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Isaacman, R.; Wouterloot, J.G.A.; Habing, H.J.

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Research Note

A Radio Search for Planetary Nebulae Near the Galactic Center

III. VLA and Optical Observations of Three Objects

R. Isaacman, J. G. A. Wouterloot, and H. J. Habing

Sterrewacht Leiden, Postbus 9513, NL-2300 RA Leiden, The Netherlands

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Summary. Three flat-spectrum sources, found in the Westerbork search for planetary nebulae near the galactic center, have been observed at λ 6 cm with the VLA. 19W109 remains unresolved with a 0ʺ.6 HPBW and cannot be a galactic center planetary. 19W43 shows a double structure, and uniform-density shell model is fit to the visibility function. It may well be a planetary nebula near the galactic center. 19W32 shows Hα and {O III} emission in addition to the radio continuum emission and so is almost certainly a planetary, but its size and reddening imply a distance of $\sim$5 kpc. Radio detection of the central star implies a mass-loss rate of $10^{-4\pm1} M_\odot$ yr^{-1}.

Key words: radio sources – planetary nebulae – galactic center

I. Introduction

Because Population II stars show high random velocities and a strong concentration to the galactic center, objects such as OH/IR stars and planetary nebulae are useful as probes of the central galactic gravitational field (Oort, 1977). Baud (1978) has investigated the distribution of 1612 MHz OH line sources with the Bonn and Dwingeloo telescopes, while a Westerbork search for planetary nebulae at 21 cm and 6 cm has been underway for some time. Preliminary 21 cm results have been presented by Wouterloot and Dekker (1979, Paper I) and by Isaacman (1980, Paper II).

Optical extinction towards the galactic center is quite severe, being as much as 29^m in some directions (Rieke and Low, 1973). The distance is too great to expect to be able to detect radio recombination lines from planetaries (PN), so a radio search is restricted to the continuum. The principle difficulty thus becomes distinguishing PN from contaminating classes of objects, principally

a) galactic supernova remnants,
b) extragalactic background sources,
c) compact H II regions

in increasing order of annoyance.

Supernova remnants do not represent a serious problem because they will very rarely be young enough to appear as point sources to the 22ʺ Westerbork (λ 21 cm) synthesized beam, as will PN. Given the size of the survey region ($\sim$4 square degrees) and the frequency of supernovae in the disk ($\sim$0.02 yr^{-1}), it is easy to calculate that along the whole line of sight only $\sim$0.4 supernova remnants are expected to be young enough to subtend less than half a beam. Moreover, SNRs have steep spectral indices and so are distinguished by 6 cm observations.

Extragalactic sources are more difficult to contend with since these occupy a wide range of fluxes, sizes, and spectral indices. However, the 21-cm flux distribution is known (Willis et al., 1977), as, to a lesser extent, is the 21 cm–6 cm spectral index distribution (Willis and Miley, 1979), so that these can be used to make statistical arguments to derive the number of galactic thermal sources in the survey sample, as was done in Paper II.

Among the thermal sources, though, will be both PN and compact H II regions. These are not to be distinguished by their radio continuum spectra, and can even be confused when optical data are present (Cohen and Barlow, 1975). Indeed, Allen (1975) has argued that NGC 7027, certainly one of the best-studied thermal objects, is not a planetary nebula at all.

Infrared detectors now under development may, through the detection of high-excitation spectral lines such as {S IV}, be able to distinguish PN from H II regions at galactic center distances, but for the time being we are confined to radio observations. Since the radio spectrum is not a useful means of distinguishing PN, we must turn to the radio structure. This is in principle a powerful method, since the shell structure of planetaries usually gives rise to a characteristic double radio structure that distinguishes PN from more uniformly-filled objects like H II regions. Numerous examples of this structure were observed by Terzian et al. (1974).

The radio evolution of planetaries causes the Westerbork galactic center survey to select in favor of PN of $\sim$0.1 pc radius because at that time they are expected to be brightest at λ 21 cm (Paper II). Therefore the expected separation of the double radio peaks is $\sim$1 arc s. For this reason, three objects which had been detected as point sources at Westerbork at both 21 cm and 6 cm wavelengths were reobserved at 6 cm with the NRAO[1] Very Large Array in an attempt to discern structure that could identify them as planetaries. One of the three is also visible in the Palomar Sky Survey, and some optical information is available.

II. Observations

The maximum expected 21 cm flux density for a galactic center planetary is $\sim$25 mJy or $\sim$60 mJy depending on whether PN are optically thick or thin, respectively, in the Lyman continuum (Paper II). These values follow from a simple model outlined in

Send offprint requests to: R. Isaacman

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Table 1

OBJECT	19W109	19W43	19W32
α(1950.0)	$17^h45^m34.83$ s	$17^h37^m24.94$ s	$17^h35^m52.36$ s
δ(1950.0)	$-29°06'45.4''$	$-28°40'07.4''$	$-28°54'59.3''$
S_{21} (mJy)	45 ± 1.4	17.3 ± 1.6	14.4 ± 0.8
S_6 (mJy)	52 ± 5	30 ± 5	20 ± 10
Date of observation	16 Sept. 1979	16 Sept. 1979	15 Sept. 1979
Integration time (hr)	1.3	3.3	4.6
RMS noise (mJy)	0.4	0.3	0.3
Frequency (GHz)		4.885	
HA Coverage (hr)		−3.8 to +3.4	
Bandwidth (MHz)		50	
Antenna Pos'ns: N arm	0.27 km		
E arm	0.04 0.09 0.15 0.97 1.59 1.95 3.19 km		
W arm	0.48 1.59 3.19 5.22 7.66 13.64 17.16 km		
Synthesized HPBW size		0.6" x 1.9"	
Beam Pos'n Angle (Clockwise from N)		19°	

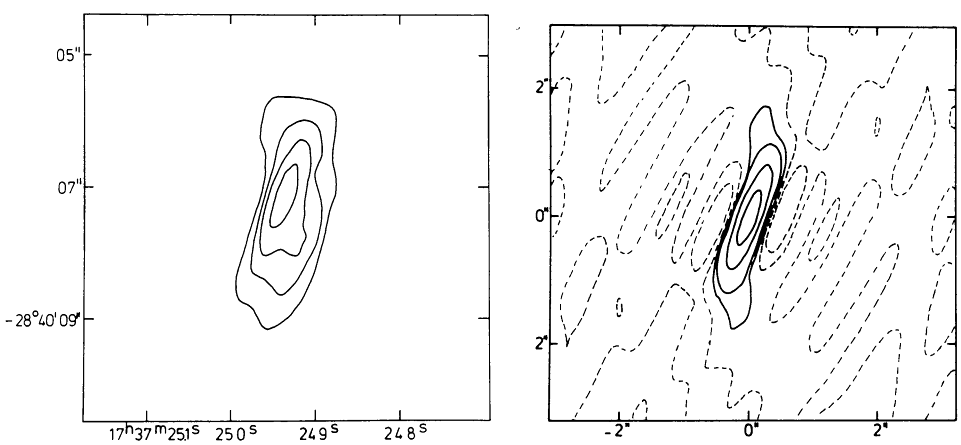

Fig. 1. a Uncleaned map of 19W43. Contour levels: 2.4, 4.8, 7.2, 10.2 mJy. **b** Corresponding "dirty" beam. Contour levels −0.15, 0.0, 0.15, 0.25, 0.50, 0.80

Paper II and are "typical" values insofar as they are consistent with the fluxes obtained by scaling local nebulae to the distance of the galactic center. Nebulae selected for VLA observation therefore had to be consistent with those fluxes, plus two other criteria:

1. point sources to the Westerbork beams,
2. 6 cm–21 cm spectral index consistent with thermal radiation.

One of the sources – 19W32[2] – had not been observed at 6 cm at Westerbork but shows extended emission on an Hα plate and so is almost certainly thermal.

A summary of the observations is given in Table 1. The galactic center source 1748-253 was used as a flux and phase calibrator. The 6 cm flux density was taken to be 0.8 Jy, though this is not accurately known and was "bootstrapped" by demanding that source flux values agree with Westerbork 6 cm fluxes. The polarization properties of neither the calibrator nor the sources were checked.

2 Source names are those given in Paper I

Typical system noise was ~0.4 mJy for one hour of integration, and phase closure errors during the calibration stage were nearly always less than 10°. Each day's run was divided into 15-min scans consisting of 4 min on the calibrator and 11 min on the source (antenna slewing time was small due to the proximity of the calibrator to the sources). Scans on the two sources observed on the second day were interleaved so as to maximize hour angle coverage for each source. (The low declination of the galactic center does not allow much more than about 6 h coverage per source.)

III. Discussion of Sources

19W109

This source was reported in Paper I to have a 21-cm flux of 45 ± 1.4 mJy, and subsequent Westerbork observations gave a flux of 52 ± 5 mJy at 6 cm. Galactic center PN would not be expected to be this bright (Paper II). In fact, it is a point source even to the

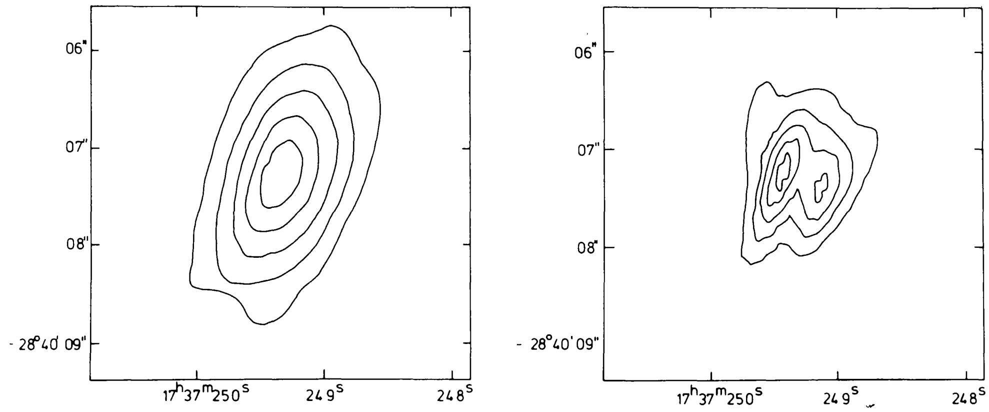

Fig. 2a and b. Cleaned maps of 19W43. Contour levels 0.20, 0.40, 0.60, 0.80 of peak. **a** Cleaned with 0.6″ × 1.9″ beam, **b** cleaned with 0.3″ × 1.0″ beam

VLA, which rules it out as a planetary nebula altogether: as a PN, its brightness would demand that it be too close to be unresolved. It is therefore more probably a flat-spectrum extragalactic source, or a compact H II region on the far side of the Galaxy.

19W43

Westerbork observations of 19W43 gave fluxes 17±2 mJy (21 cm, Paper I) and 42±5 mJy (6 cm). Virtually no background sources have such a steep positive spectral index (Willis and Miley, 1979), so the source is almost certainly thermal.

The "dirty" VLA map is shown in Fig. 1a. It appears that a double structure is being resolved along the minor axis (0.6″ FWHM) of the beam; the beam itself is shown for comparison in Fig. 1b. In order to try and bring out this structure, we have cleaned the map (Högbom, 1974) in two ways. The first, shown in Fig. 2a, uses a gaussian restoring beam that is as large as the original dirty beam but without negative sidelobes; that is, with half-power axes of 0.″6 × 1.″9 at a position angle of 19°. Most of the structure is then lost, except in the outermost contours. If, on the other hand, we "overclean" with a smaller restoring beam, the structure is emphasized. Figure 2b illustrates the result of restoring with a beam that is only half the size of the original beam. This should not be taken too seriously as a morphological model since we do not, of course, really have this much resolution. Rather, the result of the overcleaning is to show that the source is best described by more than one component.

We have chosen instead to model the visibility function of the observations, rather than the map, as it is numerically much simpler and avoids some of the peculiarities of the Fourier transform, such as aliasing. The disadvantage of this approach is that present VLA software allows averaging of visibility amplitudes only over scans and not over a whole observation, so that the signal-to-noise ratio of the visibility function is worse than that of the map.

A uniform-density shell model characterized by inner and outer angular radii θ_1 and θ_2 respectively, was adopted to fit the visibility amplitudes. This parametrization accomodates PN as well as uniform-density compact H II regions because when $\theta_1=0$ the shell becomes a sphere. Except for extremely young, dense objects, most planetaries and H II regions are optically thin at λ 6 cm, so the surface brightness is proportional to the emission measure. The unnormalized visibility amplitude then becomes.

$$V(q)=|H(\theta_1)-H(\theta_2)|, \quad (1)$$

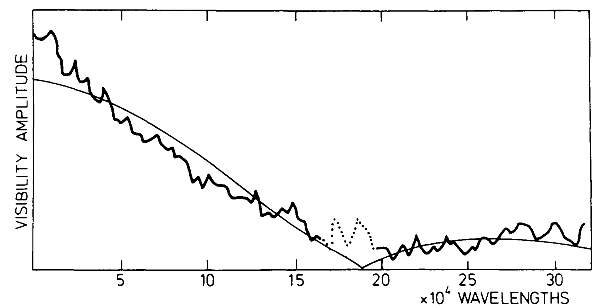

Fig. 3. Jagged line: observed visibility function of 19W43. Dotted region indicates sparse UV-sampling. Solid line: model visibility function for uniform-density spherical shell with inner radius 0.″4, outer radius 0.″7

where $q=(u^2+v^2)^{1/2}$ is the radial distance in the UV plane and $H(\theta)$ is the Hankel transform of the brightness distribution of one of the spherical components,

$$H(\theta)=\int_0^{\theta}\phi(\theta^2-\phi^2)^{1/2}J_0(2\pi\phi q)d\phi\,. \quad (2)$$

J_0 is the zeroth-order Bessel function and follows from the adoption of a circularly-symmetric model.

The best fit to the observed visibilities is given by $\theta_1=0.''4$, $\theta_2=0.''7$, and is compared to the observations in Fig. 3. Unfortunately, UV distances between 16.5 10^4 and 19.5 10^4 wavelengths are poorly sampled in the observations, so that the closest approach to zero amplitude is obscured.

Single-component ($\theta_1=0$) models give in general a worse fit, with very little power at $q \gtrsim 20\,10^4\lambda$, supporting the notion that the object is in fact a shell source and thus a planetary nebula and not a compact H II region. The ratio of the inner and outer shell radii in the best-fit model is typical of the shell thickness seen in local PN.

An outer radius of 0.″7 corresponds to 0.03 pc at the distance of the galactic center. Planetaries this young are taken to be optically thick to ionizing radiation in most models (e.g. Seaton, 1966), so it is difficult to account for the observed flux unless at least one of the following conditions holds:

1. The nebula is rather more massive than the "standard" value of $0.2M_\odot$ (Milne and Aller, 1975; Paper II).

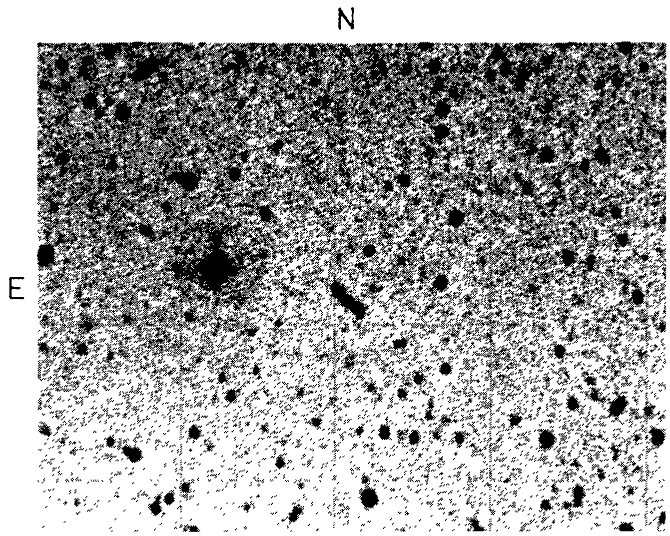

Fig. 4. Hα plate of 19W32. Lobes are each about 4″ × 7″

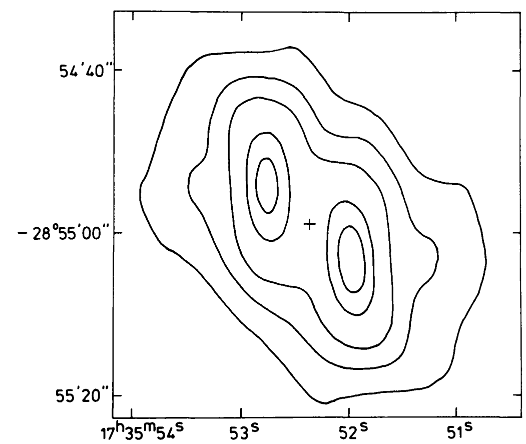

Fig. 5. Uncleaned low-resolution map of 19W32. Cross marks position of central star. Contour levels 2.3, 3.5, 5.0, 7.5, 9.0 mJy per beam

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2. The nebula is "leaky", so that part of the surrounding interstellar medium is contributing to the integrated flux. Modeling then becomes more difficult since the interstellar gas will contribute to the observed morphology.

3. The central star temperature and luminosity are high, i.e. more in line with Seaton's (1966) evolutionary curve than with the cooler, ANS-based results of Pottasch et al. (1978). In Paper II it was pointed out that Pottasch et al.'s values did a better job on average of accounting for the flux density distribution of solar-neighbourhood nebulae, but there may be wide variation within the population.

4. The object is not in fact at the galactic center but is a few kpc closer.

Without optical data – for which there is little or no prospect – there may be no way to distinguish among these possibilities.

19W32

First detected as a point source at Westerbork ($S_{21} = 14.4 \pm 0.8$ mJy), 19W32 was later found to have extended Hα emission consisting of a central star and two oppositely-directed lobes (Fig. 4). Its appearance is reminiscent of the planetaries M2–9 and NGC 2346, perhaps classifying it as one of Greig's (1971) "class *B*" ("binebulous") PN. Total size of the object is about 20″ and each lobe is roughly 4″ × 7″. Both lobes are much brighter on an Hα plate taken with an 80 Å filter than on a red continuum plate (both taken by de Bruyn with the 48″ Palomar Schmidt telescope). The red magnitude of the central star is 16 ± 0.5 on the Palomar Sky Survey print, and it is invisible on the blue print, implying $B - V \gtrsim 2^{\mathrm{m}}.5$. Colors of PN central stars are usually comparable to O-type stars ($B - V \simeq -0.5$), so the color excess in this case is $\gtrsim 3^{\mathrm{m}}$. The visual extinction is therefore $\sim 9^{\mathrm{m}}$.

De Bruyn has also taken a spectrum of this object with 3 Å resolution. The only visible feature is the {O III} doublet 4959 + 5007 Å, with an intensity of $1.0 \pm 0.5\,10^{-14}$ erg cm^{-2} s^{-1} after accounting for the fact that only one lobe was observed. (The uncertainty follows from the rough calibration and possible errors in the positioning of the 8″ diaphragm.) The radial velocity is ~ 100 km s^{-1}.

We adopt an {O III} to Hβ ratio of 10^{+10}_{-5} (Aller, 1956) and then use Milne and Alner's (1975) relationships among extinction, Hβ, and radio continuum flux to derive the extinction in an independent way. The flux at λ 6 cm (discussed below), where the object is almost certainly optically thin, is $S_6 = 20 \pm 10$ mJy. Applying Milne and Aller's method then yields an extinction of 9 ± 1 mag, in agreement with the optical continuum result. Milne and Aller (1975) further observe an average extinction in the direction of the galactic center of 1.8 ± 0.7 mag kpc^{-1}, implying a distance of 5^{+4}_{-2} kpc.

Taking their expression for the volume emissivity, we can use the distance and Hβ flux to derive an electron density of ~ 2500 cm^{-3} in the lobes. This and the size of the object are both consistent with its being an old ($r \sim 0.5$ pc) planetary nebula.

Because the lobes subtend nearly 60 beam areas at λ 6 cm at the VLA, they are largely resolved away on the full-resolution map. We have made a low-resolution map by applying a gaussian taper with a half-width to half power of 1.0 km, leading to a HPBW of 6″.2. The lobes show up clearly on the resultant (uncleaned) map shown in Fig. 5. Their size and orientation agree with the Hα image, and the integrated 6-cm flux is 20 ± 6 mJy. From this figure, we derive an electron density of ~ 1700 cm^{-3}, in agreement with the optical result given the large uncertainties in the distance and the adopted Hα flux. (In both, we assumed an electron temperature of 12,000 K.)

On the full-resolution map on which the lobes are resolved away, we also detect a 2.0 ± 0.4 mJy point source at the position of the central star, shown as a cross in Fig. 5. PN central stars are often of the WR or Of type (Lutz, 1977; Hummer, 1977), so a stellar wind and radio emission are to be expected. Mathews (1966) found that a stellar wind was required to maintain the shape of shell PN. Using the mass outflow relation found by Pahagia and Felli (1975), we find

$$\dot{M} = 1.1\,10^{-7} v_{\mathrm{exp}} d^{3/2} \quad M_\odot\,\mathrm{yr}^{-1}, \qquad (3)$$

where v_{exp} is the stellar wind velocity in km s^{-1} and d is the distance to the nebula in kpc. The uncertainty in d makes $\dot{M}$ uncertain within a factor of ~ 2, and estimates of v_{exp} range from ~ 100 km s^{-1} for the young nebula V1016 Cygni (Fitzgerald and Pilavaki, 1974) to ~ 1000 km s^{-1}. Taking 300 km s^{-1} as a representative value, we find $\dot{M} \sim 4\,10^{-4} M_\odot$ yr^{-1}, with an uncertainty of about a factor of 7 either way. The lower end of the range is more consistent with mass-loss rates of other stars (Abbott et al., 1979; Dickel et al., 1979). Since the cloud is not spherical, we expect that anisotropy in the mass would reduce the calculated value.

IV. Conclusions

Of the three would-be PN found at Westerbork and reobserved at VLA only one – 19W32 – can be said with reasonable certainty to be a planetary. It is not, however, at the galactic center. The double structure of 19W43 is very suggestive of a PN, and the size and intensity are consistent with it being near the galactic center, but without either higher-resolution or infrared observations the possibility of it being an H II region will remain. Since most of the VLA telescopes were along the east and west arms for these observations, it may be worthwhile to reobserve the object in a year or two when full north-south resolution will be available.

The best possibility of distinguishing optically-obscured PN from compact H II regions probably lies with infrared spectroscopy. Detectors now under development may be able to measure relative {S IV} and {Ne II} line strengths in faint galactic-center objects and so identify radio sources as planetaries on the basis of their degrees of excitation.

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