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UPPER LIMITS FOR THE MASS LOSS RATES FROM CENTRAL STARS OF PLANETARY NEBULAE

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RESUMEN

Sabemos que las estrellas centrales de las nebulosas planetarias tienen vientos ionizados, los cuales se caracterizan por tener tasas de pérdida de masa de 10^{-8} $M_{\odot}$ año^{-1} y velocidades de $\sim$ 2000 km s^{-1}. Este viento debe estar completamente ionizado y se espera que sea una fuente de radiación libre-libre. En la mayoría de los casos, la densidad de flujo esperado está por debajo de la sensitividad de aún los mejores radiotelescopios. Hemos seleccionado cuatro candidatos para los cuales se han estimado parámetros favorables para la detección del viento en radiocontinuo. Estas son las estrellas centrales de las nebulosas planetarias NGC 2392, NGC 40, NGC 6543, y NGC 6302. Las cuatro fuentes fueron observadas con el VLA. No se obtuvo éxito en la detección del viento ionizado, pero se obtuvieron límites superiores a las tasas de pérdida de masa de 3×10^{-7}, 2×10^{-6}, 1×10^{-6}, y 2×10^{-5} $M_{\odot}$ año^{-1}, respectivamente.

ABSTRACT

The central stars of planetary nebulae are known to possess ionized stellar winds with mass loss rates of about 10^{-8} $M_{\odot}$ yr^{-1} and velocities of $\sim$2000 km s^{-1}. This wind is expected to be fully ionized and it should be a source of free-free radiation. In most cases, the radio flux expected is below detectability for a reasonable integration time even in the best radio telescopes. We selected four favorable candidates: NGC 2392, NGC 40, NGC 6543, and NGC 6302 for a radio continuum search. These planetary nebulae were observed using the VLA. We were not successful in detecting radio continuum from the stellar winds of their central stars, but we obtain upper limits for the mass loss rates of 3×10^{-7}, 2×10^{-6}, 1×10^{-6}, and 2×10^{-5} $M_{\odot}$ yr^{-1}, respectively.

Key words: **NEBULAE-PLANETARY – STARS-MASS LOSS**

I. INTRODUCTION

It is believed that the stars located at the top of the Asymptotic Giant Branch are in an evolutionary stage preceding that of planetary nebulae. Objects in the Asymptotic Giant Branch are characterized as having slow ($v_{\infty} \simeq$ 10 - 20 km s^{-1}) and massive ($\dot{M} \simeq 10^{-5}$ $M_{\odot}$ yr^{-1}) winds. As a result of this mass loss, an expanding, neutral envelope is formed around the central star. At the end of the evolution in the Asymptotic Giant Branch the slow wind stops, while the temperature of the stellar nucleus becomes large enough to ionize the envelope. At the same time a fast wind ($v_{\infty} \simeq$ 2000 km s^{-1}) with a low mass loss rate ($\dot{M} \simeq 10^{-8}$ $M_{\odot}$ yr^{-1}) develops.

Until now the most efficient method for studying the fast winds from the central stars of planetary nebulae is based on analysis of IUE spectra. Observations of *UV* lines from ions like C IV, N V, O IV, O V, Si IV, and N IV (Cerruti-Sola & Perinotto 1985) have shown the presence of P Cygni profiles (Heap *et al.* 1978; Heap 1983), from which the parameters of stellar winds can be derived. There are other possible methods to determine the mass loss rates of central stars of planetary nebulae (Perinotto 1989). One of these involves observations of radio continuum emission from the stellar wind. These ionized winds are expected to be free-free sources. However, no attempt has been made to detect them due to the following reasons: *i)* Using the formulation of Panagia & Felli (1975) for ionized stellar winds, and typical parameters for the fast

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wind ($v_\infty \simeq 2000$ km s^{-1}, $\dot{M} \simeq 10^{-8}$ M$_\odot$ yr^{-1}), one expects a radio flux density of ~0.0003 mJy at 2 cm wavelength and a distance of 1 kpc. This flux density is below the detectability of even the VLA (~0.1 mJy with a few hours of integration), *ii)* even for the most favorable cases, the nebular emission from the surrounding planetary nebula will make the detection of a weak point source difficult.

Nevertheless, there are central stars of planetary nebulae that have much more favorable parameters for radio detection than the typical ones. Recently, Pauldrach *et al.* (1988) have developed improved non-LTE wind models (Méndez *et al.* 1988; Pauldrach 1987). From these models, Pauldrach *et al.* (1988) obtain estimates for wind parameters for some central stars of planetary nebulae such that the velocity of the wind is low and the mass loss rate is high. Since the radio flux density goes as $S_\nu \propto (\dot{M}/v_\infty)^{4/3}$, the wind parameters of Pauldrach *et al.* (1988) suggest that the radio flux densities may be detectable in some planetary nebulae. The best case is the central star of NGC 2392 (the Eskimo Nebula). The wind parameters for this star derived by Pauldrach *et al.* (1988) from self consistent calculations are $\dot{M} \simeq 10^{-6}$ M$_\odot$ yr^{-1} and $v_\infty \simeq 600$ km s^{-1}. Using the formulation of Panagia & Felli (1975) we estimate a radio flux density detectable with the VLA (0.6 mJy at 2 cm wavelength and 1 kpc).

II. OBSERVATIONS

We observed NGC 2392 at 2 and 3.6 cm wavelength using the VLA in the A configuration during January 6, 1988. The absolute amplitude calibrator was 3C286 and the phase calibrator was 0735+178. We observed the planetary nebula NGC 6302 at 6 cm wavelength using the VLA in the A configuration during July 14, 1987 (see Gómez *et al.* 1989). NGC 40 and NGC 6543 were observed in 1982 by Balick *et al.* (1987), using the VLA at 6 cm wavelength in the A configuration. We obtained these data from the VLA archives. The calibration and reduction of the four planetary nebulae data were made using standard VLA techniques.

To suppress the extended nebular emission we limited the (u,v) range of the data. The visibilities from the small baselines (short spacings) give information about regions of extended angular size. To eliminate the extended emission from the nebula and keep the compact components, our maps were made from visibility data at (u,v) distances larger than 100 kλ. This selection suppresses angular structures larger than ~2″.

III. RESULTS AND DISCUSSION

In Figures 1 to 4 we present the radio continuum maps for the observed planetary nebulae. In these figures the cross indicates the position of the centra star. In the case of NGC 6302, the central star ha not been detected and the cross marks the centroi

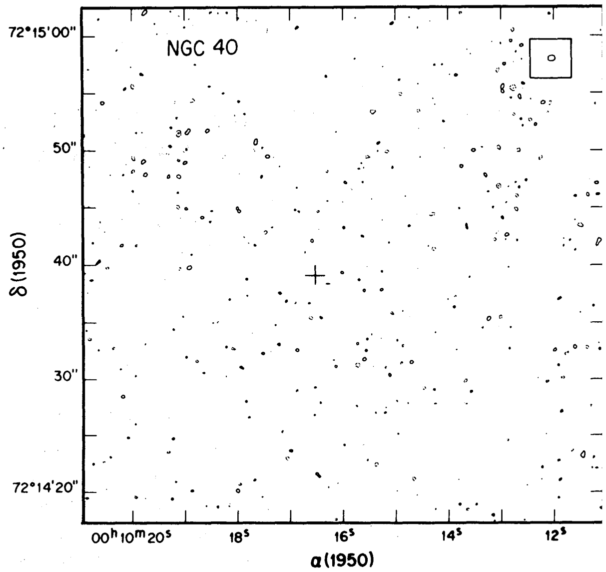


Fig. 1. Natural-weight VLA map of the 6-cm wavelength emission from NGC 40. Visibilities with (u,v) distance below 100 kλ were not used. The cross marks th position of the central star taken from the AGK3 Catalog Contours are −5, −3, 3, and 5 times 42 μJy beam^{-1} The half power contour of the beam is also shown.

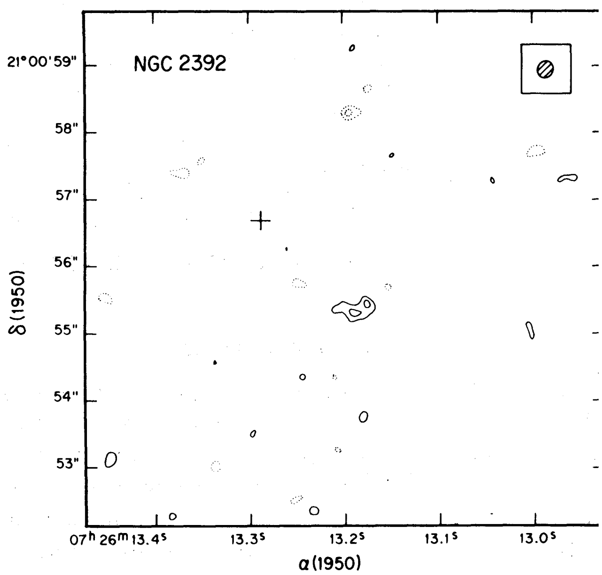
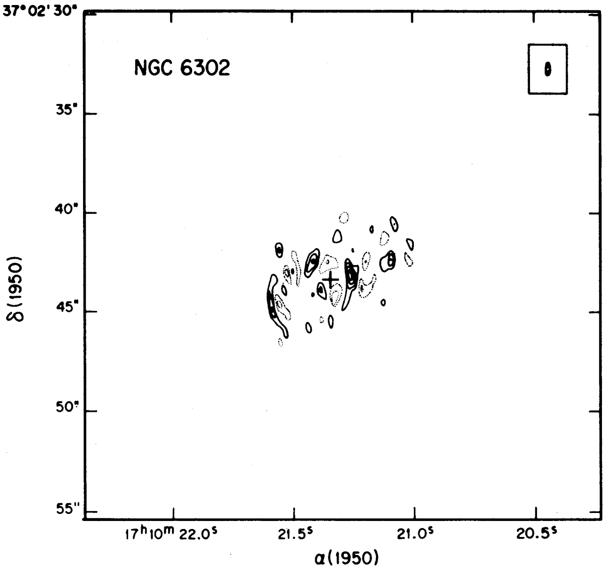


Fig. 2. Natural-weight VLA map of the 3.6-cm wave length emission from NGC 2392. Visibilities with (u,v distances below 100 kλ were not used. The cross mark the position of the central star as measured by u (see text). Contours are −4, −3, 3, and 4 times 1 μJy beam^{-1}. The half power contour of the beam is als shown.



'ig. 3. Natural-weight VLA map of the 6-cm wavelength mission from NGC 6302. Visibilities with (u,v) distances elow 100 kλ were not used. The cross marks the position f the centroid of the radio continuum emission taken rom Gómez *et al.* (1989). Contours are −9, −7, −5, −3, , 5, 7, and 9 times 350 μJy beam^{-1} . The half power ontour of the beam is also shown.

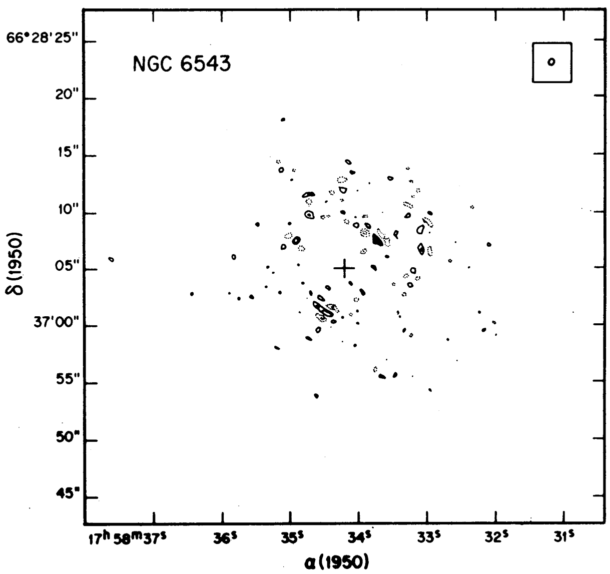


Fig. 4. Natural-weight VLA map of the 6-cm wavelength emission from NGC 6543. Visibilities with (u,v) distances below 100 kλ were not used. The cross marks the position of the central star taken from the AGK3 Catalog. Contours are −7, −5, −3, 3, 5, and 7 times 65 μJy beam^{-1}. The half power contour of the beam is also shown.

f the radio continuum map of Gómez *et al.* (1989).

The 3-σ upper limits for the flux densities for the egion of the maps near the central star are listed n column 7 on Table 1. The expected flux density rom an isotropic, isothermal, fully-ionized wind is ;iven by Panagia & Felli (1975),

$$\left[\frac{S_\nu}{mJy}\right] = 5.12\left[\frac{\nu}{10\ GHz}\right]^{0.6}\left[\frac{T_e}{10^4\ K}\right]^{0.1} \times$$

$$\times\left[\frac{\dot{M}}{10^{-5}\ M_\odot\ yr^{-1}}\right]^{4/3}\left[\frac{v_\infty}{10^3 km\ s^{-1}}\right]^{-4/3}\left[\frac{d}{kpc}\right]^{-2} . \quad (1)$$

TABLE 1

PARAMETERS OF CENTRAL STARS OF PLANETARY NEBULAE

Source	α (1950)	δ	v_∞^a (km s^{-1})	D^b (kpc)	λ (cm)	Flux Density^c (mJy)	$\dot{M}$ (M$_\odot$ yr^{-1})	$\dot{M}^d$ (M$_\odot$ yr^{-1})	Ref.^{e}
NGC 40	$00^h10^m16.5^s$	$+72°14'39''$	1600	1.1	6	0.138	$\leq 2\times10^{-6}$	3×10^{-8}	1
NGC 2392	07 26 13.3	+21 00 57	600	1.2	3.6	0.054	$\leq 3\times10^{-7}$	1×10^{-6}	2
NGC 6302^f	17 10 21.4	−37 02 43	800	2.2	6	2.400	$\leq 2\times10^{-5}$	1×10^{-5}	3
NGC 6543	17 58 34.2	+66 38 05	1800	0.6	6	0.195	$\leq 1\times10^{-6}$	2×10^{-6}	4

^{a} Wind velocities are from Pauldrach *et al.* (1988), except for NGC 6302, where it is taken from Meaburn & Walsh (1980).

^{b} Distances are from Heap & Augensen (1987), except for NGC 6302, where it is taken from Gómez *et al.* (1989).

^{c} 3-σ upper limit.

^{d} Highest value previously estimated from the literature.

^{e} References: 1) Cerruti-Sola & Perinotto 1985; 2) Pauldrach *et al.* 1988; 3) Meaburn & Walsh 1980; 4) Hutsemèkers & Surdej 1987.

^{f} Central star yet undetected in the optical. We take the position of the star to be the centroid of the radio continuum map of Gómez *et al.* (1989).

Assuming an electron temperature of 10^4 K and adopting the distances and wind velocities given in Table 1, we obtained the upper limits for the mass loss rates given in column 8 on Table 1. The wind velocities for NGC 40, NGC 2392, and NGC 6543 are those derived from *UV* data by Pauldrach *et al.* (1988). The wind velocity of NGC 6302 is taken from Meaburn & Walsh (1980). In Table 1, we also give the largest mass loss rate estimated for each object, taken from the literature.

For the sources NGC 40, NGC 6302, and NGC 6543 our upper limits are not very stringent and are not in conflict with previous estimates for mass loss rates. However, in the case of NGC 2392 our upper limit, $\dot{M} \leq 3\times10^{-7}$ $M_\odot$ yr^{-1}, is a factor of ~3 below the derived value from the self-consistent models of Pauldrach *et al.* (1988), $\dot{M} \simeq 10^{-6}$ $M_\odot$ yr^{-1}. If the ionized stellar wind were collimated, it would have even larger flux densities for the same mass loss rate (Reynolds 1986). There is observational evidence pointing to collimation in the stellar wind of NGC 2392 (Gieseking, Becker, & Solf 1985; O'Dell & Ball 1985; Miranda & Solf 1990; Cuesta, Phillips, & Mampaso 1990).

In the map of NGC 2392 we can see that at a marginal level (4-σ) there is a possible radio source at ~2″ to the southwest of the optical position of the star, as given by the AGK3 Catalog, $\alpha(1950) = 07^h\ 26^m\ 13^s.30 \pm 0^s.02$; $\delta(1950) = 21°\ 00'\ 56''.8 \pm 0''.2$.

To check if this marginal source could be actually associated with the star, we remeasured the position of the central star of NGC 2392 using plates taken in 1991 November with the 1-m Schmidt Camera at the National Observatory of Llano del Hato, Venezuela. The plates were measured with a stereo-comparator PSK2 and a linear solution was obtained with the plate-overlap method (Stock 1981). Our estimate of the position is $\alpha(1950) = 07^h\ 26^m\ 13^s.29 \pm 0^s.02$, $\delta(1950) = 21°\ 00'\ 56''.7 \pm 0''.2$, in excellent agreement with the AGK3 position. We did not attempt to correct these positions for proper motions of the star since this effect is estimated to be of order 0″.1 for several decades. The position of the centroid of the possible radio source is $\alpha(1950) = 07^h\ 26^m\ 13^s.18$; $\delta(1950) = 21°\ 00'\ 55''.3$, and the peak flux density is ~0.1 mJy. It is unclear if this possible source is real or just a noise fluctuation. If real, it could be a condensation that is part of the planetary nebula.

IV. CONCLUSIONS

We presented upper limits for the radio continuum emission in the vicinity of the central stars of the planetary nebulae NGC 2392, NGC 40, NGC 6543 and NGC 6302. These non detections imply upper limits for the mass loss rates of the central stars of 3×10^{-7}, 2×10^{-6}, 1×10^{-6}, and 2×10^{-5} $M_\odot$ yr^{-1} respectively. In the case of NGC 2392 this upper limit appears to be smaller than the value of 1×10^{-6} $M_\odot$ yr^{-1} estimated by Pauldrach *et al.* from self-consistent modeling of stellar atmospheres.

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