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DETECTION OF RADIO EMISSION FROM THE BECKLIN-NEUGEBAUER OBJECT

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ABSTRACT

We report the detection of radio emission from the Becklin-Neugebauer (BN) object at 15 and 23 GHz with the VLA. The source is smaller than $0''.07$ and has a brightness temperature greater than 11,000 K. We did not detect it with the Hat Creek interferometer at 88 GHz to a limit of 70 mJy. The spectral index is ~ 2 between 15 and 23 GHz, suggesting that the emission is optically thick in that range but becomes optically thin above ~ 40 GHz. The radio emission could arise from either a homogeneous H II region of electron density $\sim 10^{7}$ cm^{-3} or an ionized stellar wind with a finite recombination radius. In either case, the total mass of hydrogen is $\sim 10^{-6}\ M_\odot$ and the radius is $\sim 3 \times 10^{14}$ cm. The volume emission measure ($\sim 10^{60}$ cm^{-3}) derived for the wind model is consistent with the 4 μm Brα flux density. However, if the radio H II region is homogeneous, the Brα emission must come from a second, denser component of smaller angular size.

Only one other compact continuum radio source was found within 30″ of BN, at a 3 σ flux density limit of 3 mJy at 15 GHz. It has a flux density of 5 mJy and is not coincident with any of the infrared sources in the Orion-KL region. We detected no emission from IRc2.

Subject headings: infrared: sources — nebulae: H II Regions — nebulae: Orion Nebula — radio sources: spectra — stars: formation — stars: mass loss

I. INTRODUCTION

The Becklin-Neugebauer (BN) object in the Orion-KL region has been extensively studied at infrared wavelengths. Its properties are summarized by Scoville (1981) and Scoville *et al.* (1983). Observations of near-IR recombination lines show that BN has an ionized shell of gas with a volume emission measure of $\sim 2 \times 10^{59}$ cm^{-3}, assuming optically thin emission. Radio emission had been searched for but not found at 5 GHz by Simon *et al.* (1981).

We observed the Orion Nebula at 5 and 15 GHz with the Very Large Array (VLA) of the National Radio Astronomy Observatory[2] for the purpose of finding compact H II regions indicative of massive young stars. We found about 20 compact sources in the entire nebula but only two in the immediate vicinity of the BN-KL region. One of these sources was coincident with the BN object. Subsequently, we observed the BN source on two more occasions with the VLA and with the Hat Creek Millimeter Interferometer. We describe the measurement of BN in this *Letter*. The other objects are discussed by Garay (1983) and Moran *et al.* (1982).

II. OBSERVATIONS AND RESULTS

a) *VLA*

The circumstances and results of the BN measurements are listed in Table 1. The position of the radio source is:

$$\alpha(1950) = 05^{h}32^{m}46^{s}.64 \pm 0^{s}.01;$$

$$\delta(1950) = -5^{\circ}24'16''.45 \pm 0''.1.$$

The (1 σ) errors are dominated by uncertainties in the calibrator positions (Perley 1982) and other systematic effects. The radio source is coincident, within the errors, with the infrared source whose position is $\alpha = 05^{h}32^{m}46^{s}.69 \pm 0^{s}.05$, $\delta = -5^{\circ}24'16''.6 \pm 0^{s}.5$ (Downes *et al.* 1981). The radio source is unresolved, and we set a conservative upper limit on its size, based on the 1982

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TABLE 1

RADIO OBSERVATIONS OF THE BN OBJECT

Date	Instrument	Frequency (GHz)	Phase Ref.	Flux Ref.	Beam[a] (arcsec)	Source[b] (arcsec)	S[c] (mJy)	RMS[d] (mJy)
1981 Aug 9	VLA(B)[e]	4.9	0539−057	3C 147/3C 286	1.1, 1.0(−9)	...	< 2	0.7
1981 Aug 9	VLA(B)	15.0	0539−057	3C 147/3C 286	0.38, 0.32(−9)	0.37, 0.32(40)	8.5 ± 1.5	0.8
1981 Nov 16	VLA(C)	22.8	0420−014	3C 286	0.8, 0.7(−1)	0.7, 0.6(145)	22 ± 5	2.1
1982 Apr 25	VLA(A)	15.0	0539−057	3C 286	0.14, 0.10(3)	0.15, 0.10(54)	9.0 ± 3[f]	1.0
1981 Dec–1982 Apr.......	HCMI[g]	87.6	SiO maser	SiO maser	7, 2(0)	...	< 70	15

[a] FWHM beam size with uniform weight position angle of major axis in degrees in parentheses.
[b] FWHM source size before deconvolution.
[c] Flux density.
[d] RMS noise level per resolution element in interferometer map.
[e] Very Large Array with configuration in parentheses.
[f] This has been corrected assuming a coherence factor of 0.7 due to atmospherically induced phase noise.
[g] Hat Creek Millimeter Interferometer.

April data at 15 GHz, of 0″.07. The map from these observations is shown in Figure 1.

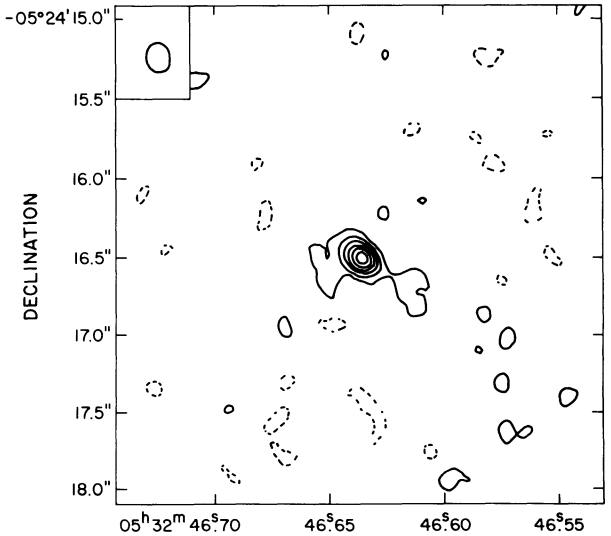

FIG. 1.—VLA map of the region around BN at 15 GHz from 1982 April. Natural weighting was used and the map was restored using the CLEAN algorithm. The contours are −30%, −15%, 15%, 30%, 45%, 60%, 75%, and 90% of the peak flux density of 9 mJy. The beam pattern is shown in the upper left corner.

The only other compact source that we detected with the VLA at 15 GHz above our noise threshold of 3 mJy (for unresolved sources) within 30″ of BN was located ~ 12″ east of BN at a position of $\alpha = 05^h32^m47^s.42$, $\delta = -05°24'18''.8 \pm 0''.1$. Its flux density is 5 mJy, and it is not coincident with any of the compact 20 μm infrared sources (Downes *et al.* 1981).

We did not detect radio emission from IRc2. If there is a radio source, then its radius must be less than 0″.025 (2×10^{14} cm at a distance of 500 pc) for an electron temperature of 10^4 K. The failure to detect an H II region associated with IRc2 may be due to the very high mass loss rate expected from that object, so the embedded star is only capable of ionizing a thin shell near the stellar surface which is too small to be detected at radio wavelengths (cf. Downes *et al.* 1981). If the inner radius of ionization is the stellar radius, ~ 10^{12} cm, the flow velocity is 10^2 km s^{-1}, and the stellar luminosity is 10^5 $L_\odot$ (corresponding to an O7 zero age main-sequence [ZAMS] star with an ionizing photon flux of 4×10^{48} s^{-1} [Panagia 1973]), then the flow will be ionized to the detectable radius only if the mass loss rate is less than 4×10^{-6} $M_\odot$ yr^{-1}. The mass loss rate deduced from molecular flows associated with IRc2 is 10^{-2}–10^{-4} $M_\odot$ yr^{-1} (Genzel *et al.* 1981), so we expect the ionized region to be confined to an exceedingly thin shell around the star.

b) *Hat Creek*

The Orion molecular cloud was observed at 3.4 mm wavelength with the two-element millimeter interferometer of the Hat Creek Observatory between 1981 December and 1982 April. The source was observed for a total of 22 hours on four baselines with projected lengths from 16 to 80 × 10^3 wavelengths. The SiO maser in IRc2, which was simultaneously observed in a multichannel receiver, was used as an amplitude and phase reference. The maser flux density of 800 Jy, averaged over a velocity range of 14.7–17.3 km s^{-1}, was calibrated with measurements of Venus and Mars using brightness temperatures given by Ulich (1981). The system operated in a double-sideband mode and covered the frequency ranges of 85.92–86.22 and 89.04–89.34 GHz. These bands contained the strong lines of HCO$^+$ and SO, which were mostly resolved on the long baselines. The map contained substantial molecular emission from the molecular cloud region but no emission at the position of BN. The rms deviation in the map away from the Kleinmann-Low Nebula was 16 mJy, close to the theo-

TABLE 2

MODELS OF RADIO EMISSION

Model[a]	r_0[b] (10^{14} cm)	n_0[c] (10^7 cm^{-3})	θ[d] (arcsec)	$\dot{M}$[e] (10^{-6} $M_\odot$ yr^{-1})	M[f] (10^{-6} $M_\odot$)	VEM(R)[g] (10^{59} cm^{-3})	F(Brα)[h] (10^{-11} ergs cm^{-2} s^{-1})	N_i[i] (10^{45} s^{-1})	ZAMS[j]
1	3.1	0.75	0.08	...	0.8	0.07	0.3	1.4	B1
2	2.2	1.4	0.06	...	0.5	0.09	0.15	1.1	B1
3	3.8	0.16	0.09	0.8	1.0	13	11[k]	260	B0
4	2.7	0.35	0.06	0.8	0.8	16	7[k]	190	B0

[a] Uniform density models: (1) $T_e = 10^4$ K and (2) $T_e = 2 \times 10^4$ K; truncated power-law models, $n_e = n_0(r_0/r)^2$, $r < r_0$, and $n_e = 0$, $r > r_0$: (3) $T_e = 10^4$ K and (4) $T_e = 2 \times 10^4$ K.

[b] Radius of ionized region.

[c] Density at r_0.

[d] Angular diameter of radio source at 15 GHz assuming a distance of 500 pc.

[e] Mass loss rate (see Panagia and Felli 1975).

[f] Mass of ionized gas.

[g] Volume emission measure assuming an inner radius of 5×10^{11} cm.

[h] Predicted flux density for the Brα line. The measured flux density, corrected for extinction, is 6×10^{-11} ergs cm^{-2} s^{-1}.

[i] Required number of ionizing photons.

[j] ZAMS (Panagia 1973).

[k] Slightly optically thick (Simon *et al.* 1983).

retically expected value of 11 mJy. We place a limit on the flux density of the BN object at 70 mJy, which is 3 σ plus a 40% allowance for error in the amplitude scale.

III. DISCUSSION

Our results strongly constrain the physical conditions of the ionized gas surrounding the BN object. Below 23 GHz, the radio source has the spectrum of a blackbody and is smaller than 0".07, which means that the brightness temperature is at least 11,000 K if the source is uniformly bright. At 88 GHz the source would have a flux of 300 mJy if it were a blackbody, but we could not detect it at the level of 70 mJy. Hence, it must have a turnover frequency in the range of 30–50 GHz, and the electron density, at least at the outer surface of the source, is probably in the range of 10^6–10^7 cm^{-3}. The electron temperature in a normal H II region is expected to be close to 10^4 K but could conceivably be as high as 3×10^4 K, the effective temperature of an early B star. The microwave flux densities imply a source radius of 0".04 or 0".013 for 10^4 or 3×10^4 K, respectively, which correspond to 20 or 7 AU. We have assumed throughout that the radio emission is due to thermal bremsstrahlung. If the emission were nonthermal, the source size could be much smaller.

The radio spectrum can be explained by two possible models. The simplest model is that the source is a compact H II region of uniform density. In this case, the size of the unresolved H II region can be derived from the flux density in the optically thick part of the spectrum, assuming an electron temperature. The electron density and ionized mass can be calculated from the radius and turnover frequency (~ 40 GHz). Parameters for two cases at 10^4 and 2×10^4 K are given in Table 2 (models 1 and 2). The resulting spectra are shown in Figure 2. The volume emission measures are about 10^{58} cm^{-3}, which are about a factor of 30 smaller than predicted from the Brα line strength, corrected for 1.2 mag of 4 μm extinction (Scoville *et al.* 1983; Simon *et al.* 1983). Hence, an additional small source of high electron density close to the star may be required to account for the excess Brα line emission, which would

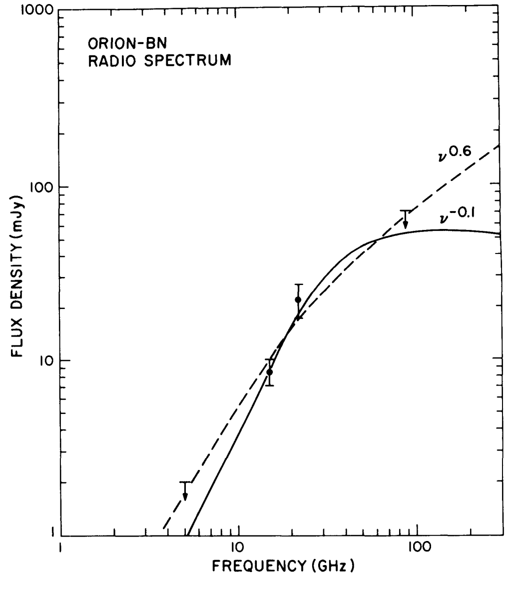

FIG. 2.—The radio spectrum of the Becklin-Neugebauer object. The error bars are 1 σ values with allowance for noise and systematic effects. The upper limits at 5 and 88 GHz are 3 σ values with allowance for systematic effects. The solid curve is the spectrum of a sphere of uniform electron density with parameters of models 1 and 2 in Table 2. The dashed curve is the spectrum of a stellar wind source of finite recombination radius with the parameters of models 3 and 4 in Table 2.

be optically thick and small enough not to contribute to the radio flux density. It is possible that this source is collisionally excited to the low principal quantum states without photoionization, thereby further enhancing the Brα flux density with respect to the free-free flux density (Krolik and Smith 1981).

The second possibility we considered is that the radio emission arises from a stellar wind source of finite recombination radius as described by Marsh (1975), Felli and Panagia (1981), and Simon *et al.* (1983). This model is prompted by the broad wings on the Brα profile, indicative of high-velocity motion. We assume that the flow has a constant temperature and velocity so the electron density is given by $n_e = n_0(r_0/r)^2$, where r is the radius and n_0 is the electron density at r_0, the recombination radius. If the flow were ionized to infinity, the radio flux density would be proportional to $\nu^{0.6}$ at all frequencies (Wright and Barlow 1975; Panagia and Felli 1975). With a finite recombination radius, the radio emission is optically thick virtually to the projected edge of the ionization at sufficiently low frequencies and the spectrum is that of a blackbody. At higher frequencies, the source becomes progressively thinner at the edges and the spectrum has a spectral index of 0.6. Parameters which fit the data are given in Table 2. The spectra for these models (3 and 4) gave the lowest possible flux at 88 GHz while not exceeding the error limits of the flux densities at lower frequencies. Hence, models of this type are just barely consistent with the spectral data. The volume emission measure in this case is

$$\mathrm{VEM} \approx 1.25 \times 10^{60} \left(\frac{n_0}{10^7}\right)^2 \left(\frac{r_0}{10^{14}}\right)^4 \left(\frac{r_i}{10^{11}}\right)^{-1} \mathrm{cm}^{-3},$$

where r_i is the inner radius. Taking r_i to be 5×10^{11} cm, a typical radius for a B0 star, gives VEM values of about 1.5×10^{60} cm^{-3}. Hence this wind model predicts more Brα emission than is observed by factors of 8 and 4 for the cases where $T_e = 10^4$ and 2×10^4 K, respectively, if the Brα emission is thin. This discrepancy can be explained if the Brα emission is slightly optically thick (Simon *et al.* 1983) or if the density decreases more slowly than r^{-2} (Scoville *et al.* 1983). The reason for the greatly increased ratio of Brα to radio flux in models 3 and 4 compared to 1 and 2 is that, in the wind model, the radio emission is optically thick except near the edge, whereas the Brα line is formed much deeper in the envelope where the electron density is very much higher. The required number of Lyman continuum photons is 4×10^{47} s^{-1} corresponding to a B0 ZAMS star. The luminosity of a B0 exciting star is about 2×10^4 $L_\odot$, while estimates of the luminosity of BN from models of the spectrum from 1 to 20 μm range from 3000 to 20,000 $L_\odot$ (cf. Aitken *et al.* 1981; Bedijn, Habing, and de Jong 1978). The agreement seems satisfactory, in view of the uncertainties.

The truncated wind model explains the Brα and microwave flux densities in a manner that is reasonably consistent with radiation due to photoionization. The finite recombination radius could be due to a limited number of ionizing photons (although only 0.1% additional photons would be needed to ionize the flow to infinity) or to a dense neutral cloud of gas surrounding the flow. The small measured diameter of the 600 K dust shell at 4 μm of less than 6×10^{14} cm (Foy *et al.* 1979) may be evidence for this neutral cloud. Centimeter observations at higher angular resolution and millimeter measurements are needed to clarify the nature of the ionized source and to distinguish between models of different density laws.

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