Part I

MOON AND PLANETS

PAPER I

RADIO ASTRONOMY AND THE SOLAR SYSTEM

INTRODUCTORY LECTURE by

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Radio astronomy has been expanding into outer space so fast in recent years that it is pleasant to find our own solar system at last receiving the attention it deserves. In this session we are concerned with everything within the system except the sun and our own planet. I start with a question, to which I shall return later: Where does the sun end? In another session you will hear of the experiments on the far-out parts of the solar corona; here we are concerned with interplanetary space as well as with the planets themselves, and what lies within this region may or may not be considered part of the solar corona.

The parts of the solar system that are accessible to radio astronomy are those that emit, reflect, refract, or absorb radio waves. Let us review first the bodies that emit thermal radio waves.

One of the most impressive technical feats in radio astronomy has been the detection of thermal radiation from the planets Venus, Mars, Jupiter, and Saturn. Today the techniques have the appearance of a tour de force, but we may perhaps become more used to measuring receiver sensitivities in hundredths of degrees. At present it is not obvious how much can be learned about the planets from measuring their radio temperatures, since it is difficult so far to follow their temperatures in detail through a complete cycle of solar illumination. One strange thing has emerged: the radio black-body temperature of Venus has been found to be double that measured in the infrared, and about double what would be expected from a simple black-body model.

Thermal radiation from the moon has been investigated in much greater detail, and the variation through the lunar cycle has already shown that the surface material of the moon has a low thermal conductivity. The most detailed experimental work, by Gibson on 35 Gc/s, shows very good agreement with models having a layer of dust at least 2 cm deep. The origin of the radio waves on this frequency lies for the most part within this 2-cm layer.

May I suggest to you a problem for entertainment only? If we look at the moon in the ordinary way, we find a very large variation of brightness through the lunar cycle, in contrast to the radio brightness, which changes by less than a factor of two. What correction should be applied to the radio brightness due to the incidence of radio waves from the quiet sun? I think you will find it is very small indeed.

The moon is also accessible to exploration by radar. Here we have the possibility of finding out two kinds of information about the surface: first, the electrical characteristics of the material; and second, the shape of the surface, that is, how much it departs from the true sphere. Reflections have now been obtained on frequencies from 30 to 3000 Mc/s, mostly by pulse radar, but sometimes with cw systems. From these results we learn that the moon is behaving much as we ought to have expected; that is to say, it reflects radio waves like any other smooth and largely featureless surface. If I suggest how the radar results may be used to provide some details of this surface, I shall do so simply to suggest lines of discussion, and I shall expect to find my ideas elementary when faced with the detailed observations now being made.

Consider first two imaginary exactly spherical moons, whose surfaces represent the two extremes of scattering according to Lambert's cosine law and of specular reflection. Let there be no absorption. The radar cross-sections, that is, the cross-section of an equivalent isotropic scatterer of these two, are πr^2 for the reflector and $(8/3)\pi r^2$ for the Lambert's law surface, two figures that are not far different. The difference between them may be related to the difference in the angular distribution of scattered energy, which is more concentrated in the direct backwards return for the Lambert's law case.

A more obvious difference in behavior concerns the surface brightness of the models as reradiators. The scatterer has a surface whose brightness falls toward the limb as a cosine law; the reflector has only a bright spot in the center, which is of course the optical image of the transmitting aerial, A radar pulse on the scattering moon returns lengthened, persisting for 11.6 milliseconds; a reflecting moon returns an unaltered pulse.

The real moon is clearly behaving more like a reflector than the scatterer, since most of the power in a returning pulse arrives within one-tenth of a millisecond. But the pulse is in fact considerably lengthened and complicated by fluctuations. How can we apply the simple model to the real echoes and find the reflection coefficient and the topography of the surface? I suggest the following reasoning:

1. The limitation of the lengthening of the pulse to 100 microseconds, with some few later returns, shows that few parts of the moon's surface slope at an angle to the normal greater than about 7 degrees.

2. The returned pulse comes from the surface parts where the angle of incidence is near normal, and the reflection coefficient concerned is effectively that for normal incidence.

3. Simple energy considerations show that the total power reflected directly backwards will be the same for a slightly irregular surface as for a regular one with the same reflection coefficient. The polar diagram of the radiated intensity will be an irregular curve of nearly the same shape as that of the perfect sphere.

4. Two things must then be done to find the reflection coefficient. First, the integrated power returned in the whole lengthened echo must be deter-

mined; and second, a time average of this quantity must be found as the moon librates, providing an average over the irregularities in the polar diagram. The returned power is then used to calculate the radar cross-section, which is now $\rho\pi r^2$, where ρ is the power reflection coefficient of the surface. This procedure is the same for using a cw reflection and measuring the average power level of the return. On the basis of this theory, the circuit loss quoted by Trexler gives a power reflection coefficient of about 0.1.

5. The topography is revealed by the details of the lengthened pulse. We may hope here to find at least some statistical information about the frequency with which various angles of tilt may be found in the moon's surface.

I have not yet mentioned diffraction in this elementary discussion, although I have already had the privilege of reading the paper by Senior and Siegel in which they suggest a quite different line of argument from mine, and invoke diffraction theory for the perfectly smooth reflecting moon, which I have treated by geometric optics. Without doubt, diffraction theory must be applied to the question of the size of the irregularities or corrugations on the moon's surface, which must obviously be large compared with the longest wavelength at which they are observed, while remaining numerous enough to account for the rapid fluctuations in echo as the moon librates.

To sum up the questions about the moon we need: (1) a theory to explain the general appearance of the echoes on all frequencies; (2) a measurement of the reflection coefficient as a function of frequency, to derive electrical characteristics of the surface material; (3) a statistical analysis of echo fading, to provide us with an average topography.

One further question: Why does the visible full moon appear as it does, not with an irregular image of the sun in its center, and not even limb darkened? The answer must concern the material of the surface, and probably indicates a granular or sandy material.

Finally, a challenge. With a cross-section of 0.1 πr^2, the moon should reflect outbursts of detectable solar radio waves. No positive evidence of this has yet been found. Simultaneous observations by widely separated observatories, in the daylight and in the dark, are required. If this proved possible, it would provide another way of measuring the reflection coefficient, this time not necessarily at normal incidence.

Nonthermal emission in the solar system is found from sunspots, and from the planet Jupiter. Reports of radiation from Venus remain unconfirmed; Saturn is mentioned in paper 8; I shall confine my remarks to Jupiter. (I ought to explain at this point that the only connection I have with the subject matter of this session is a tenuous one: I made an attempt to detect radiation from Jupiter on frequencies higher than those originally used, and failed.) The original detection of Jupiter was rather by accident, when Burke and Franklin happened to leave a narrow-beamed aerial working on the right frequency directed at the right part of the sky. They, and others after them, have made good use of this discovery.

Jupiter faces us with an unsolved problem. Radio waves are emitted from a limited region of the surface, in short bursts, circularly polarized, over a frequency range of 10 Mc/s centered on about 20 Mc/s. The bandwidth and the detailed shape of the bursts are not adequately known. This activity lasts for a few hours, and then stops.

There is, of course, much more to be found out experimentally. The polar diagram of the emission is difficult but not impossible to determine. There is likely to be much detail in the frequency spectrum and time structure of the pulses. But we know enough to start making theories of the emission process, and it is remarkable that no theories are forthcoming. The main clues must be the very large power, the very narrow frequency spectrum, and the circular polarization. The only tuned element imaginable is a Jovian ionosphere, into which the circular polarization suggests we must put a magnetic field. But the power level suggests a coherent oscillation, and we already know that for sunspot radiation this is not an easy or an obvious solution. The energy source also must be considered. The suggestion has been made that solar energy might not be enough, and that the differential rotation might be the source.

One other member of the solar system, a more temporary one, has been examined for radio emission. The comet Arend-Roland was a conspicuous visual object, with a tail that appeared to be a likely source of radio waves. The fact that it was not reported as such, at least by most observers, does not actually tell us much about the comet; and I shall mention later a search for refraction effects which is perhaps more directly useful, but which again gave a null result. If I may briefly refer to the published account of the positive identification of radio signals from the comet, I think it might be valuable if more details of these observations could be made available. There appears to be an error in the paper in which Coutrez, Hunaerts, and Koeckelenburgh attribute this radiation to a line radiation at 600 Mc/s, and this explanation of the discrepancy between their observations and others that gave a null result must be abandoned.

The rest of my remarks are concerned with the refraction of radio waves. The tail of the comet may first be dismissed by saying that no refraction was observed, although, as we shall hear, a useful upper limit on electron density was established.

An interesting observation of the lunar atmosphere is reported in paper 6. The occultation of the Crab nebula by the moon was observed at a sufficiently long radio wavelength for the effects of the most tenuous ionized atmosphere at the limb of the moon to be quite considerable. A positive effect on the limits of sensitivity was found, but we can still think of the moon's atmosphere as a nearly perfect vacuum. Radio astronomy has therefore provided the first moon traveler with detailed, but discouraging, information about his new environment. Even if he sinks up to his knees in dust, we may have separate information for him about the temperature his feet and his knees will encounter.

Finally I return to the question of the interplanetary electrons. On the one side there is the solar corona, and on the other the terrestrial ionosphere.

Somewhere in between is an interesting boundary. Can we hope to explore this region with radio waves? Radar velocities to the moon can be found to about one part in 10^4; this seems to be a less powerful way of detecting electrons than the Faraday rotation effect. The results obtained from this rotation must refer primarily to our ionosphere, but we now have a new possibility in the form of artificial satellites. Is it conceivable that a satellite can be used as a relay station in a moon radar? If it can be, we might be able to devise an experiment for a direct determination of the total electron content of the space between the ionosphere and the moon.

What of the rest of interplanetary space? We wish every success to Jodrell Bank's attempt to get a radar echo from Venus; this, however, is not the only approach. We can hope that the occultation of radio stars, and possibly of the signals from Jupiter, by the solar corona can be extended far out from the sun into this most interesting field. The most hopeful way of extending our knowledge from the ionospheric side is by the study of whistlers. I wonder when and where these two explorations will meet.