Kinematics of Diffuse Ionized Gas Halos

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Abstract.

Existing long-slit spectral data for edge-on spiral galaxies suggesting that their Diffuse Ionized Gas (DIG) halos rotate slower than their underlying disks are summarized. An attempt to characterize lagging halos using a model of purely ballistic disk-halo flow is discussed, with the result that the model fails badly for the lagging halo of NGC 891, but is somewhat more successful for NGC 5775. New two-dimensional kinematic data on the DIG halo of NGC 4302 are presented, along with a preliminary analysis of its rotation. Two-dimensional data on NGC 5775 and a preliminary analysis of its halo rotation is discussed by Heald et al. (this volume). The halo of NGC 4302 shows clear signs of lagging on its approaching side, but also strong indications of peculiar kinematics. The kinematics of the receding side are more complex.

1. Introduction

There is now much evidence for vertically extended layers of gas in spiral galaxies that are most likely produced by a star-formation-driven flow from the disk. Such layers are seen in diffuse ionized gas (DIG; e.g. Rand, Kulkarni, & Hester 1990; Dettmar 1990; Hoopes, Walterbos, & Rand 1999; Rossa & Dettmar 2003; Miller & Veilleux 2003), 21-cm emission (e.g. Swaters, Sancisi, & van der Hulst 1997; Matthews & Wood 2003; Boomsma, this volume), and X-ray emission (e.g. Bregman & Houck 1997; Wang et al. 2001), as well as radio continuum emission (e.g. Dahlem, Dettmar, & Hummel 1994) and dust absorption (e.g. Howk & Savage 1999; Alton et al. 2000; Howk & Savage 2000), among other tracers. Studies of the DIG layers strongly suggest that their brightness and vertical extent depend on the level of underlying star formation in the disk (e.g. Rand 1996; Hoopes et al. 1999; Rossa & Dettmar 2003). This suggests that while some gas may be infalling onto galaxy disks for the first time, the bulk of what we have observed so far in these tracers is more likely the result of a disk-halo flow.

While significant amounts of gas may typically participate in such flows, little is known about whether the flows cause significant radial redistribution of gas in the disk. This will depend on the shape of the galactic potential and the pressures and drag forces experienced by the halo gas. One way of attacking this question is to understand how gaseous halos rotate relative to disks. Information has begun to emerge on this question through observations of atomic (Swaters et al. 1997; Matthews & Wood 2003, Boomsma, Fraternali, Osterloo, Matthews, this volume) and ionized (Rand 1997, 2000; Tüllmann et al.

2001; Miller & Veilleux 2003) gas, and this has led to the first models of diskhalo cycling in which the flow is treated in purely hydrostatic (Benjamin 2000, Ciotti, this volume) and ballistic (Collins et al. 2002) limits. In this paper, we present the observational data on DIG halo rotation and summarize one attempt to explain the kinematics in term of a purely ballistic flow. An accompanying paper in this volume by Heald et al. describes two-dimensional kinematic data on NGC 5775.

2. Long-slit Spectroscopy of NGC 891 and NGC 5775

Evidence for lagging DIG halos in NGC 891 and NGC 5775 has been presented by Rand (1997, 2000) and Tüllmann et al. (2001). A long-slit spectrum oriented perpendicular to the plane of NGC 891, centered at 100" from the nucleus (5 kpc at the assumed distance of 9.5 Mpc) on the approaching side of the galaxy, shows increasing heliocentric mean velocities (Figure 1), consistent with a declining rotation curve (the initial decrease within 1 kpc of the midplane is an effect of dust absorption). The change in observed velocity is some 20–30 km s⁻¹ from 1 to 4 kpc off the plane. A lag is also seen in HI, but the falloff is significantly steeper at this location (Swaters et al. 1997, Fraternali, this volume).

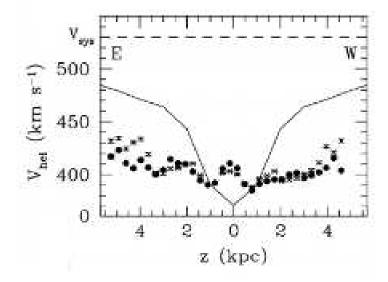


Figure 1. H α (crosses) and [N II] $\lambda 6583$ (filled circles) heliocentric line centroids are shown for a long-slit spectrum of NGC 891 centered at 100" northeast of the nucleus and oriented perpendicular to the plane. The systemic velocity of $V_{sys}=530~{\rm km~s^{-1}}$ is indicated by the dashed line. The solid curve is the prediction of a ballistic model of disk-halo cycling.

A more dramatic example is NGC 5775. This is an interacting galaxy (e.g. Irwin 1994) with a very bright and extended DIG halo, although more concentrated into large shell, filamentary and patchy structures compared to

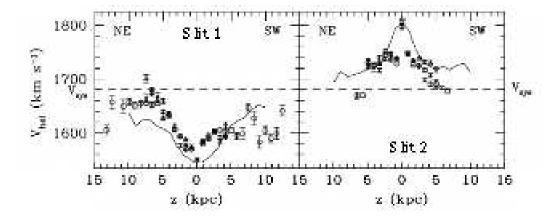


Figure 2. [N II] λ 6583 (open circles), [S II] λ 6716 (triangles), and [S II] λ 6731 (crosses) heliocentric line centroids are shown for long-slit spectra of NGC 5775 centered at 32" northwest (Slit 1) and 20" southeast (Slit 2) of the nucleus and oriented perpendicular to the plane. The systemic velocity of $V_{sys}=1680~{\rm km~s^{-1}}$ is indicated by the dashed line. The solid curve is the prediction of a ballistic model of disk-halo cycling.

the halo of NGC 891 (also in HI; see Lee et al. 2001). At some level, the halo kinematics may be modified by the interaction. Mean heliocentric velocities of DIG for two long-slits (Slit 1 on the approaching side and Slit 2 on the receding side) are shown in Figure 2. Forbidden-line velocities are shown rather than $H\alpha$ velocities because faint emission from the latter is confused by imperfect skyline subtraction. Velocities are measurable up to about 12 kpc from the plane in Slit 1. The trend for both slits is consistent with a lagging halo, with velocities approaching or reaching V_{sys} at the largest heights. Further long-slit data by Tüllmann et al. (2001), near the location of Slit 2, show a similar trend.

3. A Ballistic Model of Disk-Halo Flow

Assuming that the extraplanar gas in these galaxies is a result of disk-halo circulation, what can the lags tell us about the nature of the flow? The discoveries are new enough so that models of the circulation are not yet very sophisticated. In one limit, one can consider a purely hydrostatic continuum fluid disk (Benjamin 2000, Ciotti, this volume). In the other extreme, one can assume a purely ballistic flow with no pressure, tension, drag, or cloud interactions (Collins et al. 2002). Each approach should shed light on the true nature of the flow.

In the ballistic model of Collins et al. (2002), clouds are launched from the disk with some vertical velocity chosen from a uniform, random distribution of values between zero and some maximum velocity V_{kick} . The initial location of the clouds are chosen from an exponential probability distribution in R and a narrow Gaussian distribution in z. The potential used for most simulations is from

Wolfire et al. (1995). As the clouds rise they migrate outward in radius due to the weaker radial component of the potential they experience; they rotate slower as a consequence of conservation of angular momentum. The most important parameter governing the extent and kinematics of the halo clouds is the ratio of V_{kick} to the circular rotation speed V_{circ} . This ratio is chosen to match the vertical scale-height of the emission for the halo in question. Figure 3, showing meriodonal plots (z vs. R) for clouds launched at radii of 4, 8, 12 and 16 kpc for $V_{kick}/V_{circ} = 0.5$, demonstrates the outward migration and reduction in azimuthal velocities of the halo clouds.

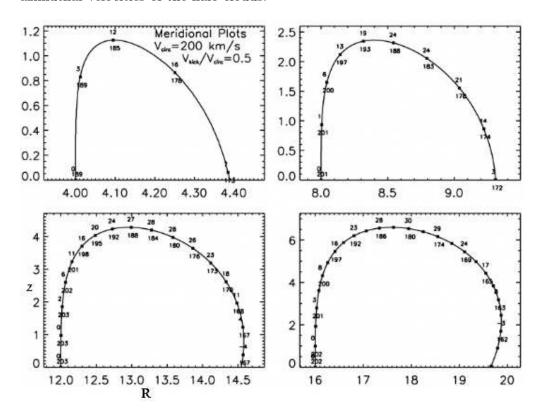


Figure 3. Meridional plots from the model of Collins et al. (2002) showing sample orbits for a case with $V_{circ} = 200 \; \mathrm{km \; s^{-1}}$ and $V_{kick} = 100 \; \mathrm{km \; s^{-1}}$. In each case, the horizontal axis is radius in kpc, and the vertical axis is height in kpc. Points note the position of the particle at 20 Myr intervals. The number above each point indicates the outward radial velocity; the number below gives the azimuthal velocity.

Figures 1 and 2 show how well the predicted mean heliocentric velocities match the data for NGC 891 and NGC 5775. The model badly overpredicts the lag in NGC 891 but fares somewhat better for NGC 5775, although the observed velocities near systemic cannot be reproduced. In NGC 891, the outward migration and resultant lag is presumably mitigated by some (magneto)hydrodynamic effect, such as a halo gas pressure increasing radially outward or a magnetic or viscous coupling to the disk (Benjamin 2000, Ciotti, this volume). In NGC 5775, with its apparently more active disk-halo flow (the emission is brighter, the gas

scale-height larger, and the morphology more filamentary than in NGC 891), the ballistic approximation may work somewhat better.

4. New 2-D Kinematic Data for NGC 4302

NGC 4302 is paired with another spiral NGC 4298, although there are no known signs of interaction. The galaxy appears extremely edge-on. The extraplanar DIG is concentrated above the inner disk, as for NGC 891, but several times fainter at comparable heights (Rand 1997). We have observed NGC 4302 with two pointings of the Sparsepak fiber-optic array (Bershady et al. 2004) on the WIYN telescope. Figure 4 shows the spatial sampling of the fibers. Total integration times are 380 and 410 minutes for the northern and southern pointings, respectively. The velocity resolution is 30 km s⁻¹, and the bright lines covered include $\text{H}\alpha$, [N II] $\lambda\lambda$ 6548, 6583 and [S II] $\lambda\lambda$ 6716, 6731. The results presented here are preliminary, and based only on mean velocities, which are indicative of, but do not accurately represent, rotation speeds.

Figure 5 shows velocities of the H α and [NII] λ 6583 lines as a function of height from the midplane for four representative distances, R, from the minor axis (negative values of R correspond to the approaching side and positive values to the receding side). A preliminary run of the ballistic model from Collins et al. (2002) is also shown in each panel. The ratio V_{kick}/V_{circ} is 0.8, but model parameter space has not yet been explored. In general, the approaching side of the galaxy suggests a reasonably well-behaved lagging halo, which can be fairly matched by the ballistic model, but at heights larger than about 25" (2 kpc) mean velocities become very close to systemic and in many cases become greater than systemic, suggesting a disturbance or possibly counterrotation. The kinematics of the receding side are more complex, with much more scatter in the velocities (the R=20" panel being typical) and a lagging halo signature apparent in only a few locations, such as at R=60" as shown here.

5. Conclusions and Future Work

There is clear evidence that ionized gas halos rotate slower than the underlying disks. The falloffs in rotation speed are not generally matched by a ballistic model of disk-halo flow, indicating that pressures and/or drag forces must affect rotation significantly. The overpredicted lag in NGC 891 suggests either a halo gas pressure that increases with radius or a magnetic or viscous drag with the faster disk. The model is somewhat more successful in NGC 5775 and NGC 4302, but cannot reproduce velocities near the systemic value at heights of several kpc in the former, while the latter shows several peculiarities in its halo kinematics. However, while mean velocities give an indication of the lagging effect, they cannot be used to determine with accuracy the decline of the rotation speed with height. It is therefore necessary to produce kinematic models that match the full spatial and spectral information available in two-dimensional kinematic data. We have begun this process using observations of NGC 5775 in the $H\alpha$ line using the Taurus Imaging Fabry-Perot Interferometer on the Anglo-Australian Telescope (Heald et al., this volume). This is a difficult process, especially given

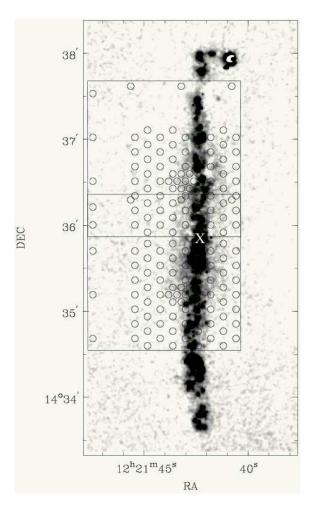


Figure 4. $H\alpha$ image of NGC 4302 from (Rand 1997) showing the two pointings of the Sparsepak array.

the 86° inclination of this galaxy. Dust further complicates the analysis. We will also apply this analysis to the data on NGC 4302 described above.

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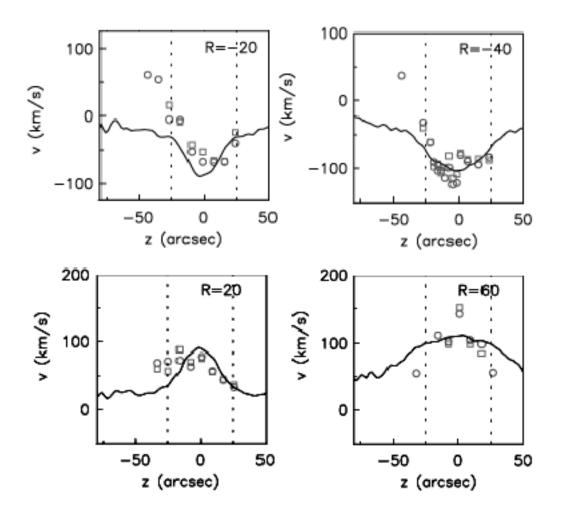


Figure 5. Velocities of the H α (squares) and [N II] λ 6583 (circles) emission as a function of height from the plane for four distances (in arcsec) from the minor axis of NGC 4302.

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