

RADIO EMISSION

from the PLANETS

By *F. D. Drake*

THE history of radio astronomy has been marked by a long series of surprises, many of which have changed the paths of advancement in the science. This has been especially true with the planets, probably the field in which fewest surprises were expected. Now, what kind of radio emission was expected from the planets? Optical studies of the planets have been made, of course, for centuries, and from these we felt that we understood well the physics of the planets. This knowledge suggested that we should expect to observe only thermal radio emission from planets, the Planck radiation due to the planets' nonzero temperature. At radio wavelengths the Planck law becomes the simple Rayleigh-Jeans approximation in which the brightness

$$b = \frac{2kT}{\lambda^2}.$$

The temperature T refers to the level in the outer layers of the planet we are observing with the telescope. This level may be in the atmosphere or it may be at the very surface of the planet itself. From this formula, we expected the spectra of planetary radio emission to follow a λ^{-2} law. The observable quantity in radio astronomy is the radio flux density which, for the planets, is the brightness multiplied by the solid angle subtended by the planet in the sky. Obviously, we would also expect this flux density to go as λ^{-2} .

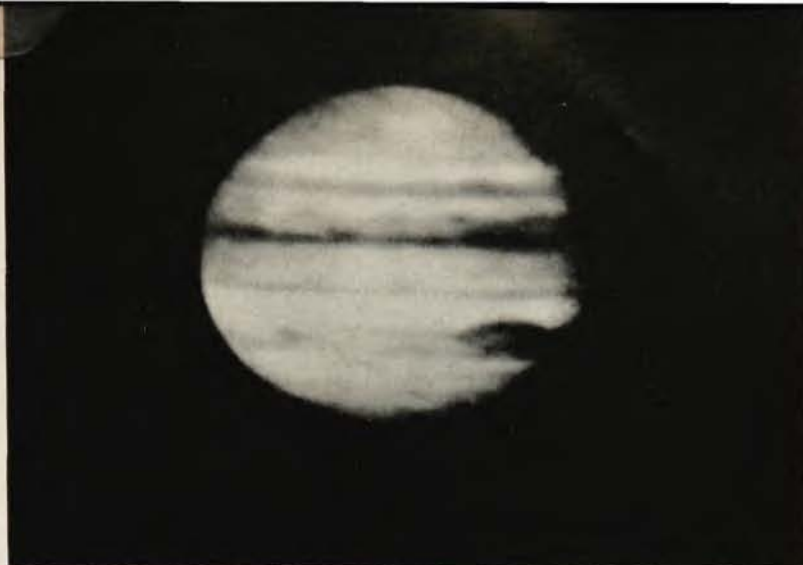
It is well to remember that our radio telescopes can detect only those flux densities greater than a certain minimum value. Over the last few years this minimum value has been roughly independent of wavelength, at microwave frequencies, with a given parabolic antenna. Obviously, then, we want to go to the shortest wavelength possible in order to measure accurately thermal radiation from the planets.

This approach is still based on the idea that the planetary emission will be simple black-body radiation. Optical infrared studies have told us what the temperatures of the visible surfaces of the planets are. We thought

we had from this a good idea of what the radio emission from the planets was to be, but it has turned out that we were in for a surprise. Of the four planets we have studied to date, only one has followed the optical predictions.

ONE of the earliest surprises was the unexpectedly strong radio emission from the planet Venus. This was first observed by the radio astronomy group at the Naval Research Laboratory, Washington, which has done most of the pioneering work in the observation of planetary radio emission. Some ten years ago the NRL group realized that studies at short centimeter wavelengths might be particularly important, and constructed a 50-ft antenna which was operable to wavelengths as short as one centimeter. The pioneering studies of such people as Mayer, McCullough, and Sloanaker were carried out with this large, precise paraboloid. One of the first planets studied by this group was Venus, and it was immediately discovered that the radio emission was very much greater—about three times more—than had been expected. In more recent years this planet has also been observed by other groups, including our own at Green Bank, and the radio astronomy group at the Lebedev Institute at Moscow. All groups have gotten very similar results, a very intense radiation, but one which does follow the black-body relationship. The National Radio Astronomy Observatory results confirm the NRL results at 3 cm wavelength to within a few percent. The average black-body temperature of the Venusian disk is found to be about 585°K at this wavelength. Nearly the same temperature has been observed by Sloanaker at 10 cm wavelength, from which we deduce that this temperature is a true physical temperature and applies to the planetary surface. A slightly lower temperature has been observed by Gibson at NRL at 8 mm wavelength. This temperature is slightly lower, as is to be expected, because at this wavelength some of the radiation comes from the surface but an appreciable fraction of it comes from the atmosphere which is at a lower temperature. Only at wavelengths of about 3 cm and longer do we see radiation coming solely from the surface. It is to be noted that the observed temperature is an average for the planetary disk,

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Jupiter

with the temperature at the poles and night side a little lower, and at the equatorial regions and day side a little higher.

The 1959 observations made at NRL, NRAO, and at Moscow, all are consistent in showing that the apparent Venusian disk temperature rises after the planet has passed inferior conjunction, or has moved out ahead of the earth in its orbital motion around the sun. This can be understood as a result of the sunrise portion of Venus being cooler than the sunset portion of Venus. From this interpretation, we conclude that Venus is rotating in a direct sense, or in the same sense as the earth.

What is to be said about this very high surface temperature? We would have expected a temperature only slightly greater than that of the earth, whereas the actual temperature is several hundred degrees above the boiling point of water. There is only one theory which seems to have any chance here and this is the theory that there is a very strong greenhouse effect on Venus. Sources of internal heating will not produce an enhanced surface temperature, simply because the conductivity of the atmosphere itself is very high compared with any conductivity we can imagine for the outer portions of the planetary body, and would carry away heat conducted to the surface too quickly to allow significant rise in surface temperature. Sagan at the Yerkes Observatory has analyzed the greenhouse effect theoretically, and has been able to show that quite a reasonable greenhouse effect will produce the very high temperature observed on Venus. What is demanded in such a theory, of course, is that the Venusian atmosphere be opaque on all wavelengths longer than about four microns, but that it be relatively transparent between four microns and something like one micron. We know, of course, that shorter than one micron it is opaque because we see the cloud layers optically. Sagan has been able to feel that such a unique greenhouse would be created on Venus by water vapor if there is about five grams per square centimeter of precipitable water in the Venusian atmosphere. Five grams per square centimeter seems a reasonable value. There is much more water than that available on the surface of the earth, for instance. It appears that what may have

happened on Venus is a sort of vicious cycle: as water first appeared after the formation of the planet, solar energy vaporized some of this water, leading to the formation of a greenhouse effect. This in turn led to a rise in surface temperature causing vaporization of more water, an enhanced greenhouse effect, more vaporization, etc. The end result was a very strong greenhouse which has in turn led to the very high observed surface temperatures.

There is a biological significance to this high temperature. According to existing biochemical knowledge, this temperature is much too high for carbon-based life forms to survive, since all biochemical reactions become highly destructive at such high temperatures. It therefore seems likely that any life forms that ever existed on Venus have been destroyed, and no living forms exist on the planetary surface at the present time.

OBSERVATIONS of the planet Mars, again made by the NRL group, have produced the only result which is consonant with our optical picture of planetary conditions. These observations were made with the 50-ft antenna and a solid-state maser, such a combination being necessary to observe the very faint radiation emanating from the planet. Even then a very large number of observations had to be averaged in order to get an accurate measurement of the radio flux from the planet. At present, there are observations at only a single wavelength, so we cannot be sure that the radio spectrum is a black-body spectrum. However, if we assume that it is, the radio flux states that the average black-body temperature of the Martian surface is about 218°K with an uncertainty of about 76°K, in good agreement with the optical measurements. This is, after all, about the only case where we should have expected good agreement because only with Mars, and Mercury, do we optically observe the solid planetary surface.

JUPITER has been the most exciting planet of the solar system to radio astronomers. At present, at least three different types of radio emission, each a result of a different physical mechanism, are known to emanate from Jupiter. The first radio emission from

Jupiter was detected by Burke and Franklin in 1955. A completely unexpected type of emission, it was found through long observations and good luck. This type of radio emission occurs only in a narrow band of frequencies between about 15 and 25 Mc/sec. It is not constant in intensity, but occurs only during short periods of time of the order of minutes. While it is occurring the radiation at times appears to consist of short bursts. These bursts last from a few tenths of a second to one second. There seems to be a tendency in this burst pattern for bursts to occur in groups of two or three. It has also been shown that this radiation is emitted from only a very few locations on the planetary surface. The total number of such locations is not well determined, but it is probably of the order of only three or four, of which one is very intense. Burke and Franklin have made further studies of this emission, and have shown that in many cases the radiation is strongly circularly polarized. The sense of the polarization is almost always right-handed, but occasionally left-handed. This, of course, strongly suggests that magnetoionic propagation mechanisms must be invoked here, and that we are dealing with an effect of the Jovian magnetic field. Through extensive studies by many groups, the rate of rotation of the regions of radiation has been found to be slightly different from the rate of rotation of the optically visible surface, which is high in the atmosphere.

This observational picture is obviously quite complex, and it is difficult to produce a comprehensive theory which explains all the peculiarities of this emission. Probably the best possible explanation to date is that

given by Zhelezniakov of the Gorky Institute, who suggests that the emission occurs as a result of plasma oscillations in the Jovian ionosphere. This is suggested by many things, such as the polarization of the radiation, and the frequency of emission which is near the ionospheric critical frequencies we might expect on Jupiter. The plasma oscillations could be excited by shock waves, of undetermined origin, moving through the ionosphere.

The second type of emission from Jupiter is the expected thermal emission, which is consistent with a black-body disk temperature of the order of 130°K .

There is a third type of emission which is observable only at microwave frequencies, and which has been known for only about a year. This emission is very weak, and requires large antennas and very sensitive receivers for its detection. For instance, when observed with the NRAO 85-ft radio telescope, the total amount of power delivered by the antenna as a result of this radiation is only about $.5(10^{-16})$ w. Fig. 1 is a summary of the observations now available of the microwave flux density from Jupiter. The observed fluxes suggest that we are observing the net effect of two types of emission having different spectra. One type of emission follows the λ^{-2} law of the black body. If we subtract from the observed points a component due to this λ^{-2} radiation, the residual flux densities will be those of the second type of radio emission. When we have done this, we see that the residual flux densities define a new spectrum in which the flux density varies very nearly as $\lambda^{+0.2}$.

This is a spectrum which has not previously been encountered in radio astronomy. It is quite different from

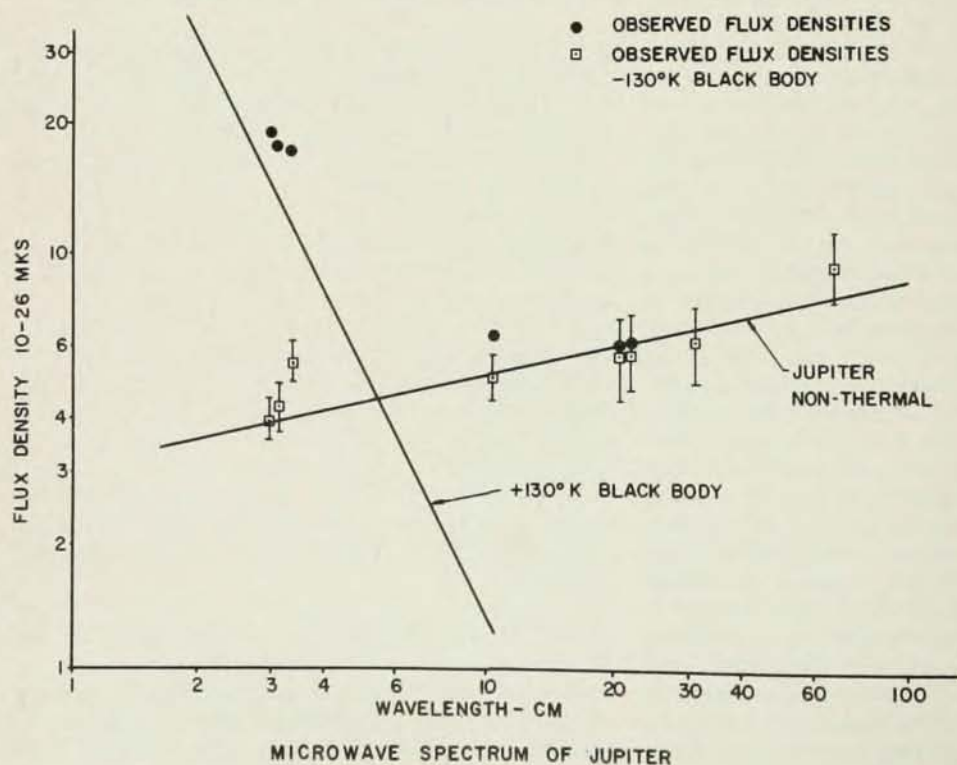


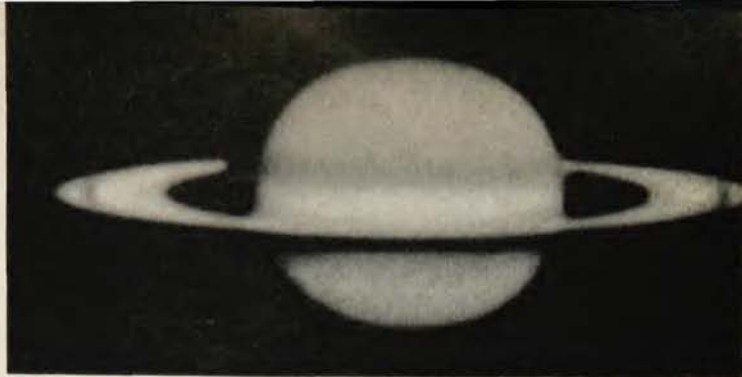
Fig. 1

the spectrum of the solid black body, and it is also a spectrum which cannot emanate from emission nebulosities. It is similar to the spectrum of the radio sources whose radiation is due to synchrotron emission, although the spectrum is not as steep in the case of Jupiter. When this emission was first discovered, the explanation in terms of synchrotron emission seemed the most likely one. This implies that the emission emanates from relativistic particles trapped in a magnetic field, and it was proposed at the NRAO that we were actually observing radio emission from the Jovian equivalent of the terrestrial Van Allen belts. For this to be true, the Jovian magnetic field has to be at least ten times the earth's field in the radiating regions, and the total number of trapped particles in the Jovian system must be of the order of 10^6 times the number in the terrestrial system, if we assume that the particle energy spectrum is similar to that observed in the terrestrial Van Allen belts. Although a factor of 10^6 in the number of particles seems rather large, it is actually not unreasonable. The Jovian system itself is scaled up by a factor of ten over the terrestrial system, or a factor of 1000 in volume, and Jupiter's greater distance from the sun should cause its Van Allen trapping regions to extend far into space because of the presumably weaker interplanetary magnetic field in the vicinity of Jupiter.

Field at Princeton has studied this problem in detail, and has shown that in addition to synchrotron emission, the observed spectrum could be produced by non-relativistic electrons in a Jovian Van Allen belt. Of course, a much larger magnetic field, as much as perhaps 10 000 gauss at the poles, is required but the disadvantage to the theory of this extreme parameter is balanced by the advantage that the number of electrons required is just what we might expect. Field has determined that we should observe a net linear polarization of about 30 percent in the radiation due to cyclotron emission, and a similar figure should be present with synchrotron emission. The radiating regions should also, of course, appear considerably larger than the disk of the planet.

These predictions were dramatically confirmed very recently by Radhakrishnan and Roberts at the California Institute of Technology. They found that the radiation was indeed linearly polarized about 30%, and that the region of radiation had a diameter more than three times that of the planet. The existence of the Jovian Van Allen belt now seems well established. It also seems well established that the Jovian magnetic field is at least ten times and perhaps 10 000 times stronger than the terrestrial field. A better approximation will not be available until we know whether synchrotron or cyclotron emission is the source of the radiation. Until this is resolved, there remains the possibility that the radiation hazard surrounding Jupiter is far greater than that surrounding the earth.

It might be noted that these results and the Venus results have an extremely large dollars and cents value. Had we not known of them, our first space probes to the near vicinity of these planets would undoubtedly



Saturn

have been improperly instrumented, perhaps to such an extent that the missions would have been complete failures. Thus the radio astronomers have probably saved the expense of at least two space probes, which actually exceeds considerably all the money ever spent on radio astronomy.

THE last planet to be discussed is Saturn, which has not yet produced very conclusive results. Smith at Yale has made a long search for Jupiter-type low-frequency radiations from Saturn. Although he has some highly suggestive evidence that such radiation emanates from Saturn, the results are not clearcut. A single imprecise measurement of the emission from Saturn at a wavelength of 3.75 cm has been made which has suggested that the microwave performance of Saturn is similar to that of Jupiter. Here, as with the low-frequency studies, a great many better observations are needed.

The results of the planetary observations to date are shown in Fig. 2, which is a slight modification of a figure prepared by Cornell Mayer. The points are the actual radio observations. The solid lines indicate the

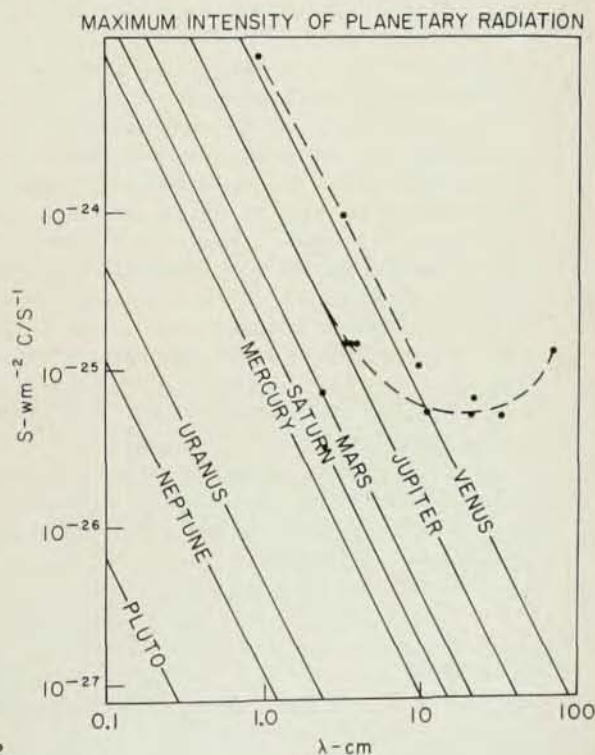


Fig. 2



Mars

black-body spectrum expected from the optical data, and the dotted lines show the observed radio spectra.

WHAT about the future? At present, the minimum flux density we can detect is slightly below the observed flux densities for Saturn. This suggests that we may observe Mercury with our existing telescopes at a wavelength of about 3 cm or shorter. When it comes to Uranus, we find we are unable to observe that planet unless we can operate at wavelengths of less than about 0.5 cm without increasing the minimum detectable flux density. We have no antennas capable of this feat at present. Obviously, what is needed is the ability to detect fainter flux densities and to operate at shorter wavelengths, if possible. Larger centimeter-wave parabolic antennas will fulfill this need. One such antenna now under construction is the 140-ft telescope being constructed at Green Bank, and another one is the 600-ft radio telescope being built at Sugar Grove, West Virginia. With the 140-ft telescope and expected improvements in receivers, it would seem likely that we will be able to push our minimum detectable flux down by a factor of perhaps 10. This will bring Uranus within reach, but probably not Neptune. With the 600-ft radio telescope, we gain at least a factor of 100, not including improvements in receivers, so that we may push the minimum detectable flux density down by a factor of two or three hundred all told. However, the minimum useable wavelength will probably not be as low as that of the 140-ft telescope. Nevertheless, we may well expect to be able to bring within reach all the planets except Pluto with the 600-ft telescope.

Recently a new and powerful means of studying the planets has been opened up by the technique of radar astronomy. Radar echoes from Venus have now been received during the inferior conjunctions that occurred during the last two years. A short time ago a radar echo was obtained from the sun. However, the greatest promise in this field has been shown by the remarkable observations made by Pettengill and his co-workers at the Lincoln Laboratory, using the moon as a target.

The technique of Pettengill and his co-workers is based on the idea that the rotation and spherical shape of typical solar-system bodies introduce an almost unique combination of Doppler effect and time delay in the radar echo returned from a given small portion of the object's surface. This has been well described by Pettengill in the *Proceedings of the IRE*, May 1960. The measurement of the range corresponding to an echo delay time establishes that the echo originated in a certain ring on the object concentric with the subearth point. A measurement of the Doppler effect in the echo establishes that the echo originated in a certain strip parallel to the axis of rotation of the object. The combination of these two bits of information for a given echo establishes that the echo originated in one of two possible locations on the object observed. Thus, by analyzing the range and Doppler information in the many radar echoes of a single transmitted pulse from a planet, we may make a pseudo map of the surface of the object, with a resolution which far exceeds the beam width of the radio telescope used. By making many such pseudo maps as the object rotates, it should be possible to make a good approximation to a true topographic map of the object, including the heights and inclinations of any irregularities that occur on the surface.

This might even allow us to detect the existence of living things on a planet as Gold has emphasized. On the earth, there are a large number of vertical objects, but they are almost all living things. Were we to remove the living things from earth, the average inclinations of the irregularities of the earth's surface would be very small. Thus a radar analysis that suggests a large abundance of objects having vertical sides would be good evidence for the existence of life on an object. By studying the wavelength dependence of the number of objects having vertical sides, we might even get a good idea as to the heights of the objects!

To apply this radar procedure, which has worked so well with the moon, we will require far more powerful radars than we have at present. However, instruments now under construction should provide this power. One of the most fascinating features of this technique is that the degree of resolution with which one may observe a planetary surface does not depend on the distance of an object or the beam width of the telescope used, but only on the resolution achievable in Doppler measurements and range measurements. We can hope that the near future will see studies of Venus and Mars, at least, by means of this technique.