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*CENTIMETER WAVELENGTH RADIO ASTRONOMY INCLUDING OBSERVATIONS USING THE MASER**

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During the past fifteen years, radio astronomy observations have been largely confined to radiation at wavelengths longer than about 20 cm. The purpose of this talk is to give a brief outline of the work to date at shorter wavelengths, in particular wavelengths less than 10 cm, and to describe some of the new techniques being used in this work. Since the extensive field of solar radio astronomy has already been reviewed by Dr. Maxwell,* this talk will be concerned only with sources other than the sun.

The radio astronomer who works at cm wavelengths faces a number of difficulties not found at longer wavelengths. He is first of all limited to observing continuum radiation since none of the spectral lines in this region has so far been detected. Secondly, the flux density and hence, for a given antenna, the antenna temperature available from the discrete nonthermal sources are approximately proportional to λ . A third difficulty is inadequate receiver sensitivity. At wavelengths of 1 m and longer receivers have been available with internal noise temperatures lower than a few hundred degrees Kelvin, which is less than the background noise at the galactic pole. At meter wavelengths, improved receiver sensitivity is not of great importance. In the cm region, however, where the background temperature is only a few degrees Kelvin, the crystal noise in superheterodyne receivers has led to receiver noise temperatures of 1000°K or more. At wavelengths shorter than 3 cm crystal noise temperatures as well as atmospheric absorption rise rapidly. Indeed apart from the sun, the moon, and Venus, no discrete sources have been detected at wavelengths between 3 cm and the optical infrared region.

The necessity of large high-precision antennas has also restricted progress at centimeter wavelengths. For example, with the use of standard superheterodyne techniques and a five second averaging time, a parabolic reflector 10 ft in diameter or its equivalent is required merely to *detect* Cassiopeia A at 3 cm wavelength. Clearly, much larger antennas, constructed with surface tolerances of the order of $\frac{1}{4}$ inch, are required for research at these wavelengths. Prior to 1958 the only large antenna suitable for observations of discrete sources at cm wavelengths was the 50-ft reflector¹ at the U. S. Naval Research Laboratory.

In spite of the experimental difficulties a number of significant observations have been made, many of them yielding information accessible only at cm wavelength.

SUMMARY OF CENTIMETER WAVELENGTH OBSERVATIONS

Spectra of the Discrete Sources.—The initial effort at observing galactic noise at cm wavelength was probably that of Reber in 1938.² Although failing to detect 9 cm radiation with relatively insensitive equipment, he was able to conclude that the spectrum of the radiation is far from that of a black body. Working at 10 cm in 1951, Piddington and Minnett³ with the use of a “beam swinging” technique found an excess flux density of $7 \times 10^{-21} \text{ w m}^{-2} (\text{c/s})^{-1}$ associated with the region near the galactic center.

Discrete sources were first detected at wavelengths shorter than 21 cm by Haddock, Mayer, and Sloanaker⁴ in the initial application of NRL 50-ft antenna. They reported flux densities at 9.4 cm of Cassiopeia A, M 1, Cygnus A, the galactic center region, Centaurus A, M 87, and IC 443.⁵ The flux densities together with those measured at longer wavelengths were found to be in rough accord with a λ^{-2} law,⁶ with the exception of a possible departure near 70 cm.⁷ The spectra of the strongest of these sources were further extended to 3 cm by Haddock and McCullough in 1955.⁸

Subsequent studies of the strong discrete sources at 10 cm and 3 cm have been made by Razin and Pletchikov,⁹ Kaydanovsky and Kardashev,¹⁰ Jennison,¹¹ Broten and Medd,¹² and others.

The region in Sagittarius near the galactic center has recently been mapped by Drake¹³ with a resolution of about 6'. Observing simultaneously at 68 cm, 21 cm, and 3.75 cm with the 85-ft antenna of the National Radio Astronomy Observatory, he has resolved four distinct centers of emission in the galactic plane arranged more or less symmetrically within 100 parsecs of the center. Professor Oort* has already commented on the correlation between this result and recent hydrogen line studies of the same region.

Ionized Hydrogen Regions.—The bright gaseous emission nebulae were identified as a new class of discrete radio source by Haddock, Mayer, and Sloanaker in 1954.¹⁴ They reported detection at 9.4 cm of the Orion Nebula, as well as M 17, M 8, M 20, and an extended region of hydrogen emission nebulae near the galactic center. The cm wavelength emission intensity from these sources is found to be proportional to the intensity of their $H\alpha$ emission corrected for optical extinction, in accord with the interpretation of the radio emission as thermal radiation arising from free-free transitions in H II.¹⁵ Further evidence for the thermal model is the radio spectrum of the Orion Nebula. The intensity is frequency independent at wavelengths shorter than about 20 cm and proportional to λ^{-2} at longer wavelengths at which the nebula is optically thick.

Thermal emission from planetary nebulae also appears to be a source of detectable radiation. In 1958 Drake and Ewen reported detection of 3.75 cm radiation associated with NGC 7293 and NGC 6853, the Helix and Dumbbell nebulae respectively.¹⁶ Although this observation has not yet been corroborated at nearby wavelengths, it appears that cm wavelength observations will become a useful and independent tool in the study of the planetaries, for many of which the optical estimates of electron density are not of high precision.

Polarization of Discrete Sources.—Polarization of radio radiation from a discrete source was first detected by Mayer, McCullough, and Sloanaker at 3.15 cm.¹⁷ They measured 7 per cent plane polarization for the Crab Nebula at a position angle

of 149° for the electric vector. A later measurement at 9.6 cm showed 3 per cent polarization at 142° .¹⁸ The close agreement of these results with others at nearby wavelengths¹⁹ and with the average optical position angle provides strong support for the synchrotron mechanism of emission from this source and indicates that Faraday rotation along the path between the Crab Nebula and the earth is small at cm wavelengths. Polarization of this source is not observed at longer wavelengths presumably because of the obscuring effect of enhanced Faraday rotation. Other strong sources studied at 10.2 cm show less than one per cent plane polarization.¹⁹ Since Faraday rotation varies as λ^2 , the cm region is uniquely suited for unambiguous polarization measurements of the discrete sources.

The Moon.—Measurements of continuum radiation at cm wavelengths from the moon and planets have yielded information on surface temperatures and on the characteristics of the surface material. The first such measurement was made by Dicke and Beringer²⁰ at 1.25 cm in 1945. They found the average disk temperature of the full moon to be 270°K . Piddington and Minnett²¹ made an extensive series of observations at the same wavelength of the phase variation of the disk temperature. They reported the disk temperature of the new moon to be 145°K and the constant component of temperature to be 234°K . The latter is presumably the temperature of a well-insulated layer far below the surface. In contrast to infrared measurements in the $8\text{--}12\ \mu$ region, the microwave thermal radiation shows a phase lag of about 45° behind the lunar phase angle. The measurements were interpreted as indicating a dust layer of the order of a few mm in thickness and an effective depth of origin of the radiation of about 40 cm. Subsequent observations of thermal radiation from the moon as a function of lunar phase angle and during lunar eclipses have been made at 10 cm,²² 3.2 cm,²³ and 8.6 mm.²⁴ Troitzky and Khaikin,²⁵ from an analysis of the 3.2 cm and optical data, calculate a constant component of radio temperature of 170°K and considerably less penetration than suggested in Ref. (21). The 8.6 mm measurements together with infrared data appear to suggest a dust layer one inch or more in thickness.²⁴ Additional and more precise observations seem necessary before a detailed and consistent model of the lunar surface is available. The radio measurements have recently been extended to 4.3 mm by Coates.²⁶ In this work scans of the lunar surface with $7'$ resolution showed distinct features with various brightness characteristics.

The Planets.—Planetary radiation at radio wavelengths was detected in 1955 by Burke and Franklin,^{26a} who identified Jupiter as the source of burstlike radiation in a narrow band around 15 m wavelength. Radiation resembling thermal emission was discovered by Mayer, McCullough, and Sloanaker^{27, 28} in observations of Venus, Jupiter, and Mars at 3 cm wavelength. The results of these and subsequent measurements at cm wavelength are listed in Table 1. The temperature T is the apparent black body temperature of the disk. The notation $C + n$ refers to an observation made n days after inferior conjunction of Venus.

The cm wavelength observations of the planets have led to the discovery of at least two unexpected phenomena whose interpretation is still not clear.

(1) Venus has an apparent temperature of about 600°K , over twice the apparent infrared temperature of the region above the cloud surface and much higher than expected near the cloud surface on the basis of solar heating and a CO_2 atmosphere. The apparent temperature appears to be roughly wavelength independent, at least

TABLE 1
CENTIMETER AND DECIMETER WAVELENGTH OBSERVATIONS OF THE PLANETS

Planet	λ cm	T, °K	Comments	Ref.
Venus	3.15	620 ± 110	C - 48 to C - 30, 1956	(27)
	3.15	560 ± 73	C - 30 to C + 1, 1956	(27)
	3.4	518 ± 47	C + 15 to C + 36, 1958	(28a)
	3.37	575 ± 58	C + 80, 1958, (with maser)	(29)
	9.4	580 ± 160	C + 3 to C + 5, 1956	(27)
	0.86	410 ± 160	C + 1, 1958	(30)
Jupiter	3.15	145 ± 26		(28)
	3.2 ± 0.2	177 ± 22	(With maser)	(45)
	3.75	$210 \pm$		(16)
	10.3	640 ± 85		(31)
	21.0	$2,500 \pm 450$		(32)
	21.1	$3,000 \pm 1,300$	Estimated from data in Ref. (34)	...
	21.4	$3,500 \pm 1,700$		(35)
	31	$5,500 \pm 1,500$		(33)
	68	$70,000 \pm 30,000$		(35)
Mars	3.15	218 ± 76	Opposition, 1956	(28)
	3.14	211 ± 28	Opposition, 1958, (with maser)	(45)
Saturn	3.75	...	Flux density $4 \times 10^{-26} \text{ w m}^{-2} (\text{cps})^{-1}$	(16)

between 0.86 and 10 cm, a behavior consistent with the interpretation that this is a real temperature, presumably that of a layer many kilometers below the cloud surface. The presence of such a high temperature would imply either a greenhouse mechanism of surprisingly high efficiency in the region of the cloud layer or the presence of an internal heat source.

(2) Jupiter is a source of high intensity radiation at centimeter and decimeter wavelengths. The radiation appears to be variable, with a suggestion in some observations of correlation with the rotation of the planet.³¹ At least at decimeter wavelengths the radiation is probably not primarily of thermal or atmospheric origin. A tentative explanation proposed by Drake and Field³⁵ is that the nonthermal component is cyclotron or synchrotron radiation. The former envisages a belt of electrons surrounding the planet and trapped in magnetic fields between 150 and 1,000 oersteds. Much smaller magnetic fields can account for the observed radiation if the particles are relativistic. However, the required flux of relativistic particles seems higher than can be accounted for in cosmic rays and solar corpuscular emission.

Radar Astronomy.—Studies of radar return from the moon, first detected in 1946,³⁷ have yielded several different kinds of information. The measurement of the reflection coefficients as a function of wavelength gives information on the electrical characteristics of the lunar surface. From an analysis of the available data at wavelengths from 10 cm to 2.5 m, Senior and Siegel³⁸ have calculated the effective permittivity and conductivity of the surface to be $8.2 \times 10^{-12} \text{ farads/m}$ and $4.3 \times 10^{-4} \text{ mho/m}$ respectively. The details of echo fading of short pulses are capable, in principle, of providing information on the topography of the lunar surface. Echo fading at meter wavelengths, on the other hand, is in part due to the Faraday effect in the earth's ionosphere, and analysis of this effect has yielded a measure of the total electron content of the ionosphere.³⁹

Precise range measurements at 10 cm wavelength using 2 μs pulses have recently led to a new estimate of the earth-moon distance with a precision of ± 3 km.⁴⁰ In addition, the data provide indirect measurements of the mean equatorial radius of the earth and the mean horizontal parallax of the moon. The values ob-

tained show small but definite deviations from the accepted values as well as unexplained monthly and diurnal variations.

The only planet detected to date by radar is Venus. Its detection at 68-cm wavelength, reported by a group at Lincoln Laboratory,⁴¹ required an 84-ft antenna, a receiver noise temperature of 170°K, and the use of automatic data processing equipment for statistical analysis of the result. Because of the marginal nature of the detection, little conclusive information could be obtained on the reflection characteristics of the planet or on the precise range.

NEW TECHNIQUES IN CENTIMETER WAVELENGTH RECEIVERS

Since future observations at cm wavelengths will probably rely heavily on recently-developed high sensitivity amplifiers as well as on antennas of increased area, it seems worthwhile to review briefly some of the new amplification techniques. The main part of this section will be devoted to a discussion of masers.

Two distinct approaches have been used to obtain greater sensitivity than is provided by the conventional superheterodyne receiver. The first consists of using a bandwidth much larger than the usual 5 or 10 mc. By an increase in bandwidth from 10 to 1,000 mc with the use of a traveling wave tube amplifier, Drake and Ewen¹⁶ have obtained an order of magnitude decrease in output fluctuation level. With an integration time of 100 sec, they report an output noise level corresponding to 0.01°K in antenna temperature, even with a receiver noise temperature of about 4,000°K. The upper limit of receiver bandwidth is determined by man-made interference and to a lesser extent by the desired spectral resolution.

The second approach is to decrease the receiver noise temperature by the addition of a low noise preamplifier such as a parametric device or a maser. With the use of a maser radiometer on the U. S. Naval Research Laboratory 50-ft antenna, Alsop, Giordmaine, Mayer, and Townes⁴² have obtained a receiver noise temperature of 85°K, including the contributions of radiation from the ground and from the atmosphere. With an averaging time of 5 sec the output fluctuation level was 0.04°K. The maser preamplifier was developed at the Columbia Radiation Laboratory. Another solid-state maser amplifier with a system noise temperature of 170°K⁴¹ was used in the radar detection of Venus and others have been or are being installed on antennas at Harvard College Observatory and the University of Michigan Observatory.

The NRL maser radiometer has already been described elsewhere in detail,⁴² and the following is an outline of its characteristics. It consists of a superheterodyne receiver preceded by a three-level⁴³ ruby maser preamplifier, both mounted adjacent to the focus of the 50-ft antenna. The maser medium is a single crystal of ruby⁴⁴ maintained at liquid helium temperature in a multiply-resonant microwave cavity, in a magnetic field of about 3,500 oersteds. Under these conditions four energy levels separated by about 1 cm^{-1} are accessible to the Cr^{+3} paramagnetic impurity atoms. The equilibrium population distribution of the levels is disturbed by continuous saturation of the first (ground) level and the third level by power at 1.3 cm wavelength. In this situation the population of the third level can be made higher than that of the second, and amplification by stimulated emission is possible at the difference frequency, in this case, 3 cm wavelength. The microwave cavity is of such dimension as to be resonant at both the "pump-

ing" frequency and the amplification frequency when completely filled with ruby. The product of (voltage gain) $\times$ (bandwidth) is about 50 mc in this device. This quantity remains constant as the gain of the amplifier is changed by varying the strength of the coupling between the input waveguide and the cavity.

The inherent noise in such a radiometer is quite low. Almost all of the 85°K noise arises from thermal radiation from ancillary components and from the ground. The contribution to the noise from spontaneous emission, which determines the ultimate sensitivity of an ideal maser amplifier, is only about 3°K.

Liquid helium is necessary in this and other masers suitable for radio astronomy at present, in order to provide a large population difference for the amplifying transition and consequently a useful gain-bandwidth product. A ruby maser has been operated at dry ice temperature, but only at great expense of gain and bandwidth.⁴⁶ In principle, however, liquid helium temperature is not essential to attain low noise temperature, and in future we may expect masers for radio astronomy that can be used with more convenient coolants.

The signal from the feed horn at the antenna focus is introduced to the reflection-type maser cavity through a ferrite circulator, which also transmits the amplified signal to the superheterodyne receiver and isolates the maser cavity from noise originating in the mixer crystals. The maser input is switched at 30 cps between the feed horn and a "reference" horn of broad beamwidth pointing at the sky. An adjustable attenuator in the reference branch allows the two signals to be balanced to within a few tenths of a degree, so that the receiver acts as a null system. With the antenna stationary, the rms gain variation is of the order of 0.01 db per minute.

The addition of the maser preamplifier provided an improvement in sensitivity of about 12 compared with the superheterodyne receiver alone, accepting both image bands. The noise temperature of 85°K can probably be reduced an order of magnitude by improvements in component and maser design and by precautions to reduce antenna spillover. A 5.4 cm traveling wave maser with horn antenna has been operated by de Grasse, Hogg, Ohm, and Scovil⁴⁴ with a total noise temperature of 18°K including contributions from spillover. With more efficient design antenna temperature sensitivities of the order of 10^{-3} °K should soon be feasible at cm wavelengths. The upper limit of useful receiver sensitivity imposed by receiver gain fluctuations, fluctuations in atmospheric absorption and background radiation, and source confusion in the case of all but the largest antennas probably occurs close to this sensitivity.

OBSERVATIONS USING THE MASER

The following is a summary of some of the results obtained by Alsop, Giordmaine, Mayer, and Townes with the use of the maser radiometer on the NRL 50-ft antenna.^{46, 47}

Venus.—The increased sensitivity of the maser permitted a measurement of the apparent temperature of Venus 80 days after the conjunction of 1958 (Table 1). At that time the antenna temperature due to Venus was 0.45°K. In the 80 days following conjunction the fraction of the visible disk illuminated by the sun increases from less than 1 per cent to about 55 per cent. During this period there appears to be no conclusive change in the apparent disk temperature. There is, however, a suggestion of a slightly lower night temperature after conjunction than

before. Such an effect, if corroborated, would be consistent with retrograde rotation of Venus. Retrograde rotation has also been suggested, although inconclusively, by spectroscopic observations. The approximate equality of the day and night temperatures, as measured by both infrared and microwave techniques, indicates that the rotation period is appreciably different from the period of revolution, and in principle can be used to set a lower limit to the rotation period.

Jupiter.—Observations of Jupiter were made on 18 days in the period April, 1958 to February, 1959 in the wavelength range 3.0 to 3.4 cm. From a total of 153 flux measurements the average apparent temperature of the visible disk was found to be $177 \pm 22^\circ\text{K}$. The observations are summarized in Figure 1. Each point represents an average of 9 measurements of peak antenna temperature on a particular day. The relative mean error is the average statistical error of each point. The absolute mean error includes possible systematic errors common to all the points, for example the uncertainty in antenna calibration. In this work individual drift curves, representing a peak antenna temperature of about 0.4°K , were analyzed with a template and the peak temperatures combined to form the daily averages.

FIG. 1.—Observations of Jupiter at 3 cm wavelength.⁴⁵

Between 3.2 and 3.4 cm wavelength there is a decrease in apparent temperature with increasing frequency of $12 \pm 11^\circ\text{K/kmc}$. The average temperature during this period appears to be significantly higher than the average temperature measured in 1957 (Table 1). The beginning of our observation period, April 16, 1958, immediately preceded an outbreak of activity in the south equatorial belt, between April 18 and April 26.⁴⁸ The anomalously high temperature recorded April 30 to May 1, about 270°K , refers to the hemisphere of Jupiter containing the head

of the outburst. One can conclude that there are detectable fluctuations in the 3 cm radiation temperature of the planet, with the suggestion that changes in the apparent temperature may be correlated with changes in the appearance of the planet.

No correlation was observed between the apparent temperature and the rotation of the planet nor between apparent temperature and solar activity as measured by the 10 cm solar flux intensity. There was no detectable linear polarization.

The magnitude of the 3 cm radiation can be interpreted^{36, 45} entirely in terms of thermal radiation from NH_3 known from spectroscopic measurements to be present in the atmosphere. NH_3 radiates in the cm region through the pressure-broadened inversion line at 1.28 cm wavelength. Let us assume that H_2 , He, and CH_4 are present in the atmosphere above the cloud surface in relative abundances corresponding to the mixtures "(a)" and "(b)" proposed by Kuiper.⁴⁹ We assume further that the region above the cloud surface has an adiabatic temperature gradient and is saturated with NH_3 . These assumptions, together with the measured NH_3 and CH_4 abundances, fix the temperature, pressure, and composition distribution above the cloud surface. The apparent temperature as a function of wavelength can then be calculated from the NH_3 absorption coefficient, whose calculation as a function of height above the cloud surface is straightforward. At 3 cm the expected temperatures are about 160 and 183°K for mixtures "(a)" and "(b)", respectively, in adequate agreement with the observed value (Table 1). The higher temperature for mixture "(b)" arises from lower atmospheric pressure at a given temperature, reduced pressure broadening, and thus deeper penetration into the atmosphere.

At longer wavelengths the temperatures predicted on the basis of reasonable models of thermal radiation from the atmosphere fall short of the observed temperatures which rise as high as 70,000°K at 68 cm. Possible nonthermal mechanisms have already been discussed.

Mars.—Radiation from Mars was measured at 3.14 cm close to the opposition of 1958. Separate drift scans at an antenna temperature of 0.08°K were readily detected and averaged in this work. The apparent black body temperature was $211 \pm 28^\circ\text{K}$. This temperature is about 50°K less than the apparent infrared temperature and presumably is the temperature of a cooler subsurface layer. Analysis of similar data at this and other wavelengths will provide a new source of information on the average surface characteristics of Mars.

In addition to the observations of the planets, a number of sources were detected at 3 cm wavelength which had previously been detected only at longer wavelengths. Among these were the following, for which flux densities were measured: Virgo A, IC443, IAU 16N04A, and the H II regions M8, M20, and NGC 6357.

A thorough search was made for several planetary nebulae, including NGC 6853, NGC 7009, and NGC 7293. Preliminary analysis of the data indicates that an upper limit of about 0.1°K can be set for the antenna temperatures associated with these objects.

DIRECTIONS OF FUTURE CENTIMETER WAVELENGTH RESEARCH

In conclusion, I would like to list briefly some of the predictable areas in which cm wavelength research is likely to proceed in the next few years. Much of this

work will require the combination of low noise amplifiers and the largest antennas.

(1) Extension of the spectra of the brighter sources to the mm region, and the spectra of many of the weaker sources to 10 and 3 cm; systematic surveys at 10 and 3 cm.

(2) Precise position measurements, facilitating efforts toward optical identification.

(3) Search for spectral lines, including the hyperfine transition in He^3 II at 3.46 cm and the fine structure transition in metastable H I at 3.03 cm.⁶⁰

(4) High resolution studies of size and brightness distribution of extended sources.

(5) Sensitive polarization measurements on the discrete sources, including the planets.

(6) Study of ionized hydrogen regions including the planetary nebulae.

(7) Study of problems connected with the planets: for example, the nature of the cloud layer and surface of Venus, the rotation period of Venus, the radiation mechanism on Jupiter, and the structure of planetary atmospheres as accessible for example through the radiation profile of the Jovian NH_3 inversion line and the absorption profile of the terrestrial lines of O_2 in the mm region.

* One of four papers presented in a symposium on radio astronomy at the Autumn Meeting of the National Academy of Sciences at Indiana University, November 17, 1959. Other papers from the symposium, by J. H. Oort, and R. Minkowski, appear on pages 1-19 (vol. 46). The remaining paper, by Alan Maxwell, will be published upon receipt.

¹ Hagen, J. P., *J. Geophys. Res.*, **59**, 183 (1954).

² Reber, G., *Proc. Inst. Radio Engrs.*, **46**, 15 (1958).

³ Piddington, J. H., and H. C. Minnett, *Aust. J. Sci. Research A*, **4**, 459 (1951).

⁴ Haddock, F. T., C. H. Mayer, and R. M. Sloanaker, *J. Geophys. Res.*, **59**, 155 (1954).

⁵ Haddock, F. T., C. H. Mayer, and R. M. Sloanaker, *Nature*, **174**, 176 (1954).

⁶ Whitfield, G. R., *M.N.R.A.S.*, **117**, 680 (1957); *Paris Symposium on Radio Astronomy* (Stanford University Press, 1959), p. 297.

⁷ Hagen, J. P., *Radio Astronomy (IAU Symposium No. 4)* (Cambridge, England, 1957), p. 142.

⁸ Haddock, F. T., and T. P. McCullough, *Astron. J.*, **60**, 161 (1955).

⁹ Razin, V. A., and V. M. Pletchkov, *Radio Astronomy (IAU Symposium No. 4)* (Cambridge, England, 1957), p. 155.

¹⁰ Kaydanovsky, N. L., and N. S. Kardashev, *Pub. of the Fifth Cosmogonical Conference* (Moscow, 1956), p. 346.

¹¹ Jennison, R. C., *Paris Symposium on Radio Astronomy* (Stanford University Press, 1959), p. 309.

¹² Broten, N. W., and W. J. Medd, *Astron. J.* (to be published).

¹³ Drake, F. D., *Astron. J.* (to be published).

¹⁴ Haddock, F. T., C. H. Mayer, and R. M. Sloanaker, *Astrophys. J.*, **119**, 456 (1954).

¹⁵ Haddock, F. T., *Radio Astronomy (IAU Symposium No. 4)* (Cambridge, England, 1957), p. 192.

¹⁶ Drake, F. D., and H. I. Ewen, *Proc. Inst. Radio Engrs.*, **46**, 53 (1958).

¹⁷ Mayer, C. H., T. P. McCullough, and R. M. Sloanaker, *Astrophys. J.*, **126**, 468 (1957).

¹⁸ Kuzmin, A. D., and V. L. Udaltsov, *Paris Symposium on Radio Astronomy* (Stanford University Press, 1959), p. 305.

¹⁹ Mayer, C. H., and R. M. Sloanaker, *Astron. J.* (to be published).

²⁰ Dicke, R. H., and R. Beringer, *Astrophys. J.*, **102**, 375 (1946).

²¹ Piddington, J. H., and H. C. Minnett, *Aust. J. Sci. Research A*, **2**, 63 (1949).

²² Akabane, K., *Proc. Japan Acad.*, **31**, 161 (1955).

²³ Zelinskaja, M. R., and V. S. Troitzky, *Pub. of the Fifth Cosmogonical Conference* (Moscow, 1956), p. 99; Kajdanovsky, N. N., M. T. Turesbekov, and S. E. Khaikin, *Ibid.*, p. 347.

- ²⁴ Gibson, J. E., *Proc. Inst. Radio Engrs.*, **46**, 280 (1958).
- ²⁵ Troitzky, V. S., and S. E. Khaikin, *Radio Astronomy (IAU Symposium No. 4)* (Cambridge England, 1957), p. 155.
- ²⁶ Coates, R. J., *Astron. J.* (to be published).
- ^{26a} Burke, B. F., and K. L. Franklin, *J. Geophys. Res.*, **60**, 213 (1955).
- ²⁷ Mayer, C. H., T. P. McCullough, and R. M. Sloanaker, *Astrophys. J.*, **127**, 1 (1958).
- ²⁸ Mayer, C. H., T. P. McCullough, and R. M. Sloanaker, *Astrophys. J.*, **127**, 11 (1958).
- ^{28a} Mayer, C. H., "The Next Five Years in Radio Astronomy" Symposium (University of Michigan, 1959).
- ²⁹ Alsop, L. E., J. A. Giordmaine, C. H. Mayer, and C. H. Townes, *Paris Symposium on Radio Astronomy* (Stanford University Press, 1959), p. 69.
- ³⁰ Gibson, J. E., and R. J. McEwan, *Ibid.*, p. 50.
- ³¹ McClain, E. F., and R. M. Sloanaker, *Ibid.*, p. 61; Sloanaker, R. M., *Astron. J.* (to be published).
- ³² McClain, E. F., *Astron. J.* (to be published).
- ³³ Bolton, J. G., and J. A. Roberts, quoted by G. B. Field, *J. Geophys. Res.*, **64**, 1169 (1959).
- ³⁴ Epstein, E. E., *Nature*, **184**, 52 (1959).
- ³⁵ Drake, F., quoted by G. B. Field, *loc. cit.*
- ³⁶ Field, G. B., *loc. cit.*
- ³⁷ De Witt, J. H., and E. K. Stodola, *Proc. Inst. Radio Engrs.*, **37**, 229 (1949); Bay, Z., *Hung. Acta Phys.*, **1**, 1 (1946).
- ³⁸ Senior, T. B. A., and K. M. Siegel, *Paris Symposium on Radio Astronomy* (Stanford University Press, 1959), p. 29.
- ³⁹ Browne, I. C., J. V. Evans, J. K. Hargreaves, and W. A. S. Murray, *Proc. Phys. Soc. (London)*, **B 69**, 901 (1956).
- ⁴⁰ Yaplee, B. S., R. H. Bruton, K. J. Craig, and N. G. Roman, *Proc. Inst. Radio Engrs.*, **46**, 293 (1958); Bruton, R. H., K. J. Craig, and B. S. Yaplee, *Astron. J.* (to be published).
- ⁴¹ Price, R., *et al.*, *Science*, **129**, 751 (1959).
- ⁴² Giordmaine, J. A., L. E. Alsop, C. H. Mayer, and C. H. Townes, *Proc. Inst. Radio Engrs.*, **47**, 1062 (1959).
- ⁴³ Bloembergen, N., *Phys. Rev.*, **104**, 324 (1956).
- ⁴⁴ Makhov, G., C. Kikuchi, J. Lambe, and R. W. Terhune, *Phys. Rev.*, **109**, 1399 (1958).
- ^{44a} de Grasse, R. W., D. C. Hogg, E. A. Ohm, and H. E. D. Scovil, *J. Appl. Phys.* (to be published).
- ⁴⁵ Giordmaine, J. A., L. E. Alsop, C. H. Mayer, and C. H. Townes, *Astron. J.* (to be published).
- ⁴⁶ Maiman, T. H., *J. Appl. Phys.* (to be published).
- ⁴⁷ Alsop, L. E., J. A. Giordmaine, C. H. Mayer, and C. H. Townes, *Astron. J.*, **63**, 301 (1958); *Paris Symposium on Radio Astronomy* (Stanford University Press, 1959), p. 69.
- ⁴⁸ Kuiper, G. P., and A. P. Lenham (private communication).
- ⁴⁹ Kuiper, G. P., *The Atmospheres of the Earth and Planets*, 2d ed., (University of Chicago Press, 1952), p. 377.
- ⁵⁰ Townes, C. H., *Radio Astronomy (IAU Symposium No. 4)* (Cambridge, England, 1957), p. 92.