Planetary Nebula Studies of Face-On Spiral Galaxies: Is the Disk Mass-to-Light Ratio Constant?

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Abstract. When astronomers study the dark matter halos of spiral galaxies, they normally assume that the disk mass-to-light ratio is constant. We describe a method of analyzing the kinematics of planetary nebulae (PNe) in nearby face-on spiral galaxies to test this assumption. Since the restoring force for stellar motions perpendicular to the galactic disk is proportional to the disk mass surface density, measurements of the vertical velocity dispersion can be used to produce an independent measure of the total amount of matter in the disk. Our steps are: (1) to identify a population of PNe by imaging the host spiral in several filters, and (2) to isolate the vertical velocity dispersion from spectroscopic observations of the PNe. Our first results for the PNe of M33 indicate that the mass-to-light ratio of the galaxy’s disk actually increases by more than a factor of 5 over the inner 6 disk scale lengths. We have begun similar studies of the PNe in five more face-on galaxies: M83, M101, M94, NGC 6946, and M74. These data will also produce additional science such as galaxy distances and constraints on the disk transparency.

INTRODUCTION AND SCIENTIFIC MOTIVATION

Dark matter, a mysterious topic, has been under intense study for many years. One way to shed some light on the subject is to examine galactic halos. In the case of spiral galaxies with weak bulges, one typically measures the total galactic mass via the system’s rotation curve (Faber & Gallagher 1979; Ashman 1992; Combes 2002), assumes that the mass near the center of the galaxy is entirely baryonic, and subtracts off the contribution of the disk by assuming a constant disk mass-to-light ratio (Kent 1986, Palunas & Williams 2000; Sofue et al. 2003). (This is the “maximal disk” method.) However, while absorption line studies (Bottema 1993; Bottema, van der Kruit, & Freeman 1987; van der Kruit et al. 2001; Gerssen, Kuijken, & Merrifield 1997, 2000) have indicated that the disk mass-to-light ratio is constant in the inner regions of spiral galaxies, there formerly were no results about the outer regions where the influence of dark matter is greatest. The extreme difficulty in separating the mass of a galaxy’s visible disk from that of its dark halo limits our understanding of almost every facet of galaxy formation. An independent method of determining the disk mass is needed to break the disk-halo degeneracy.

OUR METHOD: USING PLANETARY NEBULAE TO STUDY DISK MASS

To determine a disk’s mass-to-light ratio, one can study the vertical motions of old disk stars. Since the restoring force for stellar motions perpendicular to a galactic disk is proportional to the disk mass surface density ($\Sigma$), measurements of the vertical velocity dispersion ($\sigma_z$) immediately yield an independent measure of the amount of matter in a disk. From the isothermal disk approximation, old disk stars oscillate in $z$ according to

$$\sigma_z^2(R) = \pi G \Sigma(R) z_0,$$

where $z_0$ is the scale height of the stars (Binney & Tremaine 1987). Since studies of edge-on spirals demonstrate that $z_0$ is constant with radius (van der Kruit & Searle 1981; Bizyaev & Mironova 2002), this parameter can be fixed at some appropriate value. Then, by observing a face-on galaxy, we can see if the matter scale length does indeed decline in a manner similar to the light.

The traditional method of determining $\sigma_z$ via absorption line spectroscopy is very challenging both observationally and in terms of data analysis. Moreover, because the technique is limited by surface brightness, its effectiveness is restricted to a galaxy’s inner regions (Bottema 1993; Gerssen, Kuijken, & Merrifield 1997, 2000). An alternate method to measure $\sigma_z$ is to use planetary nebulae (PNe) as kinematic test particles. PNe are relatively numerous, easy to detect in a galaxy’s outer regions where dark matter is most important, and come from a progenitor population of low and intermediate mass stars. They are therefore representative of the old stellar disk of a galaxy. In addition, since PNe are strong emission line sources, virtually every object that can be found photometrically can be observed spectroscopically. With a medium ($R \sim 5000$) resolution instrument, radial velocity measurements to a precision of $\sim 2$ km s$^{-1}$ are obtainable without much difficulty. This makes PNe ideal test particles for probing the disk mass of face-on spirals.
FINDING THE PNE

In order to study the disk mass-to-light ratio, we must first identify a suitably large population of PNe. The spiral galaxy under study must be imaged with a 4-m class telescope in four filters: two narrow on-band filters centered at [O III] λ5007 and Hα (in the rest-frame of the galaxy), and two wider off-band filters, such as V and R. Since PNe have virtually no continuum, they can be found by blinking the on-band images against their off-band counterparts. True PN candidates are: (1) consistent with point sources, (2) detected in λ5007 but invisible in V and R, and (3) invisible or weak in Hα. These criteria exclude most or all H II regions and supernova remnants. At this stage, we can determine the distance to the galaxy via the Planetary Nebula Luminosity Function (Ciardullo et al. 2002), and attempt to constrain the transparency of the disk via PN number counts. Thus far, as part of our program, we have discovered 152 PNe in the Triangulum Galaxy, M33 (Ciardullo et al. 2004; hereafter C04), 65 PNe in the Northern Pinwheel Galaxy, M101 (Feldmeier, Ciardullo, & Jacoby 1996), and ∼200 PNe in the Southern Pinwheel Galaxy, M83 (Herrmann, Ciardullo, & Vinciguerra 2005).

PNE KINEMATICS

Once we have identified a large population of PNe and determined accurate positions, the next step is to obtain a high precision radial velocity for each object. This can be done with fiber-coupled spectrographs, such as the Hydra instruments on the WIYN and Blanco 4-m telescopes, and the Medium Resolution Spectrograph on the Hobby-Eberly Telescope. In order to minimize systematic errors, it is useful to target the PNe multiple times and to pay special attention to the wavelength calibration. Ideally, the velocity uncertainties should be < 5 km s⁻¹.

The top frame of Fig. 1 shows the preliminary radial velocities of 203 PNe in M83 after correcting for the systemic and barycentric velocities. PNe with the largest velocities away from us are clustered in the lower left of the frame, while PNe with the largest velocities toward us are in the upper right. Clearly, we are detecting the rotation of the galaxy. For a flat axisymmetric system, the radial velocity, \( v_{rad} \), is given by

\[
   v_{rad} = v_\phi \cos \phi \sin i + v_R \sin \phi \sin i + v_z \cos i,
\]

where \( v_\phi \), \( v_R \) and \( v_z \) are the azimuthal, radial and vertical components, \( i \) is the inclination, and \( \phi \) is the angle from the principal axis in the galaxy plane. The rotation component is eliminated by subtracting out \( v_{rot} \cos \phi \sin i \) where \( v_{rot} \) is taken from studies of H I gas (Tilanus & Allen 1993). The resulting residual velocities are random with position in the galaxy, indicating that the rotation has been taken out. (See the bottom frame of Fig. 1.)

If the line-of-sight velocity measurements are dominated by the vertical component of the velocity ellipsoid, then the dispersion in the residual velocities, \( \sigma_{rad} \), should be related to the disk mass surface density, \( \Sigma \), via Eqn. (1). For a constant mass-to-light ratio disk, this implies that \( \sigma_{rad} \) should fall off exponentially with a scale-length twice that of the galaxy’s light. Figure 2 shows the line-of-sight residual velocity dispersion for the PNe in M33 and M83. For M33, the dispersion clearly does not follow the light. This is not entirely unexpected, since the galaxy’s ∼56° inclination ensures that all three components of the velocity ellipsoid contribute to \( \sigma_{rad} \). Our preliminary results for M83 are similar. Thus, in both cases, we need to de-couple \( \sigma_z \) from the other components of stellar motion.
The observed line-of-sight velocity dispersion of a galaxy can be written in terms of the azimuthal ($\phi$), radial ($R$), and perpendicular ($z$) velocity dispersions via

$$\sigma^2_{\text{rad}} = \sigma^2_{\phi} \cos^2 \phi \sin^2 i + \sigma^2_R \sin^2 \phi \sin^2 i + \sigma^2_z \cos^2 i + \sigma^2_{\text{meas}},$$

where $\sigma_{\text{meas}}$ is the measurement uncertainty. (Note that to extract $\sigma_z$ from $\sigma_{\text{rad}}$, $\sigma_{\text{meas}}$ must be kept to a minimum.) Since there are three unknowns but only one equation, external constraints are needed. One such constraint is the epicyclic approximation, which allows us to remove $\sigma_\phi$ from the equation by writing it in terms of $\sigma_R$ and the radial gradient of the circular velocity (Binney & Tremaine 1987). Two others are the Toomre (1964) criterion, which requires that the disk be stable against axisymmetric perturbations, and the firehose instability, which forces us to consider only those disks that are stable against buckling (Toomre 1966; Merritt & Sellwood 1994). Finally, for non-barred galaxies, we can impose the Morosov (1980, 1981a, 1981b) criterion, which requires that a disk be stable against the formation of a bar.

Each of these constraints eliminates some combination of $\sigma_z$ and $\sigma_R$ from consideration. We can then use a maximum-likelihood analysis to determine which of the remaining combinations of the two variables are most probable. If enough PNe are observed, we can also determine the system’s asymmetric drift, and place a further constraint on the solution (Binney & Tremaine 1987).

**RESULTS FOR M33**

At present, M33 is the only galaxy for which we have a complete analysis. The most likely values of $\sigma_z$ and $\sigma_R$ are shown in Fig. 3. The data demonstrate why the line-of-sight velocity dispersion of M33 varies so little with radius. Near the center of the galaxy, the increase in $\sigma_z$ is negated by a turnover in the radial velocity dispersion. (If this did not happen, then $\sigma_R$ in the central $\sim 1$ kpc would be greater than $v_{\text{rot}}$, and the galaxy would have a bulge.) At larger radii, both $\sigma_R$ and $\sigma_z$ decline exponentially, with the scale length of $\sigma_R$ being $\sim 25\%$ larger than that of $\sigma_z$. The derived values of the dispersion ratio, as well as its radial gradient, are in excellent agreement with models of disk heating (Villumsen 1985; Jenkins & Binney 1990; Carlberg 1987).

A more surprising result is that the mass scale length inferred from $\sigma_z$ is more than twice that expected from observations of the galaxy’s infrared light. Near the cen-
of five additional galaxies which are more face-on than M33, including M83, M101, M94, NGC 6946, and M74. These data should tell us whether the spiral disks are truly super-maximal, as the M33 data suggests, or if \( \sigma_R \) and \( \sigma_\phi \) are conspiring against us.

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