Kinematics and Proper Motion of the Ansae in NGC 7009

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Abstract. We have measured the expansion velocities and proper motion of the ansae in NGC 7009 using high dispersion echelle spectra and archive narrow band HST images. Assuming that the ansae are moving at equal and opposite velocities from the central star we obtain an average system radial velocity of $-54 \pm 2$ km/s, the eastern ansa approaching and the western ansa receding at $v_r = 5.5 \pm 1$ km/s relative to this value. Only the proper motion of the eastern ansa could be measured, leading to $2.8 \pm 0.8$ arcsec/century, or $v_t = (130 \pm 40)d$ km/s, where $d$ is the distance to the nebula in kpc. Additionally, the electron temperature and density for each ansa was measured using line intensity ratios. The results are $T_e \sim 9000$ K and $n_e \sim 2000$ cm$^{-3}$ for both ansae within the errors.

1. Introduction

NGC 7009 is a good example of a planetary nebula with FLIERs\textsuperscript{1} The nebula shows two pairs of condensations along the major symmetry axis. The outer pair has been called ansae (=handles, Aller 1941). The condensations show strong emission in low ionization lines and weak emission in high excitation ones. Kinematic studies by Reay & Atherton (1985) and Balick, Preston & Icke (1987) have shown that the ansae are moving very near the plane of the sky at velocities $\sim 10^2$ km/s with respect to the central star. Here we aim to better determine the kinematics of the ansae in NGC 7009, measuring radial velocities from high dispersion echelle spectra and proper motions from archive HST images. As a by-product, the electron temperatures and densities are measured from line intensity ratios.

2. Observations and Data Reduction

The data consist of a set of echelle spectra and two sets of public HST images taken in 1996 and 2001. The spectra were obtained during the night of July 29, 2002, with the CTIO 4m echelle spectrograph, which was optimized to cover the spectral range 410 nm - 720 nm. The dimensions of the slit were $1.2'' \times 6.6''$, and the mean seeing was $1.4''$. For wavelength calibration a Th-Ar lamp was used. The flux calibration was done with observations of the star 58 Aql (HR 7596).

\textsuperscript{1}Fast, Low Ionization Emission Regions (Balick et al. 1994).
The HST images were obtained from the HST archive. The first set was taken on April 28, 1996 using the WFPC2 with a [NII] 6583 narrow band filter (Balick et al. 1998). The second set was taken in May 11, 2001 also with the WFPC2 and the same filter (Palen et al. 2002).

The echelle spectra were reduced and calibrated using standard IRAF routines. The dispersion is 0.008 nm pixel$^{-1}$, or 3.7 km.s$^{-1}$ pixel$^{-1}$ at 650 nm. The HST images were retrieved from the archive using the On The Fly Calibration option. The calibrated images of each set were median combined to eliminate cosmic rays.

3. Results

3.1. Radial Velocities

The lines that could be identified in the spectra are listed in Table 1. The central wavelength of each line was measured by fitting a Voigt profile. Almost every line could be identified in two echelle orders, thus the value quoted is the average of the two values in each order. The rest wavelengths of forbidden lines were taken from Bowen (1960), while the values for the permitted lines were taken from Moore (1945). Assuming symmetric expansion with respect to the central star, the system velocity is the average of the ansae’s velocities, namely $-54 \pm 2$ km.s$^{-1}$, whereas the radial expansion velocity with respect to the central star is $v_r = \pm 5.5$ km/s.

Table 1. Radial velocities for identified emission lines.

| Line   | $\lambda$(nm) | Eastern Ansa (km.s$^{-1}$) | Western Ansa (km.s$^{-1}$) |
|--------|----------------|-----------------------------|-----------------------------|
| [NII]  | 575.5          | -59.17                      | -47.70                      |
| HeI    | 587.6          | -56.42                      | -48.51                      |
| [OI]   | 636.4          | -62.23                      | -50.44                      |
| [OI]   | 630.0          | -61.19                      | -49.05                      |
| [NII]  | 654.8          | -59.33                      | -48.34                      |
| H$\alpha$ | 656.3      | -56.69                      | -48.46                      |
| [NII]  | 658.3          | -57.87                      | -46.48                      |
| [SII]  | 671.6          | -57.68                      | -45.34                      |
| [SII]  | 673.1          | -56.83                      | -45.46                      |
| [AIII] | 713.4          | -57.60                      | -48.97                      |
| Average|                | -58.55 ± 1.9                | -47.82± 1.6                 |

3.2. Proper Motions

The HST images have a shift between 1996 and 2001 of 20$''$ in the east-west direction, which makes the western ansa disappear from the 2001 images. Therefore, only the proper motion of the eastern ansa could be measured. The position of the ansa was determined by confining it in a box of width 5$''$ and calculating a
centroid. Three stars were selected as reference points for angular displacement measurements, namely the central star and two background stars. The results for the angular displacements are listed in Table 2. A fourth reference point was determined by looking for a point that minimized the square of the distances between the three reference stars, weighted by the error in each position. The angular displacement relative to this point is listed as Least squares. An average between the displacements with respect to each star is also listed. The proper motion is obtained by dividing the corresponding angular displacement by the time difference between both set of images, $t = 5.038170123$ yrs. All displacements occur in the same direction, outward from the central star. Using the least squares value for the proper motion, one gets a tangential velocity of $v_t = (130 \pm 32)$ km/s, where $d$ is the distance to the nebula in kpc. Computing a weighted average of 14 values from the literature (Acke et al. 1992) gave $0.86$ kpc or $v_t = (112 \pm 32)$ km/s.

Table 2. Angular displacement and proper motion of the eastern ansa, using different reference points

| Ref. point          | Ang. displacement (″) | Prop. motion (″/yr) |
|---------------------|-----------------------|---------------------|
| Central star        | 0.17 ± 0.10           | 0.03 ± 0.02         |
| Background star 1   | 0.16 ± 0.10           | 0.03 ± 0.02         |
| Background star 2   | 0.10 ± 0.02           | 0.020 ± 0.004       |
| Average             | 0.13 ± 0.04           | 0.026 ± 0.008       |
| Least squares       | 0.14 ± 0.04           | 0.028 ± 0.008       |

3.3. Line intensities, Electron Temperatures and Densities

The line intensities of the [NII] and [SII] lines were measured in order to derive the electron temperature and density in both ansae. Voigt profiles were fitted to each line using the IRAF task splot. The interstellar extinction correction was made assuming a recombination model B with $T = 10^4$ K and $n_e = 10^4$ 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 3. The latter results were obtained using the formulae from McCall (1984). The errors in the ratios were calculated from the S/N in each line.

4. Comparison with previous results

The results for the radial velocities are in good agreement with previous determinations. If we take only the results for the [OI] 6300 line, we get a result equal within the errors to that of Reay & Atherton (1984), who measured $v_r = \pm 6.2 \text{ km.s}^{-1}$ with respect to the central star using a Fabry-Perot interferometer. The only available measurement of proper motion is that of Liller (1965), who obtained 1.6″/century using photographic plates, which is almost a factor.
Table 3. Line intensity ratios and results obtained from them. $T_e$ and $n_e$ are the electron temperature and density, respectively.

| Eastern Ansa | Ratio | Observed | Corrected | Result               |
|--------------|-------|----------|-----------|----------------------|
|              | [NII](6548+6583)/5755 | 111 ± 15 | 103 ± 15 | $T_e = 9000 \pm 400$ K |
|              | [SII] 6716/6730       | 0.67 ± 0.04 | 0.67 ± 0.04 | $n_e = 2600 \pm 500$ cm$^{-3}$ |

| Western Ansa | Ratio | Observed | Corrected | Result               |
|--------------|-------|----------|-----------|----------------------|
|              | [NII](6548+6583)/5755 | 120 ± 12 | 110 ± 12 | $T_e = 8900 \pm 400$ K |
|              | [SII] 6716/6730       | 0.64 ± 0.04 | 0.64 ± 0.04 | $n_e = 1900 \pm 300$ cm$^{-3}$ |

of two smaller than the result obtained here. The electron temperatures are equal within the errors to those reported by Balick et al. (1994) and Bohigas et al. (1994), while the electron density is within a factor of two from the results of the same authors.

We conclude that the ansae are moving with total velocity $V = \sqrt{v_r^2 + v_l^2} \simeq v_t = (130 \pm 32)$ d km s$^{-1}$, at an angle $i = \arctan v_r/V = 2 \pm 1.6^\circ$ with respect to the plane of the sky.

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