SECTION VI

PLANETARY NEBULAE IN A GALACTIC AND EXTRAGALACTIC CONTEXT

A RADIO SEARCH FOR GALACTIC CENTER PLANETARY NEBULAE

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SUMMARY

This review summarizes the techniques and results of a λ21cm and λ6cm search with the Westerbork telescope for planetary nebulae within 2° of the galactic center. After accounting for background sources and compact HII regions it appears that there are $\sim$ 300 planetaries within 300 pc of Sgr A. This is consistent with a galactic population of $\sim$ 21000 and agrees with the birthrate of white dwarfs. The surface density of galactic center planetaries falls off with galactic latitude approximately as b^{-1} and is best accounted for by a bulge with a mass of 1×10^{10} $M_\odot$.

INTRODUCTION

Searches for planetary nebulae (PN) near the galactic center aim at answering these questions:

(1) What is the distribution and total number of planetaries in the galactic bulge?

(2) Are their properties (lifetimes, masses, luminosities) similar to those in the solar neighborhood?

(3) What does the distribution imply about the structure of the bulge and the total number of planetaries in the Galaxy?

When studying the mass distribution of the bulge it is convenient to seek a set of relaxed Population II "tracers" which we assume to be characterized by a Maxwellian velocity distribution, with no systematic orbital motion. If this is true then the galactic gravitational field, and hence the mass distribution, can be read from the tracer distribution in a simple way provided that the velocity dispersion σ is known. Globular clusters have been used in this way to study the structure of M 31 (Tremaine et al. 1975) as well as our own Galaxy (Oort 1977).

D. R. Flower (ed.), Planetary Nebulae, 415–422.

https://doi.org/10.1017/S0074180900093955 Published online by Cambridge University Press

Planetary nebulae can also be used. These were first shown by Minkowski (1948) to share Population II dynamics in the galactic bulge (if not in the disk). Their principal advantage over other tracers is that they are, at least above $|b| \gtrsim 2°$, discoverable via optical spectral lines as well as radio emission.

Within 2° of the center, where optical observations are no longer useful, planetaries suffer a single tremendous disadvantage: their lack of radio spectral emission makes them very difficult to distinguish from background sources and, in particular, compact HII regions. For that reason, much effort must be directed towards extracting the true distribution of planetaries from the observed distribution of all sources in a radio survey. This must be done mostly in a statistical way; identifying individual planetaries in a radio sample is much more difficult.

THE OBSERVATIONS: HOW MANY PLANETARIES?

To date, the only radio search specifically aimed at discovering planetary nebulae in the highly-obscured central bulge has been the Westerbork survey by Wouterloot and Dekker (1979) and by myself (Isaacman 1980, 1981ab). The Westerbork program concentrated on five 21-cm fields all centered within about 1.5° (i.e. about 225 pc) of the galactic center. Accounting for overlap in the fields, these covered some 3 square degrees at sensitivities ranging from about 1 mJy (1σ) at the field centers to about eight times worse at the edges. A total of 119 sources were found, of which 50 were later observed (though not all detected) at λ6cm with Westerbork and with the VLA.

Not all -- or even most -- of these 119 are planetaries, of course. Contaminating the sample are (a) nonthermal galactic sources such as supernova remnants and radio stars, (b) extragalactic background sources, and (c) compact HII regions. It is easy to show on statistical grounds that at most $\sim$1 object from the first category will be detected as a compact source in the survey. Hence supernovae, UV Ceti stars, radio binaries and the like are not an issue. Extragalactic background sources are also easily accounted for statistically because their spatial distribution is isotropic and because their flux and spectral index distributions are known (Willis et al, 1977; Willis and Miley 1979).

Compact HII regions are more difficult to extract from the data because of their similarity to planetaries at the distance of the galactic center. On an individual basis the two can be distinguished in high-resolution radio data since planetaries will often show characteristic shell structure. Several of the Westerbork objects have been observed this way at λ6cm with the VLA A-array (Isaacman 1980a and unpublished work). More generally, we know that HII regions occupy a broad range of ionized masses and emission measures (Israel 1976; Habing and Israel 1979) and thus can be either bright or dim in the radio continuum, whereas the ionized masses of planetaries seem limited to a few tenths of a solar mass (Pottasch 1980) and should consequently rarely be brighter than several tens of mJy at the galactic center. A strong tendency for the flat-spectrum (i.e. thermal) sources in the Westerbork sample to be weak should therefore imply that planetaries dominate the distribution. This is definitely the case: nearly 90% of the flat-spectrum sources have $S_{21} < 50$ mJy. On this basis we conclude that planetary nebulae greatly outnumber compact HII regions in the inner 300 pc of the galactic bulge.

Among the 85 weak (< 50 mJy) 21-cm sources we expect on the basis of earlier Westerbork source counts (Willis et al. 1977) that ∿ 59 will be extragalactic. From the spectral index arguments we therefore estimate that there are ∿ 25 planetaries in the data set. A similar argument using the Westerbork 6-cm fields and the background counts by Wall and Cooke (1975) gives the same answer.

NEBULA LIFETIMES AND RADIO FLUX DISTRIBUTION

In an aperture synthesis survey we must model the intrinsic flux density distribution of the sources in order to extract their spatial distribution. The radio flux density distribution of nearby planetaries can be reasonably well reproduced using a simple model characterized by an expanding spherical shell of $0.2 M_{\odot}$ ionized by a central star that follows the evolutionary track proposed by Seaton (1966). In this model PN are density bounded; at the distance of the galactic center they would have peak flux densities of about 60 mJy at 21cm (Isaacman 1980).

The agreement with the fluxes of local PN is improved if the luminosity and temperature of the central star in the model are scaled down by factors of 10 and 2, respectively, following the results of Pottasch et al. (1978). In this case most nebulae are ionization bounded and will emit a maximum of ∿ 30 mJy at λ21cm at a distance of 9 kpc.

It is not, however, sufficient to translate a model for local PN to the distance of the galactic center for the purpose of modelling the flux density distribution. The random velocities of PN in the bulge are much higher than in the disk, so ram pressure effects from the interstellar medium (ISM) can be important. If the velocity through the ISM (V_{ISM}) is much greater than the shell expansion velocity V_e, then it is possible to show (Isaacman 1979) that the nebula will start to break up on a time scale

$$(1) \quad T \sim 6 \times 10^5 \left[\frac{M}{\rho V_e V_{ism}^2}\right]^{1/3} \quad \text{yr}$$

where M is the shell mass in $M_{\odot}$, velocities are in km/s, and ρ is the density of the ISM in $M_{\odot}\ pc^{-3}$. The density in the inner bulge can be as high as ∿ 1 $M_{\odot}\ pc^{-3}$ due to molecular clouds (Bania, 1977); if $M = 0.2\ M_{\odot}$, $V_e = 25$ km/s, and $V_{ism} = 125$ km/s -- approximately planetaries' velocity dispersion -- then galactic center PN will live only ∿ 5000 yr. This is a factor ∿ 5 shorter than local PN, so the flux density distribution of galactic center planetaries will be affected accordingly.

In order to reconcile the number of PN in the Westerbork data with the number of optically-identified planetaries in the bulge -- after correcting the latter number for extinction -- we require that ∿ 75% of the galactic center PN be ionization bounded. The resultant model flux density distribution predicts that ∿ 1/4 of radio-identified PN should have flux densities between 30 mJy and 60 mJy, and that very few -- primarily local objects -- will be brighter than 60 mJy. This prediction appears to have been borne out in recent VLA observations by Gathier et al (1982), as shown in Figure 1. They measured the radio fluxes of a few dozen Perek and Kohoutek (PK) planetaries close to the galactic center.

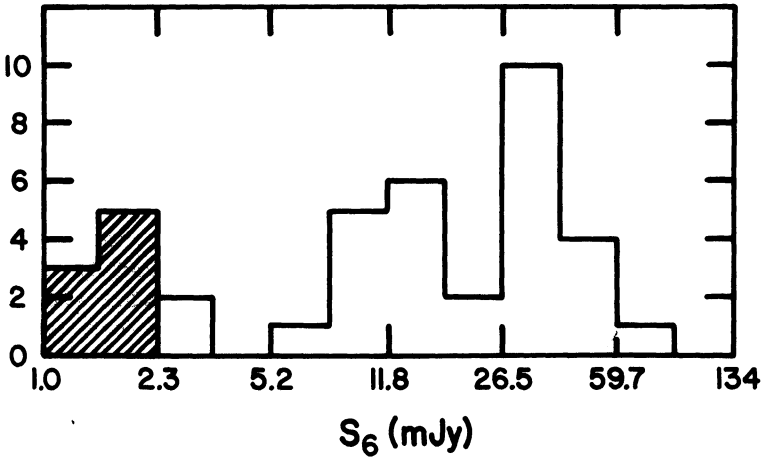

Figure 1. Radio fluxes of optically-identified galactic center planetary nebulae by Gathier et al. (1982). Hatched areas are upper limits.

THE SPATIAL DISTRIBUTION OF PN AND MASS MODELS OF THE BULGE

By using the model flux densities to correct the observed source distribution for the loss in sensitivity at the field edges we obtain the PN surface density shown by the filled circles in Figure 2. The open circles are counts of planetaries from the PK catalogue in a wedge about the galactic center that corresponds roughly to the area of the Westerbork survey. These optical counts are corrected for extinction based on an intrinsic Hβ brightness distribution derived from measurements of local nebulae.

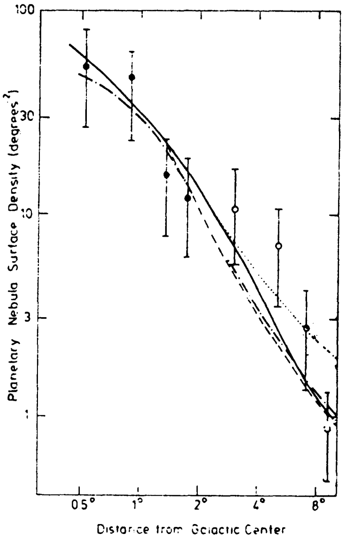

Figure 2. Corrected radio (filled circles) and optical (open circles) surface densities of galactic center planetary nebulae. Fitted curves are distributions predicted from mass models of the bulge (see text).

The average corrected source density in the radio survey (within 2° of the galactic center) leads to a PN surface density of 23.9 deg^{-2}. Within 2° (314 pc) of the center, we therefore expect about 300 nebulae. Mass models of the galactic center (e.g. Sanders and Lowinger 1972) predict masses of $\sim 2 \times 10^9$ $M_\odot$ in this region, giving a relative number of 1.5×10^{-7} $M_\odot^{-1}$. The corresponding birthrate is 3×10^{-11} $M_\odot^{-1}$ yr^{-1}. For a galactic mass of 1.4×10^{11} $M_\odot$ and a local mass density of 0.13 $M_\odot$ pc^{-3}, these figures imply a total of $\sim$ 21000 PN throughout the Galaxy, and a local birthrate of 2.9×10^{-3} kpc^{-3} yr^{-1}, comparable to white dwarf birth rates in the solar neighborhood (Weidemann 1968). A total of 21000 is in excellent agreement with most recent estimates (Alloin et al. 1976, Cahn and Wyatt 1976; Acker 1978).

The surface density shown in Figure 2 can be used to test mass models of the bulge in a straightforward way provided that PN motions are characterized solely by a single velocity dispersion σ. For axisymmetric bulge mass distributions the space density of planetaries $\rho(r,z)$ is simply:

$$\rho(r,z) = \rho_c \exp \{[\phi(r,z) - \phi(0,0)]/\sigma^2\} \quad (2)$$

where $\rho_c = \rho(0,0)$ and ϕ is the gravitational potential associated with the mass distribution. Radial velocity data for galactic center optical PN give σ = 134 km/sec (Oort 1977).

Using this assumption I have investigated two classes of mass models (Isaacman 1981b):

(a) An ellipsoidal bulge with a power-law density profile, like the one applied by Sanders and Lowinger (1972) to infrared data. Such a distribution is characterized by its total mass and the exponent of the power law.

(b) A "thickened disk" model devised by Miyamoto and Nagai (1975). This is a three-dimensional generalization of a class of thin, disk-like models derived by Toomre (1963) and is characterized by a total mass, two length parameters (whose ratio determines the degree of flattening of the system), and an "order" parameter that determines the steepness of the density distribution.

The best-fit models from each class are shown as the curves in Figure 2. These are:

Solid line: An ellipsoidal bulge of mass $0.9 \times 10^{10}\ M_{\odot}$ surrounded by an exponential disk, and having a power-law density profile with exponent 1.8. The axial ratio of the bulge is 0.4 (Okuda et al. 1977).

Dotted line: Same as solid line, but without a disk. Note that only points at $|b| > 4°$ are affected.

Dashed line: Zero-order thickened disk with scale length 200 pc and a mass of $1.3 \times 10^{10}\ M_{\odot}$.

Dashed-dot line: Second-order thickened disk with scale length 300 pc and mass $1.0 \times 10^{10}\ M_{\odot}$.

It is extremely gratifying that both classes of models are consistent with bulge masses of $\sim 1 \times 10^{10}\ M_{\odot}$. (I refer here to the mass within a radius of 1 kpc.) Moreover, for the power-law models the technique converges on the same exponent derived by Sanders and Lowinger (1972).

FUTURE WORK: INFRARED OBSERVATIONS

The thrust of future observations should be towards identifying individual planetaries. The infrared seems to be the most suitable regime, and a program is now underway at the United Kingdom Infrared Telescope (UKIRT) in Hawaii to observe several of the best Westerbork candidates in the near-IR and at 10μm.

Several infrared spectral features show some promise for separating planetaries from HII regions. Cohen and Barlow (1980) have noted that PN show a much more pronounced 9.7μm silicate feature than lower-excitation objects. The 10.5μm [SIV] and 12.8μm [NeII] lines are also excitation indicators, the ratio [SIV]/[NeII] tending to be higher in PN than in compact HII regions. However, the proximity of the [SIV] line to the silicate feature makes this technique difficult to apply to the faint objects of the Westerbork survey.

The unidentified molecular lines at 3.3μm, 3.4μm, 6.2μm, 7.7μm, 8.6μm, and 11.3μm are also particularly strong in planetaries, though some are found as well in a variety of bright infrared sources. So far, only one of the Westerbork sources -- 19W32 -- has been observed spectrally in the infrared, and was easily detected in the Brackett γ and 3.3μm lines (see Figure 3) at UKIRT. 19W32 is the only optically-identified object in the Westerbork survey (Isaacman et al 1980). It shows strong [OIII] emission at λ5007 Å and so is definitely a planetary: the first planetary nebula ever discovered by radio observations! No doubt the UKIRT program will yield more such objects.

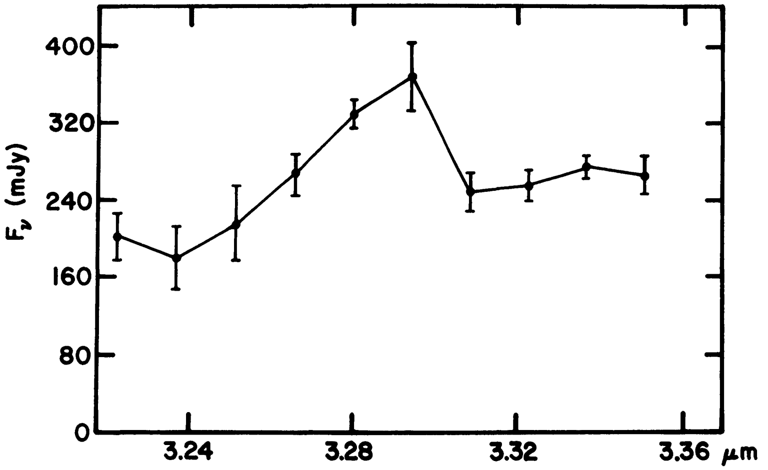

Figure 3. 3.3μm emission line in Westerbork planetary nebula 19W32.

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DINERSTEIN: How do you separate PN from H II regions? While it is true that the best observed H II regions are much brighter than PN, consideration of the luminosity function of OB stars suggests that there could be many lower luminosity H II regions which may be detected in this way.

ISAACMAN: This is the most difficult problem facing us. In practice, we eliminate all objects with S > 60 mJy.

DINERSTEIN: Regarding the structure of PN, many young H II regions also show shell structure (e.g. W3A, W3(OH)), so this might not be a good way of discriminating between PN and H II regions. Furthermore, the 3.3 μm feature, which you mentioned as being observed in one PN candidate, is also observed in the spectra of many H II regions and other types of objects.

ISAACMAN: Yes, the 3.3 μm feature is seen in a variety of objects. It would be better to look at some of the infrared lines, such as [S IV] 10.5 μm, in order to decide which objects are PN. The S IV/Ne II line ratio might provide a means of distinguishing PN.

ZUCKERMAN: Many years ago, Osterbrock pointed out that PN observed toward the Galactic center appeared to have smaller radii than those observed locally. He suggested a number of possible explanations. More recently, we suggested an additional possibility - that the masses of PN near the Galactic center are systematically smaller than those near the Sun. Since the stars in the Galactic bulge are, on the average, different from the stars near the Sun, it is not unreasonable to suppose that the resulting PN differ also. Therefore, your assumption that the Galactic center PN belong to basically the same population as nearby PN seems questionable. Furthermore, by making such an assumption, you relinquish the possibility of discovering any systematic differences which might exist.

ISAACMAN: Optical observations of Galactic centre PN are very likely to suffer from severe selection effects. My assumption regarding the properties of these objects has little to do with their dynamical or evolutionary population; I suppose only that their ionized masses be similar to those of local PN. Gathier's VLA observations give strong support to this assumption.