Research Note

A Radio Search for Planetary Nebulae near the Galactic Center

II. Flux Density Distribution

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Summary. A model of radio emission from planetary nebulae takes into account two possible evolutionary tracks of the central star. The results reproduce the solar neighbourhood PN flux density distributions and suggest that PN are mostly optically thick. The latter point implies that the ionized mass of an individual nebula will often be much less than the total shell mass. Applying the model to the Westerbork search for galactic center planetary nebulae, it is shown that detectability limitations allow about 5% of the bulge PN to be discovered via aperture synthesis. Selection effects arising from the detection threshold and radio evolution of planetary nebulae will cause the detected sample to show a 21 cm flux density distribution with a maximum near 25 mJy.

The flux distribution of 77 Westerbork sources shows an excess of 13 sources above the extragalactic background in this flux range. Preliminary 6-cm observations suggest that most of these are thermal; if planetary nebulae were born in the galactic bulge is comparable to the solar neighbourhood.

Key words: planetary nebulae – galactic center

I. Introduction

Population II objects such as RR Lyrae variables and planetary nebulae can give information on the gravitational field of the galactic nuclear disk if their velocity distribution is known (Oort, 1977a, 1977b). Because of the great optical extinction in that region, however, catalogues of optically-discovered planetary nebulae such as that of Perek and Kohoutek (1967) are very incomplete within at least ~3° from the galactic center. A radio search for thermal point sources is now underway with the Westerbork Synthesis Radio Telescope in order to surmount this difficulty (Wouterloot and Dekker, 1979, hereafter Paper I). Such sources will be either planetary nebulae (PN) or compact H II regions, which can in principle be distinguished by their infrared line characteristics.

In interpreting the results of this PN survey, two important questions must be asked, namely (1) how complete a sample can one expect to detect near the galactic center, and (2) are the characteristics of the sample comparable to those of PN in the solar neighbourhood? Question (2) arises since surveys by Webster (1975), Vorontsov-Velyaminov et al. (1975), and Kostyakova (1977) have suggested that PN seen in the direction of the galactic bulge are younger and of a lower excitation class than nearby PN. Recent high-resolution NII observations by Lacy et al. (1979) have also revealed several galactic-center compact sources whose intensities, velocity widths and emission measures are characteristic of low-excitation PN. Moreover, Zuckerman (1978) has proposed on the basis of evolutionary considerations that galactic center PN should be oxygen-rich and of lower mass than local objects, [Webster (1976), however, has analyzed optical line strengths and finds no such oxygen abundance anomaly.]

II. Radio Evolution and Detectability

We can estimate the completeness of the radio sample of galactic bulge PN by calculating the fraction of a nebula’s radio-emitting lifetime during which it is brighter than some detection threshold. This requires a model for the radio emission, a subject on which there is little agreement due to the lack of a distance scale. We will adopt a simple model that has the virtue of accounting for the 6-cm radio flux distribution of local nebulae. The salient features of the model nebula are:

1. a 4He fraction of 0.1 by number;
2. a uniformly dense shell with a thickness of 0.3 times its radius. This is in general accord with the optical and radio appearance of PN, and has been adopted by other authors (e.g. Kwok et al., 1978);
3. a shell filling factor of 0.6 (Milne and Aller, 1975, hereafter MA), again in accord with optical appearance, though there may be wide variation;
4. a constant electron temperature $T_e = 12 \times 10^3$ K. (Hummer and Seaton, 1964; Kaler, 1970);
5. a constant expansion velocity. Support for this assumption can be found in the fact that nearly all PN have expansion velocities within a factor of two of 25 km s$^{-1}$, and there does not seem to be a strong correlation between size (hence age) and expansion rate.

All of these assumptions are reasonably well supported by observational evidence. Much more uncertain, but no less important, are the related factors 1. the ionized mass of the shell; 2. the Lyman continuum output of the central star, and 3. the distance scale. Models for these generally fall into two classes depending on whether or not the shell is taken to be optically thick. Both cases will be tested against local nebulae before applying a model to the galactic center.

a) Optically Thin Shell

If a significant fraction of the ultraviolet photons escape the nebula, then free-free emission from the resultant circumnebular Strömgren sphere (Mezger, 1972; Strömgren, 1939) will influence
the flux density distribution. This can be taken into account by assuming an interstellar medium density (~1 atom cm$^{-3}$) and knowing the observing beam size.

The Lyman continuum flux of the exciting star was calculated as a function of nebula radius by using the evolutionary track given by Seaton (1966). He also gives the dependence of the shell optical depth on its radius.

The extensive list of 6-cm fluxes given by MA form a homogeneous data base against which to compare the model, so their optically thin nebula mass (0.16 $M_\odot$) was adopted. From this and the model parameters given above, a theoretical radio flux evolution curve was calculated, from which a predicted observed flux density distribution was derived as follows.

Let $R(S)$ be the nebula radius associated with a given flux density $S$, which itself depends on the distance of the nebula from the Sun. It is clear that $R(S)$ is double-valued at all $S$ except the maximum. If the flux detection threshold is $S_{\text{det}}$ then, of the detected nebulae which lie at a distance $D$, the fraction seen emitting in the flux range $S$ to $S + dS$ is

$$\Phi(D,S) dS = \frac{[dS(D)]^{-1}}{dR_1} - \frac{[dS(D)]^{-1}}{dR_2} \Delta S,$$

where the subscripts 1 and 2 represent values before and after the peak flux, respectively. The flux distribution of all local nebulae is then the mean of $\Phi(D,S)$ $S$ weighted by the fraction of nebulae in each distance interval, $a(D) \Delta D$. The observed distribution thus becomes

$$\Phi(S) dS = \int [\Phi(D,S) a(D)] dD.$$

MA's peak-to-peak noise was 15 mJy, from which we can estimate a detection threshold of 30 mJy. (This is not a measure of the completeness of the solar neighbourhood PN as it is for the galactic center since local planetaries are usually discovered optically.)

1 Longer integration times – and hence a lower detection threshold – were used for the weakest nebulae in the survey. These were excluded from the present calculations.

MA derived distances using the radio analogue of the method of Shklovskii (1956), which assumes that most PN are optically thin in the Lyman continuum. If the assumption is correct, then that distance scale enjoys the advantage of depending only weakly on the (poorly known) average nebula mass.

Equation (2) was first evaluated for nearby PN by using MA's distance distribution $a(D) \Delta D$ characterizing the 84 PN with $D \leq 3.5$ kpc with distance bins $\Delta D = 500$ pc. $\Phi(S_d) dS$ is shown as the dashed line in Fig. 1, using logarithmic flux intervals $\Delta \log S_d = 0.159$ and a detection threshold of 30 mJy. The flux distribution of the local planetaries themselves is shown as the solid line, and clearly agrees reasonably well with the model, although the latter shows an unobserved high-intensity tail. Since a galactic center search will select in favor of bright objects, this optically-thin model will predict an exaggerated detection percentage there. This can be ameliorated by assuming a lower ionized mass, but only at the expense of predicting more local low-brightness nebulae than are known to exist.

b) Optically Thick Shell

Recent work based on ANS observations suggests that most nebulae are in fact optically thick (Pottasch et al., 1978; Natta et al., 1979). Moreover, using aperture synthesis, Terzian et al. (1974) did not detect any extended radio emission from 15 bright nearby PN at 2.7 and 8.1 GHz; such emission would be expected if UV photons were available to ionize the interstellar medium.

To test the flux distribution of the optically thick model we cannot use the optically thin MA distances. Pottasch et al. (1978) preferred the synthetic scale derived by Acker (1978), which uses optical depth information. Including the effects of a non-negligible optical depth yields distances which are in general smaller than those obtained via the Shklovskii (1956) method; Pottasch et al. (1978) therefore deduced that the evolutionary track of the central star should fall about a factor of 10 in luminosity and a factor of 2 in temperature below Seaton's (1966) curve. The new observed 6cm flux density distribution for local nebula is shown as the solid line in Fig. 2; it differs from the observed distribution in Fig. 1 because the new distance scale brings more nebulae (96) within the 3.5 kpc distance cut-off than before (84).
Iterating to find the most appropriate mass for the new model yields a best-fit value of $M_e = 0.21 \pm 0.03 M_\odot$, shown as the dotted line in Fig. 2. ($M_e$ is the total, not necessarily ionized, shell mass.) The agreement is clearly much better than the optically-thin case with high central-star luminosities; in fact, the RMS deviation is better than twice as good (0.0115 for the optically-thick model vs. 0.024 earlier). In particular, the high-intensity tail has been eliminated from the model without incurring a severe excess in the expected number of low-intensity sources. Weidemann (1977) has suggested that the mean PN mass should be increased to $0.4 M_\odot$, but these results argue against such a substantial change.

This close agreement suggests that it is appropriate to apply the optically-thick model, with a shell mass of $0.21 M_\odot$, to the galactic center planetary. Of course, in practice there is considerable uncertainty and variation among the parameters which specify the model; this, with the uncertainty in the distance scale, means that the model should be thought of more as a consistency check linking the galactic center PN to the local nebulae, rather than as a narrowly-defined description of planetary systems in general.

III. Application to Galactic Center Nebulae

a) The Model

If we survey a region lying within some small angular distance $\theta$ from the galactic center and $z$ is the perpendicular distance from the galactic plane. Oort (1977a) suggested that $v \propto q^{-2.5}$ over the range $0.08 \leq q \leq 1$ kpc, though this obviously cannot be extrapolated to $q = 0$. To deal with this, we can use an exponential, $\exp(-aq)$, which approximately matches the curve $q^{-2.5}$ throughout most of the region of interest. The value $a = 12.75$ (for $q$ in kpc) gives a reasonable fit (within a multiplicative constant) over the range $0.08 \leq q \leq 0.3$ kpc, the upper limit subtending an angle $\theta \sim 2^\circ$ at the Sun. We extend the curve $\exp(-12.75q)$ to $q = 0$ and evaluate Eq. (4) at the galactic center, which we take to be a distance of $D = 9$ kpc. The relative number of (not necessarily detected) PN in a disk on the sky of $2^\circ$ angular radius and a distance $D$ from the Sun compared with such a disk centered on the galactic nucleus is then, to good approximation,

$$u(D) = \frac{N(D)}{N(9\text{ kpc})} = 178.9 \int_0^{D^{2.5}} \exp(-12.75(z^2 + (9-D)^2)^{1/2}) \, dz \cdot (D^{2.5} - 0) .$$

Fig. 3. Solid line: observed flux distribution of weak galactic center sources. Dashed line: distribution of extragalactic sources according to Willis et al., corrected for primary beam effects effectively raises the detection threshold with increasing angular distance from the field center.

Having adopted a flux evolution curve, it is possible to estimate the detectable fraction $f_{\text{det}}$ of all nebulae near the galactic center. Almost all known PN have radii $R \lesssim 0.6$ pc, so we can adopt this as the radius characterizing a typical PN lifetime. Therefore,

$$f_{\text{det}} = \frac{[R_d(S_{\text{det}}(\xi))-R_d(S_{\text{det}}(\xi))]/0.6,}{(5)}$$

where $S_{\text{det}}(\xi)$ is the detection threshold at an angular distance $\xi$ from the field center, corrected for the primary beam attenuation. This must be weighted by the characteristics of the primary beam to determine average values over the search region. The Westerhok primary beam HPBW at 21 cm is 37', causing the expected detectable fraction of all galactic center PN to be $f_{\text{det}} \approx 0.05$. On the basis of the model flux density distribution, the strongest among these is expected to have a 21 cm flux of about 25 mJy. A comparable figure is obtained simply by scaling the brightness of the strongest nearby PN to the distance of the galactic center.

b) Comparison with Observations

Two of the six 21 cm fields investigated in Paper I fall within 2° of the galactic center, and three other fields have been observed since then (Isaacman, in preparation). 116 Sources stronger than 5 mJy were found, most of which (77) were weaker than 45 mJy. A histogram of the fluxes for this group of sources, in linear bins of $S = 5$ mJy, is shown as the solid line in Fig. 3. A list of source parameters, as well as 6-cm observations of ~25 sources in the weak flux group, will be presented in a later paper.

To determine an upper limit to the number of planetary systems in the distribution of Fig. 3, it is necessary to subtract off the expected number of background sources. Westerhok source counts at 1415 MHz by Willis et al. (1977) show a flux distribution, before correction for primary beam effects,

$$dN = 310.72 S^{(-2.59 + 0.106k_\odot)} \, dS \text{ sterad}^{-1}$$

(6)
for $S$ in Jy. The primary beam corrected distribution is shown as the dotted line in Fig. 3. The expected number of background sources in any single field is 12.5 between 5 and 45 mJy; in the whole survey region it is 56, including the effects of overlapping fields. (The single-field value is derived from observations far from the galactic plane.)

In the flux range $5 \leq S_{21} \leq 25$ mJy where optically-thick PN are expected to concentrate, there are 55 sources, versus 42 expected background sources. Preliminary 6 cm observations suggest that most of the excess 13 sources are thermal, on the basis of Willis and Miley's (1979) result that ~15% of extragalactic sources have a 6-21 cm spectral index flat enough to resemble a thermal spectrum.

The galactic sources in the sample will be composed of supernova remnants, compact HII regions, and planetary nebulae. At the distance of the galactic center, a SNR will appear as a point source to the 22° Westerbork beam only during the first 500 yr of its expansion; assuming a rate of $10^{-13}$ supernovae per solar mass per year throughout the Galaxy, there is only a ~0.1 probability that we detect an SNR as a point source within 2° of the galactic center. The problem of HII regions is much more severe, since these can easily be confused with PN even when optical and IR observations are available (e.g. Cohen and Barlow, 1975). We will therefore take 13 as the upper limit of detected PN in the sample. The survey fields cover one-third of the area within 2° of the galactic center; if the 0.05 detection probability derived from the radio model is approximately correct, this implies an upper limit of 780 PN in the innermost 300 pc of the galaxy.

If we assume an average expansion velocity of 25 km s$^{-1}$, then the PN birthrate per unit mass in the galactic center follows. The largest PN have $R \sim 0.6$ pc, corresponding to a lifetime of 23,500 yr. Using the density model of Sanders and Lowinger (1972), the total mass in the inner 300 pc of the Galaxy is $\sim 1.9 \times 10^9 M_\odot$, so the PN birthrate becomes $< 780$ ($1.9 \times 10^9 \times 23,500$) $= 1.7 \times 10^{-11} M_\odot$ yr$^{-1}$. This rate falls in the range estimated by Audouze (1977) for the galactic center and is roughly the same as the rate in the solar neighbourhood. The corresponding number of PN throughout the whole Galaxy then comes to $< 60,000$, in agreement with most recent results (e.g. Alloin et al., 1976; Cahn and Wyatt, 1977; Acker, 1978).

IV. Conclusions

A simple model of the radio evolution of planetaries suggests that, as proposed by Pottasch et al. (1978), PN are optically thick in the Lyman continuum. Applying this result to distant objects, we conclude that an aperture synthesis search for planetaries within 2° of the galactic center can be expected to detect about 5% of the nebulae present. This sample should show a 21 cm continuum flux density distribution with a sharp cutoff near $S_{21} \sim 25$ mJy.

Observations in five 21 cm fields with the Westerbork telescope have yielded 55 compact sources in the flux range $5 \leq S_{21} \leq 25$ mJy, 13 more than the expected number of background sources. Preliminary 6-cm observations suggest that most of the excess sources are thermal and are therefore either PN or compact HII regions. This implies an upper limit to the planetary nebula birthrate of $\sim 1.7 \times 10^{-11} M_\odot$ yr$^{-1}$ in the inner Galaxy, and a galaxy total of $< 60,000$ nebulae.

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