Mapping the Stellar Dynamics of M31

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Abstract. Using the Planetary Nebula Spectrograph, we have observed and measured the velocities for 2764 PNe in the disk and halo of the Andromeda galaxy. Preliminary analysis using a basic ring model shows a rotation curve in good agreement with that obtained from \textsc{Hi} data out to \( \sim 20 \) kpc. Some substructure has also been detected within the velocity field, which can be modeled as the continuation of the tidal–remnant known as the Southern Stream, as it passes through Andromeda’s disk.

1 Introduction

The Andromeda galaxy, the nearest large spiral galaxy \((D \sim 770 \text{ kpc})\), provides a unique observational target. M31’s size and proximity allow surface structures to be resolved and studied in unprecedented detail. However, due to its large angular size, until now it has not been practical to perform a large survey of M31’s stellar disk dynamics. Previous dynamical studies have either measured gas in the disk (e.g. \textsc{Hi} \cite{2} and \textsc{Hii} \cite{10}) or tracer populations in the halo (e.g. globular clusters \cite{8}; and RGB stars \cite{9} and \cite{4}).

With the commissioning of the Planetary Nebula Spectrograph (PN.S) at the William Herschel Telescope in La Palma, it has become possible to perform such a survey. Nine nights of observations (13 allocated) with the PN.S and 6 nights surveying the halo with the Wide Field Camera on the Isaac Newton Telescope have led to a preliminary catalogue of 2764 PNe, delving \( \sim 4.5 \) magnitudes into the PN luminosity function, extending \( \sim 2.5^\circ \) along the major axis, \( \sim 1.5^\circ \) along the minor axis, and covering various elements of substructure in the halo’s stellar population density, such as the Southern Stream and Northern Spur \cite{3}.
A raw rotation curve for the PN.S data has been extracted by averaging PN velocities using a flat ring model (10 concentric rings of width 3.36 kpc), where PNe are assumed to lie in a thin disk and move on circular orbits. The PNe within a ring are weighted according to their angular distance from the major axis ($\phi$) and those that are closer to the minor axis than the major axis are omitted, as are PNe close to identified external objects. A 3σ–clipping routine has been used to eliminate PNe with discrepant velocities, such as halo, foreground or background contaminants.

As the Andromeda galaxy is highly inclined ($i = 77^\circ$) a correction to the raw rotation velocities must be made to account for the line–of–sight integration through the disk. This tends to reduce the observed velocities, $V_{\phi, obs}$, with respect to the rotation velocity, $V_{\phi}$, by a factor $f(R', z', i)$, where the parameters are as shown in Fig.1 , and

$$V_{\phi} = \frac{V_{\phi, obs}}{f(R', z', i)}$$

(1)

where

$$f(R', z', i) = \frac{\int_{0}^{\infty} \nu(r', z') \cos \phi dS'}{\int_{0}^{\infty} \nu(r', z') dS'}$$

(2)

Here, $\nu$ is the number density of PNe, and the primed quantities have been defined in units of the photometric disk scale length, $r_0$, i.e. $R' = \frac{R}{r_0}$, $r' = \frac{r}{r_0}$, $z' = \frac{z}{r_0}$ and $S' = \frac{S}{r_0}$. An expression for $f(R', z', i)$ can be found by combining (2), the geometrical relations in Fig.1 and the expression

$$\nu(r', z') = \nu_0 \exp \left(-r' - \frac{z' r_0}{z_0}\right)$$

(3)

which assumes that the disk is exponentially declining both radially and perpendicularly to the plane, and $z_0$ is the disk scale height.

A somewhat more significant correction is that of the asymmetric drift, which accounts for the fact that not all PNe are moving on circular orbits. The difference between the true circular rotation velocity, $V_c$, and $V_{\phi}$, or asymmetric drift, is related to the velocity dispersion. A correction for this has been performed using the method in [7], whereby it is assumed that

$$V_c^2 = \frac{V_{\phi}^2}{\sigma_{\phi}^2} (2R' - 1)$$

(4)
In order to perform this correction the velocity dispersion has been fitted as an exponential function of the form $\sigma_\phi = \sigma_0 e^{-r/r_0}$. The dynamical scale length has been set to twice the photometric value to maintain a constant disk scale height with radius [1].

The fully corrected rotation curve is shown in Fig. 2, alongside the averaged H\textsc{i} rotation curve given in [11]. With the exception of the first data point (where a number of bulge PNe are likely to be present and hence the asymmetric drift correction breaks down) it is clear that the PN.S data are in very good agreement with the H\textsc{i} rotation curve and are of very high quality out to $\sim 20$ kpc. Beyond this point there is marginal evidence that the PN rotation curve drops to a lower velocity than is seen in the H\textsc{i} data. However, there are very few PNe per ring beyond 20 kpc and we may simply be seeing halo contamination.

Figure 2 also shows a three component model fit to the PN data from all but the first ring. This shows that the PN rotation curve just reaches a radius where the dark matter halo becomes dominant.

### 3 PNe in Halo Structures

A number of PNe from this survey lie in the region of the Northern Spur (circles, Fig. 3a), an over-density of stars in Andromeda’s halo [3]. This over-density is also seen in the PNe counts (similarly positioned halo fields in the opposite quadrant have 1 or 2 PNe, while Northern Spur fields contain up to $\sim 6$). These planetaries have velocities similar to the maximum observed rotation velocities in the disk (circles, Fig. 3b). This would suggest that the Northern Spur is not a kinematically distinct substructure, but in fact forms part of the disk, implying that the stellar disk must be severely warped.
Fig. 3. Velocity Structures. (a) PNe positions. To the lower right (squares) are PNe in the region of the Southern Stream, with velocities below -130 km s\(^{-1}\); to the upper left (circles) are PNe in the Northern Spur region; and scattered through the left side of the disk (triangles) are PNe selected for their unusual velocities. The ellipse marks the 2° radius of the disk and the large circle marks the position of M32. (b) Velocity versus distance along the major axis and the orbit location; PNe are marked as above. (c) Orbit location in the \(X - Y\) plane. (d) Orbit location in the \(Z - Y\) plane. The arrow indicates the direction of the Milky Way; the short heavy line is the location of M31; and the points (pentagons) show the measured depth to the stream from [5].

PNe in the region of the Southern Stream [3] have also been targeted by this survey (squares, Figs.3a). Those PNe with velocities below -130 km s\(^{-1}\) seem to form a coherent kinematic structure (squares, Fig.3b).

4 Substructure in the Velocity Field

Clearly a number of PNe in the sample have velocities which imply that they are not just normal disk PNe. One such population has been identified whereby the PNe lie below a line for which there is no equivalent population in the opposite side of the disk (triangles, Fig.3b).

These PNe have a low dispersion (\(\sim 23\) km s\(^{-1}\), including an instrumental dispersion of \(\sim 15\) to 20 km s\(^{-1}\)) about a straight line fit. Such low dispersions are indicative of tidal streams. We therefore propose that these PNe are associated with a continuation of the Southern Stream as it passes into the disk of M31, where it can no longer be tracked via photometric methods (see also [6]).
The locations of the unusual PNe suggest a tidal stream lying almost straight along the major axis. We have therefore generated a simple orbit model (shown in Figs.3b, c and d) using a flattened singular isothermal potential,

\[ \Phi(R, z) = \frac{1}{2} v_c^2 \ln \left( R^2 + \frac{z^2}{q^2} \right) \]

where \( R \) and \( z \) are polar coordinates aligned with M31’s disk plane; \( v_c \) is set to the upper envelope of PNe velocities (250 km s\(^{-1}\)); and a value of \( q = 0.9 \) is adopted for the flattening. The orbit has been set to fall in along the path defined in [5] (Fig.3d), and turn into the disk. This orbit agrees reasonably well with the velocities of RGB stars in the Southern Stream region [4] and clearly picks up the unusual PN velocities we have detected.

The change in projection angle seen in Fig.3d between the orbit’s entry into the disk and as it moves across the disk, can explain the significantly higher number of Stream PNe seen in the disk portion of the orbit (15 PNe) compared to the southern region (probably \( \sim 5 \)).

5 Conclusion

We have mapped the dynamics of the Andromeda galaxy’s planetary nebula system for PNe some 4.5 mags into the luminosity function. From this we have constructed a stellar rotation curve which agrees well with the HI data. A simple three component model has been fit to the PN data out to the realm where the dark halo becomes dominant. It is important to measure this using the stellar population, as there can be no ambiguity as to the nature of the force producing the rotation—unlike gas, stars are subject only to gravitational forces.

Velocities have been measured for the halo structure known as the Northern Spur, supporting the hypothesis that it represents a severe warp in the stellar disk.

A number of PNe have been identified as forming a substructure within the velocity field. These have a very low velocity dispersion, suggesting they are part of a tidal stream. We have shown they can be modeled as a continuation of the Southern Stream as it turns into M31’s disk where it would no longer be detectable via photometric methods.

References

1. R. Bottema: A&A 275, 16 (1993)
2. R. Braun: Ap.J 372, 54-66 (1991)
3. A. Ferguson et al.: A.J. 124, 1452-1463 (2002)
4. R. Ibata et al.: astro-ph/0403068 (2004)
5. A. McConnachie et al.: MNRAS 343, 1335-1340 (2003)
6. H. R. Merrett et al.: MNRAS 346, L62-66 (2003)
7. E. Neistein et al.: AJ 117, 2666-2675 (1999)
8. K. Perrett et al.: AJ, 123, 2490-2510 (2002)
9. D. Reitzel and P. Guhathakurta: A.J. 124, 234-265 (2002)
10. V. Rubin and W. Ford: ApJ 159, 379 (1970)
11. L. Widrow et al.: ApJ 588, 311-325 (2003)