PROPER MOTION AND KINEMATICS OF THE ANSAE IN NGC 7009

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ABSTRACT

We have measured the proper motion (PM) and kinematics of the ansae in NGC 7009 using high-dispersion echelle spectra and archive narrowband Hubble Space Telescope images. Assuming that the ansae are moving at equal and opposite velocities from the central star, we obtain a system radial velocity of $-53 \pm 2$ km s$^{-1}$, the eastern ansa approaching and the western ansa receding at $v_r = 5.3 \pm 1$ km s$^{-1}$ with respect to this value. The PM of the eastern ansa is $28 \pm 8$ mas yr$^{-1}$, which, with our weighted distance to NGC 7009 of $0.86 \pm 0.34$ kpc, gives $V_{exp} = 114 \pm 32$ km s$^{-1}$. The electron temperature and density in both ansae were determined to be $T_e \sim 9000 \pm 400$ K and $n_e \sim 2300 \pm 400$ cm$^{-3}$. The dynamic age of the ansae is $\sim 910 \pm 260$ yr, and the implied PM of the central star is $\mu_{CS} = 1 \pm 0.5$ mas yr$^{-1}$. This is in qualitative but not quantitative agreement with previous work.

Subject headings: astrometry — ISM: kinematics and dynamics — planetary nebulae: individual (NGC 7009)

1. INTRODUCTION

Most low- and intermediate-mass stars become white dwarfs after a brief phase as planetary nebulae (PNs) caused by heavy mass loss on the asymptotic giant branch (AGB; Iben & Renzini 1983). Symmetrical and mildly asymmetrical PNs are explained by versions of the interacting wind model (Kwok, Purton, & Fitzgerald 1978), but the mechanisms causing the strong asymmetries observed in the majority of PNs are still unexplained. That both binaries and magnetic fields probably play a role is now generally accepted. For an overview of formation mechanisms, models, and asymmetries see Kastner, Soker, & Rappaport (2000).

The wealth of different PN shapes is shown in Balick (1987) and Schwarz, Corradi, & Melnick (1992), and features have been described in detail by many authors: e.g., point symmetry (Schwarz 1993), bipolarity (e.g., Corradi & Schwarz 1995), multipolarity (Sahai & Trauger 1998), BRETS (López 1997), and fast, low ionization emission regions (FLIERS; Balick et al. 1994) are all used to indicate the various observed morphologies.

NGC 7009 has long been known to have a complex morphology. Aller (1941) described the outer features as ansae (handles in Latin), and Reay & Atherton (1985) and Balick, Preston, & Icke (1987) show that these ansae are expanding near the plane of the sky at high velocities ($\sim 10^2$ km s$^{-1}$) relative to the nucleus.

Liller (1965) used photographic plate material to analyze the expansion of NGC 7009, including the ansae, for which he obtained $16 \pm 3$ mas yr$^{-1}$.

In this paper we present the kinematics and proper motion (PM) of the ansae using observational material from the Hubble Space Telescope (HST) and Cerro Tololo Inter-American Observatory$^2$ (CTIO) 4 m echelle spectrograph and show that the previous results are qualitatively but not quantitatively correct.

2. OBSERVATIONS AND DATA REDUCTION

We extracted two sets of archive HST images with the "on-the-fly" option. The WFPC2 sets were taken on 1996 April 28 (Balick et al. 1998) and 2001 May 11 (Palen et al. 2002) in an H$\alpha$/[N ii] filter.

The 2001 images are shifted 20" east from the 1996 images. As the latter covered the entire nebula, in the former the west ansa disappears from the field of view. The two images shown in Figure 1 are an average (for cosmic-ray rejection) of each set.

We took CTIO 4 m echelle spectra on 2002 July 29 with a spectral range between 410 and 720 nm and a slit of 1.2 $\times$ 6.7". The mean seeing was 1.4". Flux calibration to 10% was done with 58 Aql (HR 7596; Hamuy et al. 1992). The spectra were reduced in the usual way, using IRAF, and resulted in an rms wavelength error of 0.00037 nm, with residuals of $\leq 0.00075$ nm. Velocity resolution was 3.7 km s$^{-1}$ pixel$^{-1}$ or 10.2 km s$^{-1}$ for our slit width at 650 nm.

3. RESULTS

3.1. Distance and Proper Motion

The distance to NGC 7009 is uncertain, but we computed the weighted average of the 14 available (Acker et al. 1992) values to be $d = 0.86 \pm 0.34$ kpc.

The measurement of the position of the central star (CS) was made with the IRAF task imcentroid. For the measurement of the position of the ansa, we confined it inside a box of 5 arcsec square, computed the centroid using the imcentroid

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Fig. 1.—Average of the set of HST images taken in 1996 (left) and 2001 (right). North is down and to the left and east is down and to the right, and each image is 120" by 120". There is a shift of 20" in the east-west direction between them, which makes the western ansa disappear from the 2001 images. The two background stars marked with circles were used together with the CS as reference points for PM calculation.

Fig. 2.—Difference between the combined 2001 and 1996 images, normalized by the average flux of the three reference points chosen: CS and the two field stars. The panels show differences with respect to CS (top right), field star 1 (bottom left), field star 2 (bottom right), and the adopted least-squares fit (top left). Each image is 43" by 24".
task, and measured their displacements with respect to the CS and two field stars (shown in Fig. 1) in two ways: the displacements were measured in all the images, and an average displacement was obtained for each epoch; next, the displacements were computed from the averages of the images for each epoch. The centroid positions given in pixel values were converted to right ascension and declination using the metric task, within the STSDAS package. This task corrects for the known geometric distortions between different CCDs. The differences in the results are an order of magnitude smaller than the errors derived from centroid calculation and measurements between different chips. The various differential images are shown in Figure 2.

The displacements between the CS and the ansae are 24°85 ± 0°06 and 25°01 ± 0°05 (east; 1996 and 2001) and 26°77 ± 0°06 (west; 1996 only). The detailed measurements with their respective errors are shown in Table 1. Note that the adjusted standard deviations for 1996 and 2001 results are 0.01 and 9.6 × 10⁻³, respectively.

Even though this is a good determination for the angular displacement of the eastern ansa, it is also possible that the CS is moving. Therefore, it is important to have other reference points. The circles in Figure 1 indicate the position of the two field stars present on the images that could be measured. The angular displacements of the ansae in each frame are listed in Table 2. These measurements are all equal within the errors.

The value we adopted for the displacement was the least-squares shift of all measurements: 0°14 ± 0°04. The time between images is 158,883,733 s or ≈5 yr computed from the start time of the exposures, yielding a PM of the eastern ansa of 0°028 ± 0°008 yr⁻¹, and the tangential velocity is \( V_{\text{exp}} = 114 \pm 32 \text{ km s}^{-1} \) for \( d = 860 \text{ pc} \).

We note that the rim of the inner nebulae also shows differential motion in more or less the same direction as that of the ansae between the 1996 and 2001 images. We do not attempt to compute the PM as this rim is likely to be a moving ionization front with a very different velocity than that of the bulk motion of the gas (weak R-front; G. Mellema 2003, private communication). This is unlikely to be the case for the ansae.

### 3.2. Radial Velocities

We computed the mean observed radial velocities of the ansae from 10 emission lines fitted with a Voigt profile to be

\[ -58.5 \pm 1.9 \text{ (east)} \quad \text{and} \quad -47.9 \pm 1.6 \text{ km s}^{-1} \text{ (west)}. \]

Using only the [N \text{ ii}] and H\( \alpha \) lines (the HST images were taken in these lines), we obtain \(-58.3 \pm 1.1\) (east) and \(-47.7 \pm 0.8 \text{ km s}^{-1}\) (west). The radial velocity differences between the eastern and western ansae are \( \Delta_{\text{H}\alpha[N \text{ ii}]} = 10.6 \pm 1.4 \text{ km s}^{-1} \) and \( \Delta_{\text{H}\alpha} = 10.6 \pm 2.5 \text{ km s}^{-1} \). We also separately computed the mean values of the velocity for the forbidden and permitted lines. They were also the same to within the errors. The observed radial velocities for each detected emission line are listed in Table 3, and we also give the heliocentric and LSR velocities and their average values.

### 3.3. Electron Temperatures and Densities

The line intensities of [N \text{ ii}] and [S \text{ ii}] were measured by fitting Voigt profiles to derive the electron temperature and density in both ansae. The line intensities were corrected for reddening, assuming a recombination model B with \( T = 10^4 \text{ K} \) and \( n_e = 10^4 \text{ cm}^{-3} \) and an extinction coefficient \( c_\beta = 0.26 \) (Lame & Pogge 1996). The line intensity ratios, together with electron temperatures and densities derived from them, are listed in Table 4. The latter results were obtained using the formulae from McCall (1984). The errors in the ratios were calculated from the signal-to-noise ratio in each line.

### 4. DISCUSSION

Our radial velocities agree with those of Reay & Atherton (1985), who determined \( \pm 6.2 \text{ km s}^{-1} \) using the [O \text{ i}] \( \lambda 6300 \) line. We get \( \pm 6.1 \text{ km s}^{-1} \) using the same line.

Liller (1965) computes 16 mas yr⁻¹ for the angular expansion of the ansae; we obtain 28 ± 8 mas yr⁻¹. This difference is probably due to the low resolution of the photographic plates, as Liller comments: “... the plate scale is such that photographic grain often competes with seeing as the limiting factor in image definition.”

If the ansae were ejected at the same time from the CS and with equal and opposite velocities, we can determine the PM of the CS (relative to the point of ejection, assumed fixed in space) and the age of the ansae from our data. We find that the CS has moved 0°06 ± 0°04 since the ejection of the ansae, 910 ± 260 years ago. This gives a PM for the CS of \( \pm 0.5 \text{ mas yr}^{-1} \) or 5 mas between our two epochs, negligible compared to the motion of the ansae.

In the gas of NGC 7009, the sound speed is about 10 km s⁻¹, implying that the ansae move at supersonic speeds.

The \( T_e \) and \( n_e \) we obtain are similar to those found by others: Balick et al. (1994) quote a value of \( T_e = 8100 \text{ K} \) and \( n_e = 1000 \text{ cm}^{-3} \); Bohigas, López, & Aguilar (1994) quote a value of \( T_e = 8900 \text{ K} \) and \( n_e = 2300 \text{ cm}^{-3} \), both for the western ansa.

### TABLE 1

| Data Set | UT of Exposure | Relative Separation (arcsec) |
|----------|----------------|-------------------------------|
| 1996 Images |               |                               |
| u32e0308t | 20:48:16       | 24.85 ± 0.04                  |
| u32e0309t | 20:56:16       | 24.84 ± 0.04                  |
| u32e030at | 21:04:16       | 24.86 ± 0.04                  |
| Average   | 20:56:16       | 24.85 ± 0.06                  |
| 2001 Images |               |                               |
| u5hc6002r | 19:05:14       | 25.01 ± 0.04                  |
| u5hc6003r | 19:13:14       | 25.00 ± 0.04                  |
| u5hc6004r | 19:24:14       | 25.00 ± 0.04                  |
| u5hc6005r | 19:31:14       | 25.02 ± 0.04                  |
| Average   | 19:18:29       | 25.01 ± 0.05                  |

### TABLE 2

| Reference Point | Angular Displacement (arcsec) |
|-----------------|-------------------------------|
| Central star    | 0.17 ± 0.10                   |
| Upper star      | 0.16 ± 0.10                   |
| Lower star      | 0.10 ± 0.02                   |
| Average shift   | 0.13 ± 0.04                   |
| Least-squares shift | 0.14 ± 0.04               |
TABLE 3

Radial Velocities in km s^{-1} for Each Emission Line Identified

| LINE                | EASTERN ANSA | WESTERN ANSA |
|---------------------|--------------|--------------|
|                     | $V_{\text{obs}}$ | $V_{\text{hel}}$ | $V_{\text{LSR}}$ | $V_{\text{obs}}$ | $V_{\text{hel}}$ | $V_{\text{LSR}}$ |
| [N ii] $\lambda$5755 | -59.17       | -55.43       | -45.42          | -47.70          | -43.71          | -33.73          |
| [O i] $\lambda$6364 | -61.19       | -57.45       | -47.44          | -49.05          | -45.10          | -35.08          |
| [N ii] $\lambda$6583 | -59.33       | -55.59       | -45.58          | -48.34          | -44.39          | -34.37          |
| [S ii] $\lambda$6716 | -57.68       | -53.94       | -43.93          | -45.34          | -41.39          | -31.37          |
| [S ii] $\lambda$6731 | -56.83       | -53.09       | -43.08          | -45.46          | -41.51          | -31.49          |
| [A iii] $\lambda$7134 | -57.60       | -53.86       | -43.85          | -48.97          | -45.02          | -35.00          |
| Averages            | $-58.5 \pm 1.9$ | $-54.76 \pm 1.9$ | $-44.75 \pm 1.9$ | $-47.9 \pm 1.6$ | $-43.92 \pm 1.6$ | $-33.91 \pm 1.6$ |

TABLE 4

Derived Line Properties

| Ratio  | Observed | Corrected | Result |
|--------|----------|-----------|--------|
| [N ii] $\lambda$(6548+6583)/$\lambda$5755 | 111 $\pm$ 15 | 103 $\pm$ 15 | $T_e = 9000 \pm 400$ K |
| [S ii] $\lambda$6716/$\lambda$6730 | 0.64 $\pm$ 0.04 | 0.64 $\pm$ 0.04 | $n_e = 2600 \pm 500$ cm$^{-3}$ |
| [N ii] $\lambda$(6548+6583)/$\lambda$5755 | 120 $\pm$ 12 | 110 $\pm$ 12 | $T_e = 8900 \pm 400$ K |
| [S ii] $\lambda$6716/$\lambda$6730 | 0.64 $\pm$ 0.04 | 0.64 $\pm$ 0.04 | $n_e = 1900 \pm 300$ cm$^{-3}$ |

Note.—Line ratios (corrected for reddening) and the results obtained from them. The $T_e$ and $n_e$ are the electron temperature and density, respectively.

5. CONCLUSIONS

We conclude that the ansae in NGC 7009, which is at a distance of 860 $\pm$ 340 pc, move outward at the super-sonic velocity of $\pm114$ km s$^{-1}$ near the plane of the sky (2.7$^\circ \pm 1^\circ$), have a dynamic age of 910 $\pm 260$ yr, and have a PM of 28 $\pm$ 8 mas yr$^{-1}$ and that the CS likely moves at 1 $\pm$ 0.5 mas yr$^{-1}$.

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