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THERMAL RADIO SOURCES IN BOK GLOBULES

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ABSTRACT

We report VLA-D 6 cm continuum observations of 10 radio sources previously detected at $\lambda=3.6$ cm towards a sample of 7 Bok globules. All sources, with the exception of CB 34 VLA1, were detected at 6 cm. We find that the spectral indices $\alpha_{(6-3.6\ \mathrm{cm})}$ of the emission from these objects cover a wide range, from $\geqslant -3.5$ to 1.4. Large negative spectral indices suggesting nonthermal emission were found for the sources CB 205 VLA1, CB 205 VLA3, and CB 230 VLA1, and we cannot conclude that these sources are embedded in the Bok globules CB 205 and CB 230. Spectral indices $\alpha_{(6-3.6\ \mathrm{cm})}\geqslant -0.1$ are exhibited by the sources CB 34 VLA1, CB 54 VLA1, CB 108 VLA1, CB 171 VLA1, CB 205 VLA2, CB 230 VLA2, and CB 244 VLA1. Thus, the cm radio continuum emission from these sources is consistent with a thermal origin, indicating that the sources are embedded in the globules. In particular, we propose CB 108 VLA1, CB 171 VLA1, and CB 205 VLA2 to be genuine Class 0 protostar candidates. © *1997 American Astronomical Society.* [S0004-6256(97)01304-6]

1. INTRODUCTION

Bok globules, the smallest dark molecular clouds known in the Galaxy, are nearby, fairly isolated, and usually display regular shapes (Clemens & Barvainis 1988). Because their structures are relatively simple, the small globules are convenient for studying low-mass star formation, as well as for probing the physical properties present in molecular clouds and cores prior to the onset of gravitational collapse.

Low-mass star formation is a rather common phenomenon in Bok globules (e.g., Yun & Clemens 1990, 1994a; Alves & Yun 1995; Moreira & Yun 1995). Using a variety of means, namely *IRAS* data, millimeter spectral line, and deep near-infrared array imaging survey and photometry, the nature of the young stellar object (YSO) content in Bok globules has been assessed (Yun & Clemens 1994a, 1994b). Most studies of YSOs in these clouds were carried out at infrared wavelengths. However, the youngest (a few times 10^4 yr) protostellar sources known to date, classified as "Class 0" protostars to designate sources which have yet to accrete the bulk of their initial main-sequence mass from their infall envelopes (André *et al.* 1993), are usually undetectable at wavelengths shorter than 10 μm, but are luminous in the mm/submm and centimeter wavelength regions. A practical way used to show the existence of a protostar embedded within a dense circumstellar cocoon is the detection of a central, compact radio continuum source using the Very Large Array (VLA). In fact, most of the Class 0 candidates identified so far were detected at cm continuum wavelengths using the VLA (see Anglada 1995, 1996).

During 1995 we have carried out VLA-D 3.6 cm continuum observations towards a sample of 19 Bok globules. The main goals of our VLA observations were to search for new members of the protostellar Class 0 and to establish a more reliable sample of candidate starless Bok globules. From these observations we have detected 41 radio continuum sources (Yun *et al.* 1996, hereafter paper I). Of the 41 sources detected, 11 sources were located within the optical extent of the globules, 8 sources were located at the edge of the observed globules, and 22 sources were located far away from the optical limits of the globules (thus, likely to be background objects). Of the 11 sources located within the optical extent of the globules, 7 sources were considered to be Class 0 protostar candidates.

In this paper, we report a 6 cm continuum emission study of 10 of the 11 sources detected at 3.6 cm (paper I) toward 7 Bok globules, namely the determination of their spectral indices (between the wavelengths of 3.6 and 6 cm) in order to establish the nature of the continuum emission. Our main goal was to check the YSO nature of these sources seen towards our sample of Bok globule cores, thus better characterizing the stellar content and star formation efficiency of these clouds. In Sec. 2 we describe the observations and data reduction. In Sec. 3 we present and discuss our results, and in Sec. 4 we summarize our conclusions.

2. OBSERVATIONS AND DATA REDUCTION

Radio continuum observations at $\lambda=6$ cm were carried out toward Bok globules CB 34, CB 54, CB 108, CB 171, CB 205, CB 230, and CB 244 using the VLA of the National

TABLE 1. Bok globules observed at $\lambda=6$ cm continuum.

Bok Globule	Phase Center $\alpha(1950)$	$\delta(1950)$	Phase Calibrator[a] (1950)	rms (μJy)
CB 34	$05^h44^m02^s.44$	$+20°59'22''.0$	0528+134 (5.2)	40
CB 54	07 02 06.34	−16 18 42.0	0727−115 (3.0)	20
CB 108	18 00 02.69	−20 49 44.1	1730−130 (8.1)	60
CB 171	18 59 16.93	−04 35 32.7	1801+010 (0.8)	30
CB 205	19 43 19.85	+27 46 19.3	2021+317 (3.0)	40
CB 230	21 16 46.01	+68 05 29.8	2229+695 (0.4)	20
CB 244	23 23 48.82	+74 01 09.5	2229+695 (0.4)	20

[a]The numbers in parenthesis are the observed flux densities (Jy) of the phase calibrators.

Radio Astronomy Observatory (NRAO)[1] in the D-configuration during 1996 June 30 (02-07 LST) and September 5 (17-19 LST). A bandwidth of 100 MHz with two circular polarizations was set. We used 3C48 as flux calibrator (adopted flux density=5.6 Jy at 6 cm). In Table 1 we list the phase calibrators used for the observations, as well as their bootstrapped flux densities and the noise level (rms) reached in each map. As phase centers (Table 1) we used the positions of the radio continuum sources CB 34 VLA1, CB 54 VLA1, CB 108 VLA1, CB 171 VLA1, CB 205 VLA2, CB 230 VLA1, and CB 244 VLA1 detected at 3.6 cm (paper I). The individual on-Bok globule integration time was about one hour. The data were calibrated and processed using standard procedures of the Astronomical Image Processing System (AIPS) package of the NRAO.

3. RESULTS AND DISCUSSION

3.1 Spectral Indices

Radio continuum emission at $\lambda=6$ cm was detected towards all radio sources lying within the optical extent of the globules and previously detected at 3.6 cm, except for the source CB 34 VLA1. All the sources are compact for our synthesized beams. They are listed in Table 2 together with their positions, flux densities at both 6 cm (this paper) and 3.6 cm (paper I), and spectral indices $\alpha_{(6-3.6\ \mathrm{cm})}$ derived between these two frequencies ($S_\nu \propto \nu^\alpha$). We find that the spectral indices of the emission from the sources in our sample, in the wavelength interval from 3.6 to 6 cm, span over a wide range, from $\geqslant -3.5$ to 1.4. Sources CB 205 VLA1, CB 205 VLA3, and CB 230 VLA1 exhibit large negative spectral indices. The remaining sources have $\alpha_{(6-3.6\ \mathrm{cm})} \geqslant -0.1$. The spectral indices can be used to help in the interpretation of the nature of the sources.

3.2 Sources With Large Negative Spectral Index

CB 205 VLA1 and CB 205 VLA3 are separated from their corresponding phase centers by a distance greater than a half of the primary beam size at 3.6 cm ($\sim 5'.4$), hence a minimum primary beam correction of a factor of two to their 3.6 cm flux densities has been applied. Therefore, we can only determine lower limits for the spectral indices shown by the sources CB 205 VLA1 and CB 205 VLA3 (−1.0 and −3.5, respectively). As a result, we cannot establish reliably the nature of the radio emission from these two objects, and we will not consider these sources here any further.

The source CB 230 VLA1 exhibits a spectral index of −1.8. This value appears to be inconsistent with that expected from thermal emission. In fact, Rodríguez *et al.* (1993) have shown that sharply negative spectral indices cannot occur for thermal processes involving free-free emission and absorption. They concluded that a thermal bremsstrahlung source could display a sharply negative index only if the intrinsic source is optically thin and significant dust absorption extends to the lowest frequencies observed. For CB 230 VLA1, this would require both very large amounts of dust, and greater than centimeter-size dust grains in order to absorb 5–8 GHz photons efficiently. Thus, thermal emission, even with a component of absorption by dust, does not seem to be a viable model for this source. Therefore, the spectral index exhibited by CB 230 VLA1 provides strong evidence for nonthermal emission. However, this spectral index is much steeper than typical (−0.8 to −0.3) negative spectral indices found for nonthermal emitting sources within star-forming regions (e.g., Rodríguez *et al.* 1989; Martí *et al.* 1993; Curiel *et al.* 1993; Reid *et al.* 1995), indicating that CB 230 VLA1 might be a background source. Hence, we cannot conclude that CB 230 VLA1 is embedded in Bok globule CB 230.

3.3 Sources With Positive Spectral Index

CB 34 VLA1, CB54 VLA1, CB 108 VLA1, CB 171 VLA1, CB 205 VLA2, CB 230 VLA2, and CB 244 VLA1 exhibit positive spectral indices $\alpha_{(6-3.6\ \mathrm{cm})} \geqslant -0.1$ indicating that the radio emission from these objects is likely to be of thermal nature. Sources CB 54 VLA1, CB 108 VLA1, and CB 205 VLA2 have spectral indices of 0.0, −0.1, and 0.0, respectively, which are consistent, within the errors, with the value expected for optically thin free-free emission of −0.1. The spectral indices found for the sources CB 34 VLA1, CB 171 VLA1, CB 230 VLA2, and CB 244 VLA1 appear to indicate that the thermal emission is partially optically thick, with the emission from CB 230 VLA2 being the most opaque.

In paper I, we have proposed that the centimeter continuum emission from this sample of radio sources arises from circumstellar gas partially ionized by a powerful stellar wind (Anglada *et al.* 1992; Anglada 1995). The positive spectral indices of sources CB 34 VLA1, CB54 VLA1, CB 108 VLA1, CB 171 VLA1, CB 205 VLA2, CB 230 VLA2, and CB 244 VLA1, indicative of free-free thermal emission, suggest that these sources are internally excited, and hence, that they are associated with their central stars within the Bok globules.

From the correlation of Anglada (1996), between the momentum rate in the outflow and the centimeter continuum luminosity, we have computed the momentum rate in the outflow associated with each of the thermal sources CB 34 VLA1, CB54 VLA1, CB 205 VLA2, CB 230 VLA2, and CB 244 VLA1 (see Table 2). We find momentum rates of the order of 10^{-4} $M_\odot$ yr^{-1} km s^{-1}, which are similar to the

[1]The NRAO is operated by Associated Universities Inc., under cooperative agreement with the National Science Foundation.

TABLE 2. Radio continuum sources.

Source name	Position[a] α(1950)	δ(1950)	S_ν (6 cm)[b,c] (mJy)	S_ν (3.6 cm)[a,c] (mJy)	Spectral Index $\alpha_{(6-3.6\ \mathrm{cm})}$	$\dot{P}$[d] (10^{-4} $M_\odot$ yr^{-1} km s^{-1})
CB 34 VLA1	$05^h44^m02^s.44$	$+20°59'22''.0$	$\leqslant$0.16[e]	0.2	$\geqslant+0.4$	$\leqslant$1.4
CB 54 VLA1	07 02 06.34	−16 18 42.0	0.2	0.2	0.0	1.7
CB 108 VLA1	18 00 02.69	−20 49 44.1	6.7	6.5	−0.1	–
CB 171 VLA1	18 59 16.93	−04 35 32.7	1.1	$\geqslant$1.2[f]	$\geqslant+0.2$	–
CB 205 VLA1	19 43 07.41	+27 43 46.4	1.0	$\geqslant$0.6[f]	$\geqslant-1.0$	–
VLA2	19 43 19.85	+27 46 19.3	1.2	1.2	0.0	12.6
VLA3	19 43 32.95	+27 46 49.5	13.0	$\geqslant$2.2[f]	$\geqslant-3.5$	–
CB 230 VLA1	21 16 46.01	+68 05 29.8	0.5	0.2	−1.8	–
VLA2	21 16 53.53	+68 04 52.4	0.1	0.2	+1.4	0.8
CB 244 VLA1	23 23 48.82	+74 01 09.5	0.3	0.4	+0.6	2.7

[a]Position and fluxes measured at 3.6 cm (paper I).
[b]From this paper. Synthesized beam sizes are 16″×14″ (PA −8°), 26″×15″ (PA −10°), 26″×13″ (PA −7°), 21″×15″ (PA −14°), 16″×15″ (PA −6°), 27″×15″ (PA 86°), 25″×15″ (PA −76°), for CB 34, CB 54, CB 108, CB 171, CB 205, CB 230, and CB 244, respectively.
[c]Corrected by the primary beam response.
[d]Momentum rate derived from the correlation of Anglada (1996), $\dot{P}/(M_\odot\ \mathrm{yr}^{-1}\ \mathrm{km\ s}^{-1})=10^{-2.5}\,[S_\nu d^2/(\mathrm{mJy\ kpc}^2)]^{1.1}$, where S_ν is the flux density at 6 cm, and d the distance to the source. A mean distance of 600 pc was assumed for all sources (Clemens & Barvainis 1988).
[e]Upper limit (4σ).
[f]These sources are separated from their corresponding phase centers by a distance higher than a half of the full-width-at-half-power (FWHP) of the primary beam size at $\lambda=3.6$ cm ($\sim5'.4$). In these cases, a minimum correction of a factor of 2 to the flux densities has been applied.

values obtained by Yun & Clemens (1994b) from CO observations of the molecular outflows in Bok globules.

3.4 Class 0 Protostar Candidates

From our sample of 10 radio sources, a total of 6 sources without any infrared counterpart (CB 108 VLA1, CB 171 VLA1, CB 205 VLA1, CB 205 VLA2, CB 205 VLA3, and CB 230 VLA1) were considered to be Class 0 protostar candidates in paper I. With the present study, given the negative spectral indices found for the three sources CB 205 VLA1, CB 205 VLA3, and CB 230 VLA1, we cannot conclude that these sources are indeed associated with the globules.

On the other hand, since we find the remaining three sources CB 108 VLA1, CB 171 VLA1, and CB 205 VLA2 to be thermal radio sources associated with the corresponding Bok globules, we propose these three sources to be genuine new members of the protostellar Class 0.

In order to better characterize the nature of the centimeter thermal emission seen toward our sample of sources, a more accurate determination of the spectral indices should be performed by complementing our 3.6 and 6 cm continuum data with 20 cm continuum observations, using the VLA. Also, millimeter and submillimeter observations of these sources are needed to confirm their YSO nature and evolutionary status.

The case of CB 205 VLA2 deserves additional discussion. Star formation in Bok globule CB 205 (L810) has been known to take place since the early work of Herbst & Turner (1976). Later studies have shown that L810 is currently the site of active star formation in the form of a near-infrared extreme Class I source (L810 IRS) illuminating a near-infrared nebula (Yun *et al.* 1993) and driving a molecular outflow (Xie & Goldsmith 1990). In addition, Clemens *et al.* (1996) found evidence of a possible previous star formation event which formed one or a couple of stars (Star 12 and its very red near-infrared close companion). One of the outstanding questions lies in the relative ages of these star formation episodes which may indicate that star formation in L810 is sequentially triggered. In this scenario, an earlier star formation event formed star 12 and subsequently a later event formed L810 IRS located about 0.6 arcmin to the northeast. Interestingly, the position of CB 205 VLA2 lies about 2 arcmin north of L810 IRS. If CB 205 VLA2 is confirmed to be a bona fide Class 0 object embedded in the globule, the case for sequentially triggered star formation in L810 will be strengthened.

4. SUMMARY

We have conducted VLA-D 6 cm continuum observations of a sample of 10 radio continnum sources previously detected at 3.6 cm, seen towards 7 Bok globules. All sources, except CB 34 VLA1, were detected.

We have determined the spectral indices ($\alpha_{(6-3.6\ \mathrm{cm})}$) of the continuum emission ($S_\nu \propto \nu^\alpha$). From this study we conclude that:

(a) For CB 205 VLA1 and CB 205 VLA3 we can only determine lower limits for the spectral index ($\alpha_{(6-3.6\ \mathrm{cm})}\geqslant-1.0$ and -3.5, respectively), and we cannot establish the nature of the centimeter continuum emission seen towards these sources. A spectral index of -1.8, characteristic of nonthermal emission, was found for CB 230 VLA1, probably a background object.

(b) The remaining seven sources, CB 34 VLA1, CB54 VLA1, CB 108 VLA1, CB 171 VLA1, CB 205 VLA2, CB 230 VLA2, and CB 244 VLA1, have spectral indices $\alpha_{(6-3.6\ \mathrm{cm})}\geqslant-0.1$, which are consistent with the spectral indices expected for thermal free-free emission from young embedded sources in Bok globules.

(c) Given the detection of near-infrared counterparts to sources CB 34 VLA1, CB 54 VLA1, CB 230 VLA2, and CB 244 VLA1, these sources have been classified as Class I YSOs (paper I).

(d) We identify the remaining three thermal sources, CB

108 VLA1, CB 171 VLA1, and CB 205 VLA2, as genuine Class 0 protostar candidates.

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