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Kinematics of the dusty circumnuclear ring in the barred Seyfert galaxy NGC 4151

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Abstract. We present optical and neutral hydrogen observations of the central ∼2 kpc in NGC 4151, and examine the distribution and kinematics of neutral hydrogen in the vicinity of the optical circumnuclear dust 'ellipse'. The V-I colour map, derived from broad-band images obtained using TAURUS II in imaging mode, shows clearly the red arcs which delineate the $11'' \times 18''$ dust ellipse detected previously.

The new, high resolution ($\sim 6'' \times 5''$) HI image reveals two arcs of HI emission, which lie on the inner edges of the main bar and coincide closely with the optical arcs. The peak column densities in the HI arcs, of $\sim 1.8 \times 10^{21}$ cm^{-2} and $\sim 0.7 \times 10^{21}$ cm^{-2}, imply optical extinctions of A_v ∼1.16 and 0.45 in the northern and southern arcs respectively, which are comparable with those derived from broad-band imaging.

The kinematics of the HI, measured along the two arcs, are presented. The first order circular fit to the velocity curve yields a value of 22±5° for the PA of the line of nodes, which agrees well with that of the galaxy. If the HI is associated with the optical ellipse, the PA of the spatial major axis of the ellipse (∼48°) is offset from its kinematic major axis (∼22°), providing evidence of non-circular orbits and suggesting that ring is not an inclined circular disk, but is intrinsically elliptical and lies in the plane of the galaxy.

Key words: galaxies: active; Seyfert; kinematics and dynamics; individual: NGC 4151

1. Introduction

Galactic bars provide a mechanism to remove angular momentum from the gas in the bar, allowing the gas to flow closer to the nucleus (Roberts et al. 1979; Schwartz 1985). This mechanism is often discussed as a means of channelling fuel towards the central engine of Active Galactic Nuclei (AGN) (Shlosman, Frank & Begelman 1989). However, statistical studies of the link between bars and nuclear activity remain controversial (Arsenault 1989; Ho, Filippenko & Sargent 1997; Heckman 1980; Simkin, Su & Schwartz 1980; Moles et al. 1995). Seyfert galaxies are the nearest examples of AGN and so we can study individual structures in nearby Seyferts in much greater detail than more distant AGN.

NGC 4151 is a nearby, well-studied Seyfert galaxy (Seyfert 1943) with well defined spiral arms and an oval stellar bar. The nucleus exhibits variable broad lines (e.g. Penston et al. 1981) consistent with a Seyfert 1 classification. Unlike many Seyferts, the Narrow Line Region (NLR) is well resolved even with ground based observations (Ulrich 1973) and has recently been studied in detail by the Hubble Space Telescope (Evans et al. 1993, Boksenberg et al. 1995). The radio continuum structure associated with the nucleus has been studied in detail by Pedlar et al. (1993) showing a radio jet approximately 9 arcsecs (≃600 pc) in extent in PA 77^0. NGC 4151 also exhibits a highly elongated Extended Narrow Line Region (ENLR - Unger et al. 1987) which extends up to 20 arcsecs (1.4 kpc) and is consistent with ambient galactic gas being photoionised by a cone of nuclear UV radiation (Penston et al. 1990). Robinson et al. (1994) performed detailed long-slit spectroscopy of the components in the ENLR, confirming that AGN ionisation hypothesis. All the above phenomena appear to be embedded in a $3' \times 2'$ oval stellar bar, which also contains large quantities of neutral hydrogen (HI) (Pedlar et al. 1992). A high angular resolution study of the distribution and kinematics of HI in the bar, (Mundell & Shone 1997), revealed the presence of streaming shocks along the leading edges of the bar, with kinematics consistent with the presence of x_1 and x_2 orbits and inflow towards smaller radii.

In addition to neutral hydrogen in the main galactic bar, there is evidence of neutral gas and dust closer to the nucleus. On the smallest scales, MERLIN observations of HI absorption against the radio continuum structure (Mundell et al. 1995) suggest the presence of high column densities of neutral gas within $0.1''$ of the nucleus, possibly in the form of an obscuring torus (as advocated in Unification Schemes). On scales of 1–2″, optical CCD imaging revealed evidence of obscuration in the form of a reddened band of enhanced extinction (or low ionisation) cross-

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ing the central region, and aligned approximately perpendicular to the ENLR and radio jet. (PA $\sim$135° – Perez et al. 1989; PA $\sim$150° – Terlevich et al. 1991). On slightly larger scales, Vila-Vilaró et al. (1995) have detected two red arc-like features, possibly produced by dust extinction of the background stellar continuum, which delineate a circumnuclear elliptical ring with semi-major axis $\sim$18″.

In this paper we present optical observations of the circumnuclear ellipse with improved sensitivity and seeing conditions obtained with TAURUS II on the 4.2 metre William Herschel Telescope (WHT). As part of the detailed study of the gas dynamics in the bar of NGC 4151 we also compare the optical results with the high angular resolution VLA[1] 'B' configuration HI observations (see also Mundell & Shone 1997 and Mundell et al. in preparation). We concentrate particularly on HI in the vicinity of the optical ellipse in order to investigate any relationship between the structure and kinematics of the HI and this circumnuclear 'ring'.

Assuming a distance of 13.3 Mpc to NGC 4151 (H_o=75 km s^{-1} Mpc^{-1}), one arcsecond corresponds to 65pc in the galaxy (see Mundell *et al.* in preparation) for further discussion.

2. Observations and reduction

2.1. Optical observations

The images were taken on the night of the 6th February 1991. The seeing was stable and just under one arcsecond. The instrument used was TAURUS II, a Fabry-Perot Interferometer in f/4 imaging mode, used at the Cassegrain focus of the 4.2 metre William Herschel Telescope at the Observatorio del Roque de los Muchachos, La Palma. The detector was a cooled EEV CCD, with 799×1179, 22 μm square pixels. The projected pixel scale was 0.33 arcsecs. Harris V and I broad band images were taken of NGC 4151.

The individual frames were bias subtracted, flat-fielded using twilight sky flats and sky background subtracted. Table 1 shows the properties and total exposure times per filter used in the imaging of NGC 4151. When TAURUS is used with the f/4 camera, a bright ghost image of the telescope pupil is visible. This is the result of a reflection between the back of the last element in the camera and the front of the CCD cryostat, imaging the telescope pupil onto the detector with the intensity reduced to a few tenths of one per cent. The ghost image is easily recognisable, since the shadow of the secondary mirror and its support structure are clearly visible. The ghost image can be flat-fielded out by subtracting the ghost and then dividing by the ghost-free sky flat.

The data were reduced using standard techniques with the IRAF reduction package running on the ING SunOS cluster and with the STARLINK package, FIGARO.

A colour difference map was constructed by dividing the final (reduced and combined) V frame by the final (reduced and combined) I frame, after aligning the frames by using stars in the field. The colour map (Fig. 1b) shows the circum-nuclear ring, the ENLR, the NLR and the 'red bar'. The colour map is contaminated by line emission. The V filter includes the strong emission lines, [OIII]4959,5007Å from the nucleus and the ENLR. The I band filter is practically free of emission line contamination (see Robinson et al. 1994 for details).

[1] NRAO is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

Table 1. Properties and exposure times used in the broad-band imaging of NGC 4151.

Filter	Wavelength nm	Bandpass nm	Peak Tran %	Total Exp secs.
Harris V	545	105	88	40
Harris I	780	280	95	20

2.2. Neutral hydrogen observations

Full details of the observations and subsequent data processing techniques (including production of the moment maps) are presented in (Mundell et al. in preparation; see also Mundell 1995).

The data used in this paper are from a 63-channel, naturally weighted spectral line data cube which has an angular resolution of 6″× 5″, a velocity resolution of 10.3 km s^{-1} and a greater sensitivity (lowest detectable column density of 1.32 x 10^{20} cm^{-2}) than the higher resolution, uniformly weighted cube.

3. Results and discussion

3.1. Optical features

The V-band image of the main galactic bar, in NGC 4151, is shown in Fig. 1a. The central bright nucleus is prominent and the faint HII regions (Schulz 1985; Robinson et al. 1994) can be seen towards the SE and NW edges of the bar.

Fig. 1b shows the V-I colour difference map of the same region. Our V-I colour map is very similar to the B-I image in Vila-Vilaró et al. (1995). The outline of the bar is faintly discernable, but most prominent are the two dark (i.e., red) arcs which delineate the dust ellipse (with semi-major and minor axes dimensions of 18″ $\times$ 11″).

Knots associated with the ENLR, also present in [OIII] narrow-band images (Pérez et al. 1989; Pérez-Fournon & Wilson 1990), can be seen, in Fig. 1b, extending $\sim$20″ to the SW and 5″ to the NE of the nucleus. The nucleus and ENLR appear to be enclosed by the ellipse delineated by the red arcs. Emission line contamination may explain the incomplete appearance of the ellipse (Vila-Vilaró et al. 1995), with the main break occuring where the ring intersects the ENLR in both NE and SW directions, although the break in the ring to the NW is significantly larger than that in the SW. Close to the nucleus we also detect a small red feature which is likely to be that found by Perez et al. (1989) and Terlevich et al. (1991), termed the 'red bar', and interpreted as evidence for a nuclear torus. In contrast to these earlier studies however we detect this red feature towards the southern side of the ENLR only, rather than straddling both sides of the nucleus.

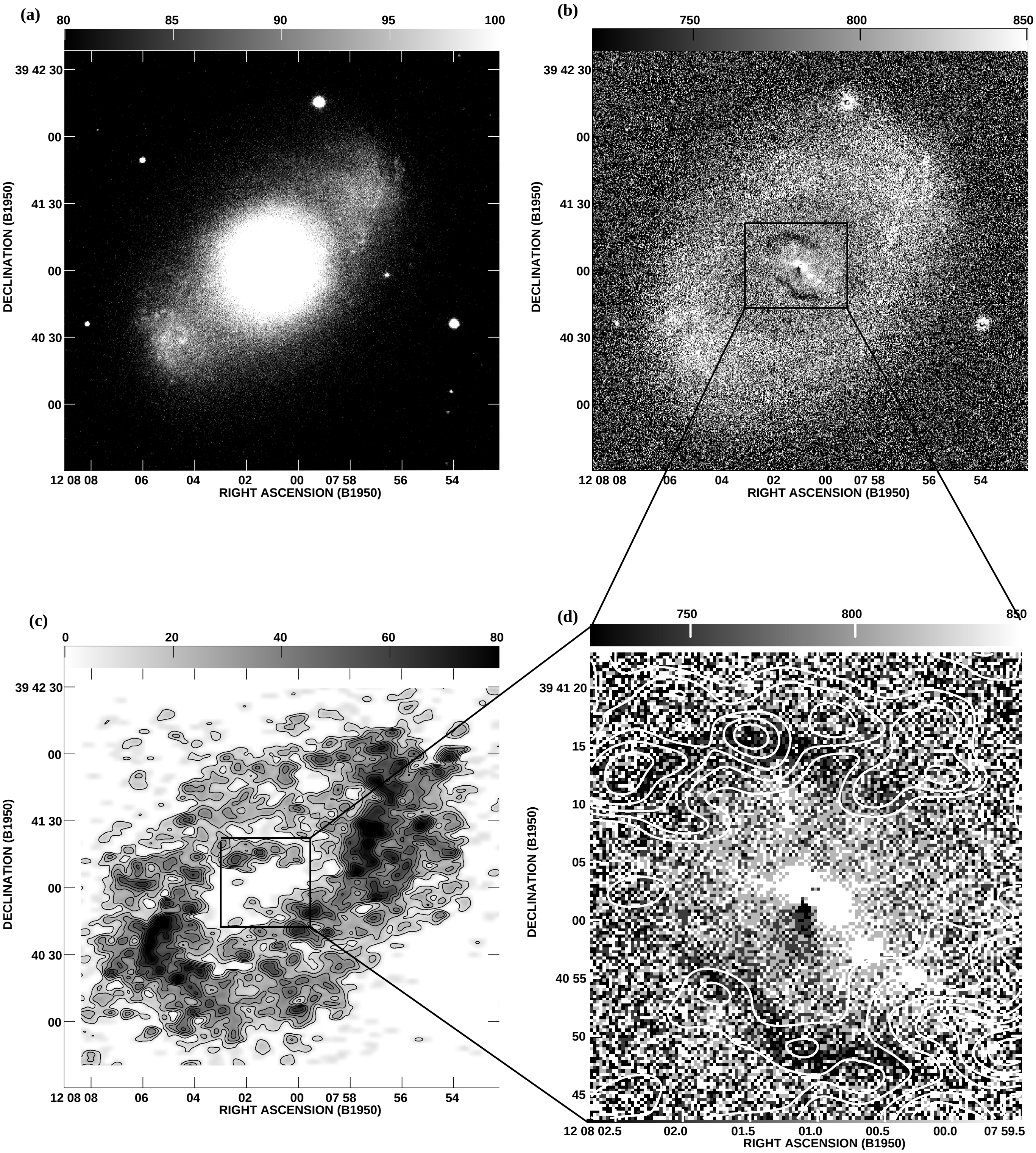

Fig. 1. a V band image of the main oval galactic bar of NGC 4151. North is up and East to the left. **b** V-I colour map of the same region as (**a**), showing the dark arcs delineating the circum-nuclear ellipse and bright knots of the ENLR. Dark is red and light is blue. The faint outline of the bar is still visible. **c** A contour-greyscale plot of the neutral hydrogen distribution (zeroth moment) of the bar in NGC 4151. Note the two ’fingers’ of HI emission winding around the nucleus and enclosed in the black box. **d** Overlay of the region highlighted in the black boxes in (**b**) and (**c**); the neutral hydrogen arcs (white contours) show a close coincidence with the red arcs (grey image) of the optical ellipse.

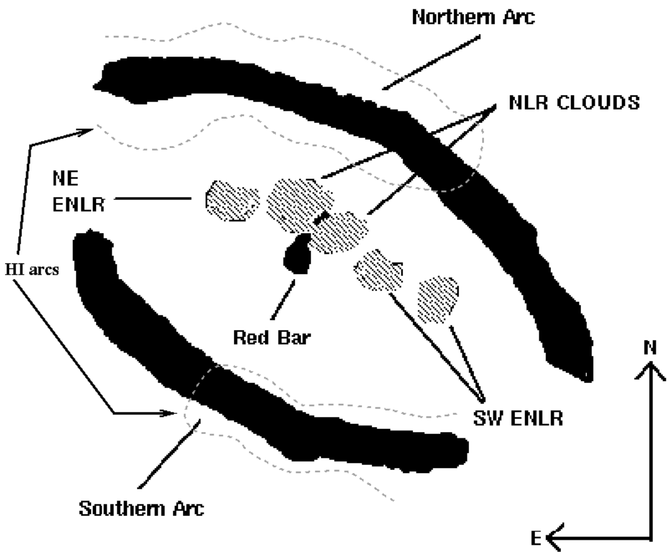

Fig. 2. A schematic representation of the components associated with the circumnuclear region in NGC 4151.

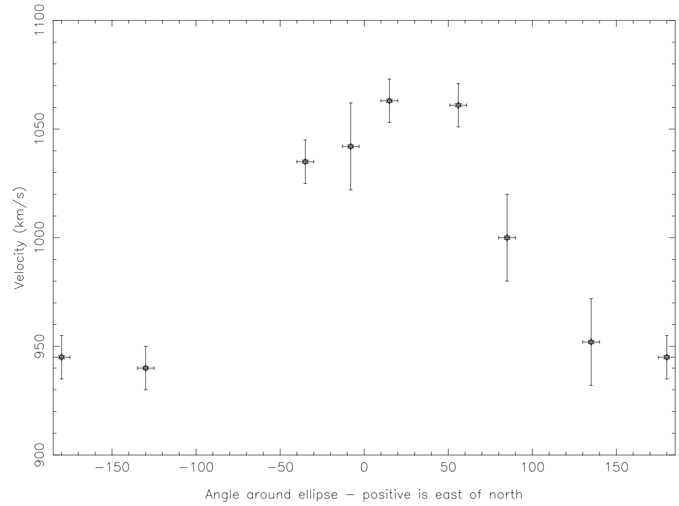

Fig. 3. Velocity of the HI peaks, along each arc, as a function of position angle around the ellipse. Zero corresponds to North and positive angles are measured East of North.

3.2. Association of optical and neutral hydrogen features

Fig. 1c shows a contour-greyscale plot of the neutral hydrogen distribution in the galactic bar of NGC 4151 (zeroth-moment map). A number of features can be seen in the HI distribution, e.g. the shocks along the leading edges of the bar (see Mundell & Shone 1997 for more discussion). However, two features of particular of interest are the two arc-like features which appear to wind clockwise around the nucleus, contained in the black box. The existence of the northern arc is well established, with a peak column density of 1.8×10^{21} cm^{-2}, and the HI peaks correspond well with the northern optical arc (as shown in Fig. 1d). The southern HI arc is considerably weaker (peak column density 0.7×10^{21} cm^{-2}), but again corresponds well with the southern optical arc.

Vila-Vilaró et al. (1995) argue that the most likely origin for the optical ellipse is dust extinction of the normal stellar continuum of the galactic bulge, rather than a population of red supergiants. The apparent reddening in the ellipse results from a local reduction in blue continuum rather than an enhancement in the red. In addition, Draper et al. (1992) find evidence of polarization associated with the ellipse, which they attribute to dichroic absorption of background starlight by magnetically aligned dust grains. If the HI column density and optical extinction follow the same relation as in the Galaxy (Staveley-Smith & Davies 1987), the above peak HI column densities imply optical extinctions of $A_v \sim$1.16 and 0.45 magnitudes in the northern and southern arcs respectively, assuming the optically thin approximation. If the HI is optically thick these values represent lower limits. These extinction values are slightly higher than those inferred from the optical measurements (0.10–0.35 magnitudes - Vila-Vilaró et al. 1995), but not significantly so.

3.3. Kinematics

The kinematics along the two HI arcs were determined, from the first-moment map, by measuring the velocity corresponding to each intensity peak along the arcs. The measured velocities of the peaks, plotted as a function of their position angle around the ellipse, are shown in Fig. 3. A sinusoid was fitted to the velocity curve, yielding a value of 22±5° for the PA of the line of nodes, which corresponds well with that of the galaxy. The change in radius vector length around the ellipse from ∼11″ to ∼18″ is not included in the fitting process. The sinusoidal fit, therefore, provides the first order approximation for circular orbits. However, if the HI is associated with the optical ellipse, this first order fit suggests that the ellipticity is not due to a circular disk inclined at $\sim 50°$ but provides evidence for the intrinsic elliptical nature of the ring which is what Vila-Vilaró et al. (1995) advocated for.

In order for the ring to be elliptical and lie in the plane of the galaxy, it is necessary for the PA of the line of nodes of the ellipse and the main galaxy to be aligned, as is the case. In addition, the PA of the major axis of the ellipse (∼48°) is offset from its kinematic major axis (∼22°), indicating the presence of non-circular orbits in the ring (a similar argument is presented in Mundell & Shone 1997, for non-circular orbits in the main galactic bar). Taken together, these two kinematic factors suggest that, if the HI and optical ring are associated, the ellipse is not an inclined circular ring but is intrinsically elliptical and lies in the plane of the galaxy.

3.4. Implications for fuelling the AGN

As discussed in Sect. 3.1, the optical ellipse surrounds and encloses the ENLR. The ENLR extends along PA ∼48°, along the major axis of the ellipse. The ENLR has also been shown to lie in the plane of the galaxy (Unger et al. 1987; Robinson et al. 1994; Asif et al. 1997) consistent with photoionisation of the ambient galactic gas by the nuclear UV radiation. We have shown that the ellipse is intrinsic and lies in the plane of the galaxy along with the ENLR. It seems unlikely that the alignment between the ENLR and the gas ring is a coincidence. The alignment does suggest that there is a dynamical link between possible bar-driven gas flows and the source of the UV collimation, which is presumed to be the torus. Gas rings or tori (assumed to be optically thick material surrounding the central continuum source, Antonucci & Miller 1985) are widely believed to produce radiation cones in Seyfert galaxies. Vila-Vilaró et al. (1995) have speculated that the bar-driven gas flows ultimately feed the torus via gravitational torques generated by the bar potential. The torus itself has to be tilted relative to the disk, however the mechanism for this is not very clear and is discussed in Vila-Vilaró et al. (1995). The fate of the gas between the ellipse and the torus could involve the possible role of hierarchial or nested bars (Shlosman, Frank & Begelman 1989). The unstable 'bars within bars' could drive inflow over periods of few dynamical timescales triggering gas flow along the stellar bar towards the inner kiloparsecs and the torus. High spatial and velocity resolution studies of HI emission (Mundell & Shone 1997) and of the optical HII regions (Asif et al. in preparation) in NGC 4151 may help determine whether non-axisymmetric gas flows in the stellar bar are responsible for inflow on scales of a few parsecs from the torus.

4. Conclusions

– The V-I colour map, obtained in good seeing conditions (0.9 arcsec), reveal 2 arc-like structures which delineate a circum-nuclear elliptical ring. The Extended Narrow Line Region (ENLR) can also be seen and is aligned with the major axis of the ellipse in PA $\sim$48°.
– New high angular resolution observations of neutral hydrogen in the galactic bar reveal two arc-like features which are coincident with the optical arcs.
– The equivalent optical extinction in the two arcs, derived from the measured HI column densities, of A_v $\sim$1.16 and 0.45 magnitudes, are in reasonable agreement with those derived from optical measurements.
– If the HI arcs are associated with the optical ellipse then position angle of the lines of nodes of the ellipse (22$\pm$5°, as derived from the HI velocity measurements) and of the main galaxy are aligned. This is a necessary condition for the ellipse to lie in the plane of the galaxy.
– The kinematic major axis of the ellipse ($\sim$22°) is offset from its spatial major axis ($\sim$48°), indicating the presence of non-circular motions in the gas.
– The HI kinematics imply that, if the HI and optical features are associated, the ellipse is not an inclined circular ring, but is truly elliptical and lies in the plane of the galaxy.

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