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CANDIDATE PLANETARY NEBULAE NEAR THE GALACTIC CENTER

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RESUMEN

En este trabajo utilizamos observaciones hechas con el VLA a 20 y 6 cm hacia una fuente de alta energía cerca del centro galáctico para estudiar la naturaleza de tres fuentes de radio no identificadas y relativamente brillantes ($S_{6cm} > 5$ mJy) que aparecen en el campo. Las tres fuentes tienen índices espectrales planos y muy probablemente son emisoras de radiación libre-libre ópticamente delgada. Tomando en cuenta su densidad de flujo, tamaño, masa y morfología, hemos identificado tentativamente a dos de estas fuentes (G359.023−0.044, G359.139−0.087) como nebulosas planetarias y a la tercera (G359.164−0.161) como una región H II compacta.

ABSTRACT

We have used sensitive VLA observations made at 20 and 6 cm toward a high energy source near the galactic center to study the nature of three relatively bright ($S_{6cm} > 5$ mJy) unidentified radio sources in the field. All three sources have flat spectral indices and are most probably optically-thin free-free emitters. On the basis of their flux densities, sizes, masses, and morphologies, we tentatively identify two of these sources (G359.023−0.044, G359.139−0.087) as planetary nebulae and the third one (G359.164−0.161) as a compact H II region.

Key words: **GALAXY - CENTER — PLANETARY NEBULAE — RADIO CONTINUUM - INTERSTELLAR**

1. INTRODUCTION

At present, about 1500 galactic planetary nebulae (PNe) have been reported (Acker et al. 1992; Acker, Marcout, & Ochsenbein 1996). These authors classify PNe as true, probable or possible in decreasing order of certainty in the classification. The classification of true PNe require optical spectroscopic confirmation. The number of known galactic PNe continues to grow and only a small percentage of the total number has been identified with certainty since 10^4-10^5 PNe are expected to exist in the Galaxy. The highest space density of PNe is expected to exist near the galactic center, where the highest density of solar-mass stars is reached (Wouterloot & Dekker 1979). However, the strong interstellar extinction toward the bulge of the Galaxy difficults greatly the identification of PNe near the galactic center using classical optical methods. From the catalog and supplement of PNe by Acker et al. (1992; 1996) we find a total of 27 true, probable, or possible PNe in the box defined by $359° \leq l \leq 1°$, $-1° \leq b \leq 1°$. Of these objects, three (Hb 5, PN G000.7−00.8, and PN G000.9−00.9) have been confirmed as true PNe. We note that only Hb 5 has a distance determination of $\sim$ 2 kpc and thus it is not located near the galactic center. Of the remaining 24 probable or possible PNe, 16 have been recently detected in the near-IR survey of Jacoby & van de Steene (1997). In addition, eight possible PNe have been identified projected near the galactic center, using radio continuum observations combined with far-infrared *IRAS* color measurements (Wouterloot & Dekker 1979; Isaacman 1981; Preite-Martinez 1988; Pottasch et al. 1988; Ratag et al. 1990; Ratag & Pottasch 1991).

The identification of planetary nebulae from radio continuum alone is not straightforward, and the main problem is clearly to discern between a planetary nebula and an H II region since both usually have flat spectral indices in the centimeter wave-

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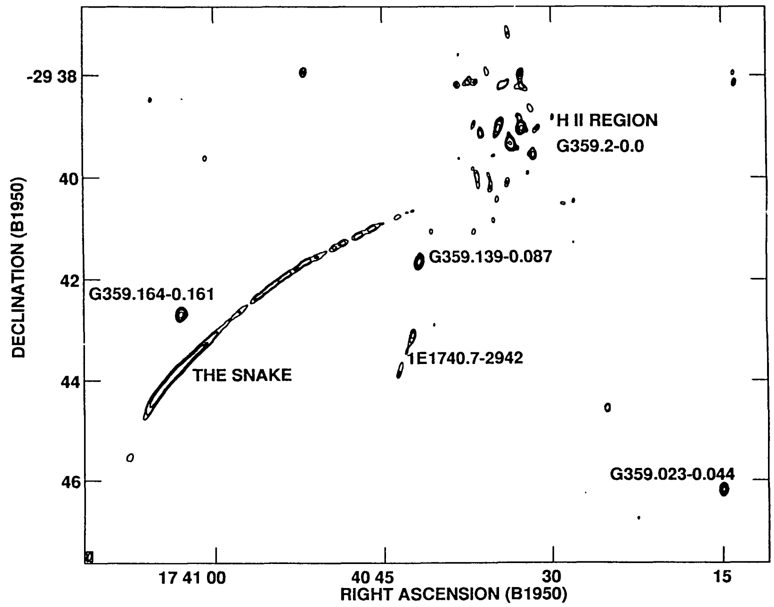

Fig. 1. VLA radio continuum map at 6 cm (C configuration) toward the high energy source 1E1740.7−2942 (Mirabel et al. 1992). Other well-studied sources in the region are the peculiar structure known as The Snake (Gray et al. 1991), and the triple-core H II region G359.2−0.0 (Caswell & Haynes 1987). The sources G359.023−0.044, G359.139−0.087 and G359.164−0.161 are discussed in the paper. Contours in the map are 4, 6, 10, 15, 30, and 50 times 50 μJy beam^{-1}. The half power contour of the synthesized beam (8.″4 × 4.″0; P.A.=−10°) is shown in the bottom left corner. This map is not corrected for primary beam response or bandwidth smearing.

lengths. It is necessary to have more information about the morphology, size, *IRAS* colors, or to complement with observations made at other frequencies. In this paper we have used high-quality 20 and 6 cm observations made with the VLA toward the high energy source 1E1740.7−2942 by Mirabel et al. (1992; 1993) to study the nature of three relatively bright (S_{6cm} > 5 mJy) flat spectrum sources in the same field.

2. OBSERVATIONS

The 20 and 6 cm observations were made during 1991, 1992, and 1993 with the VLA of the NRAO[3] in different configurations. The phase center position was at $\alpha(1950) = 17^h\ 40^m\ 43\overset{s}{.}01$; $\delta(1950) = -29°\ 43'\ 25\overset{''}{.}5$. A description of the observations and their calibration is given by Mirabel et al. (1992; 1993).

3. RESULTS AND DISCUSSION

A natural-weight map made with all the data taken at 6 cm in C configuration (angular resolution of ∼ 6″) is shown in Figure 1. The map shows the three well-studied sources in the region: 1E1740.7−2942 (Mirabel et al. 1992), The Snake (Gray et al. 1991), and the triple-core H II region G359.2−0.0 (Caswell & Haynes 1987). In addition, three relatively bright (S_{6cm} > 5 mJy), unidentified sources, labeled as G359.023−0.044, G359.139−0.087 and G359.164−0.161, are evident. Following Rodríguez et al. (1989), we estimate that the expected number of background sources with flux density above 5 mJy is less than unity (∼ 0.4). Then, even when the presence of one background source with flux density above 5 mJy could be considered as not surprising, the presence of three background sources is statistically unlikely. In addition, the spectral index (defined as α; where $S_\nu \propto \nu^\alpha$) of background sources is usually negative, while all three unidentified sources have flat spectral indices (see Table 1) consistent with the value of −0.1 that characterizes optically-thin free-free emission. This coincidence in spectral indices is very unlikely, and suggests that we are seeing this excess of bright flat-spectrum sources because the line of sight passes within ∼ 1° of the galactic center. We will then work under the hypothesis that these sources are optically-thin free-free emitters located close to the galactic center, at a distance of 8.5 kpc from the Sun. Table 1 con-

[3] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities Inc.

TABLE 1

RADIO CONTINUUM PARAMETERS OF THE FLAT SPECTRUM SOURCES

Source	Position[a](1950) α	δ	Flux Density (mJy)[b] (20 cm)	(6 cm)	Spectral Index	Deconvolved Size (arc sec)[b]
G359.023−0.044	$17^h40^m14^s.92$	$-29°46'10''.9$	18.5±1.0	17.7±0.6	+0.0±0.1	2.9±0.3
G359.139−0.087	17 40 41.89	−29 41 39.2	6.8±0.4	5.6±0.2	−0.2±0.1	3.4±0.3
G359.164−0.161	17 41 03.04	−29 42 42.3	7.8±0.4	6.9±0.2	−0.1±0.1	3.9±0.4

[a] Peak positions are from the 6 cm B configuration map. Estimated position error is $\sim 0''.2$.
[b] Flux densities and deconvolved angular sizes at 6 cm are from B configuration observations. The 20 cm flux densities are from matching beam A configuration observations. Flux densities are corrected for the response of the primary beam.

tains positions, flux densities, spectral indices, and deconvolved angular sizes for the three sources derived from 20 and 6 cm VLA data.

3.1. Derived Parameters

The observational parameters at 6 cm (4.9 GHz) given in Table 1 allow us to estimate the physical parameters for each source following the formulation of Schraml & Mezger (1969) for a homogeneous spherical source with an electron temperature of 10^4 K and assuming that the free-free emission is optically thin. The distance we adopt is 8.5 kpc. We derive the physical parameters listed in Table 2. In this table we list the diameter, L; the electron density, n_e; the number of ionizing photons needed to excite the ionized region, N_i; the emission measure, EM; the mass in ionized hydrogen, M_{H^+}; and the optical depth at 4.9 GHz, $\tau_{4.9GHz}$.

Based only on these parameters, the sources can be interpreted either as compact H II regions or as planetary nebulae. Their angular diameters (see Table 1) are all of order $\sim 3''$, that is, ~ 0.1 pc at a distance of 8.5 ± 1.0 kpc. The required ionizing photon rates are in the range $\sim 4-12 \times 10^{46}$ s^{-1}, and the masses are in the range of 0.12–0.16 $M_\odot$ (see Table 2). Then, even when the diameters, ionizing photon rates and masses of the three sources are typical of planetary nebulae (Pottasch 1984), we cannot rule out the possibility that they could be compact H II regions ionized by an early B-type star. We are left with the possibility of using the morphology of the sources in an attempt to distinguish between the PN or the H II region identifications. We will do this in the following section.

3.2. Discussion on Individual Sources

We present a brief description of these three radio continuum sources with $S_{6cm} > 5$ mJy in the field. Individual radio continuum maps of each source have been made at 6 cm, using concatenated A and B configuration data of the VLA and the AIPS task IMAGR (Figures 2 to 4). These maps have been corrected for bandwidth smearing using the AIPS task UVADC.

3.2.1. G359.023−0.044

Figure 2 shows our 6 cm map of G359.023−0.044. This source had been previously detected at 5 GHz in the VLA survey by Becker et al. (1994), and the flux density observed by them (16.3 mJy) at this frequency is in agreement with that reported here

TABLE 2

DERIVED PARAMETERS OF THE FLAT SPECTRUM SOURCES[a]

Source	L (pc)	n_e (10^3 cm^{-3})	N_i (10^{46} photons s^{-1})	EM (10^5 cm^{-6} pc)	M_{H^+} ($M_\odot$)	$\tau_{4.9\ GHz}$ (10^{-2})
G359.023−0.044	0.12±0.02	2.3±0.4	11.5±2.7	9.3±1.9	0.16±0.05	1.12±0.22
G359.139−0.087	0.14±0.02	1.0±0.2	3.6±0.9	2.1±0.4	0.12±0.04	0.25±0.06
G359.164−0.161	0.16±0.03	0.9±0.2	4.5±1.1	2.0±0.4	0.16±0.05	0.24±0.04

[a] For a homogeneous spherical source at a distance of 8.5 kpc and $T_e = 10^4$ K, with the observed angular size.

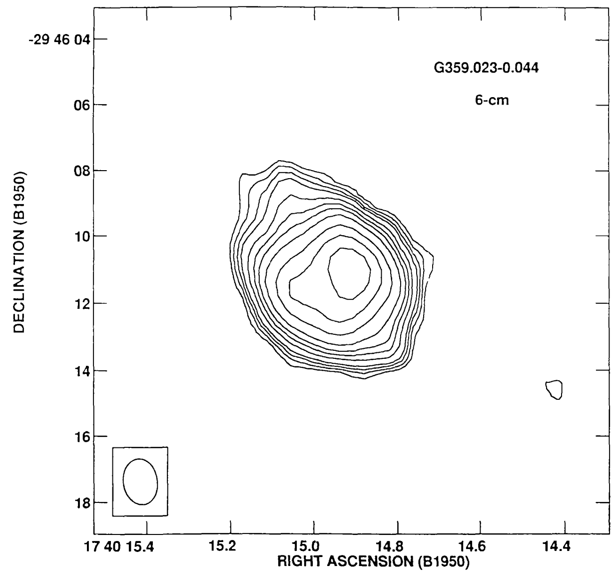

Fig. 2. VLA radio continuum map at 6 cm (A+B configurations) toward the source G359.023−0.044. Contours in the map are −4, −3, 3, 4, 5, 6, 8, 10, 12, 15, 20, 25, 30, and 40 times 83 μJy beam^{-1}. The half power contour of the synthesized beam (1.″4 × 1.″0; P.A. = +9°) is shown in the bottom left corner.

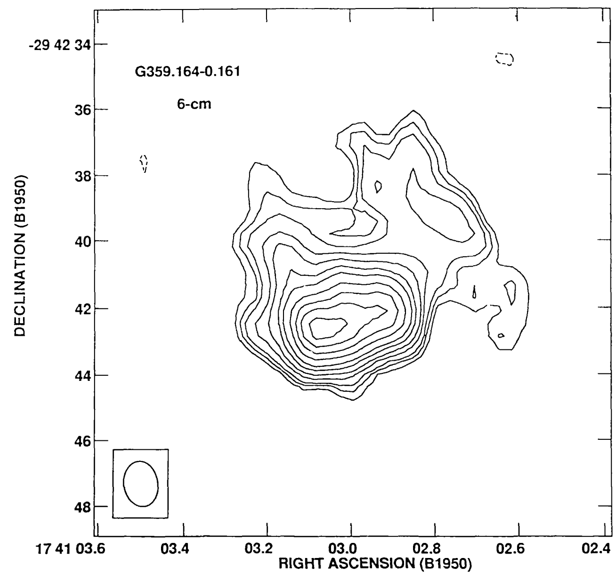

Fig. 4. VLA radio continuum map at 6 cm (A+B configurations) toward G359.164−0.161. Contour levels are −4, −3, 3, 4, 5, 7, 9, 12, 15, 20, 25, 30, 35, and 40 times 31 μJy beam^{-1}.

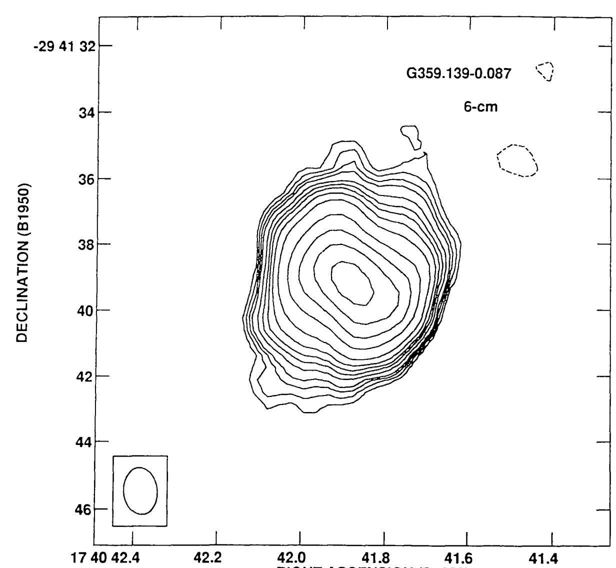

Fig. 3. VLA radio continuum map at 6 cm (A+B configurations) toward G359.139−0.087. Contour levels are −4, −3, 3, 4, 5, 6, 8, 10, 12, 15, 20, 30, 40, 50 and 60 times 17 μJy beam^{-1}.

(17.7 mJy). This radio source does not have an *IRAS* counterpart nor an optical counterpart in the Digitized Sky Survey. In the far-infrared, the region studied is very confused, and at 100 μm *IRAS* upper limits are $\sim$ 500 Jy. Then, for the three sources discussed here we have log[S(100 μm)/S(6 cm)] $\leq$ 4.7. Are these upper limits consistent with what is expected for compact H II regions and planetary nebulae? For the results of Kurtz, Churchwell, & Wood (1994) on 45 objects we estimate that on the average for compact H II regions log[S(100 μm)/S(6 cm)] = 4.2 ± 0.7. From 51 PNe listed in Pottasch (1984) with both 100 μm and 6 cm flux densities, we find on the average log[S(100 μm)/S(6 cm)] = 1.9 ± 0.4. Then, even when this flux ratio could be used to discriminate between compact H II regions and PNe, we only can conclude with the available data, that the upper limits obtained are consistent with either a compact H II region or a PN interpretation.

Our high quality radio map provides for the first time detailed information on its morphology. This morphology can be described as having sharp edges in the radio continuum emission at two opposite sides of the nebula (to the NW and SE), with a slower decrease of the intensity along an axis perpendicular to that joining the sharp edges. Furthermore, the *inner* contours of the radio map are elongated along a position angle nearly perpendicular to that of the elongation of the *outer* contours. We will refer to this morphology as biaxial elliptical. It is common to see this type of biaxial elliptical morphology in radio maps of planetary nebulae. For example, the PNe PK 248−8.1, PK 3−4.8 and PK 31−10.1 (Zijlstra, Pottasch & Bignell, 1989) exhibit in the radio a biaxial elliptical morphology similar to that of G359.023−0.044. This morphology is probably a result of the ionization of an anisotropic PN envelope produced in the AGB phase. Then, on the basis of its morphology and the physical parameters listed in Table 2, we suggest that G359.023−0.044 is a possible planetary nebula. Compact H II regions can show elliptical morphologies (Wood & Churchwell 1989; Kurtz et al. 1994). However, these elliptical sources do not have the biaxial morphology of PN; namely, the position angle of the contours remains fixed while going from the inner to the outer contours (see for example, sources G35.378−0.030, G77.965−0.006, and G25.650+1.050 in Kurtz et al. 1994).

3.2.2. G359.139−0.087

This radio source is $\sim 2'$ north of the source 1E1740.7−2942 (Mirabel et al. 1992). The proximity of this high energy source to the radio object made Leahy (1991) propose that they were associated. The studies of Mirabel et al. (1992) showed that 1E1740.7−2942 is actually associated with the twin jet source evident in Figure 1. The radio source G359.139−0.087 does not have an *IRAS* counterpart nor an optical counterpart in the Digitized Sky Survey. Figure 3 shows the 6 cm radio continuum map of the source. Its radio morphology is also biaxial elliptical, similar to that of G359.023−0.044 (see above), and thus we propose it as another possible planetary nebula.

3.2.3. G359.164−0.161

In Figure 4 we present a 6 cm radio continuum map of G359.164−0.161. This radio source lies inside the error ellipse of IRAS 17409−2942, suggesting that they are associated. The position of the *IRAS* source is $\alpha(1950) = 17^h\ 40^m\ 59\overset{s}{.}5$; $\delta(1950) = -29°\ 42'\ 43''$, and its fluxes are; $S_{12\mu m} \leq 8.6$ Jy, $S_{25\mu m} = 3.6$ Jy, $S_{60\mu m} \leq 98.2$ Jy and $S_{100\mu m} \leq 479.4$ Jy. Note that except for the 25 μm infrared flux, the other fluxes are upper limits. Thus, we cannot use the color-color diagrams to discern between PNe and H II objects (Pottasch et al. 1988; Preite-Martinez 1988; White, Becker, & Helfand 1991). However, we can appreciate in Figure 4 the cometary morphology (sharp edge to the south and diffuse tail to the north) of this radio object suggesting that it is probably an H II region excited by an early B-type star. Cometary morphologies are found in $\sim 20\%$ of compact H II regions (e.g., Wood & Churchwell 1989). A faint optical object of stellar appearance in the Digitized Sky Survey is located 15″ to the north of the radio source. This optical source, with position $\alpha(1950) = 17^h\ 41^m\ 02\overset{s}{.}63$; $\delta(1950) = -29°\ 42'\ 24\overset{''}{.}5$, could be related to the tail of the cometary nebula; but optical spectroscopy is required to establish its nature.

4. CONCLUSIONS

We present VLA radio continuum observations made at 20 and 6 cm toward three relatively bright, unidentified objects near the Galactic Center. All three sources have flat spectral indices and are most probably optically-thin free-free emitters. Based only on their bulk physical parameters, the sources can be interpreted either as compact H II regions or as planetary nebulae. We propose that two of them, G359.023−0.044 and G359.139−0.087, are candidate planetary nebulae because the elliptical morphology they exhibit is typical of planetary nebulae. The third source, G359.164−0.161, shows a cometary morphology; since this type of morphology is frequently observed in H II regions, we tentatively identify it as a member of this class.

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