RADIO CONTINUUM EMISSION AND WATER MASERS TOWARD CB 54

Itziar de Gregorio-Monsalvo1, José F. Gómez2, Guillem Anglada2, José M. Torrelles3, Thomas B. H. Kuiper4, Olga Suárez2,3, and Nimesh A. Patel6

1 European Southern Observatory, Alonso de Córdova 3107, Vitacura, Casilla 19001, Santiago 19, Chile
2 Instituto de Astrofísica de Andalucía (CSIC), Apartado 3004, E-18080 Granada, Spain
3 Instituto de Ciencias del Espacio (CSIC)-IEEC, Facultat de Fisica, Universitat de Barcelona, Planta 7a, Martí i Franqués 1, 08028 Barcelona, Spain
4 Jet Propulsion Laboratory, California Institute of Technology, CA, USA
5 UMR 6525 H. Fizeau, Université de Nice Sophia Antipolis, CNRS, OCA. Parc Valrose, F-06108 Nice Cedex 2, France
6 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

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ABSTRACT

We present high angular resolution observations of water masers at 1.3 cm and radio continuum emission at 1.3, 3.6, and 6 cm toward the Bok globule CB 54 using the Very Large Array. At 1.3 cm, with subarcsecond angular resolution, we detect a radio continuum compact source located toward the southwest of the globule and spatially coincident with a mid-infrared (mid-IR) embedded object (MIR-b). The spectral index derived between 6 and 1.3 cm ($\alpha = 0.3 \pm 0.4$) is flat, consistent with optically thin free–free emission from ionized gas. We propose the shock-ionization scenario as a viable mechanism for producing the radio continuum emission observed at cm frequencies. Water masers are detected at two different positions separated by 2′/3, and coincide spatially with two mid-IR sources: MIR-b and MIR-c. The association of these mid-IR sources with water masers confirms that they are likely protostars undergoing mass loss, and they are the best candidate as driving sources of the molecular outflows in the region.

Key words: ISM: globules – ISM: jets and outflows – ISM: molecules – masers – radio continuum: ISM – stars: formation

1. INTRODUCTION

The Bok globule CB 54 is an active star-forming region associated with the Vela OB1 cloud complex and located at 1.5 kpc (Launhardt & Henning 1997). Due to their simplicity and relatively small size (less than 10′), Bok globules offer a unique environment for studying the outcome of star formation processes in a relatively idealistic and isolated way (Bok & Reilly 1947; Clemens & Barvainis 1988).

CB 54 shows several signposts of multiple star formation. The region contains several molecular outflows. There is a main bipolar CO outflow oriented in the northeast–southwest direction and centered near the IRAS point-like source IRAS 07020−1618 (also named CB 54 YC1; Yun & Clemens 1994b). In addition, several $H_2 [v = 1−0 \ S(1)]$ line emission knots detected by Khanzadian (2003) suggest the presence of a second outflow in the east–west direction, which indicates the existence of different driving protostars. In fact, this globule harbors at its center a multiple protostellar system of young stellar objects (YSOs) at different stages of evolution. Near-infrared (near-IR) observations toward the central IRAS source revealed the presence of two bright near-IR ($K$ band, 2.2 $\mu$m) objects classified as Class I protostar candidates, CB 54 YC1-I (a confirmed Class I source; Ciardi & Gómez-Martín 2007) and CB 54 YC1-II, plus a bright elongated feature (CB 54 YC1-SW) mainly seen in $H_2 [v = 1−0 \ S(1)]$, 2.121 $\mu$m line (Yun & Clemens 1994a, 1995; Yun 1996; Khanzadian 2003). Water masers were detected by Gómez et al. (2006) and de Gregorio-Monsalvo et al. (2006) inside this southern elongated feature, suggesting the presence of an embedded protostar that pumps the maser emission. This prediction was recently confirmed by the discovery of three faint mid-infrared (mid-IR) sources clustered near the position of the IRAS source and within the near-IR elongated feature (Ciardi & Gómez-Martín 2007). They were named as MIR-a, MIR-b, and MIR-c and interpreted as very cool ($\simeq 100$ K) Class 0 protostellar candidates of masses $\sim 1.5 \ M_\odot$, $\sim 4 \ M_\odot$, and $\sim 0.2 \ M_\odot$, respectively.

Water maser emission at 22 GHz is a good tracer of the mass-loss phenomena observed at the earliest stages of the formation of stars of all masses (Rodríguez et al. 1980; Felli et al. 1992; Xiang & Turner 1995; De Buizer et al. 2005). In the case of low-mass objects, these water masers are usually associated with the youngest Class 0 protostars, produced by the interaction of powerful jets with a large amount of circumstellar material (Furuya et al. 2001), and they tend to be located close to their powering source (within several hundred AU; Chernin 1995; Claussen et al. 1998; Furuya et al. 2000, 2003). At these earliest stages of evolution, young protostars show the most powerful molecular outflows (Bontemps et al. 1996), which are believed to be driven by collimated jets (Raga et al. 1993). The central objects that power the outflows are frequently associated with weak and compact centimeter free–free continuum emission from thermal radio jets (Anglada 1995, 1996; Beltrán et al. 2001). These radio jets trace the part of the outflow closest to the exciting source. These properties make the combination of water masers and radio continuum emission well suited for pinpointing the location of Class 0 protostars.

In this work, we present sensitive interferometric observations of water masers and radio continuum at 1.3 cm, using the Very Large Array (VLA). We also show radio continuum data at 3.6 and 6 cm from the VLA archive. The main goals of these observations were to derive accurately the position of the water maser emission, to pinpoint the location of the exciting sources of the maser phenomenon, and to derive information about the driving engine of the molecular outflows that exist in the region.

This paper is structured as follows: in Section 2, we describe the observations and data processing. In Section 3, we present and discuss the results derived from radio continuum and water
masers observations. Finally, we present the conclusions of this work in Section 4.

2. OBSERVATIONS AND DATA PROCESSING

Observations toward CB 54 were performed on 2005 January 22 and 31, and February 4 using the VLA of the National Radio Astronomy Observatory (NRAO)7 in the BnA configuration (project AG684). We observed simultaneously the $6_1^{−}−5_2$ transition of H$_2$O (rest frequency = 22235.080 MHz) and continuum at 22285.080 MHz (≥1.3 cm) using the four intermediate frequency (IF) spectral line mode and processing both right and left circular polarizations. For the H$_2$O observations, we sampled 64 channels over a bandwidth of 3.125 MHz, centered at $V_{LSR} = 15$ km s$^{-1}$, with 0.66 km s$^{-1}$ velocity resolution. For continuum observations, we used a bandwidth of 25 MHz that comprised eight channels of 3.125 MHz. The total observing time including calibration was 4.5 hr per day. The splitting of the observations into three different days was required to reach the necessary sensitivity for the continuum data. Our flux calibrator was 3C48, for which we adopted a flux density of 1.1 Jy (маг – 8.44 GHz data and were processed. The time on source was 1 hr for 4.86 GHz data. The source 3C48 was selected as the flux calibrator in both cases (adopted flux density is 3.6 cm) from the VLA archive. No. 6, 2009 RADIO CONTINUUM AND WATER MASERS IN CB 54 5081

Table 1

| Frequency (GHz) | Observation Date | Project Name | R.A.* (J2000) | Decl.* (J2000) | Beam Size (′′ ×′′) | P.A. | Phase Calibrator | $S_{\nu,c}^{b}$ (Jy) |
|-----------------|------------------|--------------|--------------|--------------|------------------|------|------------------|------------------|
| 8.44            | 1995 May 19      | AY071        | $07^{h}04^{m}20^{s}$ | $−16^{°}23′20″$ | 15 × 9           | −12° | J0609 − 157      | 5.60 ± 0.01      |
| 4.86            | 1996 Jun 30      | AY073        | $07^{h}04^{m}21^{s}$ | $−16^{°}23′15″$ | 19 × 12         | −9°  | J0729 − 366      | 2.845 ± 0.006    |

Notes.

a Coordinates of the phase center.

b Bootstrapped flux densities of phase calibrators.

3. RESULTS AND DISCUSSION

3.1. Radio Continuum Emission

We have detected a compact (≈0′)2 continuum source at 1.3 cm (Table 2) at a position coinciding with the near-IR elongated feature CB 54 YC1-SW (see Figure 1). This feature was proposed to trace an embedded YSO by de Gregorio-Monsalvo et al. (2006) on the basis of its water maser emission, a result that has been recently confirmed by the detection of three mid-IR sources, within this feature, by Ciardi & Gómez-Martín (2007), who classified these objects as Class 0 protostellar candidates. Our 1.3 cm source is spatially coincident with MIR-b (see Figure 1), one of the mid-IR protostars detected by Ciardi & Gómez-Martín (2007).

Radio continuum emission at 3.6 and 6 cm is unresolved at both frequencies (see contour maps in Figure 2). In Table 2 we show detailed information about positions, flux densities, and uncertainties of the continuum emission presented in this section. From this analysis, we see that the position of the radio continuum emission at the three different frequencies is the same within the absolute positional errors, concluding that it comes from the same source, named as CB 54 VLA1 by Yun et al. (1996) and Moreira et al. (1997).

3.1.1. Origin of the Radio Continuum Emission

In order to study the nature of the radio continuum emission associated with CB 54 VLA1, we compare the centimeter continuum luminosity inferred from the radio observations with the centimeter continuum luminosity expected from Lyman continuum radiation from a zero-age main-sequence (ZAMS) star of the given luminosity of the source. The bolometric luminosity derived from the flux densities of the source IRAS 07020−1618 close to our radio continuum source is $\sim$344 $L_{⊙}$ for an adopted distance of 1.5 kpc (Wang et al. 1995), which corresponds to a B5.5 ZAMS star (Thompson 1984). We warn that the cluster of three YSOs detected by Ciardi & Gómez-
Figure 1. Left: contour plot of the 2MASS near-IR emission toward CB 54, adapted from de Gregorio-Monsalvo et al. (2006). The ellipse represents the positional error of IRAS 07020−1618, whose nominal position is marked with a filled circle. The cross represents the water maser emission detected by de Gregorio-Monsalvo et al. (2006). Right: contour map of the 1.3 cm continuum emission observed with the BnA configuration of the VLA. Levels are $-3, 3, 5$ times $0.06 \text{ mJy beam}^{-1}$, the rms of the map. The half power beam width (HPBW) of the synthesized beam is shown in the lower right corner. The crosses mark the positions of the two groups of water masers detected in this work and observed simultaneously with the 1.3 cm continuum emission. The filled circles represent the mid-IR sources MIR-b and MIR-c detected by Ciardi & Gómez-Martín (2007).

Figure 2. Map of radio continuum emission observed at 3.6 and 6 cm. Contour levels are $-3, 3, 5$, and 7 times the rms of the map (0.025 mJy beam$^{-1}$) for data at 3.6 cm wavelength, and $-3, 3, 5$ and 7 times the rms of the map (0.045 mJy beam$^{-1}$) for data at 6 cm. The crosses mark the positions of the two groups of water masers detected in this work. The half power beam width (HPBW) of the synthesized beam is represented in the lower right corner of each plot.

Martín (2007) falls within the positional error ellipsoid of IRAS 07020−1618 and they could contribute to the total luminosity of the IRAS source. Therefore, we consider this value as an upper limit. The observed radio continuum luminosity at 1.3 cm wavelength (i.e., $S_{\nu d}^2$) is $\sim 7 \times 10^{-1} \text{ mJy kpc}^2$. On the other hand, assuming optically thin free–free emission from ionized hydrogen with an electron temperature of $10^4 \text{ K}$, we derive an expected upper limit of $S_{\nu d}^2 \lesssim 7 \times 10^{-3} \text{ mJy kpc}^2$ from a Lyman continuum flux of $\sim 7 \times 10^{41} \text{ s}^{-1}$ (obtained from Thompson 1984 for a B5.5 ZAMS star). Thus, ionization by stellar photons fails by 2 orders of magnitude in explaining the observed radio emission, and another ionizing mechanism is required. This behavior has been observed before, for instance, by Torrelles et al. (1985), Rodríguez et al. (1989), and Anglada (1995) for a large set of low-mass YSOs.

A plausible mechanism for explaining the centimeter continuum emission observed is the shock-ionization scenario proposed by Torrelles et al. (1985). In this scenario, the stellar wind responsible for a molecular outflow generates shocks in the dense gas surrounding the central protostar and induces its ionization. Curiel et al. (1987, 1989) modeled the shock-ionization scenario and derived the radio continuum emission under optically thin conditions. The spectral index measured by us in the 6–1.3 cm wavelength range is $\alpha_{6-1.3 \text{ cm}} = 0.3 \pm 0.4$ (where $S_{\nu} \propto \nu^{\alpha}$), consistent, within the errors, with optically thin free–free emission. The formulation of Curiel et al. (1987, 1989) predicts a correlation between $S_{\nu d}^2$ and the momentum rate of the outflow $\dot{P}$. Assuming that the momentum rate in the outflow equals that in the stellar wind, $\dot{P} = M \dot{v}$ (where $M$ is the mass-loss rate of the wind, and $\dot{v}$ the terminal velocity of the wind, adopting a typical value of 200 km s$^{-1}$), and a typical electron temperature in the ionized wind of $10^4 \text{ K}$, the prediction of the model gives

$$\dot{P} = \frac{10^{-3.5}}{\eta} S_{\nu d}^2$$

with $S_{\nu d}^2$ in mJy kpc$^2$ and $\dot{P}$ in $M_\odot \text{ yr}^{-1} \text{ km s}^{-1}$, being $\eta$ the flux density at 6 cm and $\eta = \Omega/4\pi$ an efficiency factor that represents the fraction of the stellar wind that is shocked and produces the observed radio continuum emission.
Scaling the outflow force derived by Yun & Clemens (1994b) from CO observations, to the adopted distance of 1.5 kpc, we obtain $\dot{P} = 4 \times 10^{-4} M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$. Considering a radio continuum luminosity at 6 cm of 0.5 mJy km$^{-1}$ s$^{-1}$, we derive and efficiency factor $\eta \simeq 0.4$, which indicates that the shock-ionization mechanism could explain the observed radio continuum emission. We note that our estimate of efficient factor $\eta$ can be affected by large errors, mainly due to the uncertainty in the value of the momentum rate of the outflow from molecular lines observations (see Anglada et al. 1992; Anglada 1995 for a detailed discussion of the dependence of the error in $\eta$ with the observational parameters). The efficiency factor derived in this work is somewhat higher than the average value of $\eta \simeq 0.1$ derived by Anglada (1995) for a large set of low-luminosity objects. Nevertheless, the dispersion of the efficiency values is relatively large and the best fit to that set of data provides a value of $\eta = 10^{1.0\pm0.6}$ (adopting an uncertainty of 2$\sigma$), i.e., $0.025 < \eta < 0.4$.

The observations presented here make CB 54 VLA a very good candidate for driving a molecular outflow. Nevertheless, higher angular resolution observations at centimeter and millimeter wavelengths should be made to study the presence of a jet–disk system; since these structures are typically observed with sizes of $\lesssim$100 AU ($\simeq$0.07 at a distance of 1.5 kpc), see Anglada (1996). In particular, high angular resolution observations of 3.6 and 6 cm emission, optically thicker than that at 1.3 cm, could better trace low-brightness structures, and therefore, would be useful to prove the presence of a thermal radio jet with a morphology elongated in the same direction of the large-scale molecular outflow. On the other hand, radio continuum millimeter data would be useful to reveal the presence of heated dust associated with a possible protoplanetary disk.

### 3.2. Water Maser Emission

Table 3 contains the results of our water maser observations with the VLA. We observe three independent spectral features (see Figure 3, left panel). One of the features is approximately at the velocity of the cloud ($V_{\text{LSR}} = 19.5 \text{ km s}^{-1}$; Clemens & Barvainis 1988) and the rest are blueshifted within 10 km s$^{-1}$ from the cloud velocity. All of them were detected on the three different days of observation. The masers are found at two different positions separated by $2.286 \pm 0.004$ distance from the southern component to the northern reference feature, $\simeq$3400 AU at a distance of 1.5 kpc; see Figure 1. The northern group of masers is spatially associated with the mid-IR object MIR-b and shows three spots at velocities 10.4, 13.7, and 19.6 km s$^{-1}$, separated by a few centi-arcseconds (see Figure 3, right panel). The southern group is composed by a single spot at a velocity of 9.7 km s$^{-1}$, spatially associated with the mid-IR object MIR-c.

The water maser emission in the region shows high variability, which is typically observed in both low- and high-mass YSOs (Reid & Moran 1981; Wilking et al. 1994; Claussen et al. 1996; Gómez et al. 2006), using the Robledo 70 m antenna, detected a water maser spectrum composed of a single water maser spectral feature observed at $V_{\text{LSR}} = 13.7 \text{ km s}^{-1}$ in 2002, at 7.9 km s$^{-1}$ in 2003, and at 8.7 km s$^{-1}$ in 2005. In addition, de Gregorio-Monsalvo et al. (2006), using the VLA, detected two different features at 15.8 and 17.8 km s$^{-1}$ in 2004 February. In the observations reported here, we do not detect any of the maser spectral features in the region that were mentioned in previous works except the feature at 13.7 km s$^{-1}$. This component shows a variation in its intensity by a factor of $\sim$2 between 2005 January 22 and 2005 January 31 (see Figure 3, left panel). On the other hand, the features at 10.4 and 19.6 km s$^{-1}$ have not been reported before.

Water masers associated with the northern YSO MIR-b are located at a distance $\lesssim$100 AU (assuming a distance of 1.5 kpc to the Bok globule) from the compact radio continuum source CB 54 VLA we detected at 1.3 cm, which suggests this object as the exciting source of the northern group of water masers. This short distance $\lesssim$100 AU between water masers and their exciting source is typically observed in a large set of low-mass star-forming regions (Chernin 1995; Claussen et al. 1998; Furuya et al. 2000). The right panel of Figure 3 shows the spatial distribution of the three northern spots obtained on the second day of observation, which corresponds to the data with the best signal-to-noise ratio. All the spots show similar positions on the 3 days of observation. They delineate a spatial structure of $\simeq$0.06 (90 AU), elongated in the north–south direction. To ascertain whether the masers are associated with the molecular outflow or with disk material (i.e., whether they are tracing unbound or bound motions), for each maser component we estimate its velocity ($V$) with respect to the mean velocity of the maser structure, and we calculate the mass ($M$) necessary to bind the gas that shows the maser emission as $M = V^2 R G^{-1}$, where $R$ is the distance of the maser structure to the central YSO, and we have conservatively assumed a value of $R \simeq$ 100 AU for the maser components (this distance to the center is an upper limit). A mass of $M \simeq$ 2.8 $M_{\odot}$ is enough to bind the gas responsible for the maser features. Since the mass of this source is estimated to be $\sim$4 $M_{\odot}$ (Ciardi & Gómez-Martín 2007), we cannot discard bound motions.

On the other hand, the spatial association of the southernmost water maser emission with the mid-IR YSO MIR-c suggests this object as the pumping source of the southern maser emission. In this case, we do not detect 1.3 cm continuum emission toward this object with a $3\sigma$ upper limit of 0.17 mJy. Furuya et al. (2001) found that water masers in low-mass YSOs are usually excited by Class 0 sources due to the
interaction of powerful jets with a large amount of circumstellar material. Therefore, since sources that host water maser emission are good candidates for being in a very early stage of its evolution, as well as for being the exciting source of the mass-loss phenomenon, we propose the sources MIR-b (CB 54 VLA1) and MIR-c as the best candidates to be the driving engine of the molecular outflows that exist in this Bok globule.

4. CONCLUSIONS

We presented high angular resolution VLA observations of water masers and continuum emission at 1.3 cm toward the Bok globule CB 54. We complemented our observations with VLA archive data in the radio continuum at 3.6 and 6 cm. The main conclusions are the following:

1. Our subarcsecond angular resolution observations at 1.3 cm allow us to establish that the radio continuum emission detected to the southwest of the Bok globule is associated with the mid-IR source MIR-b. The spectral index of the emission between 6 and 1.3 cm is flat, consistent with optically thin free–free emission from ionized gas. A shock scenario mechanism is needed to produce the radio continuum luminosity at cm wavelengths.

2. Water masers are found in two different regions. The northern group of masers coincides within <100 AU with the source CB 54 VLA1, which is associated with the mid-IR protostar MIR-b, and whose position at 1.3 cm is reported in this paper. The southern region of water maser emission is located ∼2″ SW, toward the position of the faint mid-IR object MIR-c, without detectable radio continuum emission.

3. The association of the mid-IR sources MIR-b and MIR-c with water masers confirms the embedded protostellar nature of both objects and suggests these protostars are the best candidates for driving the molecular outflows observed in the region.

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