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A CLUSTER OF RADIO SOURCES NEAR GGD 14

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ABSTRACT

We present sensitive Very Large Array (VLA) radio continuum observations at 3.6 cm toward the star-forming region GGD 14 (also known as GGD 12/13/14/15, G213.88-11.84, and AFGL 890). In addition to the previously known cometary H II region, we report the detection of a cluster of six compact radio sources, all with a nearby 2 μm counterpart. These new sources appear to be ultracompact H II regions ionized by B2–B3 zero-age main-sequence (ZAMS) stars. The kinematic age of these six compact radio sources, assuming expansion at 10 km s^{-1}, is less than 25 yr, and we conclude that they must be confined by some mechanism. The sources are so compact that they could be gravitationally bound to the star. One of the new detections, the source VLA 7, is located near the center of the CO molecular outflow. We suggest that VLA 7 is associated with the powering source of the molecular outflow and that the infrared sources IRS 9M and IRS 9E, between which lies VLA 7, could be the lobes of a bipolar reflection nebula tracing the outflow at small scales.

Subject headings: H II regions — ISM: individual (GGD 12–15) — ISM: jets and outflows — radio continuum: stars

1. INTRODUCTION

Molecular outflows, water masers, and ultracompact H II regions are important indicators of star-forming activity. The study of their physical parameters and the relationship between these components provide important clues for the understanding of the star formation process. The red nebulous objects GGD 12/13/14/15 (Gyulbudaghian, Glushkov, & Denisyuk 1978) are embedded in the Monoceros molecular cloud at a distance of ∼1 kpc (Racine & van den Bergh 1970; Rodríguez et al. 1980). In particular, there is ample observational evidence that one of these nebulosities, GGD 14, is associated with an active star-forming region characterized by 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), dense gas traced by ammonia observations (Rodríguez et al. 1980; Güsten & Marcaide 1986; Torrelles et al. 1989), and a compact H II region located at ∼30″ from the water maser. The region also contains submillimeter dust emission centered near the position of the H II region (Little et al. 1990). Several infrared studies from 2 to 100 μm have shown evidence of a recently formed cluster in the vicinity of the H II region (Reipurth & Wamsteker 1983; Olofsson & Koornneef 1985; Harvey et al. 1985; Hodapp 1994). The H II region has a cometary morphology, is associated with the *IRAS* source 06084−0611 with a luminosity of $\sim 10^4\ L_\odot$, and seems to be ionized by a B0.5 zero-age main-sequence (ZAMS) star (Rodríguez et al. 1980; Kurtz, Churchwell, & Wood 1994; Tofani et al. 1995; Gómez et al. 1998). A kinematic study of the ionized gas, using hydrogen recombination lines, suggests that this H II region is undergoing a champagne flow (Gómez et al. 1998). A near-infrared source has been detected at the position of the water maser (Harvey et al. 1985; Hodapp 1994), but no 3.6 m radio continuum emission has been found at a 3 σ upper limit of 0.3 mJy (Tofani et al. 1995). In this paper we present new high angular resolution observations of radio continuum at 3.6 m that are of much better sensitivity, in order to search for fainter, compact radio continuum sources in the region.

2. OBSERVATIONS

The 3.6 m (8.3 GHz) radio continuum observations of GGD 14 were made during 1997 January 6 in the A configuration using the Very Large Array (VLA) of the NRAO.[1] All the data were taken with an effective bandwidth of 100 MHz, for an on-source integration time of 4.1 hr. The data were edited and calibrated following standard procedures, and maps were made using the NRAO software package Astronomical Image Processing System (AIPS). The phase calibrator was 0605−085, with a bootstrapped flux density of 2.840 ± 0.008 Jy. The flux density scale was determined from observations of the amplitude calibrator 1328+307, for which we assumed a flux density of 5.26 Jy. The synthesized beam for maps made with the IMAGR task of AIPS, setting the robust parameter of Briggs (1995) to 0, is 0″.27 × 0″.23 at P.A. = 27°.

3. RESULTS AND DISCUSSION

3.1. *Radio Continuum and Near-Infrared Sources*

Figure 1 shows the 3.6 cm high angular resolution radio continuum map toward the cometary H II region in GGD 14, which we hereafter call VLA 1. The rms noise of the map is 0.013 mJy beam^{-1}, and it is possible to identify, in addition to the cometary H II region VLA 1, six much fainter compact radio continuum sources above a 5 σ level (0.065

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

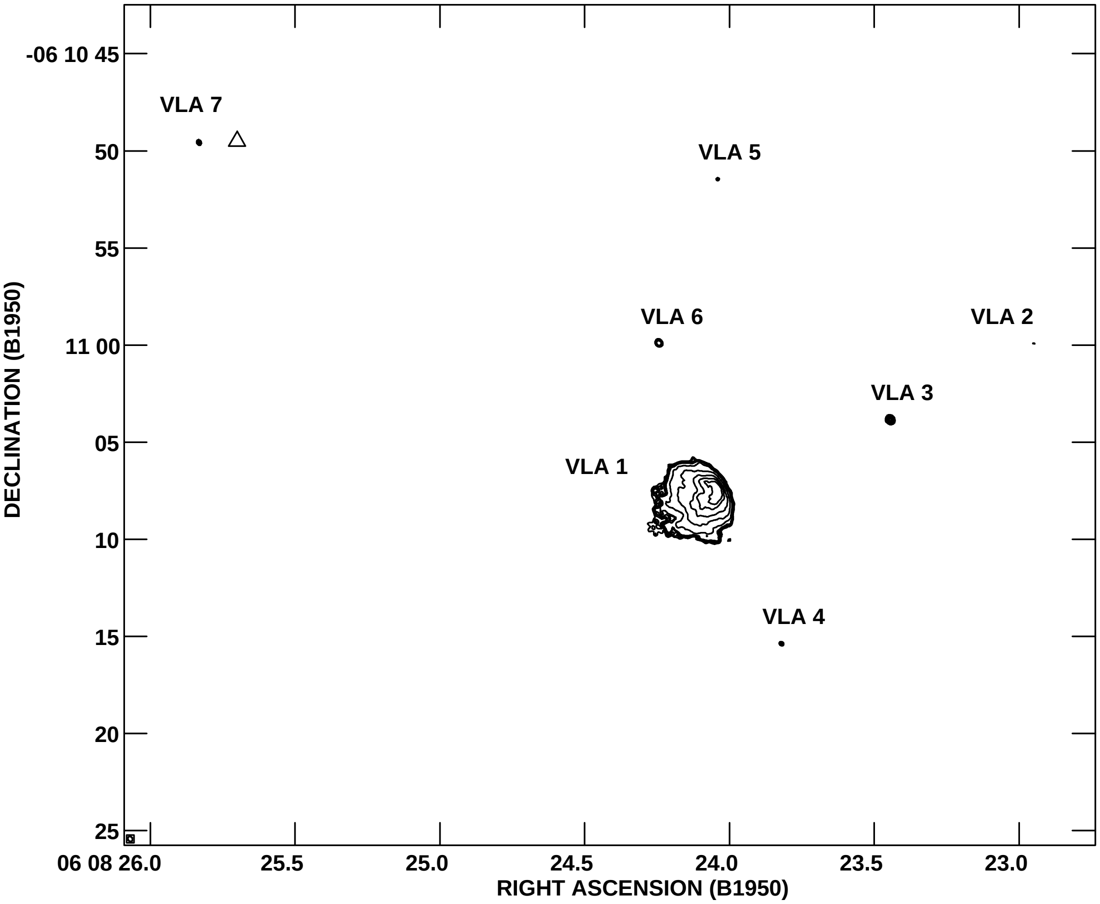

FIG. 1.—VLA continuum map toward the star-forming region GGD 14 at 3.6 cm. The angular resolution is 0".27 × 0".23 at P.A. = 27°. Contour levels are 5, 6, 7, 8, 9, 15, 30, 50, 70, and 90 × 13 μJy beam^{-1}, the rms noise of the map. A total of seven sources were detected. The triangle shows the position of the water maser (Tofani et al. 1995).

mJy beam^{-1}), and we call them VLA 2 through 7. These six radio continuum sources are new detections, and individual maps of them are shown in Figure 2. The parameters of the radio continuum sources are listed in Table 1. It was possible to find a nearby 2 μm counterpart source for all the new radio continuum components. For this reason, in Table 1 we list each radio source with its associated near-infrared source (Harvey et al. 1985; Hodapp 1994). VLA 1 is the dominant source of ionized gas in the region and does not have a 2 μm counterpart (Harvey et al. 1985; Hodapp 1994), as result of its very large extinction ($A_V \geq 40$ mag; Harvey et al. 1985). However, as we will discuss below, the positional associations between radio and near-infrared sources are not exact.

The six new detections have flux densities 2–3 orders of magnitude smaller than that of VLA 1. What is the nature of these six relatively faint sources? One possibility is that they could be ionized thermal jets, collimated flows of gas being ejected by the associated stars (e.g., Rodríguez 1997). However, only one of these sources, VLA 7 (see below), is

TABLE 1

3.6 CM CONTINUUM PARAMETERS

Source[a]	α(1950)	δ(1950)	Flux Density (mJy)	Possible Near-infrared Counterpart[b]
VLA 1	06 08 24.04	−06 11 07.7	97 ± 2	...
VLA 2	06 08 22.95	−06 10 59.9	0.10 ± 0.02	IRS 6
VLA 3	06 08 23.45	−06 11 03.8	1.04 ± 0.02	IRS 5
VLA 4	06 08 23.82	−06 11 15.4	0.12 ± 0.02	IRS 2
VLA 5	06 08 24.04	−06 10 51.5	0.10 ± 0.02	IRS 8
VLA 6	06 08 24.24	−06 10 59.9	0.41 ± 0.02	IRS 7′
VLA 7[c]......	06 08 25.83	−06 10 49.6	0.17 ± 0.02	IRS 9M

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] The recommended full names for these sources are GGD 14: VLA 1, 2, 3, ...

[b] Near-infrared sources (IRS) from Harvey et al. 1985.

[c] Also near an H_2O maser (Rodríguez et al. 1978; Tofani et al. 1995).

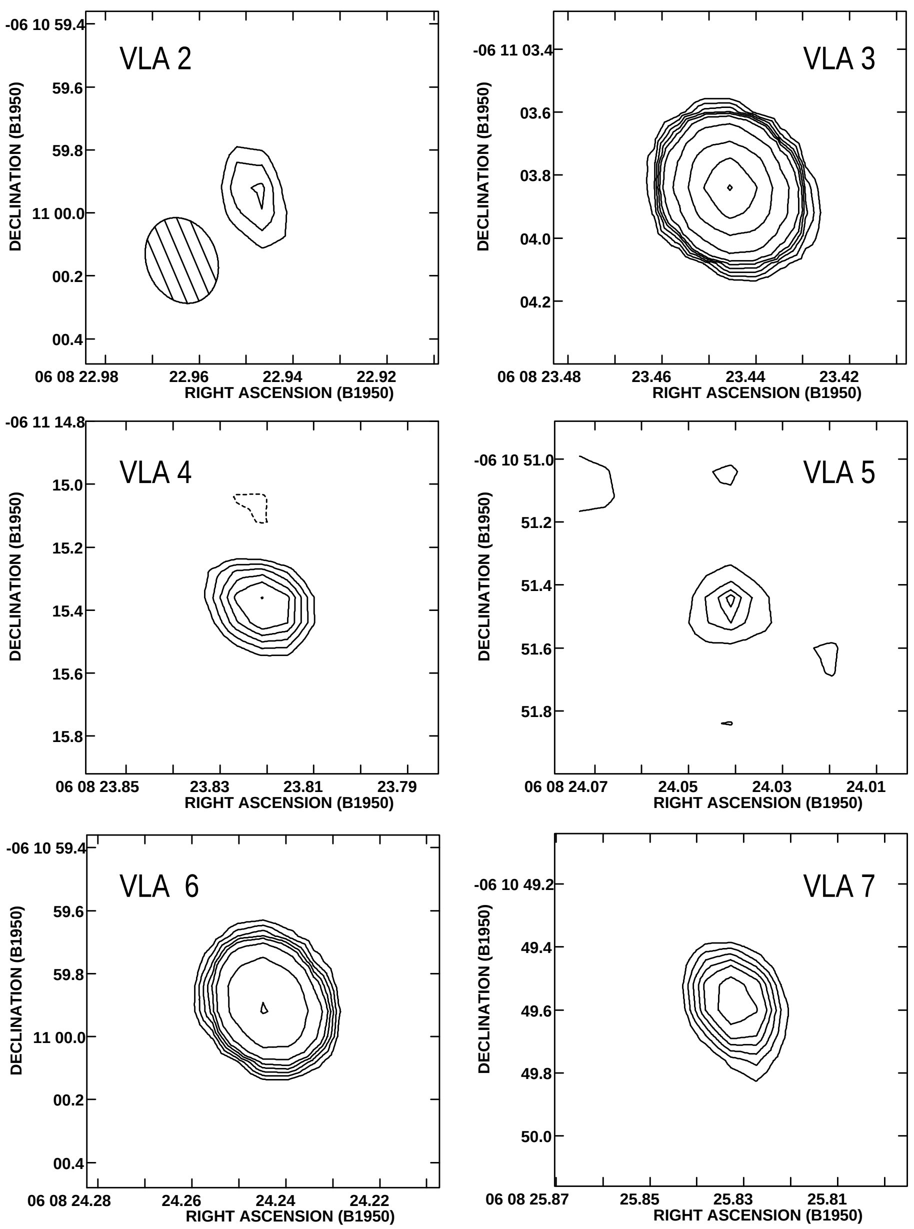

FIG. 2.—Individual VLA maps of the new sources detected, VLA 2 through 7. The beam is shown as a hatched ellipse in the top left panel. Contour levels are −3, 3, 4, 5, 6, 7, 9, 15, 30, 50, and 70 × 13 μJy beam^{-1}, the rms noise of the map.

found to be associated with a molecular outflow. We then conservatively interpret these new radio continuum sources as small H II regions ionized by B2–B3 ZAMS stars, assuming that the radio continuum emission is optically thin free-free radiation. In the case of the second brightest source in the field, VLA 3, there is also a 6 cm detection (Gómez et al. 2000, in preparation), and the spectral index is found to be flat, a result consistent with our assumption. However, in the case of VLA 7 (see below) the radio source may be a thermal jet.

In Table 2 we present the physical parameters derived from the 3.6 cm radio continuum observations for the six new detections and for the compact cometary H II region, VLA 1. All the parameters were determined assuming a distance of 1 kpc to the region GGD 14. The results for VLA 1 are in agreement with those reported in previous works (Rodríguez et al. 1980; Tofani et al. 1995; Gómez et

TABLE 2

DERIVED PARAMETERS FROM THE 3.6 CM SOURCES[a]

Source	N_i (photons s^{-1})	Luminosity ($L_\odot$)	Spectral Type
VLA 1......	9.2×10^{45}	1×10^4	B0.5
VLA 2......	9.5×10^{42}	1×10^3	B3
VLA 3......	9.9×10^{43}	2×10^3	B2
VLA 4......	1.1×10^{43}	1×10^3	B3
VLA 5......	9.5×10^{42}	1×10^3	B3
VLA 6......	3.9×10^{43}	1×10^3	B3
VLA 7......	1.6×10^{43}	1×10^3	B3

[a] The ionizing fluxes were derived following Schraml & Mezger 1969 and assuming a distance of 1 kpc, optically thin free-free emission, an electron temperature of 10^4 K, and that the ionization is produced by a ZAMS star. The luminosities and spectral types are from Thompson 1984.

al. 1998). The total luminosity implied by the radio continuum observations, $\sim 1.7 \times 10^4\ L_\odot$, is larger than the *IRAS* luminosity of $\sim 1.0 \times 10^4\ L_\odot$. However, given the uncertainties involved in these estimates, we do not consider this discrepancy to be serious.

The probability of finding an extragalactic source at 3.6 cm above 0.065 mJy in a box of $30'' \times 30''$ is very low (~ 0.02), so we conclude that all the sources detected are almost certainly embedded in the cloud. Unlike VLA 1, which has an angular extension of $\sim 2''.5$, the other six VLA sources are unresolved ($\leq 0''.1$). At a distance of 1 kpc, this corresponds to an upper limit of 50 AU for the radii of those H II regions and to a lower limit of $\sim 8 \times 10^4\ \mathrm{cm}^{-3}$ for their electron density. If they were expanding at $\sim 10\ \mathrm{km\ s}^{-1}$, the kinematic age of all of them would be less than 25 yr, obviously a most unlikely situation. The problem of the ages of ultracompact H II regions (Wood & Churchwell 1989) is well known: there are too many of them in the Galaxy, implying that they are not freely expanding but that some mechanism confines them and extends their life considerably. This mechanism remains unknown, although several hypotheses have been proposed, including ram pressure of infalling matter (Wood & Churchwell 1989), bow shocks (van Buren & Mac Low 1992), photoevaporating disks (Hollenbach et al. 2000; Richling & Yorke 1997), mass-loaded flows (Dyson, Williams, & Redman 1995; Lizano et al. 1996), and dense molecular environments (De Pree, Rodríguez, & Goss 1995; García-Segura & Franco 1996; Xie et al. 1996; Akeson & Carlstrom 1996). Recent reviews of this problem are given by Garay & Lizano (1999) and Kurtz et al. (2000). The new sources reported here are very small, and if they do coincide spatially with the star, even gravity could be important in their confinement. For a stellar mass of $\sim 10\ M_\odot$, the escape velocity at a distance of 25 AU is of order $10\ \mathrm{km\ s}^{-1}$, comparable to the sound speed of ionized gas with an electron temperature of 10^4 K. However, a detailed hydrodynamical calculation that includes the stellar radiation and wind is needed to investigate whether these H II regions can be gravitationally bound to their stars.

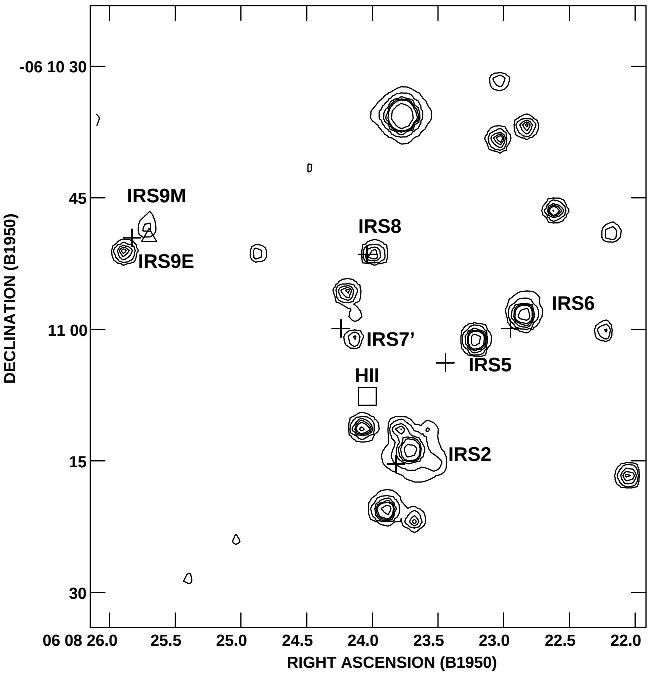

FIG. 3.—Near-infrared 2 μm image from Hodapp (1994) toward GGD 14. The crosses mark the peak positions of the new 3.6 cm radio sources. The triangle marks the position of the water maser (Rodríguez et al. 1980), and the square shows the position of the compact cometary H II region, VLA 1. Contour levels are in arbitrary units and increase in factors of 2. The names of the near-infrared sources were taken from Harvey et al. (1985).

We also find a near-infrared counterpart very close to all the new radio sources, supporting the idea that the radio emission is arising from ionized gas excited by the star traced by the near-infrared observations. Figure 3 shows the 2 μm image from Hodapp (1994) with the new 3.6 cm radio sources shown as crosses. In order to do the astrometry for the 2 μm image of Hodapp (1994), we used the optical positions from nearby stars found both in the Hodapp (1994) image and in the Digitized Sky Survey. The astrometric transformation of the 2 μm image from Hodapp was made using the XTRAN task of AIPS. We estimate that the 2 μm positions listed in Table 3 have errors of order $1''$. Indeed, the positions of most of these near-infrared sources have been given previously by Harvey et al. (1985), and we find agreement between the two sets of positions at the $1''$ level. The *K* magnitudes given by Harvey et al. (1985) for the near-infrared sources associated with the new 3.6 cm sources are consistent with early B-type stars. In general we observe a near coincidence between the positions of the radio and near-infrared sources, with an average separation of $\sim 2''$ (see Table 3). There is no systematic shift in position that will bring the radio and near-infrared positions into full agreement. The reason for these offsets is not known, but they can be attributed to spatial displacements between the ionizing star and the ionized gas. If these offsets are real, they may imply that only a fraction of the ionizing photons of the stars are being absorbed by the radio H II regions and that the real spectral types of the stars should be earlier than those derived from the radio continuum data.

3.2. *VLA 7: the Powering Source of the Molecular Outflow*

Detection of the powering source of molecular outflows is very important for determining the physical characteristics of the first stages of young stellar objects. The CO molecular outflow in GGD 14 (Rodríguez et al. 1982; Little et al. 1990) consists of two extended lobes with the red lobe to the northwest and the blue lobe to the southeast. A water maser

TABLE 3

NEAR-INFRARED POSITIONS[a]

Name	α(1950)	δ(1950)	Separation from Nearest Radio Source (arcsec)
IRS 2	06 08 23.72	−06 11 13.8	2.2
IRS 5	06 08 23.21	−06 11 01.1	4.5
IRS 6	06 08 22.84	−06 10 58.3	2.3
IRS 7′........	06 08 24.14	−06 11 01.0	1.9
IRS 8	06 08 23.98	−06 10 51.8	0.9
IRS 9M......	06 08 25.70	−06 10 48.8	2.1
IRS 9E	06 08 25.89	−06 10 51.1	2.7

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Measured by us, using the 2 μm image of Hodapp 1994. Near-infrared names are from Harvey et al. 1985.

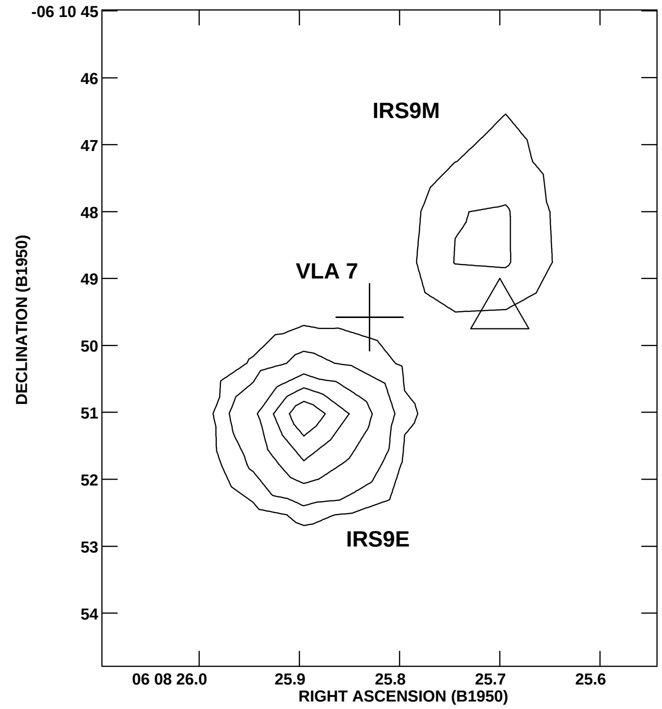

FIG. 4.—Close-up of the map shown in Fig. 3,which indicates with a cross the position of the object VLA 7, the possible powering source of the bipolar CO molecular outflow. The triangle shows the position of the water maser, and the contours are as in Fig. 3.

is located at the center of the outflow, at the position $\alpha(1950) = 06^{h}08^{m}25^{s}.66$, $\delta(1950) = -06^{\circ}10'49''.6$, with an uncertainty of less than $0''.1$ (Tofani et al. 1995). The water maser shows strong variability in the intensity of its features (Rodríguez et al. 1980; Tofani et al. 1995). The new radio continuum source detected by us, VLA 7, has a peak position of $\alpha(1950) = 06^{h}08^{m}25^{s}.83$ and $\delta(1950) = -06^{\circ}10'49''.6$, which is only $\sim 2''$ (~ 0.01 pc) away from the H_2O maser and is spatially centered with respect to the molecular outflow, suggesting that it is closely related to the powering source of the bipolar CO outflow. Figure 4 shows the position of VLA 7 relative to the 2 μm structures IRS 9M and IRS 9E. It is interesting to see that these near-infrared structures are aligned with the axis of the molecular outflow and that the radio continuum source appears just at the center, suggesting that the 2 μm structures could be a bipolar reflection nebula tracing the outflow at small scales, as seen, for example, in HH 111 (Reipurth et al. 1999). Furthermore, the brighter 2 μm structure is on the blue CO lobe, and the fainter is on the red CO lobe, as is expected when dust extinction is taken into account. Harvey et al. (1985) detected 20 μm emission close to the near-infrared source 9M (associated with the water maser), suggesting that it could be related to the powering source of the molecular outflow. The two 2 μm components are located at both sides of the 20 μm emission along the main axis of the molecular outflow in the northwest-southeast direction. Harvey et al. (1985) conclude from photometry data that the component 9E is arising from reflected light from an embedded object. The water maser position does not coincide with VLA 7, but we know that in star-forming regions the masers are not necessarily at the same position as the radio continuum source (Gómez, Rodríguez, & Martí 1995; Tofani et al. 1995). All this suggests that VLA 7 is the powering source of the molecular outflow in GGD 14, but more sensitive observations are needed to see whether it has an elongated structure in the direction of the molecular outflow and also to determine its spectral index to confirm that it is really a thermal jet (Rodríguez et al. 1994; Anglada 1996; Rodríguez 1997) exciting the bipolar outflow.

3.3. *A Condensation in the Cometary* H II *Region VLA 1*

Here we are interested in assessing whether or not there are compact structures inside the cometary H II region VLA 1. Since visibilities from baselines with short spacings give information about regions of extended angular size, it is possible to suppress the extended ionized emission from a nebular region, by limiting the (u, v) range of the data. This technique is used when one wants to find compact objects, like stellar winds embedded in more diffuse emission (Gómez et al. 1992). By using visibility data at (u, v) distances larger than 200 kλ, we eliminate emission from angular structures larger than $\sim 1''$, while keeping emission from compact components. In the case of these observations, these long baseline visibilities are 66% of the total data. In Figure 5*a* we show a 3.6 cm map of VLA 1 made with all the (u, v) data to compare with the map made with baselines larger than 200 kλ, shown in Figure 5*b*. In the latter map we find two main compact structures. The first structure to the NW of the region is elongated and is interpreted as resulting from the sharp edge of the cometary H II region. The second structure has a peak position at $\alpha(1950) = 06^{h}08^{m}24^{s}.10$ and $\delta(1950) = -06^{\circ}11'07''.8$, a peak intensity of 0.36 ± 0.04 mJy beam^{-1}, a flux density of 0.57 ± 0.04 mJy, and a deconvolved angular size of $0''.29 \times 0''.16 \pm 0''.05$ at P.A. = 53°.

Given the position of this condensation, close to where the exciting star is expected to be, one could attempt to interpret it as an ionized stellar wind. However, an ionized stellar wind would appear as a very compact, optically thick source with a brightness temperature of $T_B \simeq 10^4$ K. In contrast, the condensation has $T_B \simeq 200$ K. Another possibility is that the condensation is an ionized clump with electron density of $\sim 6 \times 10^4$ cm^{-3} embedded in the cometary H II region, which has an average electron density of $\sim 2 \times 10^4$ cm^{-3}. However, at an expansion velocity of ~ 10 km s^{-1}, it would have a kinematic age of only 50 yr. Finally, this source could be an additional line-of-sight compact H II region or an externally ionized structure similar to the Orion proplyds (O'Dell 1998). To discern the nature of this compact condensation, it will be necessary to take sensitive observations at several frequencies to determine its spectral index.

4. CONCLUSIONS

We present high angular resolution VLA observations at 3.6 cm toward the star-forming region GGD 14. In addition to VLA 1, the previously known compact cometary H II region, a cluster of six new radio sources was found. These sources are probably ionized by B2–B3 ZAMS stars and must be confined to impede their expansion. We propose that, given the small size of these sources, they could be gravitationally bound to their stars. In particular, we propose that VLA 7 is the powering source of the bipolar molecular outflow, because it is located at the center of the molecular outflow. At 2 μm we note the presence of two

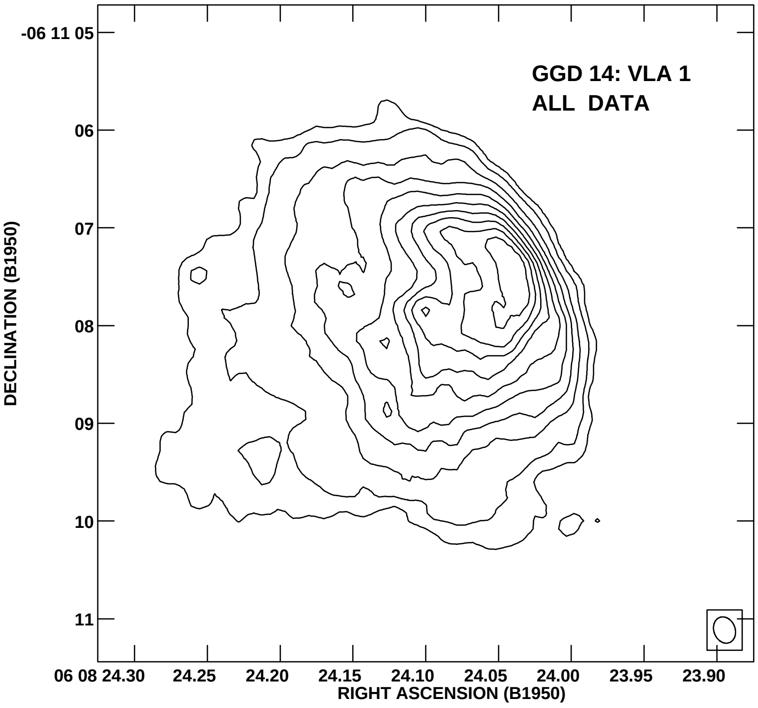

FIG. 5*a*7

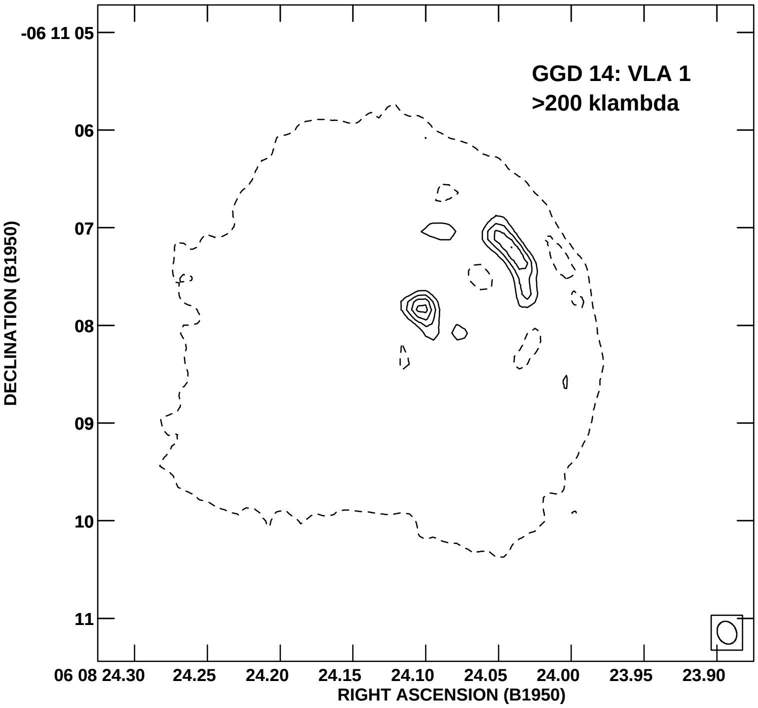

FIG. 5*b*

FIG. 5.—(*a*) VLA 3.6 cm continuum map toward the cometary H II region, VLA 1. Contour levels are −5%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% of 1.5 mJy beam^{-1}, the peak flux of the map. (*b*) 3.6 cm continuum map with visibilities larger than 200 kλ, thus suppressing extended structures. Contour levels are −30%, 30%, 50%, 70%, and 90% of 0.36 mJy beam^{-1}, the peak flux of the map. The dashed line sketches the external edge of the radio continuum emission and has a contour level of 5% of the peak of the map shown in (*a*).

sources, IRS 9M and IRS 9E, along the CO bipolar outflow with the radio source VLA 7 at its center. The 2 μm sources have different intensities, and we propose that they may form a bipolar reflection nebula that traces the outflow at small scales.

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