In summarizing what is known and speculated about Jupiter, the largest of our planetary neighbors, the following article also serves as an indication of how much still remains to be known. The authors are astronomers Rupert Wildt and Harlan J. Smith of Yale and physicists Edwin E. Salpeter of Cornell and Alastair G. W. Cameron of the Institute for Space Studies.

THE PLANET JUPITER

By ***R. Wildt, H. J. Smith, E. E. Salpeter,*** *and* ***A. G. W. Cameron***

APPROXIMATELY forty astronomers and physicists met on October 16 and 17, 1962, at the Institute for Space Studies in New York City, to discuss the properties of the planet Jupiter. The Institute is part of the Goddard Space Flight Center, National Aeronautics and Space Administration. The meeting was organized by R. Wildt and H. J. Smith of the Yale University Astronomy Department, and members of the Institute, directed by Robert Jastrow, acted as hosts.

Jupiter is the largest planet of the solar system, its mass being almost the geometrical mean of the masses of the earth and the sun. Its composition is much like that of the sun, in that the bulk of its mass appears to be hydrogen and helium. Indeed, if Jupiter had precisely the solar composition, then its content of "rocky" materials such as those that constitute the majority of the earth would be comparable in mass to the earth itself. This comparability in itself poses a major problem for cosmogonists who attempt to unravel the early history of the solar system, for why should Jupiter have retained the volatile gases while the earth did not?

The major differences in composition of Jupiter and the earth are not only of great interest in themselves, but they should cast new light on those properties that the planets have in common, such as the strong dipole magnetic fields and their associated radiation belts. Studies of the strong radio emission from Jupiter have recently been yielding interesting information about the Jovian magnetosphere and its associated trapped particles, and this provided much of the stimulus for holding the conference at this time.

Jupiter emits radio waves in at least three ranges of wavelengths. Short waves of wavelengths less than about 5 cm are generated thermally, corresponding to Jupiter's blackbody temperature of 130 degrees. As one goes to slightly longer waves—some tens of centimeters in length—a nonthermal component appears: the decimeter radiation (see Fig. 1). After a gap around the meter-wavelength region, the decameter part of the spectrum brings in the radio-noise storms with their markedly different characteristics, also nonthermal.

There was much discussion of the magnificent interferometric observations on decimeter radiation by D. Morris, V. Radhakrishnan, and others of the California Institute of Technology, and of the corroborating observations and interpretations of other groups. According to these studies, the decimeter radiation comes from equatorial zones primarily about 3 radii

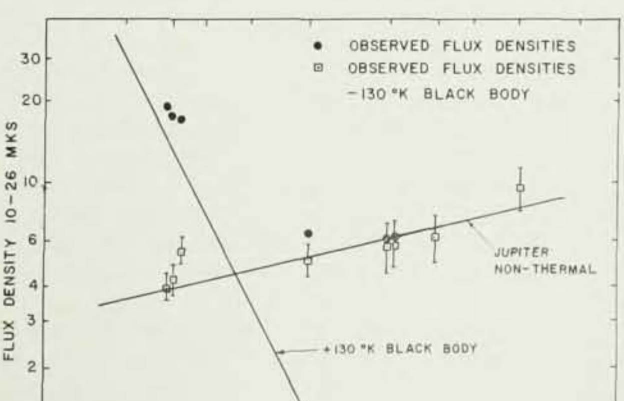

Fig. 1. The observed flux densities in the centimeter and decimeter regions of the Jovian spectrum showing the decomposition into thermal and nonthermal parts.

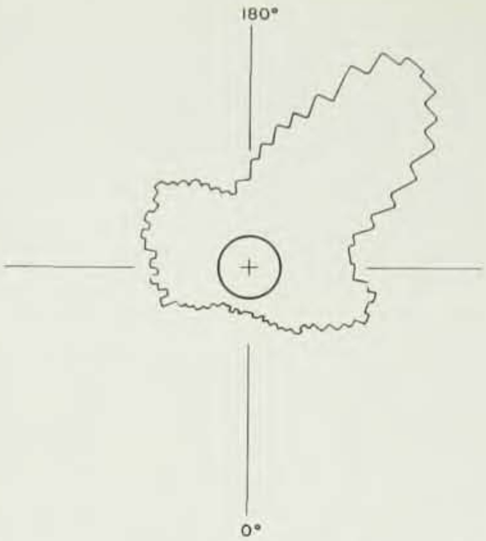

Fig. 2. The longitude dependence of the observed noise storms in the decameter range of the spectrum. This is the combined data for the twelve years 1950 through 1961 at all frequencies.

from the center of the planet. This radiation is partially linearly polarized in a plane approximately parallel to Jupiter's equator. This plane rocks with the rotation of the planet, indicating a 9 to 10 degree inclination of the magnetic axis to the rotation axis. The radiation shows very little polarized component when the feed of the receiver is set to receive polarization in a plane parallel with Jupiter's axis of rotation. When the Caltech observers attempted to measure the distribution across the sky of the source, they found very little difference between the two components.

M. S. Roberts of the Harvard Observatory interpreted many Harvard 21-cm observations, plus those of other workers, as an indication that the decimeter radiation consists of an outer strongly polarized component which has variations correlated with those of the solar activity, and an inner nonpolarized component much less correlated with solar activity. The polarized component is presumably produced in some way in the outer Jovian magnetosphere by corpuscular radiation from the sun, and the decay time is quite rapid—hours to days. This component is approximately forty percent of the radiation. The nonpolarized component presumably has a longer decay time, and the Harvard group would have preferred to interpret it as arising from the ionosphere. However, the interferometric measurements of the Caltech group show that the nonpolarized component has almost, but not quite, as large a spatial extent as the polarized component.

A better suggestion seems to be that one is observing not one but two radiation belts. The reason why the inner belt does not show obvious polarization was hinted at by theoretical work of D. B. Chang of Caltech, who showed that very flat helices are required for the particles in the radiation belts in order to permit observation of a residual polarization. For an inner belt of more energetic particles, it is possible that polarization effects would be so washed out as to be difficult to detect. There was general agreement that synchrotron radiation is the only valid mechanism capable of producing the decimeter waves, at least the polarized component.

The decameter noise-storm radiation, in contrast to the rather steady decimeter emission, shows an extremely complicated pattern of intensity variation with time. This variation ranges from fine structure, of the order of hundredths of a second, to the entire duration of the storms, which may be of several hours. Evidence was offered by J. N. Douglas of the Yale Observatory that most, if not all, of the fine structure is not intrinsic to the source, but rather arises in the ionosphere or the exosphere of the earth, or perhaps in the interplanetary medium. The fact that the decameter radiation is heard only sporadically, and with rather abrupt beginnings and endings, suggests that the mechanism is either turned on and off rather suddenly, or that it is emitted in sharply focused cones, or both. The hypothesis of sharply focused cones is strongly supported by the fact that one can establish from the decameter observations alone a very precise rotation period within which certain longitude regions on the surface of Jupiter appear to radiate actively while others appear to be essentially dead (see Fig. 2). Moreover, at least at frequencies of 20 megacycles or more, the Jovian radiation is emitted in a generally trilobed pattern with a very strong central lobe and two flat lobes which flank the major one at about 90 degrees. It may be significant that the major lobe coincides with the orientation of the magnetic axis as determined by the decimeter observations.

The mechanisms offered for the origin of the decameter radiation all suggest that it comes from Jupiter's exosphere, with the local gyro frequency as an extremely important factor. Leona Marshall of New York University presented her work with Landovitz, suggesting a spin-flip transition that is stimulated by hydromagnetic shock waves. G. Field of Princeton University proposed an "antisynchrotron" mechanism based on amplification of a weak electromagnetic disturbance moving along magnetic-field lines and encountering particles spinning at a similar local gyro frequency. He took certain important effects into account, including the relativistic mass change of the particles as they speed up, and the Doppler shifts between the particles and electromagnetic waves encountering each other. In his mechanism the electrons lose energy to the electromagnetic waves; this is the reverse of the operation of a synchrotron.

J. Warwick of the High Altitude Observatory, Boulder, Colo., supported his published model in which the radiation is emitted by the spiralling electrons at the gyro frequency in the regions where the local plasma frequency also has about the same value—a sort of Čerenkov cyclotron mechanism. However, in this model, as well as in the others, the radiation is generated by particles spiralling in along magnetic-

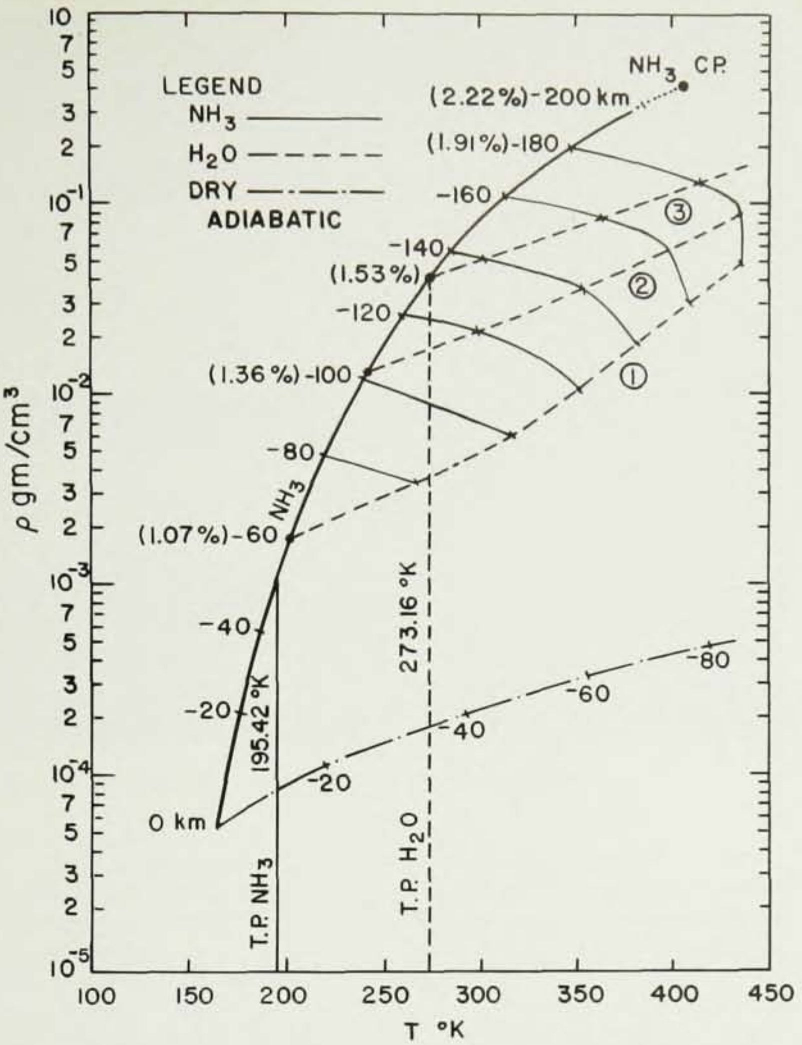

Fig. 3. Structure of the Jovian atmosphere according to calculations by R. M. Gallet. The bottom curve shows the dry adiabat; the steep curve shows the wet adiabat which will eventually follow one of the dashed lines that correspond to various assumed abundances of ammonia in the atmosphere.

force lines toward the poles. Thus all interpretations, including the one presented by T. D. Carr of the University of Florida, are based on an attempt to work out detailed pictures of how a magnetic dipole, tilted and displaced from the center of Jupiter, would so orient the field lines as to generate the radiation either directly or by reflection from the top of Jupiter's ionosphere. It would have to be emitted in the direction of the earth with the appropriate precision of orientation to produce the complicated and apparently permanent fine structure as a function of longitude which is observed for this radiation.

All this radiation-belt activity presumably involves frequent dumping of such particles into the atmosphere of Jupiter. The question was raised as to whether this should lead to very pronounced Jovian analogs of the aurora. No conclusive answer has yet been provided, but J. Jelley of Harwell and H. J. Smith were agreed that there was no evidence for hydrogen-alpha enhancement significantly greater than about one percent of the intensity of hydrogen alpha in the spectrum of sunlight reflected from the disc of the planet. This upper limit would correspond to a hydrogen-alpha auroral intensity 1000 times that observed on the earth.

A highlight of the conference was the suggestion by R. M. Gallet of the National Bureau of Standards, Boulder, Colo., that previous models of the atmosphere of Jupiter cannot be correct because they neglect the changes produced by the condensation of ammonia and water vapor on the structure of the atmosphere. With allowance for the heat released in this condensation, Gallet calculates a marked reduction of the temperature gradient, but a sharp increase in the pressure gradient for an atmosphere in adiabatic equilibrium. The net effect is to reach quite high densities and pressures at relatively low temperatures and relatively small distances below the top of the apparent cloud deck (see Fig. 3). This implies the presence of ammonia ice-crystal clouds probably of the order of 50 km thick. Below these lies a region in which ammonia rainstorms may be a prominent feature. At still deeper layers the ammonia would be gaseous. A few kilometers below the ammonia

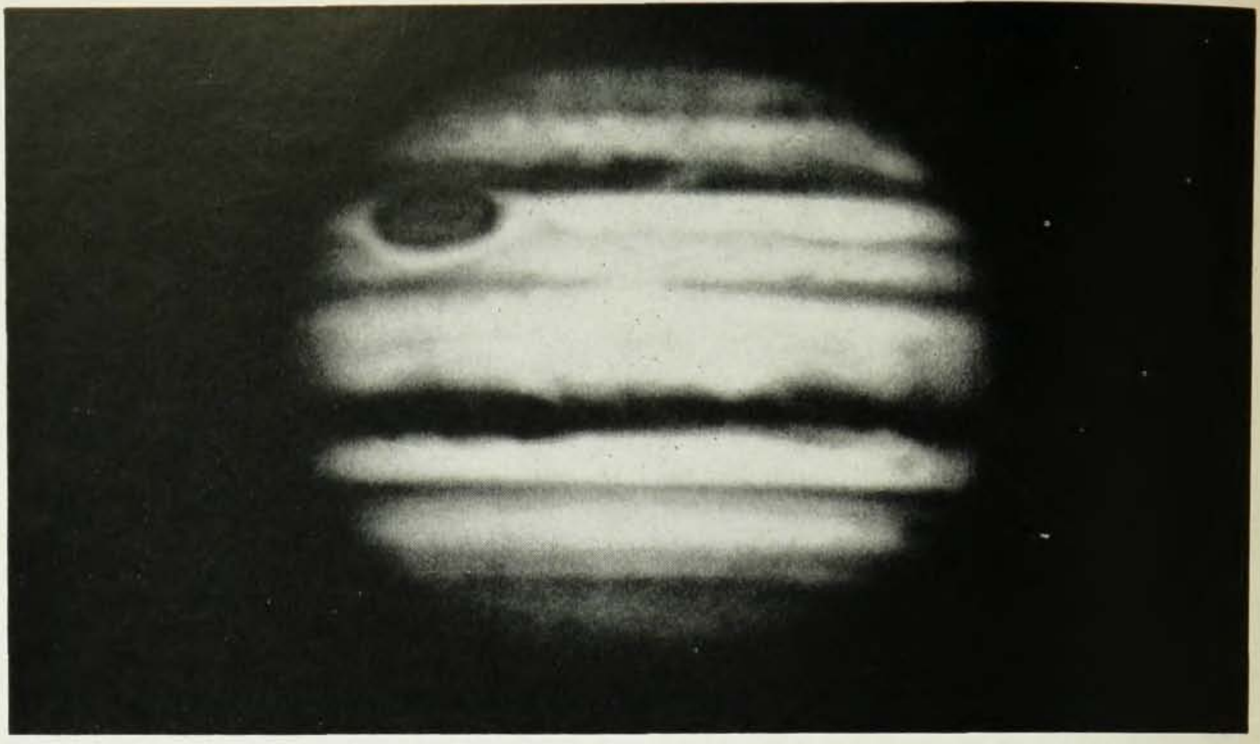

Fig. 4. Jupiter, a 200-in Palomar photograph, taken in blue light, showing the Great Red Spot.

clouds, a similar phenomenon occurs with water, so that there may be a certain thickness of water clouds and then water vapor below that.

If the interior of Jupiter is warm enough to produce an appreciable outward heat flow, the atmosphere would have to have an approximately adiabatic temperature gradient. According to previous calculations, this would have led to unreasonably high temperatures at the bottom of the atmosphere. According to Gallet's calculations, even with an adiabatic atmosphere, one can reach high enough pressures at low enough temperatures a few hundred kilometers below the top of the clouds to solidify the material, i.e., to reach the surface of a solid mantle.

C. Sagan of the University of California noted that, if Gallet is correct, one could even imagine several strata of complex chemicals which might build into a biosphere of Jupiter. Highly complex pseudo-organic molecules might be produced from solar radiation and atmospheric electrical charges. These molecules would be quite soluble in the droplets of liquids present, creating the conditions necessary for the complex organic reactions under which life might arise.

H. Spinrad of the Jet Propulsion Laboratory, California Institute of Technology, gave details on his recent measurements of older high-dispersion spectra of Jupiter. He found that the ammonia lines did not occur with the expected tilt corresponding to the rotation of the planet, but rather with a tilt suggesting Doppler shifts characteristic of a much slower rotation. Translated into shear velocities, this amounts to a reverse flow of the ammonia gas at a relative velocity of about 7 or 8 kilometers per second, probably several times faster than the speed of sound in the Jovian atmosphere. This effect seems markedly variable with time and perhaps with Jovian latitude; some recent plates do not show it clearly at all.

As yet little is known about the actual height above the clouds where the ammonia lines are formed. They may be formed in a simple stratosphere in equilibrium with the ammonia ice crystals on top of the clouds. The composition of the atmosphere may be different from that in the interior in the sense that the atmospheric hydrogen is greatly depleted.

There seems to be general agreement now that the bulk structure of Jupiter is very different from that of a cold planet. W. D. DeMarcus of the University of Kentucky stated that as long as the interior temperature is not above 10^5 °K the radius is not altered very much. Jupiter, effectively, is not supported by the pressures generated by hot gases, and probably has a surface of solid hydrogen several hundred kilometers below the clouds, even though its core may be warm enough to be molten.

This main body of Jupiter, according to the calculations of DeMarcus and others, is approximately eighty percent hydrogen, as no other substance is light enough to permit building a cold body of Jupiter's mean density. However, the meager information available suggests that the atmosphere is largely helium, and one faces the problem of the "cream separator" mechanism which has allowed this segregation of the planet into a helium-rich atmosphere and a predominantly hydrogen body. Actually the sole evidence for helium in the atmosphere is the high mean molecular weight, about 3.5 to 4, coupled with the fact that helium is the most abundant of the constituents one would expect apart from hydrogen. In turn, the mean molecular weight has been derived from very uncertain observations and interpretations of scale heights of the atmosphere previously thought of as representing a mixture of hydrogen and helium only. Gallet argued that if methane and neon are taken into account, the helium may be reduced to something closer to solar proportions.

It was presumed that at a depth of several hundreds of kilometers a surface is formed of molecular hydrogen solidified under pressure. Such a surface would not be expected to have high structural strength, but there might be relief of two kinds: (1) elevations, produced by either orogenic processes or remnants of catastrophic effects from without, or (2) depressions, perhaps sustained by a mechanism originally suggested in another context by Gallet. If Jupiter's surface is produced by a phase transition that is temperature sensitive, a local mechanism feeding sufficient heat to the surface in a particular region could cause a very substantial depression of the phase boundary nearby.

This general picture of the Jovian surface provides for the first time a rational explanation of the Great Red Spot (see Fig. 4) in terms of hydrodynamics. R. Hide of the Rotating Fluids Laboratory, Massachusetts Institute of Technology, believes that a surface discontinuity over which an atmosphere is flowing on a rotating planet will set up a vertical Taylor column (see Fig. 5). The column can have a very much greater height than that of the surface discontinuity, and marked stability around which the atmosphere will tend to flow. Such a mechanism can account for the remarkable stability of the Red Spot over the past 150 years during which it has been a pronounced visual feature. The surface discontinuity must exceed a rather large critical size in order to set up a stable Taylor column through so extensive an atmosphere as Jupiter's, hence it is not surprising that there should be few of these; the fact that there is only one may simply be an accident within the variation of the few.

If Hide's theory is correct, the rotation of the solid portion of Jupiter can be obtained by direct visual observations of the Red Spot (currently $9^h55^m42^s$). The long-known and well-observed variations in the Red Spot periodicity would then give a direct measure of variations in the rotation of the solid mantle of the planet. This in turn may ultimately tell us a good deal about the moment of inertia of that region and its interactions either with the magnetic field or with the atmospheric circulation currents (in the case of the earth, such atmospheric currents are primarily responsible for small variations in the rotation of the solid mantle). Similarly, the decameter observations led to

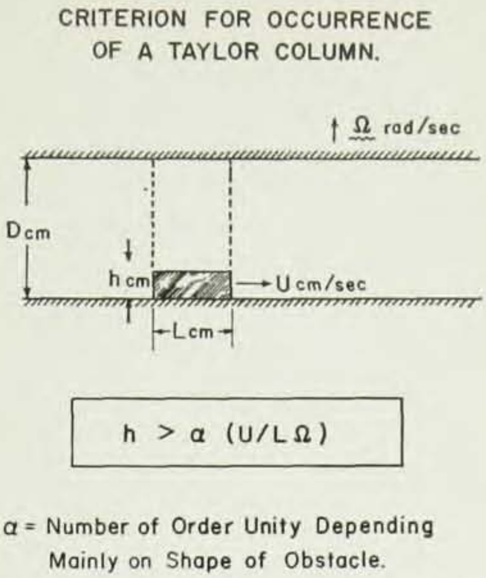

Fig. 5. The condition under which a Taylor column of stationary gas can be obtained, according to R. Hide. In this figure an obstacle of height *h* and diameter *L* exists in a stream of fluid of thickness *D* which is flowing past at a velocity *U* and rotating with an angular velocity Ω.

an extremely well-defined rotation period ($9^h55^m29^s.37$), which according to Douglas is rather stable, and which may well be that of a liquid planetary core in which the principal exospheric magnetic field is presumably generated. On this picture the 13-second difference in Red Spot and decameter periods would mean that Jupiter's core rotates that much faster than its mantle.

In this connection, calculations by DeMarcus and others indicate that, as one goes deeper into the interior, the solid hydrogen probably has a phase transition to a metallic form. With a reasonable rise of temperature inwards, liquefaction of the metallic hydrogen may occur, producing conductivity conditions in the liquid core similiar enough to those of the earth's core, so that whatever mechanism generates the earth's basic dipole magnetic field might generate the Jovian field also. Without such a generating mechanism in a liquid core, any primordial magnetic field frozen into the planet would most probably decay in a time much shorter than the age of the planet.

The regularities of cosmic abundance of the elements lead one to suspect that several parts per hundred of a mixture of elements heavier than hydrogen or helium, colloquially referred to as "mud" or "salt and pepper", are scattered throughout the Jovian structure. There might even be a small heavy innermost core of mud.

Two further points were made very clearly at the conference: that there is a great need for more laboratory work, and that it is regrettable that so little time with big telescopes has been made available for planetary spectroscopy.