The Astrophysical Journal, 571:901–905, 2002 June 1

THE NATURE OF THE CLUSTER OF RADIO SOURCES IN GGD 14

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Received 2002 January 7; accepted 2002 February 6

ABSTRACT

We present sensitive radio continuum observations at 3.6 and 6 cm made quasi-simultaneously toward the star-forming region GGD 14. The observations reveal the presence of nine extremely compact ($\leq 0\farcs3$) and faint radio sources in a region of $\sim 30''$ around the bright cometary H II region, VLA 1. Most of these sources show variability at radio wavelengths, and their spectral indices are characteristically negative. Four of the faint sources have an infrared counterpart. We propose that gyrosynchrotron radiation from an active magnetosphere explains the emission from almost all the faint compact sources, suggesting that the GGD 14 region harbors a cluster of low-mass, pre–main-sequence stars. Two sources that do not show time variability are VLA 1, the cometary H II region, and VLA 7. The derived spectral index for VLA 7 ($+0.6 \pm 0.3$) fits the stellar wind model better than other possibilities, supporting the idea that VLA 7 is the powering source of the molecular outflow observed toward the GGD 14 region.
Subject headings: H II regions — ISM: individual (GGD 14) — ISM: jets and outflows — radio continuum: ISM — stars: pre–main-sequence

1. INTRODUCTION

The GGD 14 region (Gyulbudaghian, Glushkov, & Denisyuk 1978) is a peculiar optical nebulosity found in the Monoceros molecular cloud at a distance of $\sim$1 kpc (Racine & van den Bergh 1970; Rodríguez et al. 1980). This region contains a well-known cometary H II region (VLA 1) ionized by a B0.5 zero-age main-sequence (ZAMS) star (Rodríguez et al. 1980; Tofani et al. 1995; Gómez et al. 1998; Gómez, Rodríguez, & Garay 2000, hereafter GRG00). Observational evidence shows that GGD 14 is associated with star formation activity as manifested by the presence of a CO bipolar outflow (Rodríguez et al. 1982; Little, Heaton, & Dent 1990), water masers at the center of the outflow (Rodríguez et al. 1978, 1980, 1982; Tofani et al. 1995), and ammonia emission (Rodríguez et al. 1980; Güsten & Marcaide 1986; Torrelles et al. 1989). Infrared studies from 2 to 100 μm (Reipurth & Wamsteker 1983; Olofsson & Koornneef 1985; Harvey et al. 1985; Hodapp 1994) and radio continuum studies at 3.6 cm (GRG00) have provided evidence for the presence of a recently formed cluster of sources in the vicinity of the H II region.

GRG00 found in the immediate surroundings of the bright cometary H II region, within a region of 30″ in radius, several faint and compact ($\leq 0\farcs1$) radio continuum sources. If these are ultracompact regions of ionized gas, then their flux densities imply that they are being excited by B2–B3 ZAMS stars. However, as GRG00 pointed out, their extremely small sizes (less than 50 AU in radius) would require a very efficient confining mechanism. Alternative interpretations for these sources include ionized winds (Rodríguez 1997) or gyrosynchrotron emission from stellar magnetospheres (Dulk 1985; Feigelson 1987; Hughes 1991; Feigelson & Montmerle 1999; Rodríguez, Anglada, & Curiel 1999; Wilner, Reid, & Menten 1999). In particular, GRG00 detected radio continuum emission at 3.6 cm from the candidate powering source of the molecular outflow (labeled as VLA 7) and proposed that the emission most probably originates in a collimated stellar wind. In this paper, we present new high angular resolution and sensitive radio continuum observations at 3.6 and 6 cm, made quasi-simultaneously in order to determine the spectral indices of the sources and to search for variability in their emission by comparing with the 1997 data.

2. OBSERVATIONS

The 3.6 cm (8.3 GHz) and 6 cm (4.9 GHz) radio continuum observations toward GGD 14 were made during 2001 May 27 in the B configuration, using the Very Large Array (VLA) of the NRAO.[1] The data were taken with both circular polarizations and an effective bandwidth of 100 MHz, with an on-source integration time of about 2 hr at each frequency. The data were edited and calibrated following standard procedures, and images were made using the NRAO software package AIPS. The phase calibrator was 0605−085, with a bootstrapped flux density at 3.6 and 6 cm of 1.943 ± 0.005 and 2.019 ± 0.008 Jy, respectively. The flux density scale was determined from observations of the amplitude calibrator 3C 48, for which we assumed a flux density at 3.6 and 6 cm of 3.2 and 5.5 Jy, respectively. The strong compact H II region, VLA 1, was used to self-calibrate the data in phase and amplitude, resulting in rms noises of 0.012 mJy beam^{-1} at 3.6 cm and 0.021 mJy beam^{-1} at 6 cm. The synthesized beams at 3.6 and 6 cm for images made with the task IMAGR of AIPS, setting the robust parameter of Briggs (1995) equal to 0, are respectively

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

$1''.1 \times 0''.8$ at P.A. $= -11°$ and $1''.5 \times 1''.2$, at P.A. $= -11°$. We searched unsuccessfully for circular polarization in the Stokes parameter V, setting 4 σ upper limits of 72 and 104 μJy beam^{-1} at 3.6 and 6 cm, respectively.

3. RADIO CONTINUUM SOURCES

Figure 1 shows an image of the 3.6 cm radio continuum emission observed toward the GGD 14 region. In addition to the cometary H II region, we detected emission from six faint (although with signal-to-noise ratios greater than 5) and compact ($\leq 0''.3$) radio continuum sources. Four of them were previously reported by GRG00 (objects VLA 2, 4, 6, and 7) and two are new detections (objects VLA 8 and VLA 10). Sources VLA 3 and VLA 5, detected in 1997 (GRG00), were below the detection limits in this new epoch, suggesting that they are variable. Figure 2 shows an image of the 6 cm radio continuum emission observed toward GGD 14. In addition to VLA 1, we detected five compact sources with signal-to-noise ratios greater than 5. Four of these (objects VLA 2, 4, 6, and 7) were previously detected (GRG00), and one source, labeled as VLA 9, is a new detection. Figure 3 shows a close-up of the new compact sources detected at 3.6 and 6 cm. The parameters of the radio continuum sources are listed in Table 1. In column (4), we give the flux density at 3.6 cm observed during 1997 January 6 (GRG00), and in columns (5) and (6), the flux densities at 3.6 cm and 6 cm observed during 2001 May 27. For those sources not detected in one epoch, we give an upper limit equal to the 3 σ rms level, measured at the position of the source, as determined at the other epoch. Even though the flux density at 6 cm of VLA 10 during 2001 is below the 5 σ level (Fig. 2), we detected weak emission at its position, and the flux density is listed in Table 1.

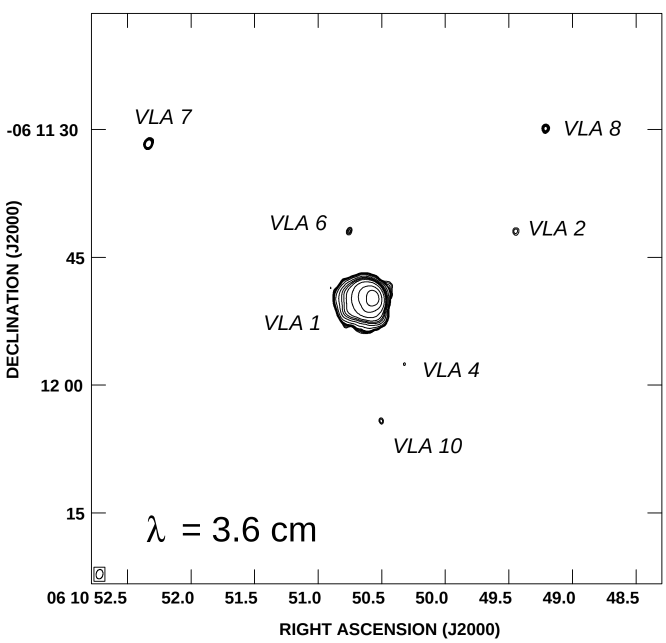

FIG. 1.—VLA continuum image toward the star-forming region GGD 14 at 3.6 cm. Angular resolution is $1''.1 \times 0''.8$ at P.A. $= -11°$. Contour levels are 5, 6, 7, 8, 9, 15, 30, 50, 70, 100, 200, 500, and 1000 × 12 μJy beam^{-1}, the rms noise of the image. VLA 8 and VLA 10 are new detections.

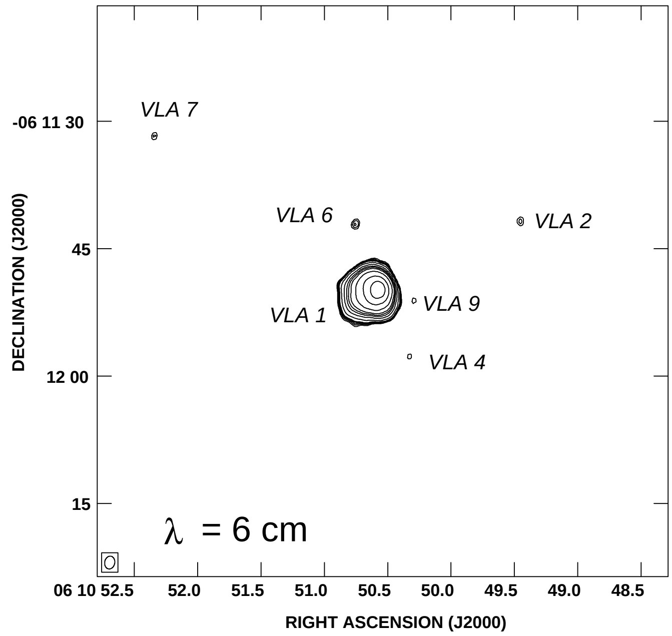

FIG. 2.—VLA continuum image toward the star-forming region GGD 14 at 6 cm. Angular resolution is $1''.5 \times 1''.2$ at P.A. $= -11°$. Contour levels are 5, 6, 7, 8, 9, 15, 30, 50, 70, 100, 200, 500, and 1000 × 21 μJy beam^{-1}, the rms noise of the image. VLA 9 is a new detection.

4. THE NATURE OF THE FAINT SOURCES: A CLUSTER OF LOW-MASS, PRE-MAIN-SEQUENCE STARS?

Taking into account our 1997 and 2001 VLA observations, we have detected a total of 10 sources in the GGD 14 region. Except for VLA 1, all the other sources are unresolved ($\leq 0''.3$), and assuming a distance of 1 kpc, this angular upper limit corresponds to an upper limit of 150 AU for the radii of those compact regions. Since the probability of finding an extragalactic source at 3.6 cm with a flux density above 0.06 mJy in a box of $30'' \times 30''$ is very low (~0.04; Windhorst et al. 1993), GRG00 concluded that all the weak sources detected are almost certainly galactic and embedded in the cloud. It was suggested that the faint compact objects could be "hypercompact" H II regions ionized by B2–B3 ZAMS stars. However, we find that all sources, except VLA 1, VLA 7, and VLA 9, are time variable (see Table 1), which seems to seriously question this interpretation. We note that the 3.6 cm flux density of VLA 1 for 1997 seems to be somewhat lower than that of 2001. We attribute this to the fact that the source is extended and to a poorer (u, v) coverage of the short spacings in the 1997 data. We also note that even though the flux densities of VLA 2 at 3.6 cm reported in Table 1 are consistent with no time variability, unpublished observations made by us in 1997 July 24 at 6 cm give a flux density of 0.6 ± 0.1 mJy, a much larger value than the 0.16 ± 0.02 mJy observed in 2001. We then consider VLA 2 also as time variable. Variability on a timescale of years is still consistent with an explanation in terms of hypercompact H II regions. From the parameters of GRG00, we find that under the hypercompact H II region interpretation, these sources would have an electron density of $\sim 10^5$ cm^{-3} and a recombination time of order 1 yr. However, as we discuss below, the spectral indices and the time

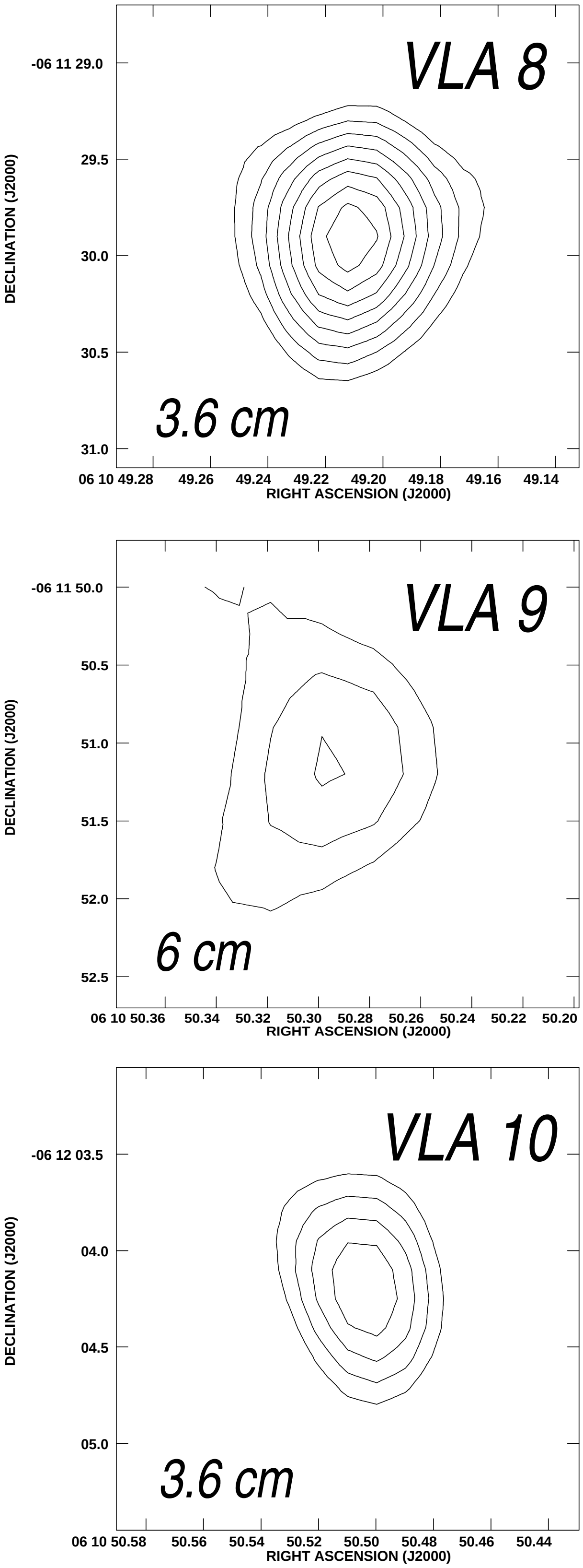

FIG. 3.—Individual VLA images of the new detected sources VLA 8, VLA 9, and VLA 10. Contour levels are at 3.6 cm for VLA 8 and VLA 10, -3, 3, 4, 5, 6, 7, 9, and 10×12 μJy beam^{-1}, the rms noise of the image, and at 6 cm for VLA 9, -3, 3, 4, and 5×21 μJy beam^{-1}, the rms noise of the image.

variability favor a different explanation for the radio sources.

We were also able to determine spectral indices for six of the eight time-variable sources. Of these, four have clearly negative spectral indices. Negative spectral indices below -0.1 cannot be produced by free-free (thermal) processes (Rodríguez et al. 1993). We then propose that the emission from these radio sources has a nonthermal origin, most likely gyrosynchrotron from an active magnetosphere. Circular polarization can be present in gyrosynchrotron emission (Dulk 1985; White, Pallavicini, & Kundu 1992). We failed to detect circular polarization in any of these sources. However, since the sources are relatively faint, the upper limits for circular polarization are of the order of $\sim$50% and not particularly stringent.

The compact H II region VLA 1 has a radio continuum density flux of $\sim$100 mJy, and adopting a distance of 1 kpc, we estimate that the region is excited by a B0.5 ZAMS star with a luminosity of $\sim 1.0 \times 10^4$ $L_\odot$. On the other hand, for the *IRAS* 06084$-$0611 source associated with the compact H II region, we estimate from the *IRAS* data a total luminosity of $\sim 9.6 \times 10^3$ $L_\odot$, similar to the luminosity obtained from the radio continuum. This suggests that the B0.5 star associated with VLA 1 is the dominant object in luminosity of the region. Submillimeter observations made by Little et al. (1990) show that the brightest peaks are centered near the position of the H II region. All these results make it difficult to think that there are many more early B-type stars in the cluster, and most likely the eight faint sources are associated with low-mass, pre-main-sequence stars. A crude statistical estimate suggests that there could be more time-variable, radio-emitting sources in the region. If the total number of these sources is m and they are detectable a fraction (f) of the time, we expect to detect in the order of $n \simeq mf$ at a given time. The number of sources that will be detected in two given occasions will be $n' \simeq mf^2$. Then, the total number of sources will be $m \simeq n^2/n'$. Since for the GGD 14 cluster we detect eight sources in both epochs, $n \simeq 8$, and since only four of them are detected in *both* epochs, we have $n' \simeq 4$. We then estimate the total number of time-variable, radio-emitting sources in the region to be $m \simeq 16$, of which we have detected about one-half. A similar compact cluster of time-variable radio sources has been found in the HH 124 region by Reipurth et al. (2002).

To compare our accurate radio positions with near-infrared data, we overlapped them on the near-infrared *K*-band image of the Two Micron All Sky Survey (2MASS), as shown in Figure 4. We find that four of the radio sources coincide closely (within 0."5) with *K*-band sources. In Table 2, we summarize the observational parameters of the 10 sources in GGD 14. VLA 1 is clearly an optically-thin H II region, with its flat spectral index and detected radio recombination lines (Gómez et al. 1998). VLA 7 is most likely a thermal jet, with the characteristic spectral index of 0.6 for ionized outflows (Panagia & Felli 1975; Reynolds 1986) and its location at the center of the bipolar outflow in the region (Rodríguez et al. 1982; Little et al. 1990). For VLA 9, we only have a detection at one wavelength in one epoch. The remaining seven sources are all time variable, four have clearly negative spectral indices, and four are coincident with near-infrared sources. We then believe that, as a group,

TABLE 1
RADIO CONTINUUM PARAMETERS OF THE SOURCES

Source (1)	α(2000) (2)	δ(2000) (3)	Flux Density (mJy) 3.6 cm (1997) (4)	Flux Density (mJy) 3.6 cm (2001) (5)	Flux Density (mJy) 6 cm (2001) (6)	Spectral Index (7)
VLA 1	06 10 50.57	−06 11 49.7	97 ± 2	112 ± 1	114 ± 1	−0.03 ± 0.01
VLA 2	06 10 49.45	−06 11 41.8	0.10 ± 0.02	0.10 ± 0.01	0.16 ± 0.02	−0.8 ± 0.3
VLA 3	06 10 49.93	−06 11 45.8	1.04 ± 0.02	<0.04[a]	<0.05[a]	...
VLA 4	06 10 50.32	−06 11 57.6	0.12 ± 0.02	0.07 ± 0.01	0.11 ± 0.02	−1.0 ± 0.4
VLA 5	06 10 50.55	−06 11 33.5	0.10 ± 0.02	<0.04[a]	<0.05[a]	...
VLA 6	06 10 50.75	−06 11 41.9	0.41 ± 0.02	0.09 ± 0.01	0.15 ± 0.02	−1.0 ± 0.3
VLA 7	06 10 52.34	−06 11 31.7	0.17 ± 0.02	0.18 ± 0.01	0.13 ± 0.02	+0.6 ± 0.3
VLA 8	06 10 49.21	−06 11 29.9	<0.04[a]	0.13 ± 0.01	<0.05[a]	> −0.4
VLA 9	06 10 50.30	−06 11 51.1	<0.04[a]	<0.04[a]	0.11 ± 0.02	< +0.2
VLA 10 ...	06 10 50.50	−06 12 04.2	<0.04[a]	0.08 ± 0.01	0.09 ± 0.02[b]	−0.2 ± 0.5

NOTE.—R.A. is in hours, minutes, and seconds; decl. is in degrees, arcminutes, and arcseconds.
[a] 3 σ rms noise obtained at the position of each source.
[b] Source detected at the 4 σ level at the position determined at 3.6 cm.

these sources are most probably a cluster of young, low-mass stars with active magnetospheres. We note that the four sources with a near-infrared counterpart (VLA 2, 4, 8, and 10) are all located in the periphery of the cluster, suggesting that because of increased obscuration toward the center of the cluster, we may not be detecting the near-infrared counterparts of sources VLA 3, 5, 6, and 9. A deeper *K*-band image may reveal the stellar counterparts of these radio sources.

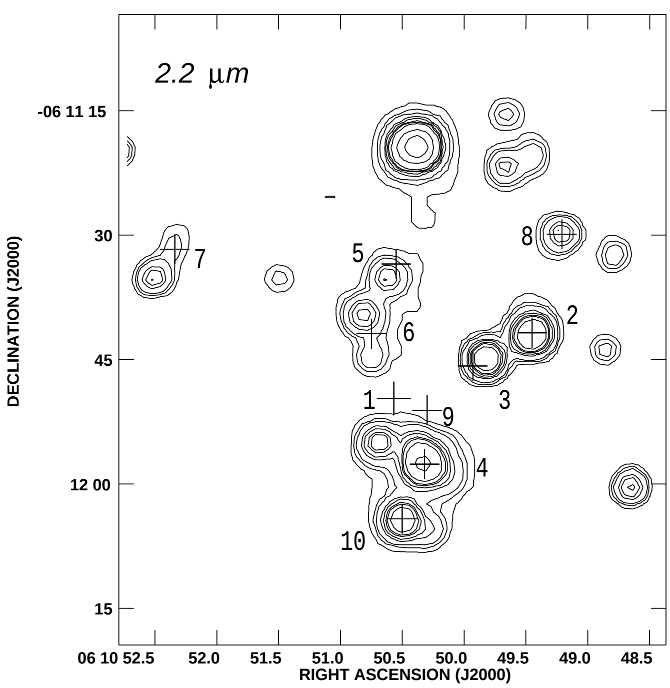

FIG. 4.—Infrared image in the K band toward the star-forming region GGD 14, taken from the Two Micron All Sky Survey. Crosses mark the peak positions of the compact radio sources. VLA 1 is the bright cometary H II region. Contour levels are 11.6%, 11.8%, 12%, 12.6%, 13%, 13.6%, 14%, 15%, 20%, and 30% of the peak value.

TABLE 2
NATURE OF THE SOURCES

Source	Spectral Index	Time Variable?	Coincidence[a] with near-IR	Possible Nature
VLA 1	Flat	No	No	H II region
VLA 2	Negative	Yes	Yes	T-Tauri
VLA 3	...	Yes	No	T-Tauri?
VLA 4	Negative	Yes	Yes	T-Tauri
VLA 5	...	Yes	No	T-Tauri?
VLA 6	Negative	Yes	No	T-Tauri?
VLA 7	Positive	No	?	Jet
VLA 8	?	Yes	Yes	T-Tauri
VLA 9	?	Yes	No	T-Tauri?
VLA 10	?	Yes	Yes	T-Tauri?

[a] Coincidence is assumed when the radio and near-IR positions overlap within 0″.5.

5. CONCLUSIONS

We present high angular resolution VLA observations at 3.6 and 6 cm toward the star-forming region GGD 14. In addition to VLA 1, the previously known compact cometary H II region, a cluster of nine radio sources was found. The source VLA 7 is almost certainly a thermal jet that powers the outflow in the region. The remaining eight sources cannot be hypercompact H II regions ionized by B2–B3 ZAMS stars since, in general, they are time variable and their spectral indices are negative, suggesting that the emission mechanism is gyrosynchrotron from the active magnetospheres of T-Tauri stars.

L. F. R. and Y. G. acknowledge financial support from DGAPA-UNAM and CONACyT-Mexico. G. G. acknowledges support from the Chilean Fondecyt project 1010531. The 2MASS project is a collaboration between The University of Massachusetts and the Infrared Processing and Analysis Center (JPL/Caltech), with funding provided primarily by NASA and the NSF.

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