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# EXPANSION PARALLAX OF THE PLANETARY NEBULA IC 418

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RESUMEN

Presentamos observaciones en dos épocas en radio contínuo de la nebulosa planetaria IC 418, las observaciones están separadas por más de 20 años y fueron realizadas usando el arreglo muy largo, o VLA. Estos datos nos permiten mostrar que la tasa de expansión angular del frente de ionización en IC 418 es $5.8 \pm 1.5$ msa año$^{-1}$. Si la velocidad de expansión del frente de ionización es igual que la velocidad de expansión del gas en la línea de visión, medida usando espectroscopía óptica, entonces para la velocidad de expansión de 30 km s$^{-1}$, obtenemos una distancia a IC 418 de $1.1 \pm 0.3$ kpc. Si tomamos en cuenta que el frente de ionización podría estar expandiéndose 20% más rápido que el gas, entonces la distancia a IC 418 incrementaría a $1.3 \pm 0.4$ kpc.

ABSTRACT

In this paper, we present radio continuum observations of the planetary nebula IC 418 obtained at two epochs separated by more than 20 years using the Very Large Array. These data allow us to show that the angular expansion rate of the ionization front in IC 418 is $5.8 \pm 1.5$ mas yr$^{-1}$. If the expansion velocity of the ionization front is equal to the expansion velocity of the gas along the line of sight as measured by optical spectroscopy, then using the value of 30 km s$^{-1}$ for the expansion velocity, we obtained a distance to IC 418 of $1.1 \pm 0.3$ kpc. If we take into account that the ionization front may be expanding about 20% faster than the material, then the distance to IC 418 would increase to $1.3 \pm 0.4$ kpc.

*Key Words:* planetary nebulae: individual (IC 418) — radio continuum: stars

## 1. IC 418

The Spirograph Nebula (IC 418, G215.2-24.2) has a rather simple morphology: both at optical and radio wavelenghts, it has an elliptical ring shape, with a major axis of 14″ and a minor axis of 10″. It is surrounded by a low-level ionized halo, which is itself enshrouded in a neutral envelope with an angular size of about 2″ (Taylor & Pottasch 1987; Taylor et al. 1989). Widely discrepant estimates of the distance to the planetary nebula (PN) IC 418 have been obtained using different statistical methods. To our knowledge, the shortest distance ever proposed is 360 pc (Acker 1978), whereas the largest one is 5.74 kpc (Phillips & Pottasch 1984). In recent years, the most popular value appears to have been 1 kpc (Meixner et al. 1996; Pottasch et al. 2004), although the reason for this is not entirely clear.

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## 2. RESULTS AND DISCUSSION

The data were taken using the Very Large Array (VLA) of the NRAO[4] at 6 cm (5 GHz) in its second most extended (B) configuration on June 28, 1986 (1986.49) and November 6, 2007 (2007.85). This is a time separation of 21.36 yr. The resulting images are shown in Figure 1.

The difference image between the two epochs, shown in the bottom left panel of Figure 1 was produced following Guzmán et al. (2006). We estimated the expansion rate of the nebula by comparing the difference image of the data with the model. To generate the model difference, we image the data twice. The first image was made using a fixed pixel size of $0''\!.1$, whereas the second one was made using pixel sizes of $(1 + \epsilon) \times 0''\!.1$, with $\epsilon \geq 0$, but $\epsilon \ll 1$. See Guzmán et al. (2009) for more detail. To identify the best model, we repeated the procedure described above for a set of values of $\epsilon$. For each value, we compared the model difference with the real difference. The best model clearly corresponds to the situation where the two differences are as similar to each other as possible. The best value for $\epsilon$ that we obtained was $\epsilon = 0.018 \pm 0.005$. Using the image of the second

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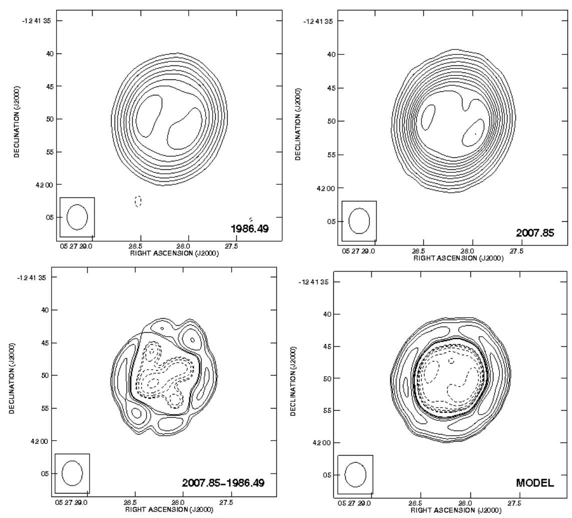


Fig. 1. Top: contour images of the 6 cm emission form IC 418 for 1986.49 (left) and 2007.85 (right). The contours are $-5$, 5, 10, 30, 50, 60, 80, 100, 150, 200, 250 and 300 times 350 $\mu$Jy, the average rms noise of the images. Bottom: contour images of the 6 cm difference image (left) and of the model (right) obtained as described in the text. The contours are $-20$, $-15$, $-10$, $-7$, $-5$, $-4$, 4, 5, 7, 10, 15 and 20 times 460 $\mu$Jy, the rms noise of the difference image.

epoch we estimated the radius of maximum emission, $\theta$ to be $6''.700 \pm 0''.006$. Using this value and $\epsilon$'s value we can calculate the angular expansion rate, $\dot{\theta}$ to be $5.8 \pm 1.5$ mas yr$^{-1}$.

To deduce the distance from the angular expansion rate calculated above, one must know the physical velocity $v_{\rm exp}$ at which the ionization front is expanding: $[{\rm D/pc}] = 211[v_{\rm exp}/{\rm km\ s^{-1}}][\dot{\theta}/{\rm mas\ yr^{-1}}]^{-1}$.

Traditionally, $v_{\rm exp}$ has been estimated using high spectral resolution observations of some emission lines and assuming a relation between the shape of the line profile and the movement of the emitting gas. For this nebula IC 418, we used the high resolution spectra of H$\beta$, [NII] and [OIII] lines published by Gesicki et al. (1996). Using a detailed three-dimensional photoionization model of the nebula, Morisset & Georgiev (2009) reproduced these three profiles using a $V \propto R^4$ expansion law. According to this model, the expansion velocity near the outer edge of the nebula (where we detect the expansion at radio wavelengths) is 30 km s$^{-1}$. Using this value we can calculate the distance to IC 418, we obtained a distance of $1.1 \pm 0.3$ kpc.

To calculate this distance we have assumed that the velocity of the ionization front (pattern velocity) is the same as the Doppler velocity of the material itself, deduced form spectral lines. For conditions appropriate for planetary nebulae (PNe), Mellema (2004) showed that the ionization front tends to expand somewhat faster than the material. Using their Figure 5, we estimated that the expansion velocity of the ionization front in IC 418 is $1.2 \pm 0.1$ faster than the expansion velocity of the gas. Taking this effect into account leads to a distance to IC 418 of $1.3 \pm 0.4$ kpc.

TABLE 1

PHYSICAL PARAMETERS OF IC 418

| Parameter | Value |
|---|---|
| $t_{\rm dyn}$ | 1200 yr |
| EM | $(5.05 \pm 0.01) \times 10^{-6}$ cm$^{-6}$ pc |
| $n_e$ | $(6.2 \pm 1.7)(d/1.1\ {\rm kpc})^{-0.5} \times 10^3$ cm$^{-3}$ |
| $M_i$ | $(8.7 \pm 2.4)(d/1.1\ {\rm kpc})^{2.5} \times 10^{-2}\ M_\odot$ |

Using the distance value, we can derive the physical parameters of the nebula like the electron density ($n_e$) and the mass of ionized gas ($M_i$) and using the angular expansion rate we can derive the dynamical age of the nebula ($t_{\rm dyn}$). All these parameters together with the emission measure (EM) calculation are listed in Table 1.

## 3. CONCLUSIONS

In this document, we presented observations of the 6 cm radio continuum emission from the well studied PN IC 418 obtained at two epochs separated by more than 20 years. This data allowed us to detect the angular expansion of the nebula, and to estimate its distance. Depending on the assumption made on the relative velocity of the matter and of the ionization front, we obtained a distance of $1.1 \pm 0.3$ kpc, or $1.3 \pm 0.4$ kpc. Using this distance we derived the physical parameters of the planetary nebula IC 418.

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