OBSERVATIONS OF RADIO SOURCES AT 9.4 GC/S WITH MASER AND HIGH-RESOLUTION INTERFEROMETER

Haruo TANAKA, Takakiyo KAKINUMA
and Takashi YAMASHITA
(The Research Institute of Atmospherics, Nagoya University)

Hidenari UCHIDA and Humio INABA
(The Research Institute of Electrical Communication, Tohoku University)

Hiroshi TSURU, Kenichi TAKAHASHI, Syogo YOSHIKAWA,
Hidekichi HOZUMI and Hiromi HAYASHI
(Communication Research Laboratory, Nippon Electric Co., Ltd.)

Abstract

The observations at 9.4 Gc/s of Cygnus A, Taurus A, Orion Nebula and Omega Nebula have been made with the 2.2′ fan beam of the 16-element interferometer and the maser amplifier. Cygnus A has also been observed with the 0.7′ fan beam of the compound interferometer.

The maser amplifier for radio astronomical observations has been developed, with special emphasis on the high stable performance and the convenience of adjustment and handling in the field installations. The voltage-gain band-width product is about 100 Mc/s, the noise temperature is 40 °K and the gain instability is 0.1 db up to 30 minutes and 0.2 db up to 2 hours.

The brightness distributions, sizes and flux densities of the radio sources have been compared with the results of the earlier observations.

Flux densities of the sources have been derived from that of the sun, comparing the areas under the drift-curves of the sources with that of the sun. The results of flux density measurements show that our scale of flux density at 9.4 Gc/s of the solar observations is nearly equal to the average scale of the galactic or extragalactic observations.

1. Introduction

The observations of the detailed structures of the radio sources are important for the study of their physical nature. Little[1] and Swarup, Thompson and Bracewell[2] have shown that the multiple element interferometer with high resolving power can directly measure the brightness distribution of the source and is very useful for the study of the galactic or extragalactic sources. Little has observed several radio sources with Stanford grating-type interferometer, which produces 2.3′ fan beam. Swarup, Thompson and Bracewell have directly resolved Cygnus A at 3.3 Gc/s using 52″ fan beam of Stanford compound interferometer. Labrum, Harting, Krishnan and Payten[3][28] have also made the observations of the radio sources with 1.5′ beam of the compound interferometer at 1.42 Gc/s.

As described on page 27 in these Proceedings, the sensitivity of Toyokawa multipleelement interferometer at 9.4 Gc/s has been increased, while the Nippon Electric Company, in cooperation with Tohoku University, has specially developed the maser amplifier for the radio astronomical observations and it enabled us to observe some strong sources with 2.2′ or 42″ beam. Then four strong sources, that is, Taurus A, Cygnus A, Orion Nebula and Omega Nebula were selected and the observations were made in July and October, 1964. Taurus A, Orion Nebula and Omega Nebula were observed with 2.2′ beam and Cygnus A was resolved with 42″ beam. These sources have also been observed by Zakharenkov, Kaidanovskii, Pariiskii and Prozorov[4] with 1′ beam of the large Pulkovo telescope. The brightness distributions of the sources obtained by this work generally agree with their results.

As we observed these radio sources using the same antenna system and the same calibration method as the solar observations, we can derive the flux densities of the sources from that of the sun. While Taurus A and Cygnus A have been observed over a wide range of frequency and their spectra based on flux densities relative to Cassiopeia A are given by Whitfield[5] and Conway, Kellermann and Long.[6] Kuzmin has also given the spectra based on the observations with 22m radio telescope of the Lebedev Physical Institute.[29] Therefore, we can compare the scale of flux density of the solar observation with that of the galactic or extragalactic observation. This comparison is one of the purposes of this work.

2. X-band maser for radio astronomy

A microwave solid-state maser operating at X-band is used to improve the sensitivity of radiometers.[7][8][9] In addition to the low noise characteristics, the gain of the maser for use in radiometer should be as stable as possible. A maser for the radiometer operating at 9 Gc/s has been developed, with special emphasis on the high stable performance and the convenience of adjustment and handling in the field installations. Because of the simplicity of the system, this maser employs single tuned cavity using 0.05% ruby which is operated at pushpull operating point at 4.2 °K. In order to simplify the filling procedure of liquid helium from container in the field, we use the glass dewars for convenience. The magnetic field is supplied by a permanent magnet, and it can be slightly adjusted by the exciting current through the two trimming coils wound on the pole pieces. The photograph of this maser is shown in Fig. 1 and its block diagram is in Fig. 2. The characteristics and the methods to improve the gain stability of this maser are as follows.

2. 1. Operating characteristics

The main characteristics of this maser are as follows;

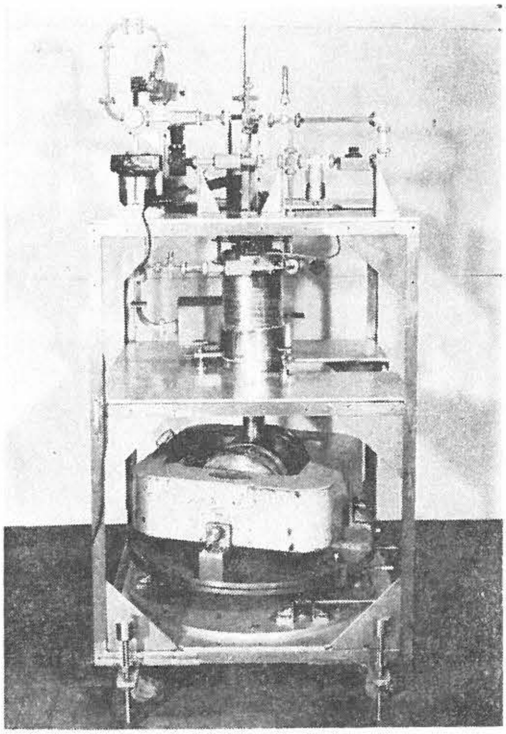

Fig. 1. The maser for the radiometer.

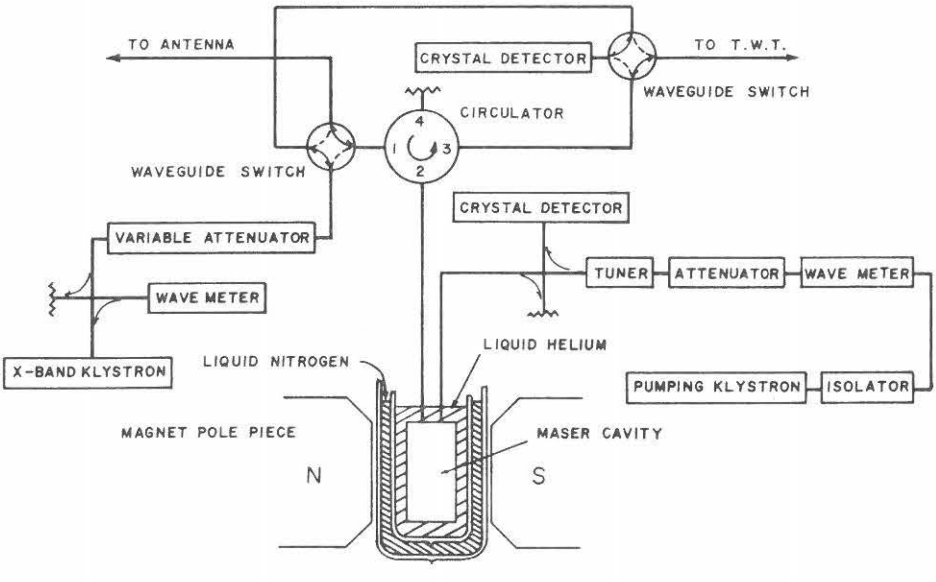

Fig. 2. Block diagram of X-band cavity maser.

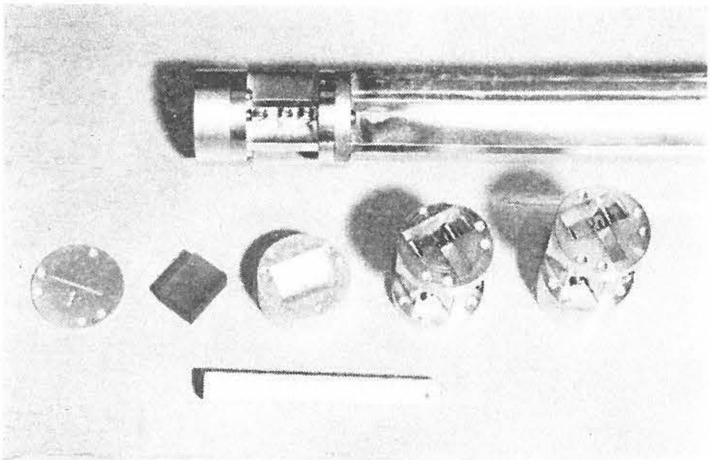

Fig. 3. The cavity assembly.

(1) signal frequency $f_s = 9{,}420$ Mc/s
(2) pumping frequency $f_p = 23{,}700$ Mc/s
(3) gain band-width product $\sqrt{G \cdot B} \simeq 100$ Mc/s
(4) noise temperature $T_n \simeq 40$ °K
(excluding the second stage)
(5) angle between dc field and c-axis $\theta \simeq 54.7° = \cos(1/\sqrt{3})$
(6) gain stability
short term < 30 minutes = 0.1 db
long term < 2 hours = 0.2 db

Since the conventional circulator with 0.3 db insertion loss is used at the input circuit, the noise temperature of the maser is relatively high.

2. 2. Stability

High stable performance of the maser is important particularly for a radiometer, because the variation of the maser gain directly affects the sensitivity of the system. It should be better to divide the factors which affect the maser gain stability into two major items; mechanical and electrical factors.

2. 2. 1. Gain variation due to mechanical factors

Because of the small pole-piece diameter of the magnet, even an extremely small relative motion between cavity and pole pieces results in great gain variation. In order to reduce the variation of the relative position due to vibration and other motions, particular care has been taken to hold the dewar rigidly to the frame. The remote control devices to adjust the coupling and resonant frequency of the cavity were not used in this maser, because they are apt to cause gain instability. The structure and the component parts of the cavity are shown in Fig. 3. The right hand view is the assembled structure of the cavity and the component parts are shown on

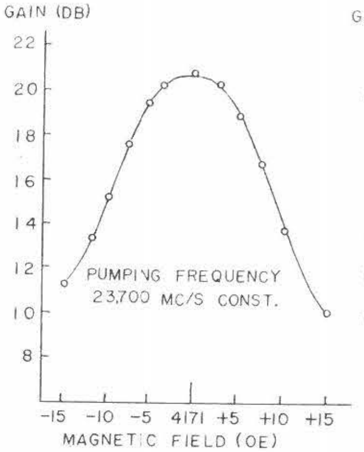

Fig. 4. Change of maser gain as a function of the applied magnetic field (Oe).

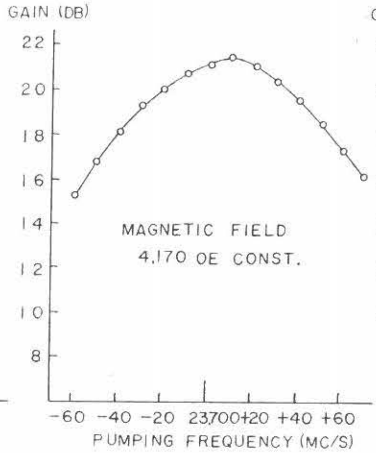

Fig. 5. Change of maser gain as a function of pumping frequency (Mc/s).

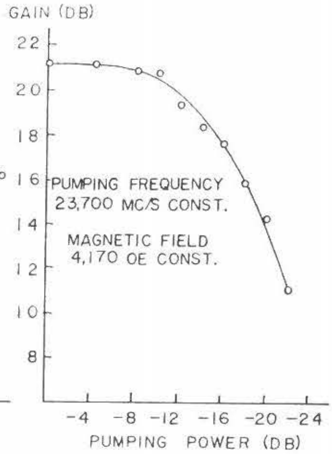

Fig. 6. Change of maser gain as a function of pumping power (db). Pumping power 0 db $\simeq$ 200 mW.

the left side of the Figure. The inner size of the cavity is equal to the dimension of the ruby.

2. 2. 2. Gain variation due to electrical factors

There are four major items which are considered to affect the gain stability; (a) variation of the magnetic field, (b) variation of the pumping frequency, (c) variation of the pumping power and (e) variation of the liquid-helium level in the waveguide. The stability of power supplies is considered to have a large influence on the items (a) to (c). Figs. 4, 5 and 6 are the experimental curves taken to estimate the degree of stability required for the power supplies. From Fig. 4 it is observed that the gain variation is 0.1 db for the field variation of $\pm$ 1 gauss. Therefore, the magnetic field should be stabilized up to 0.01 %. Referring to Fig. 5, pumping frequency variation of $\pm$ 3 Mc/s results in gain variation of 0.1 db. From this it can be said that, since the pumping frequency variation is not so effective to the gain variation, no AFC circuit is required, if a well regulated klystron power supply is used. Referring to Fig. 6, since the pumping power is saturated, APC is not needed. The gain variation due to the variation of liquid-helium level is almost suppressed by filling the waveguide with Polyfoam. Without Polyfoam in the waveguide, gain variation is about 2 db in 2 hours.

2. 3. Adjustment.

Since no external mechanical adjustment is used in this maser, as described above, the structure of the cavity, which is the heart of the maser, is very simple and easy to adjust. Furthermore, that neither AFC nor APC is needed for this maser makes

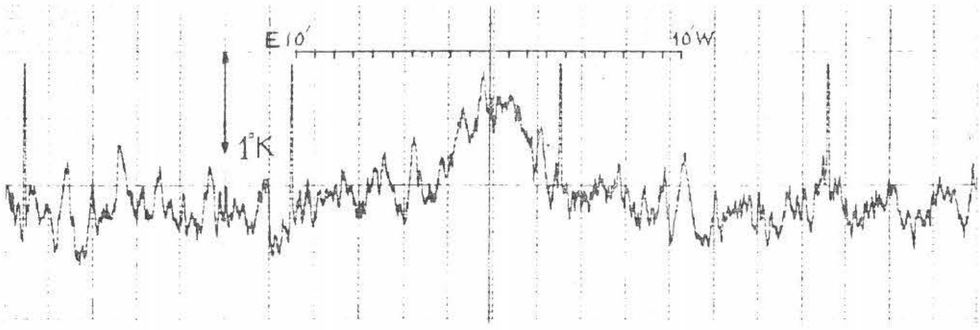

Fig. 7. The chart record of Taurus A.

the whole system very simple. The total power supply for this system is 300 watts. The 1.5 litre helium capacity of dewar allows for 10 hours' continuous operation.

3. Observations

As reported on page 27 in these Proceedings, the interferometer has multiple fan beams and the beam width is 2.2 min. arc near the meridian when it is used as the adding-type interferometer. When it is used as the compound interferometer, the beam width is 0.7 min. arc. The beam spacing is 40 min. arc and the source is scanned by these beams in the east-west direction.

The matched load of room temperature and the pyramidal horn directed toward the zenith were used for the calibration of the receiver, in the same manner as in the solar observations. For the adding-type interferometer, Dicke system was used and another horn directed toward the zenith and the dial attenuator were used for balancing. The integration time was 1.5 seconds and the pen recorder was used.

Even though the maser amplifier was used, the signal to noise ratio was very small, as shown in Fig. 7, because of the small collecting area of the antenna and a large transmission loss. Therefore, the observations were made for one hour on either side of the transit time and every source was scanned about 20-30 times. These scan curves were digitized by hand and superimposed to reduce fluctuations. At the higher order fringes, the beam width becomes wider and the scanning angle gradually changes. But these effects can be neglected approximately up to the 15th fringe.

The right ascensions and the declinations of the radio sources used for the observations are shown in Table I. These values are calculated from the positions of 1959 given by Sloanaker and Nichols.[10] In Figs. 8-12, the origin of the angular scale coincide with the transit time in Table I.

Table I. Position data of the radio sources used for the observations.

Radio Soruce	Epoch	Right Ascension	Declination
Cygnus A	1964. 83	$19^h\ 58^m\ 14.0^s$	40° 36. 4′
Taurus A	1964. 58	$05^h\ 32^m\ 21.8^s$	21° 57. 1′
Orion Nebula	1964. 58	$05^h\ 33^m\ 30.0^s$	− 5° 27. 2′
Omega Nebula	1964. 58	$18^h\ 18^m\ 21.6^s$	− 16° 14. 0′

4. Results.

The averaged drift-curves of the radio sources are shown in Figs. 8 - 12. Figs. 8 - 11 are the drift-curves obtained with 2. 2 min. arc beam. Fig. 12 is the drift-curve of Cygnus A obtained with 0.7 min. arc beam.

The area under the drift-curve of the sun, corrected for the effect of the sharpness of the beam produced by each element of the interferometer compared with the size of the sun (see page 30), is proportional to the flux density of the sun at this frequency which is continuously measured with 1. 2 m dish and the calibrated radiometer. Therefore, flux densities of the radio sources can be calculated from the areas of the drift-curves shown in Figs. 8 - 11. Sizes and flux densities of the radio sources are shown in Table II. The size of the source was calculated from the half-power width of its scan curve, assuming that the brightness distribution of the source and the beam are Gaussian.[1,10,16]

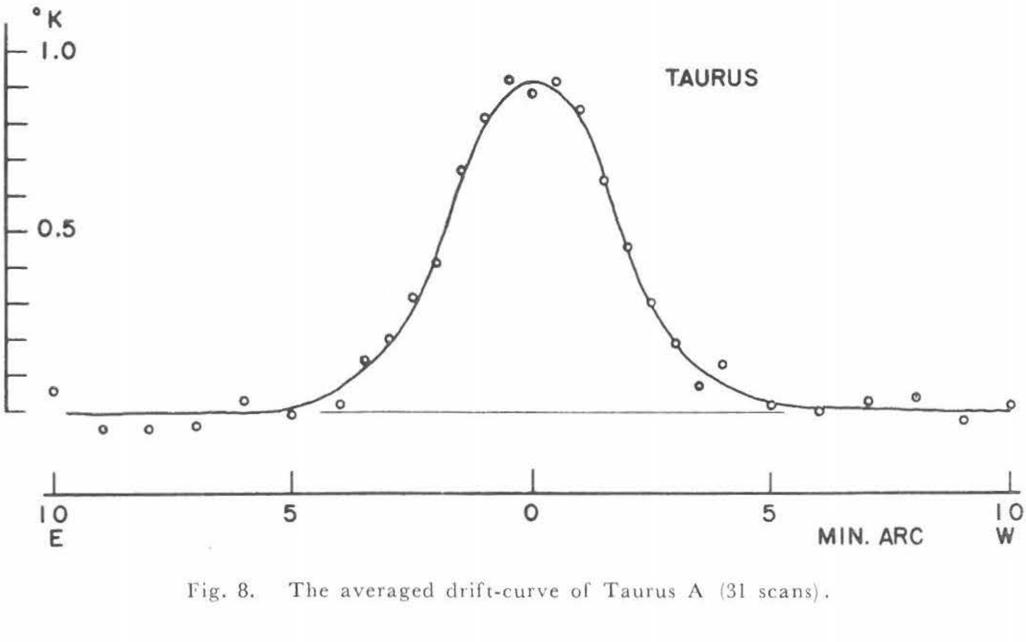

Fig. 8. The averaged drift-curve of Taurus A (31 scans).

Table II. Sizes and flux densities of the radio sources, derived from the observations with 2.2 min. arc fan beam.

Radio Sources	Source Size (min. arc)	Flux Density (10^{-24} W $m^{-2}(c/s)^{-1}$)
Cygnus A	2.8	1.8
Taurus A	3.3	4.5
Orion Nebula	4.4	3.0
Omega Nebula	4.9	4.7

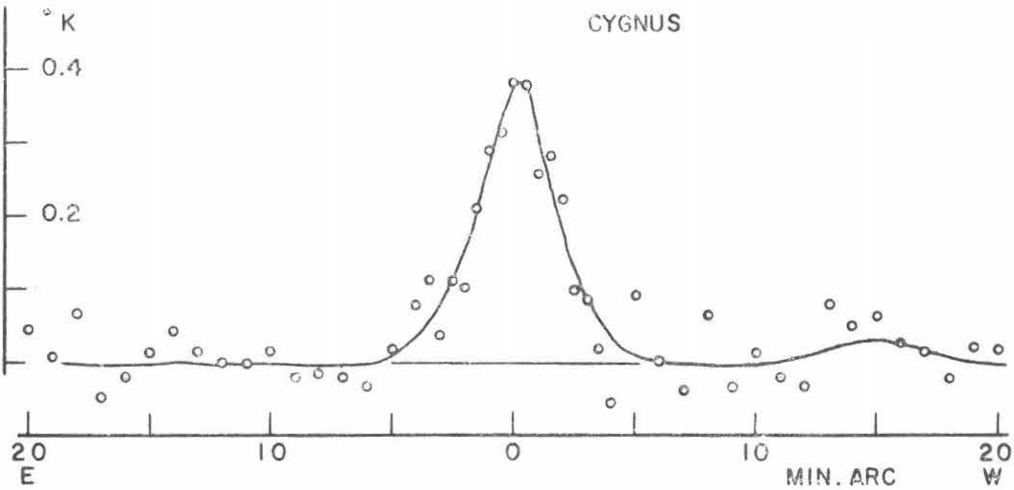

Fig. 9. The averaged drift-curve of Cygnus A (23 scans).

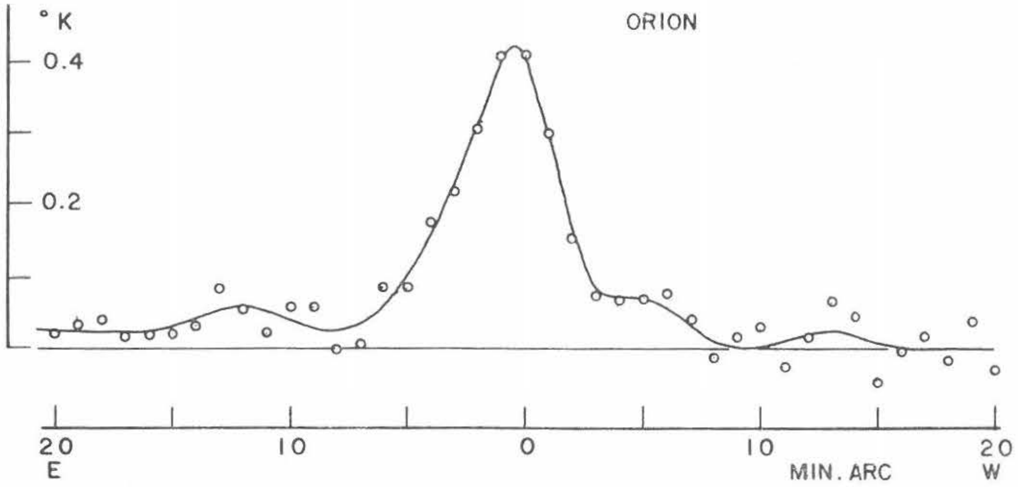

Fig. 10. The averaged drift-curve of Orion Nebula (34 scans).

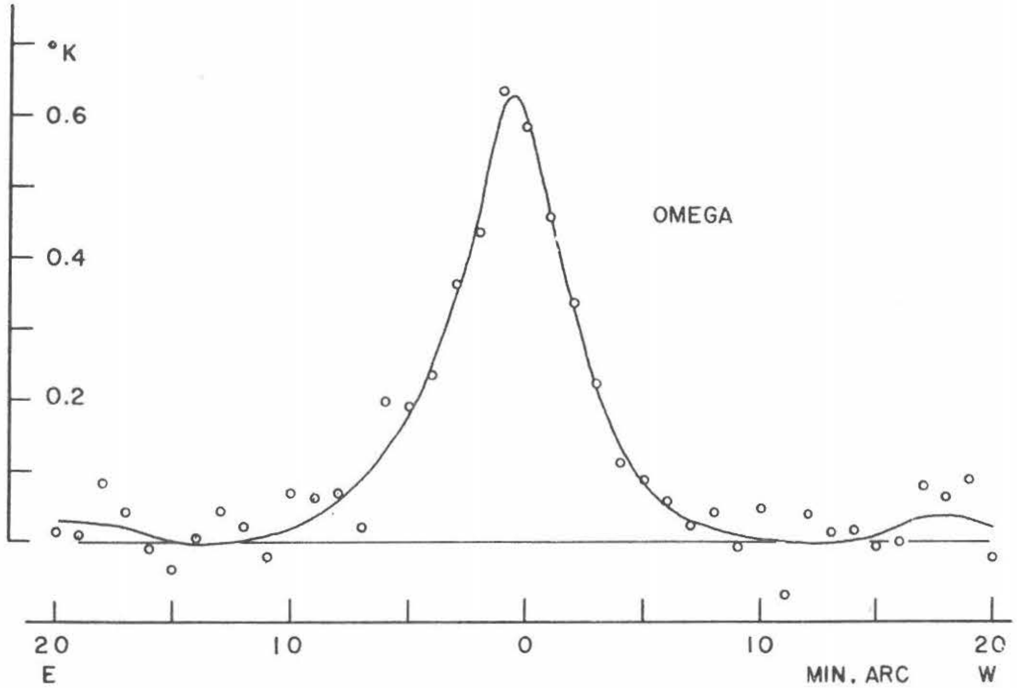

Fig. 11. The averaged drift-curve of Omega Nebula (22 scans).

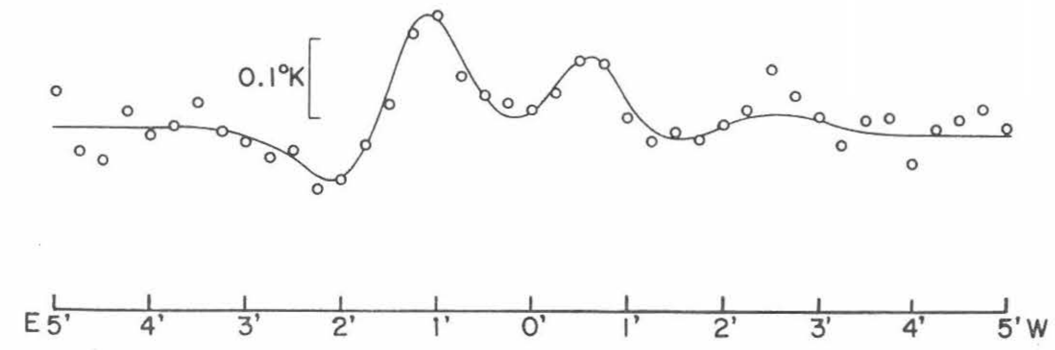

Fig. 12. The averaged drift-curve of Cygnus A, obtained with 0.7 min. arc beam (76 scans).

4. 1. Taurus A.

The angular size is 3.3 min. arc in the east-west direction. The earlier observations, summarized by Little, gave the sizes of 3.25-3.5 min. arc in a range of frequency 1.42 Gc/s to 9.4 Gc/s. Flux density is 4.5 units (1 unit $=10^{-24}$ W $\cdot$ $m^{-2}(c/s)^{-1}$), which agrees with the value read from the spectrum given by Whitfield[5] and is about 10% less than the value read from the spectrum given by Conway, et. al.[6] and 20% less than the value read from the spectrum given by Kuzmin.[29]

4. 2. Cygnus A.

Flux density is 1.8 units, which also agrees with the values read from the spectra given by Whitfield,[5] Conway, et. al.[6] and Kuzmin.[29]

The observation with 0.7 min. arc beam shows, as well known, the double structure. The separation of two components is 100 seconds and the eastern component is about 1.5 times stronger than the western component. Zakharenkov, et. al.[4] have shown that the eastern component is 1.25 times stronger than the western component at this frequency. The observations by Swarup, Thompson and Bracewell[2] at 3.3 Gc/s have shown that the flux densities of two main components are equal and the spacing between them is 98 ± 4 seconds arc. Lequeux[11] has shown that the source consists of two main components spaced 100 seconds arc and a bridge of emission between them and that the intensity ratio of two main components is 1.2 : 1 at 1.42 Gc/s. According to Moffet and Maltby,[12] the intensities of two components are equal at 960 Mc/s and Jennison's[13] observation has shown that the western component is 20% stronger than the eastern component at 127 Mc/s. The discrepancy between the results at 9.4 Gc/s and at 127 Mc/s has been pointed out by Zakharenkov, et. al.[4]

Swarup, Thompson and Bracewell have derived a model of the source, which consists of three components of Gaussian brightness distribution, that is, the component I, which has the half power width of 15 seconds arc, the component II located at a distance of 101 seconds arc from the component I, which has the same flux density as the component I and the half power width of 23 seconds arc, and the component III, which is located between the components I and II and at a distance of 43 seconds arc from the component I and the half power width of 78 seconds arc and the relative flux density of 0.25 at 1.42 Gc/s and 0.38 at 127 Mc/s. The calculated drift-curve from their model for 0.7 min. arc beam, shown by the curve (a) in Fig. 13, does not agree with the observed curve. If the relative flux densities of the components I, II and III are assumed to be 0.376, 0.244 and 0.380 respectively and the angular distances from the component I of the components II and III are taken to be 114 seconds arc and 56 seconds arc respectively, the calculated drift-curve, shown by the curve (b) in Fig. 13, becomes quite similar to the observed one. As the signal to noise ratio is small, we can not derive a definite model of the source. However, our observations seem to show that there is an extended source between two main components and the eastern main component is stronger than the western one.

4. 3. Orion Nebula

The angular size is 4.4 min. arc, which is wider than the 2 min. arc given by Zakharenkov, et. al. and narrower than the 5.1 min. are given by Karachun, et. al.[14] and the 6 min. arc given by Lazarevskii, et. al.[15] Barrett[16] gave a size of 4 min. arc at 16.7 Gc/s. Little[1] gave a source size of 3.5 min. arc at 3.3 Gc/s. Twiss, et. al.[17] and Labrum, et. al.[28] reported a size of 3 min. arc and Lequeux[11] gave a width of 4

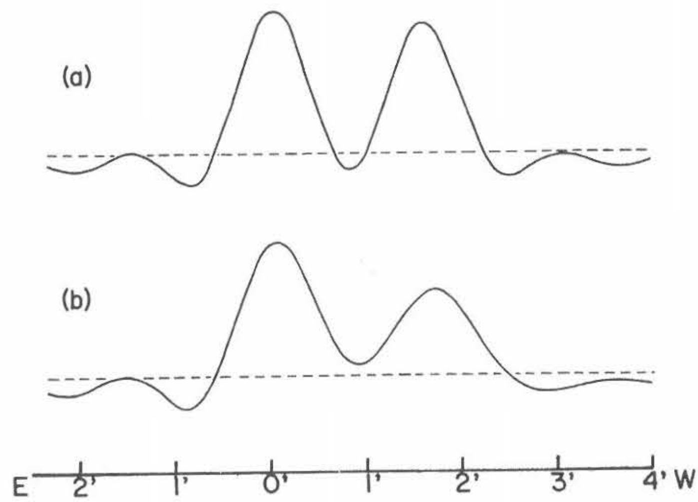

Fig. 13. The theoretical drift-curve for 0.7 min. arc beam of
(a) the model of Cygnus A given by Swarup, et. al. and
(b) the modified model of Cygnus A.

min. arc at 1.42 Gc/s.

Flux densities obtained by earlier observations at 9.4 Gc/s, summarized by Lazarevskii, et. al.,[15] are scattered in a range 2.1 units to 4.5 units. This scattering may be considered to be due to the differences in the resolving power and the sensitivity of the observations. Our observation gives 3.0 units, which is the value inferred from flux densities of 3.43 units at 960 Mc/s and 3.40 units at 3.2 Gc/s given by Conway, et. al.[6] Emission measure of this thermal source is estimated to be 2.4×10^6 pc/cm^6, which agrees with Menon's value.[18]

4. 4. Omega Nebula

The angular size in the east-west direction is 4.9 min. arc, which is narrower than the 5.8 min. arc at 9.4 Gc/s given by Karachun, et. al.[14] and at 1.42 Gc/s given by Lequeux,[11] the 7 min. arc at 16.7 Gc/s given by Barrett,[16] the 7.5 min. arc at 2.93 Gc/s given by Sloanaker and Nichols[10] and the 8 min. arc given by Wilson and Bolton[19] at 960 Mc/s.

Little has shown that this source has a considerable extension on the eastern side and consists of the main strong source 4.3′ wide and two weak sources. The drift-curve at 3.3 Gc/s obtained with 2.3 min. arc beam has a hump on the eastern slope and shows the existence of a weak source located about 3 min. arc east of the main peak. Labrum, et. al.[28] have also shown the existence of the eastern component. The drift-curve in Fig. 11 shows that the source extends on the eastern side, but not explicitly the existence of the eastern weak source.

Flux density is 4.7 units. Karachun et. al.[14] and Zakharenkov, et. al.[4] gave the flux densities at 9.4 Gc/s of 5.0 units and 5.6 units respectively, assuming that the

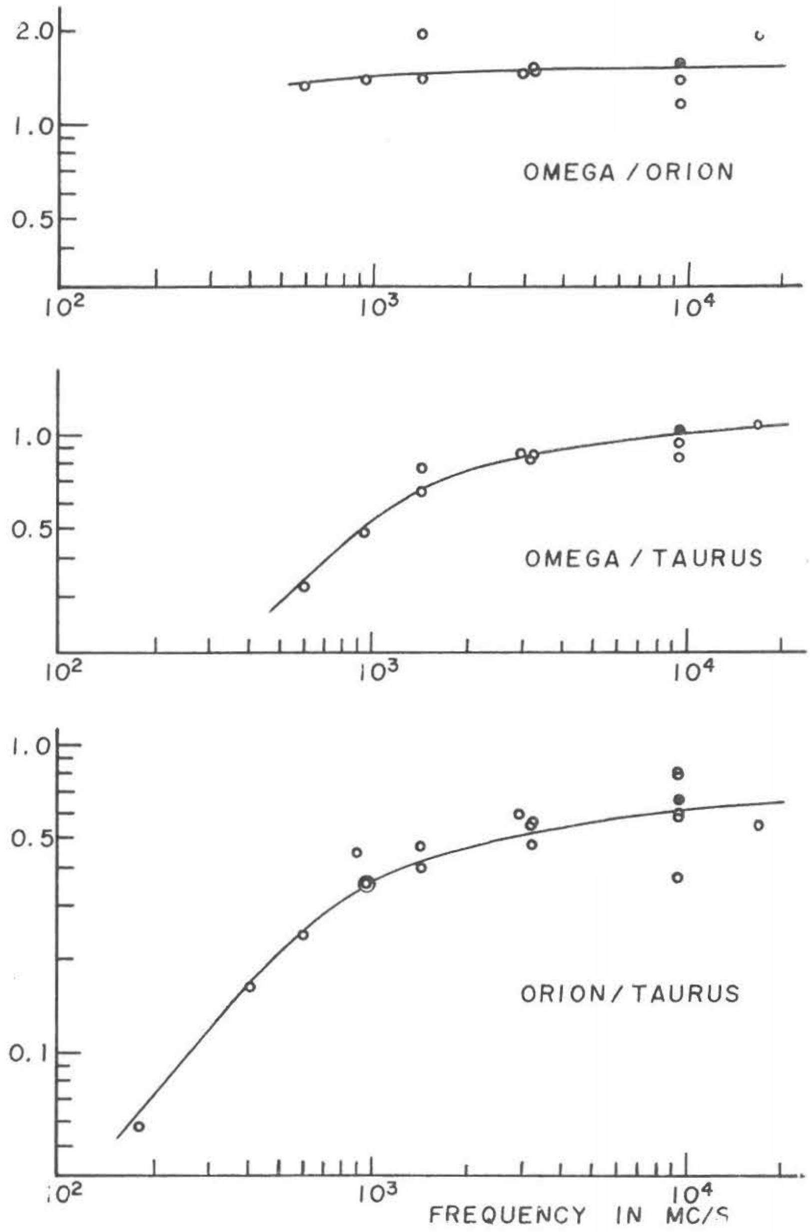

Fig. 14. The frequency spectra of Omega/Taurus, Orion/Taurus and Omega/Orion flux density ratios. Our values are plotted by closed circles.

flux density of Taurus A is 6.0 units.

The estimated emission measure of this source is 3.0×10^{6} pc/cm^{6}, which is about 10 times larger than that given by Hobbs[20] and nearly equal to that of Orion Nebula.[11][21]

The frequency spectra of Omega/Taurus, Orion/Taurus and Omega/Orion flux density ratios are shown in Fig. 14.[4][6][10][11][14][15][16][19][22][23][24][25][26][27] Our ratios seem to lie within

5% of the smoothed spectra.

From the above results of flux density measurements, we may conclude that our scale of flux density at 9.4 Gc/s of the solar observations is nearly equal to the average scale of the galactic or extragalactic observations. The difference may be considered to be less than 10%.

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