A COLLIMATED, IONIZED BIPOLAR STRUCTURE AND A HIGH DENSITY TORUS IN THE PLANETARY NEBULA IRAS 17347–3139

D. Tafoya, Y. Gómez, N. A. Patel, J. M. Torrelles, J. F. Gómez, G. Anglada, L. F. Miranda, and I. de Gregorio-Monsalvo

1 Centro de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Apdo. Postal 3-72 (Xangari), CP 58089, Morelia, Michoacán, México; d.tafoya@astrosmo.unam.mx, y.gomez@astrosmo.unam.mx
2 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; npatel@cfa.harvard.edu
3 Instituto de Ciencias del Espacio (CSIC)-IEEC, Facultad de Física, Universidad de Barcelona, E-08028, Spain; torrelles@ieec.fcr.es
4 Instituto Astrofísica Andalucía, CSIC, E-18008 Granada, Spain; jfg@iaa.es, guillem@iaa.es, lfm@iaa.es
5 European Southern Observatory, Alonso de Córdova 3107, Vitacura, Casilla 19001, Santiago 19, Chile; idegreg@eso.org

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ABSTRACT

We present observations of continuum ($\lambda = 0.7, 1.3, 3.6, \text{and} 18$ cm) and OH maser ($\lambda = 18$ cm) emission toward the young planetary nebula IRAS 17347–3139, which is one of the three planetary nebulae that are known to harbor water maser emission. From the continuum observations, we show that the ionized shell of IRAS 17347–3139 consists of two main structures: one extended (size $\sim 1.5''$) with bipolar morphology along P.A.$ = -30^\circ$, elongated in the same direction as the lobes observed in the near-infrared (NIR) images, and a central compact structure (size $\sim 0.25''$) elongated in the direction perpendicular to the bipolar axis, coinciding with the equatorial dark lane observed in the NIR images. Our image at 1.3 cm suggests the presence of dense walls in the ionized bipolar lobes. We estimate for the central compact structure a value of the electron density at least $\sim 5$ times higher than in the lobes. A high-resolution image of this structure at 0.7 cm shows two peaks separated by about $0.13''$ (corresponding to 100–780 AU, using a distance range of 0.8–6 kpc). This emission is interpreted as originating in an ionized equatorial torus-like structure, from whose edges the water maser emission might be arising. We have detected weak OH 1612 MHz maser emission at $V_{\text{LSR}} \sim -70$ km s$^{-1}$ associated with IRAS 17347–3139. We derive a $3\sigma$ upper limit of $< 35\%$ for the percentage of circularly polarized emission. Within our primary beam, we detected additional OH 1612 MHz maser emission in the local standard of rest velocity ranges $-5$ to $-24$ and $-90$ to $-123$ km s$^{-1}$, associated with the sources J17380406–3138387 and OH 356.65–0.15, respectively.

Key words: planetary nebulae: general – planetary nebulae: individual (IRAS 17347–3139) – radio continuum: stars – stars: AGB and post-AGB – stars: mass loss – stars: winds, outflows

1. INTRODUCTION

The study of transition objects from the asymptotic giant branch (AGB) to the planetary nebula (PN) phase is very important to understand the processes by which low and intermediate mass stars evolve. It has been observed that planetary nebulae (PNs) display a large variety of morphologies, including bipolar or multipolar structures (Balick 1987; Schwarz et al. 1992; Manchado et al. 1996). However, it is not well understood how they develop such morphologies. Given that the transition phase occurs in a very short time scale of $\sim 1000$ yr (Kwok 1993), only a few objects are expected to be in this evolutionary stage, making the observational study of the physical conditions under which they evolve a difficult task. A simple model, which, in general, explains the development of bipolar morphologies in PNs, is the generalized interacting stellar winds (GISW) model (Kahn & West 1985; Balick 1987; Icke 1988, Mellem et al. 1991). This model assumes that the “superwind,” expelled during the AGB phase, produces a circumstellar envelope (CSE) which has a latitude-dependent density profile, with an enhancement in the equatorial region and monotonically decreasing toward the poles. Subsequently, the slow massive wind is replaced by a fast tenuous wind; the latter hydrodynamically interacts with the former, resulting in the creation of the bipolar lobes (Mellem et al. 1991, Frank et al. 1993, García-Segura et al. 1999, Balick & Frank 2002).

High angular resolution and sensitive images of PNs obtained with the Hubble Space Telescope (HST) have revealed collimated structures whose formation cannot be explained by the GISW model (Miranda & Solf 1992; Sahai & Trauger 1998). The presence of a companion, collimated outflows (e.g., Sahai & Trauger 1998; Soker & Rappaport 2000; Velázquez et al. 2007), or magnetic fields (e.g., García-Segura et al. 1999) is required in most cases to explain the formation of such collimated structures. Nonetheless, the existence and study of a disk or an equatorial density enhancement in the CSE are considered a key ingredient to understand the processes that form bipolar lobes. A detailed study of particular PNs can provide crucial information about the physical conditions under which they develop their morphologies, and help to determine the relevance of the different shaping mechanisms proposed.

IRAS 17347–3139 is a young PN with a clear bipolar morphology, as revealed by the near-infrared (NIR) images (de Gregorio-Monsalvo et al. 2004, hereafter dGM04; Sánchez-Contreras et al. 2006; Sahai et al. 2007). The lobes show an extent of $\sim 4''$, separated by a dark lane, which is probably tracing a dense dusty equatorial region. Sánchez-Contreras et al. (2006) suggested that the limb-brightened appearance of the lobes could be indicating the presence of bubble-like structures with dense walls and tenuous interiors, presumably excavated by jet-like winds.

dGM04 detected water masers arising from this young PN. Up to now, only two other PNs are known to exhibit water maser emission (Miranda et al. 2001; Gómez et al. 2008). Since the
water maser emission is expected to last for a very short period after the intense mass-loss rate stops, at the end of the AGB phase (~100 yr; Gómez et al. 1990), the detection of this emission suggests that these stars have entered the PN phase only some decades ago, making these objects good candidates to study the early stages of PN formation. However, the nature of the radio continuum emission in IRAS 17347−3139 has been discussed by dGM04 and Gómez et al. 2005 (hereafter G05). These authors showed that the flux density of IRAS 17347−3139 rises with frequency, deriving a spectral index \( \alpha \simeq 0.7 \) (\( S_\nu \propto \nu^{\alpha} \)), between 4.9 and 22 GHz, which was interpreted in terms of free–free emission from an ionized nebula. Moreover, G05 found that the radio continuum flux density increases rapidly with time. They estimated a dynamic time scale for the ionized envelope of ~100 yr, supporting the idea that this star entered the PN phase only some decades ago.

OH maser emission at 1612 MHz toward IRAS 17347−3139 was first reported by Zijlstra et al. (1989). Recently, Szymczak & Gérard (2004) presented single-dish polarimetric observations of OH masers toward this source. However, the association of this emission with the PN is uncertain due to the low angular resolution of their observations.

In order to clarify some questions that originated in previous works, and to further investigate the PN IRAS 17347−3139, we have carried out high sensitivity and angular resolution continuum and OH maser observations with the VLA. This work is structured as follows. In Section 2, we describe the new observations that allowed us to image with higher sensitivity and higher angular resolution the ionized envelope of this source. The results are presented in Section 3, the analysis of the data is discussed in Section 4, and the conclusions are given in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

On 2005 January 27, we used the VLA of NRAO\(^5\) in the hybrid configuration BnA, to carry out continuum observations of IRAS 17347−3139 at frequencies of 8.46, 22.46, and 43.34 GHz (\( \lambda = 3.6, 1.3, \) and 0.7 cm, respectively). We used two intermediate frequencies covering a total bandwidth of 100 MHz with two circular polarizations. At 0.7 and 1.3 cm, we used the fast switching mode, changing from a source to phase calibrator every 80 s in order to correct for the quick variations in the troposphere. As the phase tracking center, we used the position of the peak of the radio continuum reported by dGM04:\(^\alpha\)

\[ \alpha(J2000.0) = 17^h38^m00^s.586, \delta(J2000.0) = -31^\circ40'55''67. \]

The source J1335+305 (3C 286) was used as the flux calibrator while J1744−312 was the phase calibrator. Table 1 lists the flux densities of the calibrators at the different frequencies. The total time on source was 0.6, 0.5, and 1.1 hr at \( \lambda = 3.6, 1.3, \) and 0.7 cm, respectively.

We also carried out, with the VLA-BnA configuration, spectral line observations of four OH transitions with rest frequencies of 1612, 1665, 1667, and 1720 MHz. The 1665 and 1667 MHz observations were carried out on 2005 January 28, while the 1612 and 1720 MHz observations were carried out on 2005 January 29. For each transition, we observed both right and left circular polarizations (RCP and LCP, respectively). We sampled 256 channels in a total bandwidth of 1.5625 MHz, centered at \( \nu_{\text{LSR}} = -40 \text{ km s}^{-1} \), resulting in a spectral resolution of 6.1035 KHz (\( \sim 1.1 \text{ km s}^{-1} \)). In addition, for the 1612 MHz transition, we used a narrowband filter to avoid radio frequency interference due to the Iridium satellites. The sources 3C 286 and J1751−253 were the flux and phase calibrators, respectively (see flux densities in Table 1). From the spectral data of each transition, we have obtained a continuum data set by averaging channels free of maser emission. The four continuum data sets were calibrated separately. Subsequently, during the imaging process, they were concatenated to produce a single continuum data set.

The calibration and data reduction were carried out using the Astronomical Image Processing System (AIPS) of NRAO. We followed the standard procedures for reducing high-frequency data outlined in Appendix D of the AIPS Cookbook.\(^8\) Since 3C 286 is resolved at some of the observation frequencies, we used an image model for this source in the calibration process. The data for the continuum observations were self-calibrated in phase (except at \( \lambda = 18 \) cm), then Fourier transformed, weighted, and CLEANed to generate the final images.

3. RESULTS

3.1. Radio Continuum

Since the first detection by Zijlstra et al. (1989), it is known that IRAS 17347−3139 presents radio continuum emission. However, there were no radio images of this source reported in the literature. From our observations, we have obtained high sensitivity and high angular resolution interferometric images of IRAS 17347−3139 at wavelengths 18, 3.6, 1.3, and 0.7 cm (Figures 1–4, respectively). This is the first time that the radio emission from this PN has been spatially resolved.

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\(^{5}\) The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

\(^{8}\) For 2007 data of http://www.aips.nrao.edu/CookHTML/CookBook.html.
Figure 1. VLA image of IRAS 17347−3139 at wavelength 18 cm using a ROBUST weight parameter = 0. Contours are $-3.7, 3.7, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90,$ and $99\%$ of $2.4 \times 10^{-2}$ Jy beam$^{-1}$, the peak value of the brightness. The first contours are $-3$ and $3$ times the rms noise of the image, $2.9 \times 10^{-4}$ Jy beam$^{-1}$. The synthesized beam is shown in the bottom right corner, and its size is $3.38 \times 2.67$ (P.A. = $52^\circ$). The position of the OH 1612 MHz maser associated with IRAS 17347−3139 is show as a filled triangle.

Figure 2. Contours: VLA image of IRAS 17347−3139 at wavelength 3.6 cm using a ROBUST weight parameter = 0. Contours are $-0.31, 0.31, 1, 2, 3, 4, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90,$ and $99\%$ of $7 \times 10^{-2}$ Jy beam$^{-1}$. The value of the first contour is $3$ times the rms noise of the image, $7.2 \times 10^{-5}$ Jy beam$^{-1}$. The synthesized beam is shown in the bottom right corner, and its size is $0.65 \times 0.60$ (P.A. = $-65^\circ$). Gray scale: HST IR image of IRAS 17347−3139 at 1.1 $\mu$m obtained with the NIC1 in the F110W filter. In order to make the nominal position of the IR emission coincide with the peak of the radio continuum, the IR image has been shifted $\sim 0.5$ to the southeast.

At 3.6 and 1.3 cm (Figures 2 and 3, respectively) the radio continuum emission shows a bright central region and a fainter extended structure elongated in the northwest-southeast direction (P.A. = $-30^\circ$). Particularly, in the image at 1.3 cm, the extended emission shows a double horn structure in the northwest-southeast direction with an opening angle of about
Figure 3. Contours: VLA image of IRAS 17347−3139 at wavelength 1.3 cm using a ROBUST weight parameter = 0. Contours are −0.53, 0.53, 1, 2, 3, 4, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 99% of 1.1 × 10⁻¹ Jy beam⁻¹, the peak value of the brightness. The value of the first contour is 3 times the rms noise of the image, 2.1 × 10⁻⁴ Jy beam⁻¹. The synthesized beam is shown in the bottom right corner, and its size is 0.′′25 × 0.′′23 (P.A. = −88°). Gray scale: HST IR image of IRAS 17347−3139 at 1.1 μm obtained with the NIC1 in the F110W filter.

Figure 4. Contours: VLA image of IRAS 17347−3139 at wavelength 0.7 cm using a ROBUST weight parameter = 0. Contours are −2.5, 2.5, 3, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 99% of 7.35 × 10⁻² Jy beam⁻¹, the peak value of the brightness. The value of the first contours are −3 and 3 times the rms noise of the image, 6.2 × 10⁻⁴ Jy beam⁻¹. The synthesized beam is shown in the bottom right corner, and its size is 0.′′14 × 0.′′10 (P.A. = 46°). Gray scale: HST IR image of IRAS 17347−3139 at 1.1 μm obtained with the NIC1 in the F110W filter.

30°. This structure also appears in the NIR emission (also see dGM04; Sánchez-Contreras et al. 2006; Sahai et al. 2007). The bright emission of the central region at 1.3 cm seems slightly elongated in the direction perpendicular to the extended structure. This elongation of the central region is more clearly seen in the image at 0.7 cm (Figure 4).

We fitted two bidimensional Gaussian components to the emission observed at 3.6 cm, and also to the emission at 1.3 cm,
in order to estimate the size and orientation of both the compact (central region) and extended emissions. At 18 and 0.7 cm, only one Gaussian component was fitted. For the fitting process, we used images reconstructed with the ROBUST parameter (Briggs 1995) set to +5 in order to recover as much faint extended emission as possible; then we used the task JMFIT of AIPS to fit the Gaussians. The results of the fitting are shown in Table 2. From these images (ROBUST = +5), we also measured the total flux density of the source within a box containing the whole emission (Table 3). We notice that the total flux density at 1.3, 3.6, and 18 cm is compatible with the sum of the flux densities of the fitted Gaussian components. At 0.7 cm, the flux of the fitted Gaussian is lower than the total flux of the source. This is probably due to the presence of extended faint emission not fitted by a single Gaussian component. Therefore, in Table 2, we attribute the residual flux density from the Gaussian fitting at 0.7 cm to the extended structure.

In Figure 5, we compare our measurements of the total flux density with those of previous works and epochs. We noticed that the flux densities that we obtained follow an increasing trend with time, just as was previously found by G05. A possible explanation of the increase in flux density could be the expansion of the ionized nebula (given that the spectral index does not vary significantly between the different epochs). From our observations, we estimate a kinematical age for the ionized nebula of about 100 years. This value is consistent with the result obtained by G05.

In Table 3, we list the continuum peak positions of the source at different frequencies. At \( \nu = 8.46, 22.46, \) and 43.343 GHz (for which the source is better resolved), they coincide within 0.06\,arcsec from each other. When this position is compared with the nominal IR position of the nebula obtained from the \textit{HST} image, the difference is of about 0.5. We note, however, that the position we have measured for the peak emission differs by about 0.9 from that given by dGM04, which was obtained from data with a lower angular resolution. Since the newer specific procedures to calibrate high frequency data were not used by dGM04, we attribute this difference to their absolute positional error, which appears to be \( \sim 1\,\text{arcsec} \).

### 3.2. OH Maser Emission

Among the four OH maser transitions observed at \( \lambda \sim 18 \) cm, we only detected the line at 1612 MHz toward IRAS 17347−3139. In Table 4, we give the parameters of the OH maser line detected. The OH 1612 MHz maser emission is slightly displaced to the northwest from the peak of the radio continuum at 18 cm (\( \sim 0.5; \) Figure 1). In Figure 6 (left panel), we present the spectra of the RCP and LCP \( (S_{RCP} \) and \( S_{LCP} \), respectively) as well as the total flux density \( (S) \) and the circular polarization (Stokes \( V = (S_{RCP} - S_{LCP})/2 \) spectra. In both polarizations, there is only one feature at velocity \( V_{LSR} \sim -70 \) km s\(^{-1} \) with a flux density of \( \sim 40 \) mJy. From the Stokes \( V \) spectrum, we do not find evidence of the presence of circular polarized emission. We estimate a 3\( \sigma \) upper limit of \(< 35\% \) for the percentage of circularly polarized emission \( (m_c = |V|/I) \).

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**Table 2**

Parameters of the Gaussian Fitting to the Continuum Emission of IRAS 17347−3139

| Frequency (GHz) | Flux Density (mJy) | Size (arcsec × arcsec) | P.A. (degrees) |
|----------------|-------------------|------------------------|---------------|
| 1.666a         | ...               | ...                    | ...           |
| 8.460          | 56 ± 1            | 0.33 × 0.19            | 16.1          |
| 22.460         | 207 ± 1           | 0.25 × 0.22            | 57.8          |
| 43.340         | 375 ± 2           | 0.25 × 0.19            | 50.4          |
| 31 ± 1         | 2.20 × 0.40       | 29.8                   |
| 70 ± 1         | 1.57 × 0.40       | 32.9                   |
| 69 ± 2         | 1.42 × 0.47       | 32.7                   |
| 65 ± 10d       | ...               | ...                    |

Notes.

a. Two Gaussian components fitting, except for the data at 1.666 and 43.340 GHz.

b. Deconvolved size.

c. Average frequency of the four OH transitions (see Section 2).

d. Residual flux density from the single Gaussian fit of the compact region (see Section 3.1).

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**Table 3**

Continuum Emission of IRAS 17347−3139

| Frequency (GHz) | Flux Density (mJy) | R.A. (J2000) (h m s) | Decl. (J2000) (′′ ′′) | Position Uncertainty (arcsec) |
|----------------|-------------------|---------------------|----------------------|-----------------------------|
| 1.666a         | 31 ± 1            | 17 38 00.61         | -31 40 55.0          | 0.4                         |
| 8.460          | 127 ± 1           | 17 38 00.63         | -31 40 54.9          | 0.1                         |
| 22.460         | 280 ± 2           | 17 38 00.624        | -31 40 54.90         | 0.05                        |
| 43.340         | 440 ± 10          | 17 38 00.624        | -31 40 54.91         | 0.05                        |

Notes.

a. Total flux density of the emission. The uncertainties were obtained using 1\( \sigma \) of the rms noise of the image.

b. Position of the emission peak obtained from a Gaussian fitting.

c. Absolute position error.

d. Average frequency of the four OH transitions (see Section 2).

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9. We tried to fit two Gaussian components to the emission at 0.7 cm but, due to the low signal-to-noise ratio (S/N) of the extended structure, the fitting was doubtful.
In addition to the OH 1612 MHz maser emission coming from IRAS 17347–3139, we also detected this line from two other positions that are located within the primary beam of our observations, which is 30′ at this frequency. One is ∼2.5 northeast from IRAS 17347–3139 and the other is ∼11′ south from this PN (see Table 4). The maser emission located toward the northeast appears in the velocity range from −125 to −95 km s\(^{-1}\) (right panel of Figure 6), which is very similar to the velocity range of the OH maser emission that Zijlstra et al. (1989) reported to be associated with IRAS 17347–3139. However, from our observations, we found that the position of the OH maser emission in this velocity range coincides with the Two Micron All Sky Survey (2MASS) source J17380406–3138387. However, the emission located toward the south of the position of IRAS 17347–3139 appears in the velocity range from −23 to 5 km s\(^{-1}\) (right panel of Figure 6). This emission is associated with the source OH 356.65 − 0.15, and was already reported by Bowers & Knapp (1989). Recently, Szymczak & Gérard (2004) reported OH maser emission toward IRAS 17347–3139 in the same velocity range. However, due to the low angular resolution of their observations, probably they were contaminated by emission from the source OH 356.65−0.15.

4. DISCUSSION

The spectrum of the free–free emission of an ionized region depends on the geometry, as well as on the electronic density and temperature distributions inside the region. For the simplest case of an isothermal, homogeneous ionized region, the value of the spectral index, \(\alpha\) (where \(S_\nu \propto \nu^\alpha\)), ranges from +2 (at low frequencies, where all the emission is optically thick) to −0.1 (at high frequencies, where all the emission is optically thin). The maximum flux density is reached at the “turnover frequency,” \(\nu_{\text{m}}\), where the optical depth is of the order of unity and the spectrum becomes flat. In general, for a nonhomogeneous ionized region, the spectral index of the free–free emission is the result of contributions from lines of sight (LOSs) with different optical depths. For the case of an isothermal, ionized region, where the electron density goes as the inverse square of the radius (\(n_e \propto r^{-2}\)), the emission from the inner part of the region would be optically thick, while that from the outer parts would be optically thin, resulting in a constant value of the spectral index \(\alpha = +0.6\) over a wide range of frequencies (Panagia & Felli 1975; Olonon 1975; Reynolds 1986). If the ionized region is truncated at an inner radius \(r_0\), there is a turnover frequency, where all the emission is optically thin and the spectrum becomes flat. These properties are true for both a spherically symmetric region and a biconical (constant opening angle) region. This is also true for a constant velocity ionized spherical (or biconical) wind since in this case, the electron density also decreases as the square of the radius (if the ionized fraction remains constant). If the density decreases steeply (e.g., in an accelerating wind), then the value of the spectral index would be higher than +0.6, while a smaller value of the spectral index would indicate a flatter density distribution (e.g., in a decelerating wind).

The spectral index of the radio emission from IRAS 17347–3139 is \(\alpha \simeq 0.81\) (Figure 5) in the range of frequencies from 1.6 to 43 GHz. This can be interpreted in terms of an ionized region in which the electron density decreases as \(n_e \propto r^{-2.3}\). This density distribution could correspond to a wind with an almost constant velocity (\(\nu \propto r^{0.3}\)). dGM04 and G05

![Figure 5. SED of IRAS 17347–3139 in the range ~1–43 GHz. The filled squares represent the flux densities obtained from our observations (epoch 2005.1). The open triangles come from the observations carried out by G05 (epoch 2004.2). The open circles come from the observations carried out by dGM04 (epoch 2002.5). Note the increasing trend of the flux density of the source with time. The dashed line is a linear fit to the data from our observations.](image-url)

Table 4

| Source Name | R.A.(J2000) \(^{b}\) | Decl.(J2000) \(^{b}\) | LSR Velocity Range (km s\(^{-1}\)) | Flux Density \(^{c}\) (mJy) | rms Noise (mJy beam\(^{-1}\)) \(^{d}\) |
|-------------|-----------------|-----------------|------------------|----------------|-------------------|
| IRAS 17347–3139 | 17 38 00.57 | −31 40 54.9 | −70 | 38 ± 7 | 4 |
| OH 356.65−0.15 | 17 38 00.66 | −31 51 54.4 | 3 | 335 ± 7 | 4 |
| J17380406−3138387 | 17 38 04.10 | −31 38 38.3 | −95 | 543 ± 7 | 4 |
| J17380406−3138387 | 17 38 04.06 | −31 38 38.6 | −123 | 200 ± 7 | 4 |

Notes.

\(^{a}\) No emission has been detected from the 1665, 1667, and 1720 MHz OH maser transitions. The rms noise is 4 mJy beam\(^{-1}\) for all the transitions.

\(^{b}\) Position of the emission peak of the observed spectral feature obtained from a Gaussian fitting. The absolute position error is 0′04

\(^{c}\) Peak flux density of the observed spectral feature (the integration region was 6′5 × 5′5 for IRAS 17347−3139, and 8′ × 8′ for OH 356.65 − 0.15 and J17380406 − 3138387). The uncertainties were obtained using 1σ of the rms noise of the image.

\(^{d}\) 1σ of the rms noise per channel. The size of the synthesized beam is 4′4 × 2′8 (P.A. = 65°)
discussed the possibility of the presence of an ionized wind in IRAS 17347−3139, but the mass-loss rate derived from that assumption, \( M_\text{w} \simeq 10^{-4} (D \text{ kpc}^{-1})^{1/2} M_\odot \text{ yr}^{-1} \), is far larger than the values observed in central stars of PNs and pre-PNs (\( \lesssim 10^{-7} M_\odot \text{ yr}^{-1} \); Patriarchi & Perinotto 1991; Vassiliadis & Wood 1994). As a result, these authors interpreted the emission as being arising from a recently ionized nebula.

Our new observations provide further insights into the nature of the radio emission of IRAS 17347−3139. As mentioned in Section 3.1, our high angular resolution images reveal the presence of two structures elongated in more or less perpendicular directions. In fact, the Gaussian fitting to the continuum emission of IRAS 17347−3139 (Section 3.1) shows that the central compact structure is elongated in the direction with P.A. \( \simeq 50^\circ \), while the extended structure is elongated in the direction with P.A. \( \simeq -30^\circ \). These directions correspond to those of the dark lane and the bipolar bright lobes observed in the IR images, respectively (see Figures 2–4). This alignment suggests that the radio continuum emission could be arising from two different components: an equatorial ionized torus-like structure and two ionized bipolar lobes. To test this hypothesis, we separately analyzed the two components.

4.1. The Extended Ionized Emission

Since, as mentioned above, the spectrum of the free–free emission from an ionized region depends on the geometry and physical properties \((T_e \text{ and } n_e \text{ distributions})\), we can use this information to infer some of the properties of the extended structure. In Figure 7 (left panel), we have plotted the spectrum of the extended component, resulting from the values of the flux density obtained from the Gaussian fitting (Section 3.1). From 8.4 GHz to 43 GHz, the spectrum is flat, indicating that the turnover frequency is \( v_m < 8.4 \text{ GHz} \). There is only one measurement at frequencies lower than 8.4 GHz and, therefore, only a lower limit, \( \alpha > +0.5 \), can be obtained for the spectral index in the partially opaque regime. High angular resolution observations at 6 cm would be useful to constrain the value of this spectral index. Our observations show that the geometry of this component is not spherical, but has an aperture angle of \( \theta_0 \simeq 30^\circ \); therefore, it can be better described as a collimated
ionized region. If we assume that the aperture angle is constant as a function of the distance to the central star (biconical structure), and that the inclination of this structure with respect to the plane of the sky is small, by adopting a spectral index $\alpha \simeq +0.5$, a turnover frequency $v_{\text{m}} \simeq 8$ GHz, and an electronic temperature $T_e = 10^4$ K, we derive an inner radius $r_0 \simeq 0.3$ and a density profile $n_e \propto r^{-1.9}$ (Equations (15) and (18) from Reynolds 1986). A value of the spectral index higher than +0.5 would result in a density distribution decreasing steeply.

The electron density at radius $r_0$ is independent of $\alpha$, and can be estimated from Equation (13) of Reynolds (1986) as

$$n_e \left[ \frac{\text{cm}^{-3}}{\text{arcsec}^{-1}} \right] = 1.12 \times 10^3 \left[ \frac{w_0}{\text{arcsec}} \right]^{-0.5} \left[ \frac{T_e}{\text{K}} \right]^{0.675} \left[ \frac{v_{\text{m}}}{\text{GHz}} \right]^{1.05} \left[ \frac{D}{\text{pc}} \right]^{-0.5},$$

where $w_0 = \theta_0 r_0/2 \simeq 0\kern-0.5em.08$ is the width of the ionized cone at radius $r_0$ and $D$ is the distance to the source. For a distance range from 6 to 0.8 kpc (G05), we derive an electron density at the base of the lobes of $n_e = 2 \times 10^5$ to $6 \times 10^6$ cm$^{-3}$. Although this is the maximum value of the density in the lobes, and the average value would be smaller (e.g., at $r = 1''$, the electron density would be ten times smaller than $n_0$), this high value of the electron density in the bipolar lobes supports the idea that this is a very young PN and that the double horn structure seen at 1.3 cm (Section 3.1) could be tracing high density walls.

If we further assume that the extended emission arises from a biconical ionized wind with an expansion velocity of 1000 km s$^{-1}$, using Equation (19) from Reynolds (1986), we estimate a mass-loss rate of $M_\ast \simeq 1.3 \times 10^{-5}(D \text{ kpc}^{-1})^{1/2}$. This value is, once again, much larger than those observed in the stellar winds of other PNs, favoring the idea that the emission arises from an ionized nebula. Nonetheless, the relatively high degree of collimation of this emission is worth noting. Moreover, in the image at 3.6 cm, the presence of a subtle point symmetry is suggested. In the northern lobe, this emission extends all the ways toward the tip where there is a bow-shaped structure. This morphology could be indicating that the extended ionized regions were excavated by a collimated wind (see Section 4.3).

### 4.2. The Central Region: A High Density Ionized Torus?

In Figure 7 (right panel), we show the spectral energy distribution (SED) of the central compact region from 8 to 43 GHz. For this range of frequencies, the spectral index is $\alpha \simeq 1$, and seems to become shallower at higher frequencies. The value of the spectral index of this component indicates that the geometry or the density distribution of the ionized gas is different than in the extended component. Also, the fact that the flux density apparently continues to increase for frequencies as high as 43 GHz indicates that part of this component is still optically thick at such frequencies. Considering that the optical depth is of the order of unity near the turnover frequency, $v_{\text{m}} \geq 43$ GHz, assuming a constant electronic temperature, $T_e = 10^4$ K, and that the size of this component along the LOS is similar to the width obtained from the Gaussian fit ($\sim 0.25''$; Table 2), we obtain a lower limit for the electron density of $n_e \geq 1 \times 3 \times 10^6$ cm$^{-3}$ for the distance range from 6 to 0.8 kpc. This value for the density is 5 times larger than the maximum value found for the extended emission. Considering this higher value of the density, and the elongation of this component in the direction perpendicular to the lobes of the extended emission, we suggest that the radio continuum emission traces the ionized regions of an equatorial torus-like structure, which is observed in the IR image as a dark lane, or waist (see Figures 2–4).
To further confirm this suggestion, we made images at 0.7 cm using only the baselines longer than 500 k. (and ROBUST parameter = 0) to improve the angular resolution (Figure 8). In this image, a double-peaked structure is observed, with the peaks symmetrically separated with respect to the position of the radio continuum peak measured at other frequencies. The separation between the peaks (~0′′.13) corresponds to 100–780 AU for a distance range of 0.8–6 kpc. A similar double-peaked structure was observed in the PN NGC 2440 by Vázquez et al. (1999). From their observations of radio continuum and recombination lines, these authors inferred the presence of large extinction toward the central region, as well as a rotating, ionized toroid, roughly perpendicular to the bipolar lobes. In the case of IRAS 17347−3139, the two radio continuum peaks appear toward the dark lane observed in the IR images, and they are aligned in the direction perpendicular to the axis of the lobes, suggesting that the emission also arises from an ionized torus-like region.

The water masers detected toward IRAS 17347−3139 by dGM04 appear distributed in an elliptical structure with its angular resolution. In Figure 8, we have superimposed the positions of the observations of dGM04 on the radio continuum emission at 0.7 cm from our observations. In order to do this, we have shifted the positions of the observations of dGM04, so that the position of the continuum peak emission of their observations coincides with that of our observations at λ ≃ 1.3 cm. From this figure, there is no clear evidence of the presence of a secondary companion associated with the maser emission as suggested by dGM04, although this possibility cannot be completely ruled out. If we consider that the emission at 0.7 cm traces an ionized torus around the central star(s), the relative positions of the maser and the continuum emission suggest that the water masers arise from the outer parts of the ionized torus.}

4.3. Collimated Winds and Tori in PNs

It is now well known that several proto-PNs and PNs show the presence of collimated structures that often have point-symmetric morphology (Schwarz et al. 1992; Sahai & Trauger 1998; Balick & Frank 2002). It has been suggested that these structures are created by collimated winds or jets. Lim & Kwock (2000, 2003) detected collimated radio emission in the core of the PN M2-9, which they interpreted as arising in an ionized jet. More recently, Lee et al. (2007) found optically thick radio cores in narrow-waist bipolar nebulae. They suggested that the radio continuum emission arises in collimated ionized winds, which would be responsible for the shaping of the PNs.

As mentioned in Section 4.1, from our radio continuum observations, we found that the ionized extended component of the PN IRAS 17347−3139 shows a relatively high degree of collimation and that its spectral index is consistent with that of an ionized wind. We also note that the image of IRAS 17347−3139 at 3.6 cm (Figure 2) suggests that the extended emission shows a subtle point symmetry. Furthermore, a close look at the emission at 1.3 and 0.7 cm (Figures 3 and 4) reveals that it also shows point symmetry which is consistent with the point symmetry observed at 3.6 cm. In particular, the emission at 0.7 cm has two faint bumps, one toward the north and the other toward the south. These point-symmetric morphologies have been observed in several proto-PNs and PNs (Corradi et al. 1993; Guerrero et al. 1999; Miranda et al. 2001). They have been interpreted as the result of the presence of precessing jet-like winds excavating the slowly expanding envelope ejected during the AGB phase (Miranda et al. 2001; Volk et al. 2007). Consequently, based on its morphological structure, we suggest that part of the emission of the extended component of IRAS 17347−3139 could be arising in a precessing ionized wind. Radio recombination line observations could be useful to probe the kinematics of the ionized nebula and confirm the presence of an ionized wind in this source.

The collimated winds have been successful at explaining the formation of point-symmetric morphologies in proto-PNs and PNs (Garcia-Segura 1997; Velázquez et al. 2007). However, the mechanisms responsible for the launching and collimation of such winds remain poorly understood. It has been observed that the pre-PNs and PNs that present collimated winds often also show the presence of an equatorial torus (Miranda et al. 2001; Sahai et al. 2005; Uscanga et al. 2008). It has been proposed that the equatorial tori somehow could be related to the formation of the collimated winds (Mellema et al. 1991; Frank et al. 1993; Huggins 2007). In the GISW model, the torus channels the fast wind toward the polar regions; however, it cannot collimate it (García-Segura et al. 1999). Our observations reveal that a torus could be present in the equatorial region of IRAS 17347−3139 (see Section 4.2); however, given its narrow waist and the possible presence of a precessing collimated ionized wind, the GISW model cannot explain the shape of this PN.

One of the mechanisms proposed to produce collimated outflows assumes that the fast wind is magnetized. Additionally, in the presence of a binary companion, the wind could undergo precession, producing a point-symmetric morphology (García-Segura 1997). However, in these models, while the presence of an equatorial torus is possible, it is not indispensable for the collimation of the jets. However, Nordhaus & Blackman (2006) proposed that a secondary companion could spiral-in the AGB CSE, enhancing the magnetic field by dynamo action. During the spiral-in process, an equatorial torus could be ejected, while the enhanced magnetic field could drive a collimated wind. The latter scenario could produce a configuration with an equatorial torus and collimated winds as observed in IRAS 17347−3139.

It has been estimated that the outflow driven by the dynamo action would be explosive and last ≲ 100 years (Nordhaus & Blackman 2006). This value is similar to the kinematical age of the ionized component of IRAS 17347−3139. However, this age represents only a lower limit for the age of the bipolar lobes, suggesting that the collimated wind has been present for more than 100 years. Furthermore, given the low percentage of polarization derived from our OH 1612 MHz maser observations (see Section 3.2), it is probable that the magnetic field is not very strong. This result suggests that the magnetic fields could not be playing a major role in the formation of the collimated structure of this PN. More measurements of the strength and geometry of the magnetic field are required to further test this model.

Another mechanism, proposed to explain the formation of collimated winds and the ejection of equatorial tori, also assumes that a binary companion spirals-in through the CSE of the AGB star, providing energy to detach the torus. When the spiral-in process of the secondary stops, it could undergo Roche lobe overflow to form an accretion disk around the primary star.
Alternatively, the companion could reach a region where it is shredded by gravitational tidal forces to form an accretion disk. Therefore, in a way similar to the star-forming regions, these disks may blow collimated winds that shape the PNs. These models predict the presence of an equatorial torus and a collimated wind. They also predict that the ejection of the equatorial torus precedes the formation of the jets. For the case of the PN IRAS 17347–3139, as mentioned above, we estimate that the age of the collimated wind must be greater than 100 years. In addition, from our high-resolution image at 0.7 cm (Figure 8), we can estimate an inner radius for the torus, which is of the order of half the separation between the two intensity peaks (∼0.06); for a distance range of 0.8–6 km, and assuming a typical expansion velocity of 10 km s⁻¹ (Huggins 2007), we find that the torus was completely ejected ∼25–185 yr ago. To determine if the torus was previously ejected than the collimated wind, and thus to be able to test these models, we need a more accurate estimation of the distance to this source.

5. CONCLUSIONS

We have carried out sensitive high angular resolution VLA observations of the young PN IRAS 17374–3139. We present the first images of its ionized structure at cm wavelengths. The radio continuum images revealed the presence of a bright central structure and an extended more tenuous bipolar component.

A double Gaussian fit shows that the extended component is elongated in the same direction as the bipolar lobes observed in the NIR images, while the central structure shows an elongation in the perpendicular direction, parallel to the dark lane observed in the IR images. We interpret that the radio continuum emission arises in two extended ionized lobes and in an equatorial ionized torus. The electron density at the base of the lobes is 2 × 10⁵ cm⁻³, for a distance range as above. A high-resolution image at 0.7 cm reveals the presence of a double-peak structure in the central component, supporting the interpretation of the equatorial torus. We compared the discrimination of the water maser emission with our high-resolution radio continuum images; the relative positions of the maser and the continuum emission suggest that the water masers arise from the outer parts of the ionized torus.

We detected OH maser emission at 1612 MHz toward IRAS 17347–3139. The spectrum shows only one weak feature at V_LSR = −70 km s⁻¹, which spatially coincides with the continuum emission. We derived a σ upper limit of < 35% for the percentage of circularly polarized emission (m_c = V/I). We also report the detection of OH 1612 MHz maser emission coming from two other sources, J17380406 − 3138387 and OH 356.65 − 015, located within our primary beam.

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