KINEMATIC EVIDENCE FOR HALO SUBSTRUCTURE IN SPIRAL GALAXIES

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ABSTRACT

We present the results of a kinematic study of planetary nebulae in the extreme outskirts of two spiral galaxies, M83 (NGC 5236) and M94 (NGC 4736). We find that in the inner regions of the galaxies, the vertical velocity dispersion ($\sigma_v$) falls off exponentially with the light, as expected for a constant mass-to-light ratio, constant thickness disk. However, starting at four optical scale lengths, $\sigma_v$ asymptotes out at roughly 20 km s$^{-1}$. Our analysis finds evidence for significant flaring in the outer regions as well, especially in M94. These observations are in excellent agreement with predictions derived from models of disk heating by halo substructure, and demonstrate how kinematic surveys in the outer disks of spirals can be used to test hierarchical models of galaxy formation.

Key words: galaxies: individual (NGC 5236, NGC 4736) – galaxies: kinematics and dynamics – galaxies: spiral – planetary nebula: general

1. INTRODUCTION

The cold dark matter (CDM) paradigm has proven to be very successful in explaining the large-scale structure of the universe and galactic clusters (Tegmark et al. 2004), yet problems still exist at the galactic level. One such issue is the “missing satellite” problem: according to numerical simulations, the structure of a galactic halo should look like a small version of a galaxy cluster and contain many small subhalos (e.g., Moore et al. 1999; Klypin et al. 1999). The recent discoveries of satellite galaxies tidally stripped by the Milky Way (Ibata et al. 1994; Newberg et al. 2002; Jurić et al. 2008, and references therein) and Andromeda (Ferguson et al. 2005; Ibata et al. 2007) help us to solve this problem. These small companions have a profound effect on the morphology and kinematics of thin galactic disks. Specifically, numerical models of satellite halo bombardments predict

1. the formation of faint stellar streams above the disk plane (which would be very difficult to observe in any but the nearest galaxies),
2. the generation of long-lived, low-surface brightness, dynamically cold, ring-like features in outer disks,
3. the growth of a strong bar,
4. the production of a pronounced flare, and
5. the development of a thick disk

(Kazantzidis et al. 2008, and references therein). Though many simulations (Quinn et al. 1993; Font et al. 2001; Hayashi & Chiba 2006; Kazantzidis et al. 2008, and references therein) have been performed to explore disk heating by halo substructure, observationally the results from this process have proven to be rather elusive. Only recently have teams begun to detect signs of this process in the Andromeda galaxy (Richardson et al. 2008) and other nearby galaxies (de Jong et al. 2008). Here we describe kinematic evidence for halo substructure derived from the velocity dispersion of planetary nebulae (PNe) in the extreme outer disks of two nearby, face-on spirals. We use stability arguments to show that the disks of M83 (NGC 5236) and M94 (NGC 4736) must flare at radii greater than ~4 scale lengths and demonstrate that at these large radii, the $z$ velocity dispersions of the old disk stars agree with the results of numerical simulations of a disk heated by halo substructure (Hayashi & Chiba 2006).

2. THE SURVEY

Flat rotation curves indicate the presence of dark matter in the outer regions of spiral galaxies and allow us to determine total galactic mass (e.g., Sofue & Rubin 2001). However, rotation curves alone cannot decouple the mass contribution of the disk from that of the dark halo (Barnes et al. 2004). To break this degeneracy, we have been using the motions of PNe in low-inclination spirals to measure disk mass directly via the $z$ motions of stars. PNe are ideal particles for this purpose; they are bright, abundant to $>5$ scale lengths, representative of the old disk, relatively easy to distinguish from H$\text{II}$ regions (via their distinctive [O$\text{III}$]–H$\alpha$ ratio; Ciardullo et al. 2002), and amenable to precise (~2 km s$^{-1}$) radial velocity measurements with fiber-fed spectrographs.

In Herrmann et al. (2008) (Paper I), we presented the results of a narrow-band imaging survey of six low-inclination nearby spirals (IC 342, M74 (NGC 628), M83 (NGC 5236), M94 (NGC 4736), NGC 5068, and NGC 6946) in which we identified 165, 153, 241, 150, 19, and 71 PNe, respectively. In two upcoming papers (K. A. Herrmann & R. Ciardullo 2009a, 2009b, in preparation, Papers II and III), we will detail our spectroscopic follow-up observations, present high-precision radial velocities for 550 of our PN candidates, and use the data to estimate dynamical disk masses.

Here, we focus on the data set for the two galaxies for which we have the largest radial coverage, the SBc spiral M83, which is at a distance of 4.8 Mpc, and the earlier Sab system M94 at $D = 4.4$ Mpc (Paper I). Our PN velocity sample for the former galaxy consists of 162 objects at radii between 2.5 and 24.7 kpc, i.e., between ~1 and 10 optical disk scale lengths. These data, which were taken with the Hydra bench spectrograph on the Cerro Tololo Inter-American Observatory (CTIO) 4 m telescope, have typical velocity uncertainties of $\sigma_v \sim 6.5$ km s$^{-1}$.
and in all cases, \( \sigma_v < 15 \text{ km s}^{-1} \). For M94, our data set contains 127 planetaries observed with the Hydra spectrograph on the WIYN (Wisconsin, Indiana, Yale & NOAO) telescope. These PNe have galactocentric radii between 0.5 and 8.8 kpc (0.4 < \( R < 7 \) disk scale lengths), and typical velocity uncertainties of \( \sigma_v \approx 4 \text{ km s}^{-1} \), again with \( \sigma_v < 15 \text{ km s}^{-1} \) for all objects (see Paper II).

Since neither galaxy is exactly face-on, we began our analysis by removing the effects of galactic rotation from the PN sample. This was done using velocity maps from The H I Nearby Galaxy Survey (THINGS; Walter et al. 2008) with a correction for asymmetric drift. We then binned the planetaries by radius (with 15–16 PNe per bin in M83, and 17–18 PNe per bin in M94), and identified those objects more than \( \sim 2.5 \sigma \) away from their bin mean as possible halo contaminants. (In practice, this made very little difference to the analysis, since the procedure eliminated only six objects in M83 and three in M94.) Finally, to extract the component of the velocity dispersion perpendicular to the galactic disk, \( \sigma_z \), from the other two constituents of the velocity ellipsoid, we began by using the epicyclic approximation for near-circular orbits to couple \( \sigma_\rho \) to \( \sigma_R \). We then constrained the shape of the disk velocity ellipsoid using the limits imposed by the physics of disk scattering (\( \sigma_z < \sigma_R \); Villumsen 1985; Jenkins & Binney 1990) and bending instabilities (\( \sigma_z > 0.25 \sigma_R \); Toomre 1966; Araki 1985; Merritt & Sellwood 1994), and computed the likelihood that each combination of \( \sigma_z \) and \( \sigma_R \) could produce the line-of-sight dispersions observed within our bins (see Paper III).

Figure 1 shows the results of this analysis, displaying contours which enclose 38% (0.5\( \sigma \)), 68% (1\( \sigma \)), 86% (1.5\( \sigma \)), and 95% (2\( \sigma \)) of the probability. Note that these contours have a slight tilt to them. This is a consequence of the galactic inclination: neither galaxy is precisely face-on (\( i \sim 24^\circ \) for M83, \( i \sim 35^\circ \) for M94), and the larger the inclination, the more difficult it is for our maximum likelihood procedure to extract \( \sigma_z \) from the line-of-sight velocity dispersion. Nevertheless, the figure does demonstrate that our measurements of \( \sigma_z \) are reasonably well defined, especially for M83.

For spiral galaxies, the velocity dispersion perpendicular to the disk is related to disk surface mass, \( \Sigma(R) \), and the disk scale height, \( h_z \), by
\[
\sigma_z^2(R) = K G \Sigma(R) h_z, \tag{1}
\]
where \( K = 2\pi \) for the isothermal case, \( K = \pi \) for disks whose vertical mass density drops exponentially, and \( K = \pi^2/2 \) for the intermediate sech\( (z) \) case (van der Kruit 1988). If (1) the disk mass-to-light ratio is constant, (2) the disk light of the galaxy decays exponentially with a single scale length (\( h_R \)), and (3) the disk scale height is also constant, then \( \sigma_z \) should decrease exponentially, with a scale length twice that of the light. As the marginalized probabilities of Figure 2 illustrate, this is not the case in either galaxy. While \( \sigma_z \) does track the light in the galaxies’ inner regions, the curve flattens out at distances more than four disk scale lengths from the nucleus. The minimum dispersion of \( \sigma_z \sim 20 \text{ km s}^{-1} \) is much greater than the typical measurement error of \( \lesssim 5 \text{ km s}^{-1} \), and greater than the \( < 15 \text{ km s}^{-1} \) values expected from the velocity dispersion of ionized gas and HI regions (i.e., Zaritsky et al. 1990; Fathi et al. 2007). Moreover, it is difficult to conceive of any way that internal extinction could create such an effect. While it is true that nonisothermal disks may have velocity dispersions that increase with height above the plane (see van der Kruit 1988), any layer of dust that is thick enough to effect our derived values of \( \sigma_z \) would also extinct the bulk of the PN population below the detection threshold and alter the distribution of PN [O \text{ iii}] line ratios (see Paper II). Finally, large-scale warping of the disks is not a solution: even with modeling isophotal twists by adjusting the disk position angle and inclination by \( \sim 70^\circ \) and \( \sim 15^\circ \), respectively, we cannot produce the dispersion curve seen in Figure 2 (see Paper III).

The flat velocity dispersion profile of M94 is partially explained by its unique 3.6 \( \mu \text{m} \) band radial profile, which has one scale length (\( h_R = 1.22 \text{ kpc} \)) in its inner regions, then breaks to follow a shallower profile (\( h_R = 7.16 \text{ kpc} \)) at radii greater than 5 kpc (de Blok et al. 2008). (A recent deep R-band profile shows the same broken shape (Erwin 2009, private communication).) But M83’s disk has no such break, as its simple exponential profile (\( h_R = 2.45 \text{ kpc} \)) extends over \( \sim 20 \text{ kpc} \) to the edge of our survey area (de Jong et al. 2008). Moreover, even with its broken disk profile, M94’s \( \sigma_z \) values are much higher than possible for a constant \( M/L \), constant \( h_z \) disk.

These high \( \sigma_z \) values also bring up another issue. To be stable against axisymmetric perturbations, a thin stellar disk must obey the Toomre (1964) criterion
\[
\sigma_R > \frac{3.36G \Sigma}{\kappa}, \tag{2}
\]
where \( \kappa \) is the epicyclic frequency of the orbits. Combining this criterion with Equation (1) yields a constraint on the allowable values of \( \sigma_z \):
\[
\sigma_z < \left( \frac{K h_z \kappa \sigma_R}{3.36} \right)^{1/2}. \tag{3}
\]
Because our galaxies are low-inclination systems, \( h_z \) is not directly obtainable from our observations. However, imaging surveys of large, edge-on, noninteracting spirals demonstrate that the scale length to scale height ratio of galactic disks ranges from \( \sim 10 \) in late-type systems to \( \sim 5 \) in earlier-type objects (e.g., de Grijs 1998; Kregel et al. 2002). When applied to the two galaxies studied here, this relation implies that \( h_z \) should
be between 200 and 300 pc for both the Sab spiral M94 \( (h_R = 1.22 \text{ kpc}; \text{de Blok et al. 2008}) \) and the SBc system M83 \( (h_R = 2.45 \text{ kpc}; \text{de Jong et al. 2008}) \). Yet, as the curves of Figure 1 indicate, outer disks as thin as this are unlikely, as our solutions for \( \sigma_z \) in M83 and especially M94 lie predominantly above the stability limit. This suggests that the stellar disks of these systems flare dramatically in their outer regions.

Could this flaring and higher than expected values of \( \sigma_z \) be due to heating of the disk by halo substructure? We can address this question by comparing our results to \( N \)-body simulations of dark subhalo interactions with large galaxies. In particular, Hayashi & Chiba (2006) have modeled the heating of a Milky Way-like galaxy by a population of subhalos, distributed according to a Hernquist (1990) law. Figure 2 compares our \( \sigma_z \) velocity dispersion profile to their Model F, which reproduces interactions between an initially thin, stable, constant mass-to-light ratio disk, and a few \( \lesssim 300 \) massive \( (\lesssim 10^9 M_\odot) \) subhalos, totaling \( M_{\text{sh}} \lesssim 0.15 M_{\text{disk}} \) and distributed with a half-mass radius of \( \sim 210 \text{ kpc} \). Although their model only probes out to \( \sim 5 \) disk scale lengths, the agreement between observations and theory is excellent. Their model not only reproduces the run of \( \sigma_z \) versus radius seen in our galaxies, but also predicts an amount of disk flaring that is consistent with our analysis. Moreover, Strigari et al. (2008) have recently reported that, of the 23 known Milky Way satellite galaxies, the 18 with dynamical mass measurements all have masses of \( M \sim 10^7 M_\odot \) within a radius of 0.3 kpc. This suggests that these satellites once had total masses of \( \sim 10^9 M_\odot \) before encountering the Milky Way’s potential (Strigari et al. 2008). This value is in excellent agreement with the subhalo masses used in Hayashi & Chiba (2006), and supports the idea that interactions with subhalos could be responsible for the flat dispersion profiles seen in the outskirts of galaxies.

4. CONCLUSIONS

The existence of persistent very thin disks in spiral galaxies has long been recognized to be a significant constraint for models of structure growth (see Moore et al. 1999). Major mergers destroy thin disks, while large asymmetries or substructure in extended dark matter halos will warp or heat these structures (Quinn et al. 1993; Font et al. 2001). Conversely, evidence for extended thick disks (or thin young disks embedded within older, thicker disks) can preserve direct evidence of past mergers and/or episodes of externally triggered star formation.

The two galaxies considered here have very different radial profiles: while the slope of M94’s “antitruncated” stellar disk changes dramatically at a radius of \( \sim 5 \text{ kpc} \) (de Blok et al. 2008), M83’s exponential profile appears undisturbed out to \( \sim 10 \) disk scale lengths (de Jong et al. 2008). Thus, while M94 may have been involved in a minor merger some years ago (Younger et al. 2007), the only evidence for interaction in M83 is the warping of its extreme outer H I disk, which begins \( \sim 8 \) scale lengths from the nucleus (Huchtmeier & Bohnenstengel 1981). Yet in both these systems, the kinematic evidence suggests that the stellar disk flares dramatically past \( \sim 4 \) disk scale lengths, and that at these large distances, the \( z \) velocity dispersion is independent of radius. This result is consistent with cosmological models of hierarchical structure formation, where a thin disk is heated by a relatively small number of massive subhalos, which are either embedded within the parent dark halo with a relatively small initial spatial spread (Hayashi & Chiba 2006), or initially on radial orbits (Hopkins et al. 2008). Since simulations indicate the disk heating does not scale linearly with the mass and number of subhalos, this is potentially a strong constraint on substructure. While there are several different processes that may combine to heat a disk, cooling such a disk back to a low velocity dispersion state is difficult. (The slow accretion of extremely large amounts of cold gas could, in theory, lead to adiabatic compression of the disk. However, in such a process, the gas mass would need to be many times that of the stellar disk, and even then, there would be stability issues.) Our current measurements of \( \sigma_z \) at large radii already rule out some models for halo substructure, and are directly consistent with models where there are fewer, more massive subhalos on orbits with relatively low angular momentum.

More data are required to explore this constraint further. In particular, measurements over a wider range of galaxy masses, radii, and Hubble types are needed. Fortunately, such data
are relatively straightforward to obtain with moderate-sized telescopes. Planetary nebula surveys in the extreme outer disks of the low-inclination, late-type spirals M74, M101, and IC 342 are already under way, and observations in earlier systems, such as M95 and NGC 1291, are possible. Thus, a robust comparison to hierarchical models of structure formation should be possible in just a few years.

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