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SUPERBRIGHT RADIO "KNOTS" IN THE H II REGION W51

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ABSTRACT

Fringes have been detected from the H II region W51 at a wavelength of 11 cm with an interferometer of lobe separation $\sim 0''.6$. These observations indicate that the brightness temperature may be in excess of 10^5 ° K. Some possible implications of this result are discussed.

I. INTRODUCTION

A map of the brightness temperature of the H II region W51 (G49.5−0.4) has recently been synthesized with the National Radio Astronomy Observatory's three-element interferometer at a wavelength of 11 cm by Turner *et al.* (1970; hereafter referred to as TBCH). The synthesized beam had a half-width of $\sim$8 seconds of arc. The map shows that, within the extended background of G49.5−0.4, there are at least two small components. Component I has a maximum brightness at $\alpha = 19^h24^m21^s.0$ and $\delta = 14°24'50''$, and has a flux density of $\sim$4 f.u. It is elongated to the southeast by about 20″ and appears to contain two subcomponents or "knots" of comparable intensity near its extremities. Component II lies $\sim$30″ to the northwest; its flux density is $\sim$2.3 f.u., and its size is not significantly larger than the beam. Observations at the largest available baseline (2.7 km) show a fringe amplitude of about 0.75 f.u. for each component. Higher-resolution studies of these components were clearly warranted.

II. OBSERVATIONS

The components were observed simultaneously with the NRAO radio-link interferometer at a wavelength of 11 cm (2695 MHz). The baseline was 35 km at an azimuth of 220°, and the minimum lobe separation was $0''.6$. A detailed description of the instrument and calibration procedure will be given elsewhere (Miley and Basart 1970). The elements of the interferometer are a fixed 85-foot paraboloid at Green Bank, West Virginia, and a portable 42-foot antenna. The signal is transmitted to Green Bank by means of a phase-stable radio link. The amplitude and phase were sampled every 15 seconds; within this time interval the rms system noise corresponds to $\sim$0.4 f.u. The finite system bandwidth of $\sim$7 MHz restricts the field of view, or delay beam width of the interferometer (Allen *et al.* 1962), to $\sim$1 minute of arc. Thus the position of a source to be observed must be known to much better than this accuracy before the observations can be performed. For G49.5−0.4 the position used was that of the brightest part of Com-

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ponent I, so that both components of the TBCH synthesis observations were within the delay beam width.

In order to obtain observable fringes on a weak source it is necessary to integrate over several sampling intervals, and the phase change must be small within this integration period. Since the rate of change of phase is proportional to the source offset from the center of the field of view, the dimensions of the field of view are set by the integration period. The field center can be positioned to any point within the delay beam width. A long integration period will improve the signal-to-noise ratio while narrowing the field of view.

III. RESULTS

Fringes were detected from Component I. Their observed amplitude was ~0.3 f.u., or approximately half that measured for Component I using the 2.7-km baseline.

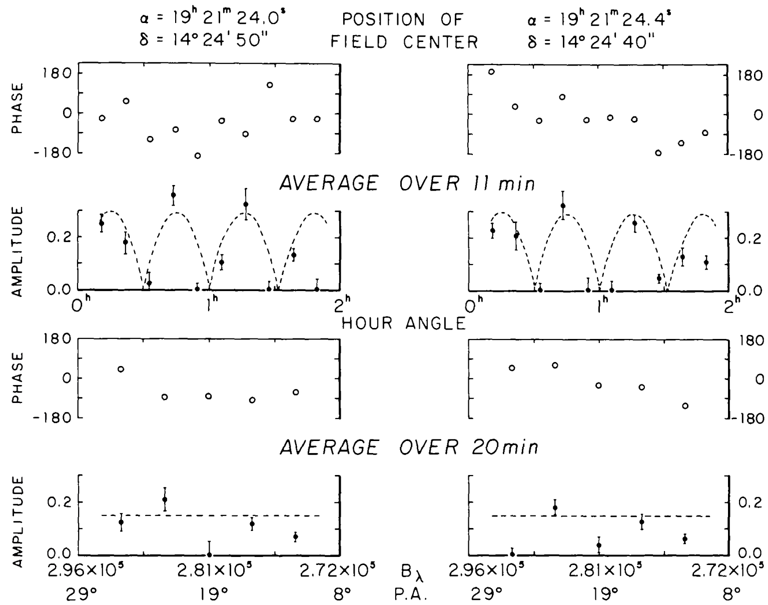

FIG. 1.—Vector averages of the fringe amplitude (in flux units) and phase (in degrees) obtained by centering the field of view at the two strongest points of Component I. Dashed lines represent the fringe amplitude behavior expected from two small sources separated by 12″ in Component I (see text). B_λ is the length of the effective baseline in wavelengths, and P.A. is the position angle of the effective baseline measured from north through east.

Thus the fringe visibility of Component I was still appreciable even though the baseline was 12 times longer. It is therefore probable that a significant fraction of the radiation from Component I is contained in structure less than about 0″.6 in size.

No definite fringes were detected at the position of Component II, although there is some suggestion in the fringe phases of a weak source.

The field of view was centered on each of the two bright knots of Component I as determined from the TBCH synthesis map. Figure 1 shows the vector averages of the fringe amplitudes and phases over 11 and 20 minutes for both positions. The magnitude and orientation of the projected baseline are also indicated.

Both 11-minute averages in Figure 1 suggest beating between two or more small components whose strengths, if unresolved, are 0.15 f.u. with a probable error of 0.05 f.u. For this averaging time the field of view includes all of Component I. The observed beating is consistent with the two "knots" previously mentioned within Component I and spatially separated by about 12″, but the phase behavior indicates that the detailed source structure may be more complex.

Further evidence for the existence of the knots is seen in the 20-minute averages. Each of these had a field of view sufficiently small to exclude sources separated by 12″ in Component I. The phase behavior is seen to be regular and consistent with small knots located within 0″.5 of lines through the centers specified in Figure 1 at a position angle of 20°. Noise is more apparent in the fringe amplitudes, but Vinokur (1965) has shown that they are less responsive to weak signals than the fringe phases. The phase behavior was less regular when the field of view was centered just outside Component I, implying that no comparable structure was in the field.

Any derivation of the brightness temperature depends critically on the structure of the knots, which cannot be established without observations at additional baselines. If we adopt a circular Gaussian model, the minimum possible brightness temperature is $\sim 7 \times 10^5$ ° K. Although other models, particularly highly elongated ones, could yield a lower value, the brightness temperature of the knots is probably not less than 10^5 ° K and could be much greater.

IV. DISCUSSION

In terms of the currently accepted values for the electron temperatures of H II regions between 4000° and 10000° K, brightness temperatures of $\sim 10^5$ ° K are surprising. We shall consider two possible emission mechanisms for these sources assumed to be physically related to W51.

a) Thermal Bremsstrahlung

This process requires the electron temperature T_e to be equal to or greater than the observed brightness temperature T_b. If it is assumed that in the present case $T_e \sim T_b \sim$ 100000° K, then the emission measure, $\int n_e^2\, dl$, along the line of sight is greater than $\sim 6 \times 10^8$ pc cm^{-6}. At the distance of W51, 6 kpc, the observed structure has a linear size of order 0.015 pc, and the electron density n_e is greater than $\sim 2 \times 10^5$ cm^{-3}, a value corresponding to a total mass of $\sim 10^{-2}\, M_\odot$. If, however, the emission originates from several smaller sources, then n_e and T_e must be greater.

From the discussion of Rubin (1968) we derive that at least one star earlier than an O6 is required to account for the observed flux density if it is the only source of ultraviolet radiation exciting the knots. However, Terzian and Balick (1968) note that at least fifty O5 stars are needed to explain the continuum radiation from the whole of G49.5−0.4 within which these sources are located. These might easily provide sufficient excitation for the small components.

In the subsequent discussion, based on that of Hjellming (1966), we investigate the conditions under which T_e can approach 10^5 ° K if thermal processes are assumed. The source of excitation is taken to be several O5 stars. We consider an H II region in equilibrium, i.e., no time-dependent terms and no large-scale energy gradients exist except at the boundaries. The electron temperature is determined by the balance between the heating rate from photoionizations and the cooling rate from (1) recombinations to levels other than the ground state in H and He, (2) free-free emission, and (3) collisionally excited forbidden-line emission of coolants such as C, N, O, and Ne.

The maximum value of T_e obtainable from a solution of the equation of energy balance given by Hjellming under these conditions is 14000° K. Here a density of 2×10^5 cm^{-3} and currently accepted values of the abundances were used. The derived temperature does not change significantly for densities less than 10^6 cm^{-3} and is not sensitive to changes in the coolant abundances by a factor of 2 or to the number of O5 stars.

However, for $T_e < 10^6$ ° K, densities greater than 10^6 cm^{-3} are sufficient to allow collisional de-excitation to dominate over spontaneous emission in the forbidden lines (Osterbrock 1965). In this case, or if the abundances of the coolants are an order of magnitude below their accepted values, cooling from forbidden-line emission can be neglected in the equation of energy balance. Then we derive an electron temperature of $\sim 10^5$ ° K throughout the nebula if we neglect cooling from collisionally excited transitions in H and He. However, the assumption of equilibrium is not valid; mechanical-energy terms which would tend to lower the derived temperature are probably important.

The above detailed calculations corroborate the conclusions of Spitzer (1968) that it would be very difficult to explain a value of T_e greater than 10^5 ° K. Even in a pure-hydrogen H II region T_e is less than the effective color temperature of the exciting star in the far-ultraviolet. T_e is at most a few times the blackbody temperature of the star because of selective absorption of the longer-wavelength ultraviolet radiation.

Thus if temperatures of order of those observed are to be found in nebulae where stellar ultraviolet radiation is the only source of heating, they would probably occur in a young, rapidly evolving H II region where mechanical terms are offset by other effects such as higher densities. Alternatively, if temperatures of this magnitude are to be maintained, then there must be additional sources of energy input. Several of these have been proposed, including bombardment by cosmic rays (Hjellming 1969, 1970), interactions with stellar winds (Pikel'ner 1968; see also Pikel'ner and Scheglov 1969), and mass loss by atmospheric expansion in OB supergiants (Hutchings 1969).

b) Nonthermal Emission

We consider the possibility that the high brightness temperature observed may be produced by nonthermal emission, such as has been proposed for the total flux of compact H II regions by Hughes (1969). He suggests that an interstellar cloud, with associated magnetic field, collapses to form stars; the magnetic energy is dissipated in the acceleration of particles, producing nonthermal radio sources. The cutoff of flux density is attributed to synchrotron self-absorption; and the nearly flat spectrum at high frequencies to normal synchrotron emission. Hughes also suggests that recombination lines can be excited by low-energy cosmic rays which are produced in the source.

The "pre-protostellar" sources considered by Hughes have sizes from 1 to 100 a.u. By comparison, our condensations have sizes of order 3000 a.u. or less. In addition, using the theory of synchrotron self-absorption, he derives cutoff frequencies which are typically 5000 MHz, whereas we would derive a value of 30 MHz if we assumed an angular size of 0".6, a flux density of 2.0 f.u., and Hughes's estimate of 1 gauss for the magnetic field. However, if our condensations consist of several smaller objects, they could be similar to the "pre-protostellar" sources considered by Hughes.

V. CONCLUSIONS

We have established that within one H II region there exists structure on a scale of 0".6. The continuum brightness temperature is the highest yet reported in an H II region of predominantly thermal emission. A detailed understanding of the physical processes involved in the radiation is not possible without more detailed information on the radio knots.

There is at present no information on the spectrum of the very small knots. None can be derived from the spectrum of G49.5−0.4 observed with larger beamwidths ($\sim 2'$) because only 8 percent of its flux originates from Components I and II at 11 cm. Observationally it will be interesting to measure the polarization and spectra. In addition, time variations may be detectable. It has been suggested that star formation takes place in H II regions, and it is possible that the intense knots represent a stage of protostellar contraction. On the other hand, if the knots are clouds of hot gas expanding into a vacuum, they would expand at 3 times the velocity of sound (Smith 1964). If the temperature of the gas is greater than ~ 100000° K, then the sound velocity is greater than ~ 40 km sec^{-1}. At this rate the clouds would double their diameter in less than a century.

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