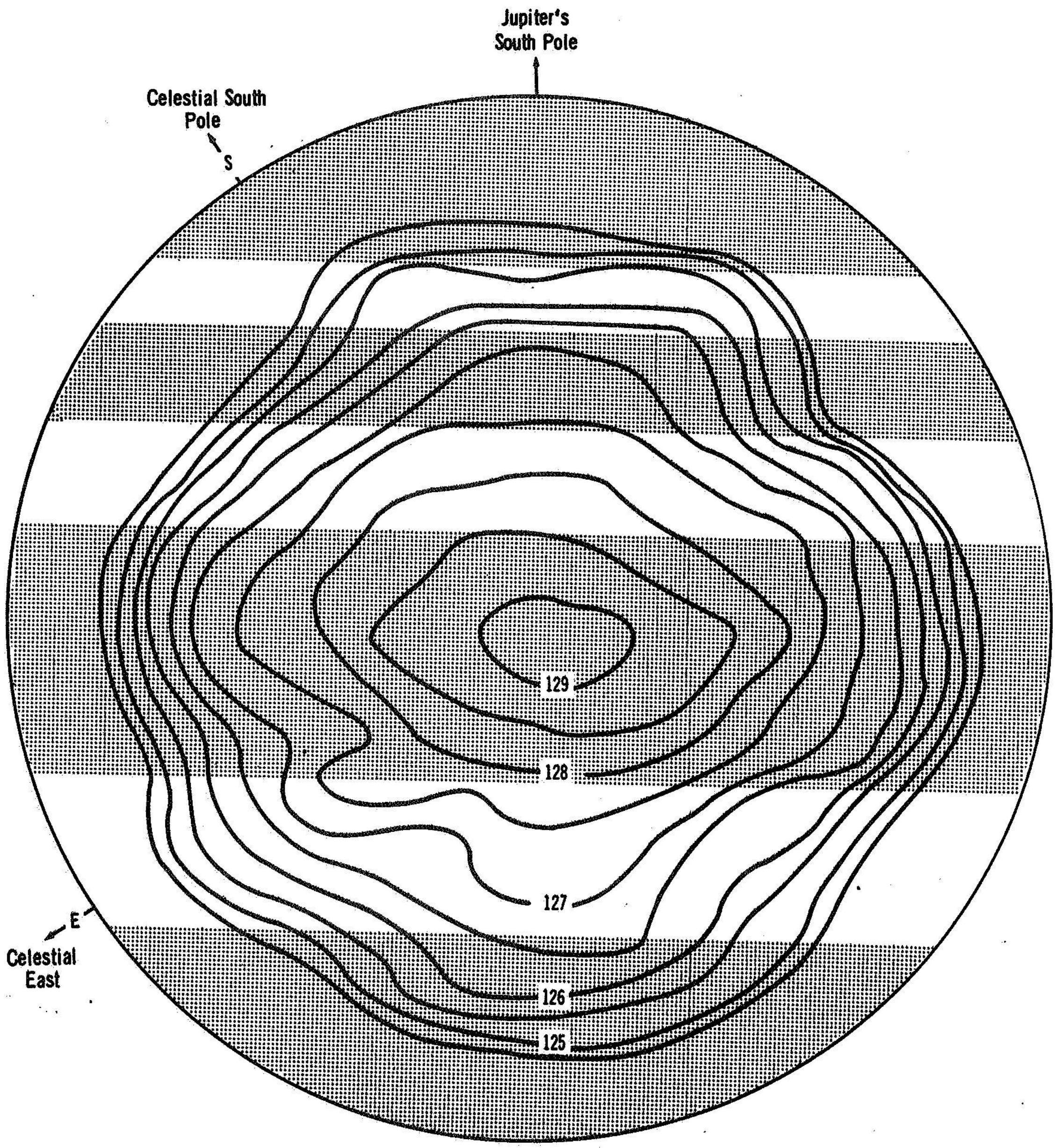
FIGURE CAPTIONS

Fig. 1. Distribution of 8 - 12μ brightness temperatures over the Jovian disc as measured by B.C. Murray and R.L. Wildey in 1968.

Fig. 2. A model temperature distribution in the atmosphere of Jupiter above the clouds. Assumptions: radiative equilibrium; cloudtop temperature 150^{o}K; optical thickness of ammonia (τ) = 0.9.

Fig. 3. Energy distribution as a function of wavelength for the thermal emission from Jupiter calculated from Fig. 2 and the absorption band intensities of NH_3. Superposed are several Planck Curves for temperatures ranging from 100^{o}K to 150^{o}K.

Fig. 4. A recent photograph of Jupiter taken by Dr. Roger Lynds of the Kitt Peak National Observatory. The colorful cloud bands and the giant red spot are the most conspicuous features of the planet, (from Jastrow & Rasool, Science Journal, 1967).



Jupiter's
South Pole
Celestial South
Pole
S
E
Celestial
East
129
128
127
126
125

Figure 1.

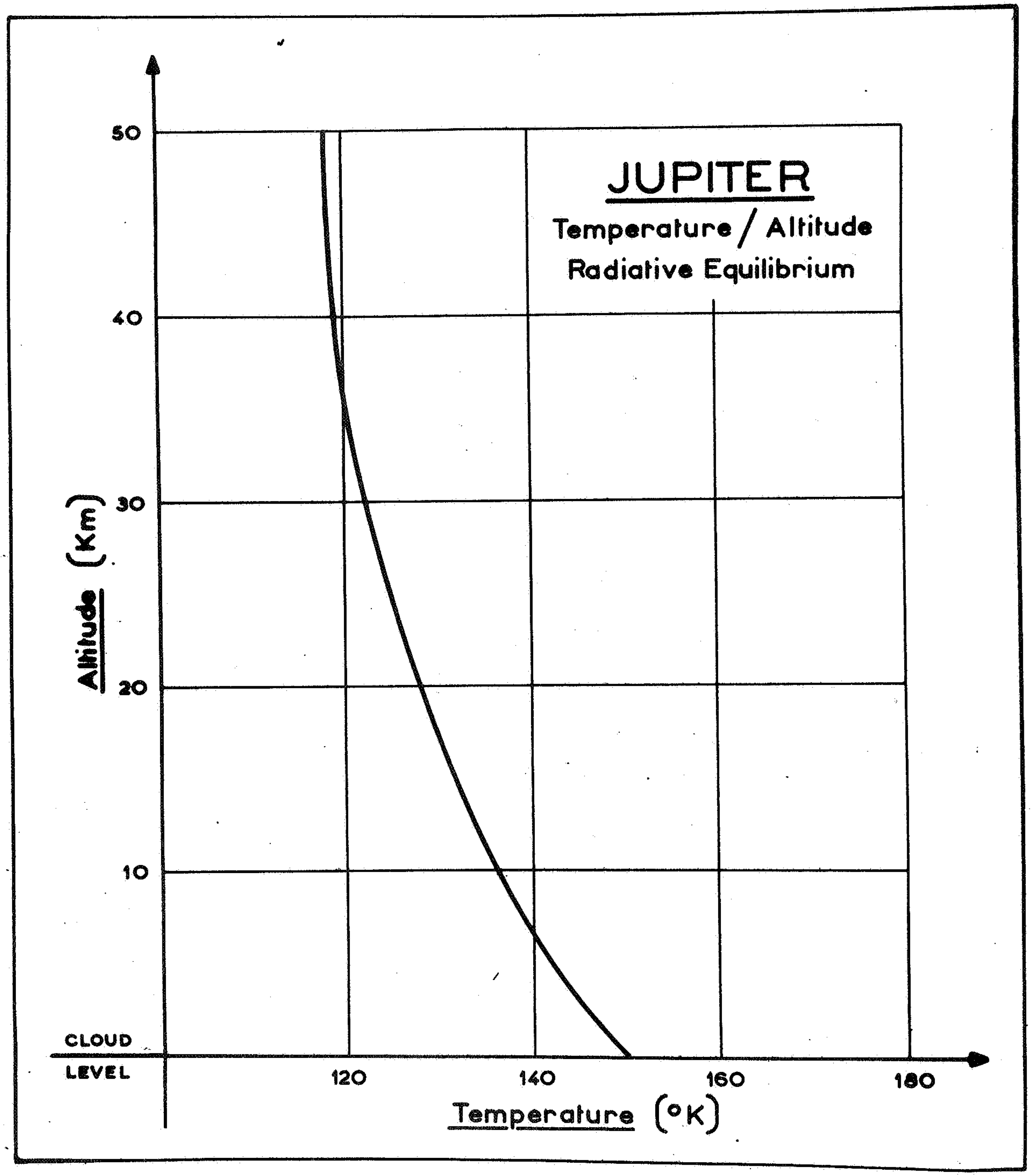

JUPITER
Temperature / Altitude
Radiative Equilibrium
50
40
30
20
10
Altitude (Km)
CLOUD
LEVEL
120
140
160
180
Temperature (°K)

Figure 2.

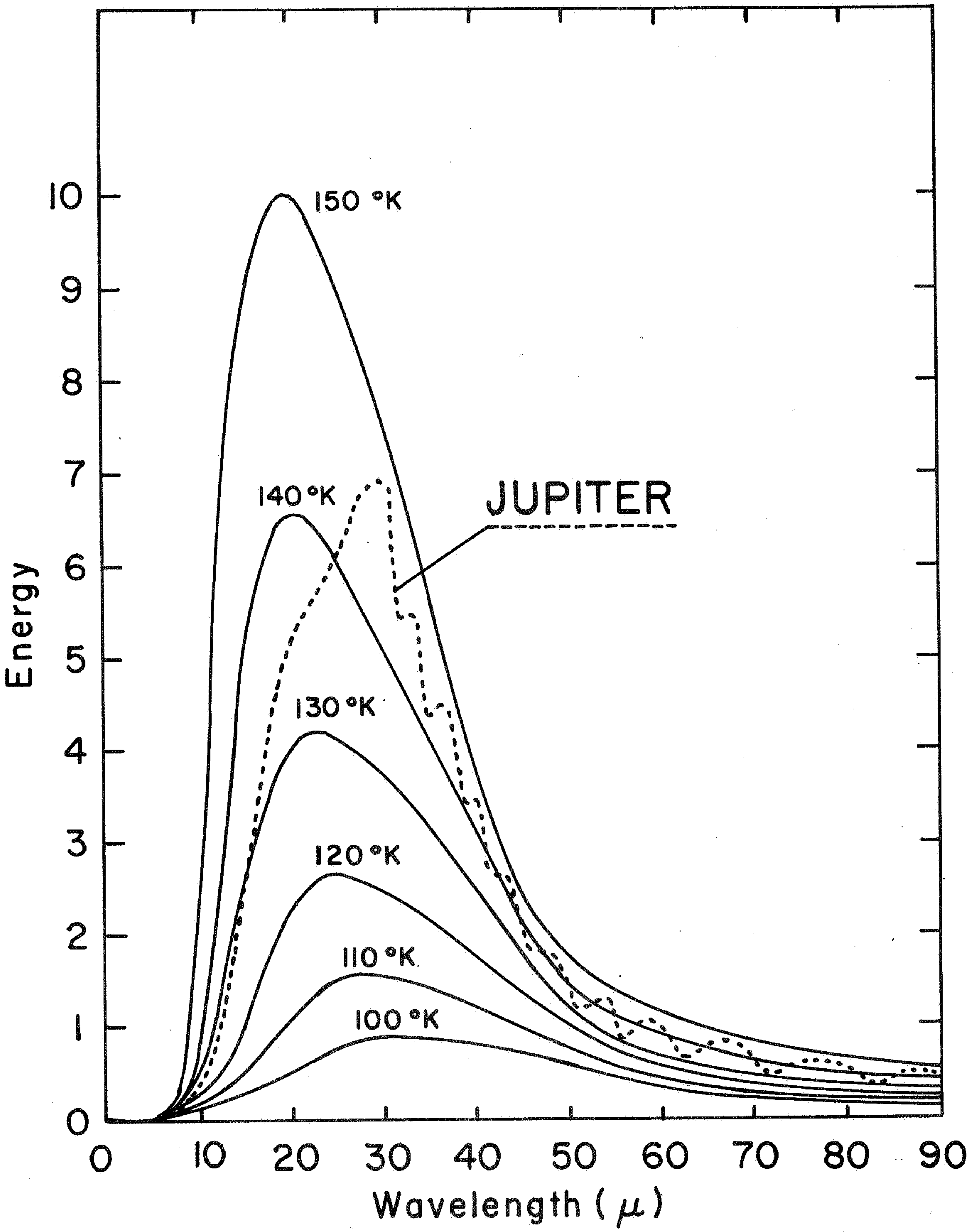


Figure 3.

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Figure 4.