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PROPER MOTIONS OF THE ANSAE IN THE PLANETARY NEBULA NGC 7009

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RESUMEN

Para la nebulosa planetaria NGC 7009, presentamos una comparación de dos conjuntos de datos sin publicar del archivo del Very Large Array tomados con una separación temporal de 8.09 años para confirmar los movimientos propios observados en el óptico en sus ansas. Determinamos valores de 23±6 y 34±10 mas año^{-1} para las ansas este y oeste, respectivamente. Hay evidencia marginal de que las densidades de flujo de los chorros que conectan a las ansas con el cuerpo principal de la nebulosa disminuyeron en un 30% en el periodo que separa a las dos observaciones. También establecemos un límite superior para la expansión del cuerpo principal de la nebulosa planetaria, y obtenemos un límite inferior de ∼700 pc para la distancia a ella.

ABSTRACT

For the planetary nebula NGC 7009, we present a comparison of two unpublished Very Large Array archive data sets taken with a time separation of 8.09 years to confirm the proper motions of its ansae observed in the optical. We determine values of 23±6 and 34±10 mas yr^{-1} for the eastern and western ansae, respectively. There is marginal evidence suggesting that the flux densities of the jets that connect the ansae with the main body of the nebula diminished in about 30% over the period between the two observations. We also set an upper limit to the expansion of the main body of the planetary nebula, setting a lower limit of ∼700 pc for its distance.

Key Words: **PLANETARY NEBULAE: INDIVIDUAL (NGC 7009) — TECHNIQUES: INTERFEROMETRIC**

1. INTRODUCTION

NGC 7009 (PN G037.7-34.5), the "Saturn Nebula", is a well-studied elliptical PN, which has a jet-like system as well as a pair of low-ionization knots along its major axis. This type of knots, also known as ansae (Aller 1941), are now known to be present in many planetary nebulae and have received the names of bipolar, rotating, episodic jets BRETS (López, Vázquez, & Rodríguez 1995; López 1997), and fast, low ionization emission regions (FLIERS; Balick et al. 1993; 1994). There are several models proposed to explain the origin of these structures, but no one is generally accepted (for a discussion, see Steffen, López, & Lim 2001). The radial velocity observations of several of these objects by Balick, Preston, & Icke (1987) indicate velocities in the order of several tens of km s^{-1} with respect to the systemic velocity of the planetary nebula. On the other hand, proper motions of these knots have been measured only for a handful of objects (KjPn 8; Meaburn 1997, Hen 2-90; Sahai et al. 2002, NGC 7009; Fernández, Monteiro, & Schwarz 2004). In particular, at radio wavelengths there are, to our knowlewdge, no measurements of proper motions of ansae in planetary nebulae. In this paper we present such a measurement for the ansae in NGC 7009. We also discuss an apparent change in the flux density of the jets of this object and study the expansion of the main body of the nebula, setting a lower limit to its distance.

2. OBSERVATIONS

The two sets of observations used in this study were taken from the archive of the VLA of the

NRAO[1]. The epochs of the observations were 1989 March 28 (epoch 1989.24) and 1997 April 29 (epoch 1997.33), with a time separation of 8.09 years. Both sets of observations were made at 3.6 cm in the B configuration and each has a total of ∼7 hours of on-source integration. In both epochs the source 1331+305 was used as an absolute amplitude calibrator (with an adopted flux density of 5.21 Jy) and the source 2131-121 was used as phase calibrator (with a bootstrapped flux density of 3.19±0.01 Jy for the first epoch and of 2.68±0.02 Jy for the second epoch).

The data were reduced using the standard VLA procedures in the software package Astronomical Imaging Processing System (AIPS) of NRAO and then cross-calibrated using the procedure of Masson (1986; 1989a; 1989b).

3. INTERPRETATION AND RESULTS

3.1. *Proper Motions of the Ansae*

In Figure 1 we present 3.6 cm images for the two epochs analyzed. Three main structures are evident in the images. The first is the bright, main body of the nebula with an elliptical shape and angular dimensions of about $32'' \times 24''$. The second structure is constituted by the faint jets that emanate from the main body of the nebula and extend about $8''$ to the east and west. Finally, the third structure are the ansae, with angular dimensions of a few arc sec and that possibly are the termination points of the jets.

The images were made with the ROBUST weighting parameter (Briggs 1995) of AIPS set to 0 and a tapering of 150 kλ in the (u,v) plane to smooth the angular resolution and enhance the signal-to-noise ratio of the relatively faint and extended ansae. The expanding proper motions of the ansae are evident in the images. In Table 1 we present the values of these proper motions. The peak positions of the ansae have been obtained with the task MAXFIT of the AIPS software package. The errors in the positions were estimated following Condon (1997) and Condon & Yin (2001). There are two previous reports of these proper motions in the literature. Liller (1965) estimated a value of ∼16 mas yr^{-1} for the proper motion of the ansae in NGC 7009. A more modern determination is that obtained by Fernández et al. (2004), who used HST images to obtain a value of 28±8 mas yr^{-1} for the eastern ansa (the western ansa was not included in one of the archive images they used). This value compares well with the value of 23±6 mas yr^{-1} derived by us (see Table 1). Assuming a distance of 0.86±0.34 kpc, the average of 14 available values (Acker et al. 1992; Fernández et al. 2004), and taking into account the error from our proper motions as well as the relatively large error in the average distance, we obtain crude estimates for the velocities in the plane of the sky of 100±50 and 140±70 km s^{-1}, for the east and west ansae, respectively.

If we assume that the ansae move ballistically (i.e. with no acceleration or deceleration) we estimate an age of ∼850 years if they originated from the central star and of ∼300 years if they originated from the edge of the main body of the planetary nebula.

3.2. *A Decrease in the Emission from the Jets?*

There is marginal evidence in Figure 1 that, between the two epochs observed, the emission from the jets that connect the ansae with the main body of the planetary nebula has decreased. For both the east and west jets, we find that the flux density decreased from ∼0.9±0.1 mJy in 1989.24 to ∼0.6±0.1 mJy in 1997.33, a decrease of about 30%. The ansae themselves, at the tip of the jets, do not show evidence of variation within the noise.

The possible decreases in the flux densities from the jets over the 8-year period are marginally consistent with recombination theory. The electron densities of the jets have been estimated to be between 1,000 and 4,000 cm^{-3} (Bohigas, López, & Aguilar 1994; Balick et al. 1994; Gonçalves et al. 2003; Sabbadin et al. 2004), implying recombination timescales of 30 to 120 years. Evidence of variation in the surroundings of NGC 7009 has been found by Bohigas et al. (1994), who report a previously undetected [SII] condensation about $20''$ to the NE of the main body of the nebula. On the other hand, as a whole, the planetary nebula has a flux density of 654±3 mJy in 1989.24 and of 649±5 mJy in 1997.33, so the total flux density remains constant within ≤1%.

3.3. *An Upper Limit to the Expansion of the Nebula*

Comparison of data taken with years or decades of separation often reveal the expansion signature in planetary nebula (e.g. Guzmán, Gómez, & Rodríguez 2006). When subtracting the older data from the more recent one, the characteristic expansion signature shows as an outer region of positive emission, surrounding an inner region of "negative" emission. In Figure 2 we show an average image from the data of the two epochs (obtained by concatenating both data sets) and a difference image,

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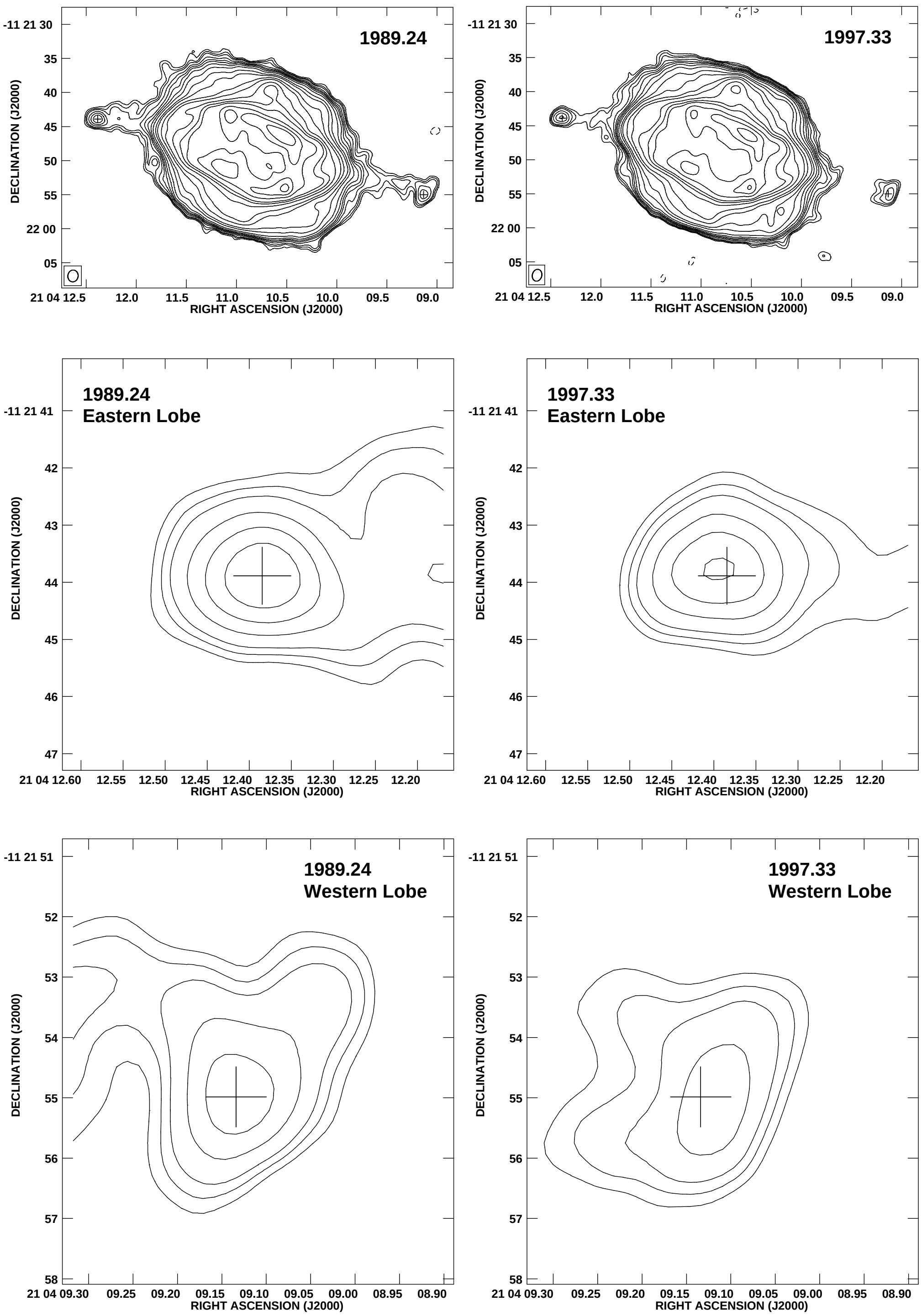

Fig. 1. 3.6 cm contour images of NGC 7009 for 1989.24 (left) and 1997.33 (right). The top part of the panel shows the whole of the nebula, while the middle and bottom parts of the panel show the eastern and western lobes, respectively. The crosses mark the peak position of the lobes for 1989.24. Note the small displacement of the peak position of the lobes for 1997.33. The contours are -4, 4, 5, 6, 8, 10, 12, 15, 20, 30, 40, 60, 80, 120, 200, 300, 400, and 500 times 19.5 μJy beam^{-1}, the average rms noise of the two images. The synthesized beams ($1''.74 \times 1''.50$ with a position angle of -8° for 1989.24 and $1''.76 \times 1''.38$ with a position angle of -15° for 1997.33) are shown in the bottom left corner of the top two images.

TABLE 1

PROPER MOTIONS[a] OF THE ANSAE

Ansa	Δ_{RA}(")	Δ_{DEC}(")	Δ_{TOTAL}(")	P.A. (°)	μ (mas yr^{-1})
Eastern	$+0.14\pm0.05$	$+0.11\pm0.05$	0.18 ± 0.05	52 ± 16	23 ± 6
Western	-0.23 ± 0.08	-0.14 ± 0.08	0.27 ± 0.08	239 ± 17	34 ± 10

[a] Δ_{RA} is the displacement in right ascension, Δ_{DEC} is the displacement in declination, Δ_{TOTAL} is the total displacement, P.A. is the position angle of the displacement, and μ is the total proper motion.

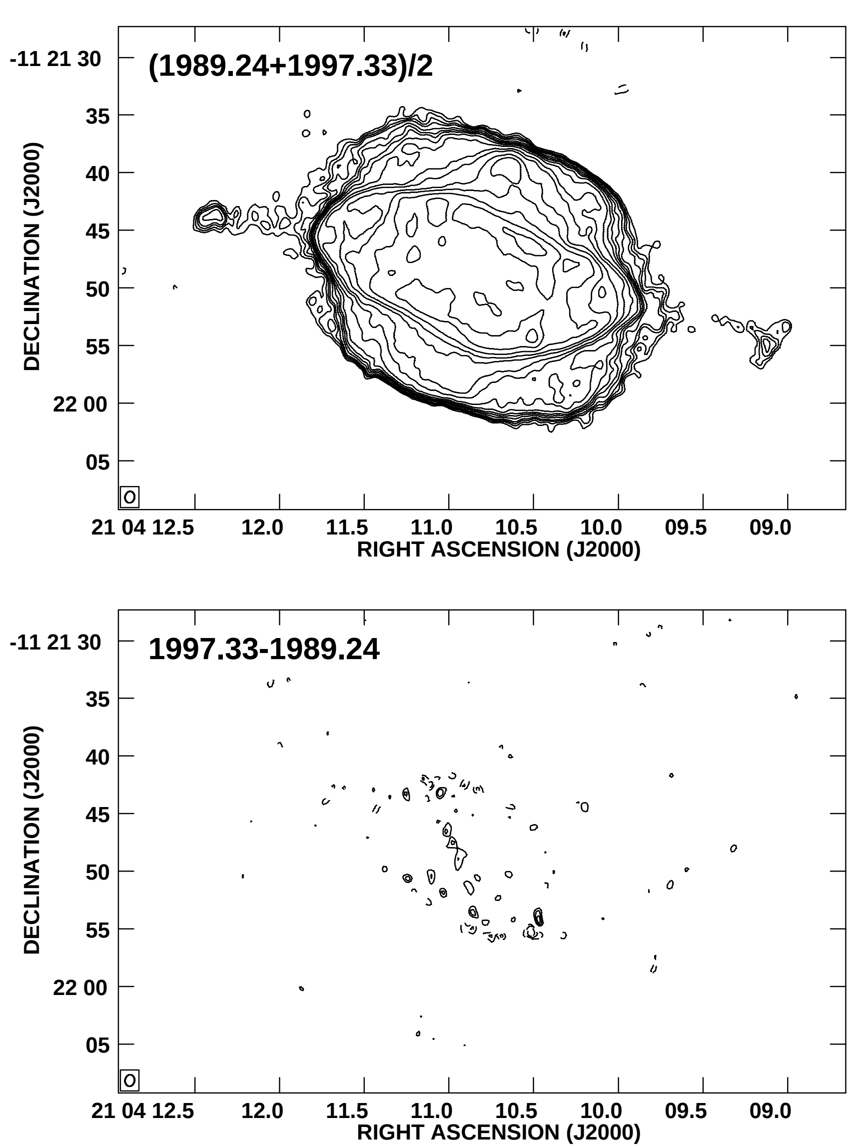

Fig. 2. 3.6 cm contour images of NGC 7009 for all the data (top) and the difference 1997.33−1989.24 (bottom). The contours are -4, -3, 3, 4, 5, 6, 8, 10, 12, 15, 20, 30, 40, 60, 80, 120, 200, and 300 times 12 μJy beam^{-1} for the top image and -5, -4, -3, 3, 4, and 5 times 20 μJy beam^{-1} for the bottom image. The synthesized beam ($1\farcs00 \times 0\farcs81$ with a position angle of $-10°$) is shown in the bottom left corner of the images.

1997.33−1989.24 (obtained by subtracting the clean components of the 1997.33 image from the (u,v) data of 1989.24). These images were made with the ROBUST weighting parameter of AIPS set to 0 and no tapering. Although there is evidence of residual emission in the brightest parts of the nebula, we failed to detect a clear expansion signature (see bottom of Figure 2). An upper limit to the expansion can be obtained following Gómez, Rodríguez, & Moran (1993) and Guzmán et al. (2006). We assume that the nebula expands in a self-similar way by a factor of $(1 + \epsilon)$, where $\epsilon \ll 1$. From the non-detection of an expansion pattern, we estimate that $\epsilon \leq 0.007$. A larger value of ϵ would produce residuals in the difference image larger than those observed. A lower limit to the distance, D, of the planetary nebula is then given by

$$\left[\frac{D}{pc}\right] \geq 0.211 \left[\frac{\theta}{''}\right]^{-1} \left[\frac{v_{exp}}{km\ s^{-1}}\right] \left[\frac{\Delta t}{yr}\right] \epsilon^{-1},$$

where θ is the average angular radius of maximum emission, v_{exp} is the expansion velocity of the nebula at the radius of maximum emission, and Δt is the time interval between observations. NGC 7009 is an elliptical nebula and we approximate the angular radius of maximum emission as the geometric mean of the major and minor semiaxes. From Figure 2, we estimate $\theta \simeq 12''$. From Weedman (1968) we find that at this angular distance $v_{exp} \simeq 35\ km\ s^{-1}$. We then obtain $D \geq 700$ pc, a lower limit consistent with the weighted average of 14 available values (Acker et al. 1992; Fernández et al. 2004), 860±340 pc. It should be noted that the expansion parallax distance technique can be affected by the motion of the shock or the ionization fronts (Mellema 2004) and that our lower limit could be underestimated by 20-30%.

4. CONCLUSIONS

We analyzed archive VLA observations of the planetary nebula NGC 7009 for two epochs separated by 8.09 years. Our main conclusions are:

1. We measured the proper motions of the ansae, obtaining values of 23±6 and 34±10 mas yr^{-1} for the eastern and western ansae, respectively. This is the first time that proper motions of ansae in planetary nebulae are determined with radio observations.

2. There is marginal evidence suggesting that the flux densities of the jets that connect the ansae with the main body of the nebula decreased by about 30% over the 8.09 years spanned by the observations.

3. We failed to detect the expansion of the main body of the planetary nebula, obtaining a lower limit of ∼700 pc for its distance.

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