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Tracing the star stream through M31 using planetary nebula kinematics

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ABSTRACT

We present a possible orbit for the Southern Stream of stars in M31, which connects it to the Northern Spur. Support for this model comes from the dynamics of planetary nebulae (PNe) in the disk of M31: analysis of a new sample of 2611 PNe obtained using the Planetary Nebula Spectrograph reveals ~ 20 objects whose kinematics are inconsistent with the normal components of the galaxy, but which lie at the right positions and velocities to connect the two photometric features via this orbit. The satellite galaxy M32 is coincident with the stream both in position and velocity, adding weight to the hypothesis that the stream comprises its tidal debris.

Key words: Local Group – galaxies: individual: M31 – galaxies: interactions – galaxies: kinematics and dynamics – galaxies: structure

1 INTRODUCTION

It is now generally accepted that mergers play a key role in the formation of galaxies (White & Rees 1978). Since galaxy evolution is an ongoing process, we might therefore expect to catch a number of systems in the nearby Universe mid-merger. Indeed, dramatic major mergers with complex tidal tails have been documented for quite some time (see, for example, Schweizer 1986). Perhaps of greater importance to the more passive evolution of galaxies, and as a possible cause of phenomena such as thick disks (Quinn, Hernquist & Fullager 1993), evidence for the more common minor mergers is now coming to light. In these cases, the detritus of the events has a high enough surface brightness be visible as a stellar stream. The Sagittarius Dwarf Galaxy provides a fine example in the Milky Way (Majewski et al. 2003), and one need look no further than the closest good-sized galaxy, M31, to find another dramatic stream of stars (Ibata et al. 2001), which is presumably the remnant of a similar minor merger. The proximity of these streams indicates quite how common this phenomenon must be, but it also offers prime laboratories for studying the merger process in detail. The Sagittarius Dwarf is inconveniently placed behind the centre of the Milky Way, and also presents the usual problems of geometry when trying to study an object inside our own galaxy, so the M31 stream is probably the best candidate for analysis. However, even this is not without its problems: the large extent of M31 necessitates a very extensive data set for any complete survey, and the low surface brightness of the feature renders the stream hard to detect particularly against any of the brighter parts of M31. The faintness of the stream and its constituent stars also makes it very challenging to obtain the kinematic observations that would tie down the full dynamical structure of the stream, and thus unequivocally demonstrate its nature.

In this paper, we seek to overcome these difficulties by supplementing the existing photometric data with a new sample of 2611 planetary nebulae in the disk of M31. The kinematics of these discrete stellar tracers can be used to pick out the star stream right through the brighter parts of

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M31's disk as well as helping determine its dynamics. The remainder of this paper is laid out as follows. In Section 2 we review the existing photometric data on the M31 stream features and the hypothesis as to how they may be connected. Section 3 presents the kinematic data, which strengthens the case for such a link. Section 4 shows an orbit model that quantitatively marries these photometric and kinematic features, and presents the evidence that the stream may arise from M32's tidal debris. Section 5 concludes.

2 THE PHOTOMETRY OF THE STREAM

The star stream in M31 was first reported by Ibata et al. (2001), who demonstrated that this dramatic low-surface-brightness linear feature protrudes to the south-east of the galaxy out to a distance of tens of kiloparsecs (see Figure 1). The stream is oriented such that it points almost directly at two of M31's satellites, M32 and NGC205, raising the intriguing possibility that it may be associated with one or other of these galaxies [although, as Ferguson et al. (2002) point out, a tidal association with NGC205 is difficult to reconcile with the absence of any extension in the stream beyond this galaxy].

A subsequent study by McConnachie et al. (2003) confirmed the existence of this "Southern Stream," traced it to larger distances, and was even able to measure a distance gradient along it, placing it at some 60 degrees to the line of sight. Combining the new angular extent with the angle to the line of sight, they found that the stream is more than 100 kpc in length.

One of the peculiarities of the stream is that although it is plainly detected to the south-east of the galaxy, it does not appear in anything like a symmetric form to the north-west. There is some indication of a detection of the stream on this side of the galaxy in the detailed analysis by McConnachie et al. (2003), but it is clear that if the continuation of the stream exists at a similar strength then it must be oriented in such a way as to be mostly hidden. It was this asymmetry that led Ferguson et al. (2002) to hypothesize that the stream's continuation might turn closer to the disk of M31, and its re-emergence might be associated with a feature known as the Northern Spur (see Figure 1).

The Northern Spur is a peculiar low-surface-brightness structure sticking out of M31's disk, which contains a metal-rich stellar population. Since it lies in the direction of M31's gaseous warp (Newton & Emerson 1977), its projection away from the plane is usually attributed to a severe warp in the stellar disk. However, if so then it would have to be more extreme than the warps found in any other stellar disks (Walterbos & Kennicutt 1988). It would also have to be an uncomfortably short-lived asymmetric feature, since there is no comparable spur to the south of M31. It therefore seems at least as plausible that this feature is associated with the star stream rather than the warp (although there is also always the third possibility that it is unrelated to either of these phenomena).

A direct link between the Southern Stream and the Northern Spur would be hard to detect photometrically against the bright disk, especially since the width of the Southern Stream (~ 0.5 degrees; McConnachie et al. 2003) is comparable to the scale-length of the disk against which it appears projected, so no sharp features would stand out. However the kinematics of any stars forming such a link would be expected to be quite different from those of disk stars, so would be worth trying to detect.

3 THE KINEMATICS OF THE STREAM

As part of a project to study the stellar kinematics of the disk of M31, we have obtained radial velocities of 2611 M31 planetary nebulae (PNe) using a novel purpose-built device, the Planetary Nebula Spectrograph (PN.S). The instrument, mounted on the William Herschel Telescope, obtains both positions and line-of-sight velocities for PNe in a single observation using a form of slit-less spectroscopy; details of the method and design of the PN.S can be found in Douglas et al. (2002). PNe provide an ideal kinematic tracer of the stellar population. They can be readily identified as point-like emission line sources, and their kinematics can be measured using the same emission lines. Since PNe are just ordinary stars that we happen to catch at the ends of their lives, they are fairly representative of the bulk stellar population of the galaxy. Such discrete tracers are particularly good for searching for stellar streams because they provide a direct measure of the line-of-sight velocity distribution. More traditional absorption-line studies of unresolved stellar components require a deconvolution to obtain a measure of the velocity distribution, and the noise-amplifying properties of this process would hide any small kinematic subcomponent like a star stream. The resulting PNe data set is presented in Figure 1. The overall rotation of the disk is clearly visible, and a few of M31's satellites are also apparent both spatially and from their distinct kinematics.

To identify any possible stream stars, we need a mechanism for identifying PNe whose kinematics are inconsistent with their being members of either M31's bulk disk population or one of the known satellites. To this end, we have implemented a simple "friendless" algorithm. For each PN we identify its N nearest neighbours on the sky, and calculate their mean velocity $\overline{v}$ and velocity dispersion σ. If the PN in question has a velocity that lies more than $n \times \sigma$ from $\overline{v}$, then it is flagged as friendless. This non-parametric approach selects pretty much the same PNe that one would pick out by eye as having discrepant kinematics, and turns out to be fairly robust in that the exact values of N and n chosen do not affect the results dramatically. Simulations of simple disk models show that only a very small number of "false friendless" PNe would be found in a system that only contains a disk population. For the present analysis, we have adopted $N = 30$ and $n = 4$; the 23 friendless PNe found with these parameters are highlighted in Figure 1.

The first thing that is apparent from the friendless PNe is the asymmetry in their distribution: away from the minor axis, there are 13 PNe at $X < -0.2$ and $v_{\rm los} < 0$, whereas the corresponding quadrant on the other side of the galaxy ($X > 0.2$ and $v_{\rm los} > 0$) contains only 5 PNe. A binomial test reveals that this lopsidedness is inconsistent with a symmetric distribution at 95% confidence. Such an asymmetric distribution cannot be reconciled with any simple explanation for these friendless PNe, such as the extreme tail of a hot disk population (including a possible thick disk component), or a relaxed halo population; indeed, any contami-

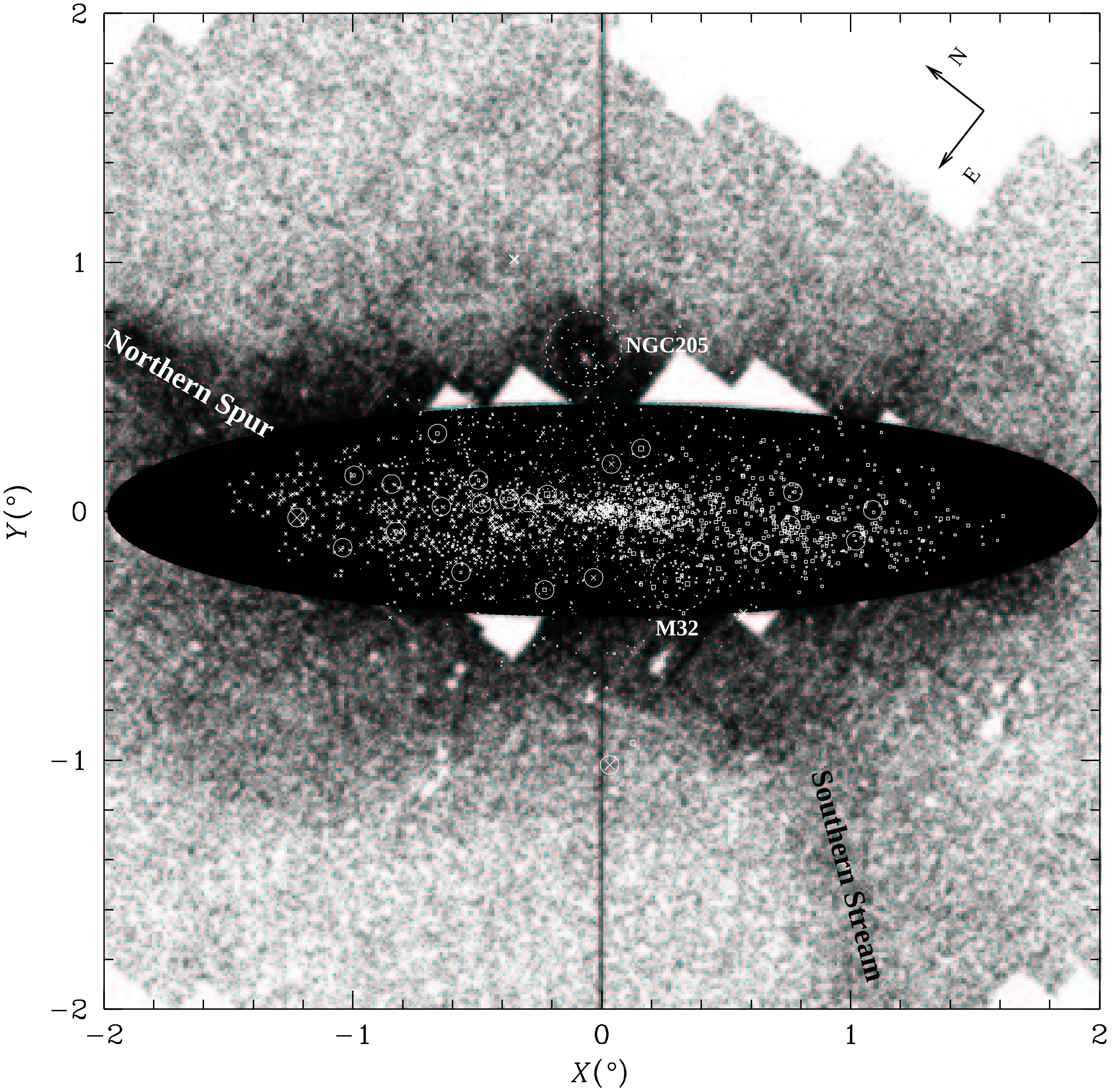

Figure 1. Composite illustration of the data on the star stream in M31, presented in a coordinate system in which X lies along the major axis of M31, increasing toward the SW, Y increases along the minor axis toward the NW, and Z increases along the line of sight. The greyscale shows the star-count data, as published in Ferguson et al. (2002), with the Southern Stream and Northern Spur annotated. The black ellipse indicates the extent and inclination of M31's disk, and the locations of NGC205 and M32 are also marked. The points show the PNe detected in the PN.S survey, with the size of the symbols encoding their line-of-sight velocities relative to M31 (crosses receding, boxes approaching). The circled points are "friendless" PNe that lie more than 4σ in velocity from their 30 nearest neighbours.

nation from these axisymmetric populations would tend to eradicate such an asymmetry. The friendless PNe do, however, lie in exactly the region one would expect to link the Southern Stream and the Northern Spur, so perhaps they could form the linking part of the stream, or possibly they could have been kicked out of the original disk through gravitational interaction with such a stream. As noted above, the width of the stream means that no subtler evidence for the stream can be found in the spatial distribution of friendless PNe, but, as we shall see in the next section, there is more information to be gleaned from their kinematics.

4 THE ORBIT OF THE STREAM

We now seek to model the stream features, and test whether the resulting kinematics are consistent with those of the putative stream PNe that lie between the photometric features. A full simulation of the merger, incorporating realistic tidal stripping and dynamical friction, is beyond the scope of this report. However, a simple single orbit model will go a long way toward describing the shape of this feature and picking out its likely kinematic signature.

One immediate constraint on possible orbits comes from the rather sharp angle through which material must turn in order to get from the Southern Stream to the Northern Spur. The only way for the stream to make such a sudden detour is if it follows a fairly radial orbit that takes it close to the centre of the potential. Further, the potential cannot contain a large "softening" core, which would inhibit the strong gravitational interaction necessary to produce the sharp deviation. Fortunately, as we shall see below, the rotation curve of M31 stays nearly flat all the way to very small radii, so there is no evidence for a significant core in this galaxy. We therefore adopt a flattened singular isothermal potential, $\Phi(R,z) = \frac{1}{2}v_c^2 \ln(R^2 + z^2/q^2)$ where R and z are polar coordinates aligned with the disk plane of M31. For the amplitude, we use the upper envelope of the PNe velocities, $v_c = 250\,\mathrm{km\,s^{-1}}$; for the flattening, we adopt a value of $q = 0.9$, in line with what is found in other galaxies [for example, Majewski et al. (2003)] although the value of the flattening turns out not to be an important factor in this case. The resulting rotation curve is consistent with previous studies of M31 (e.g., Kent 1989).

The orbit must fit two major photometric constraints. In the coordinate system of Figure 1, the Southern Stream is a rather linear feature which enters at projected X, Y values $(1.0, -2.0)$, and is inclined to the sky by some 60 degrees, with more negative values of Y lying further away from us (McConnachie et al. 2003). The Northern Spur has a sharp outer edge near $(-2.0, 0.6)$. Identifying this edge with a turning point of the orbit implies that the speeds in X and Y are very small there. Thus, we are left with two free parameters for the orbit in the Northern Spur, which are the unknown values of Z and v_Z in this region. We have therefore searched the space afforded by these parameters to find if there are any orbits that reproduce the structure of both the Northern Spur and the Southern Stream.

It turns out that these constraints are strongly restrictive, but an orbit does exist that meets all these requirements; it is illustrated in Figure 2. As the upper panel of this figure shows, in addition to matching the three-dimensional structure of the Southern Stream and the turning point in the Northern Spur, it is interesting to note that this orbit originates in the rather confused "G1" region [although Ferguson et al. (2002) point out that the colour of the G1 region differs from that of the stream, bringing into question any direct association].

The lower panel of Figure 2 shows the kinematics of the PNe along the major axis. Note how the upper envelope of the main disk population stays constant at $\sim 250\,\mathrm{km\,s^{-1}}$ at all radii, justifying the choice and normalization of the singular isothermal potential. This normalization is the only use made of the kinematic data in the orbit fitting, yet the friendless PNe trace the projection of the orbit remarkably well. Although a few of the PNe closest to the low-velocity envelope of the main disk population are probably just the tail of the disk component, most follow the velocity of the orbit, including its decline with radius, rather closely. A full model of the stream would have to incorporate the fact that the stream is not in reality a single orbit, but a family of adjacent orbits. The impact of this dispersion is amplified by the singular nature of the potential, which can scatter adjacent orbits in significantly different directions, increasing the spread in velocities: an initial velocity dispersion of $\sim 15\,\mathrm{km\,s^{-1}}$ in the stream stars can lead to a spread of $\sim 100\,\mathrm{km\,s^{-1}}$ in the observed line-of-sight velocities after pericentre passage, much as seen in the data.

Fortunately, the observed major-axis kinematics of the stream are a rather generic indicator of any of the orbits that may connect the two photometric features, irrespective of the details of the adopted model. The geometry of the Southern Stream places the stars within it on an almost radial orbit, so that when they arrive in the disk of M31 they will be travelling at high velocities. However, the sharp edge of the Northern Spur is the signature of a turning point of the orbit, indicative of low velocities. Thus, stars on this link would be expected to show a velocity gradient along M31's major axis from above the circular speed near the Southern Stream to close to zero at the radius of the Northern Spur. The width of the stream and the concentration of the survey toward the plane of M31 means that there is less information in the minor axis projection. However, there is a notable concentration of PNe around arrow 2 on the stream orbit in both velocity projections in Figure 2. Thus, both the asymmetry in the distribution of friendless PNe and their major axis kinematics point to them providing the "missing link" between the Southern Stream and the Northern Spur.

One interesting question is whether the progenitor of the stream still exists as a coherent object, or whether the detritus is all that remains. It is interesting to note that the orbit passes very close to M32 both in position [as pointed out by Ferguson et al. (2002)] and in velocity. If this is not just a chance superposition, then it implies that the streams are the tidal tails of M32 that have been ripped off as it orbits M31. Several less direct lines of argument support this hypothesis:

(i) M32, the Northern spur and the Southern stream all have a red giant branch that is particularly red compared to the rest of the halo of M31 (Ferguson et al. 2002).

(ii) M32 sits more or less in the middle of the populated part of the orbit: the Southern Stream (which leads M32 in the model) is seen to extend to at least 3 degrees towards the south, comparable in length to the trailing part of the orbit which extends through the Northern Spur and back towards the center of M31.

(iii) M32 has the appearance of a highly tidally stripped galaxy. Crudely speaking, one might expect such a tidally stripped galaxy to have lost around half its total luminosity: much less than half, and it would not appear to have been stripped; much more than half and it would have disappeared entirely. It is therefore interesting to note that the number of PNe detected in the stream is similar to what is detected in M32 itself.

Note that this model implies that M32 at present lies about 4 kpc behind the centre of M31, but in front of the disk

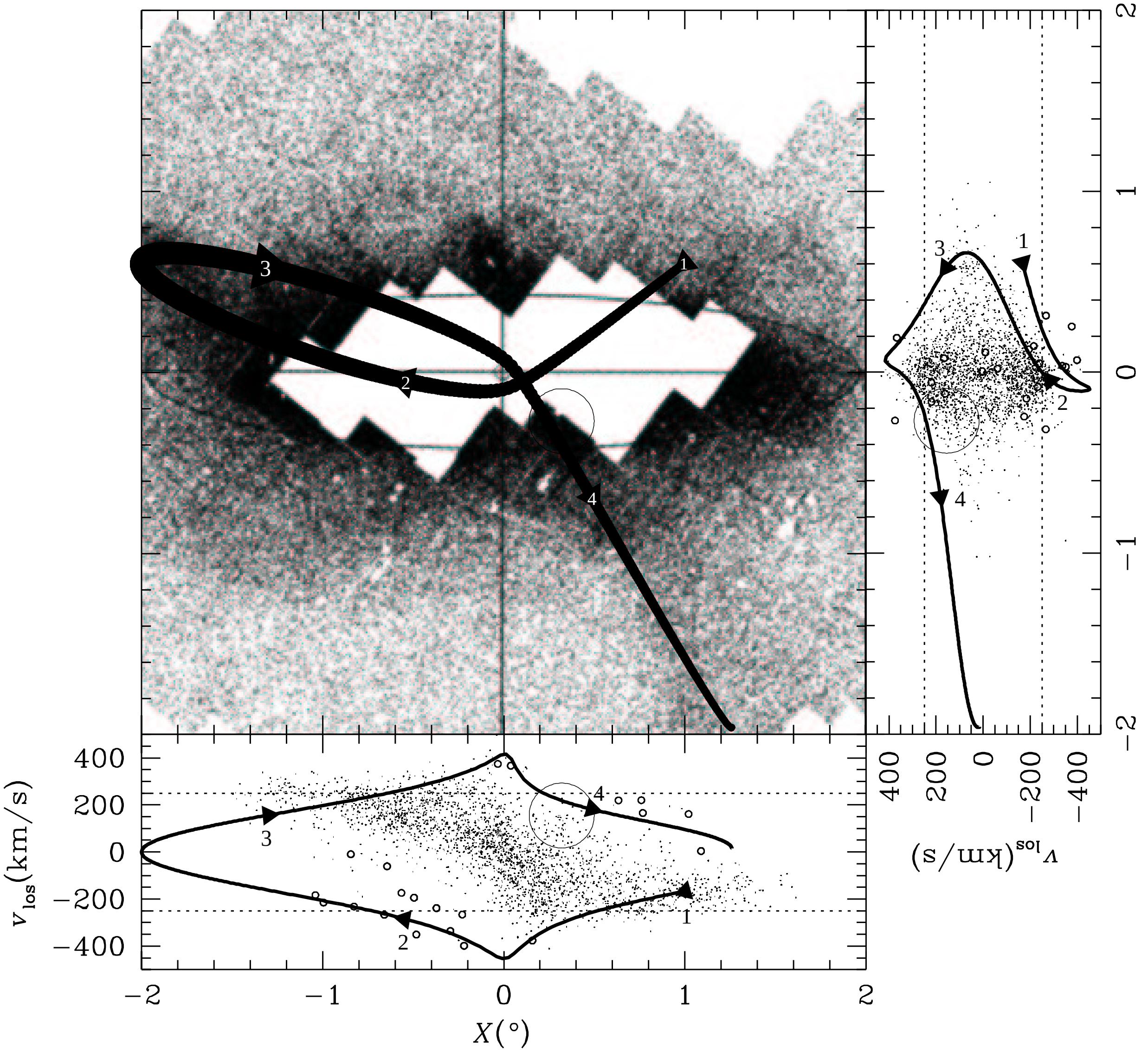

Figure 2. An orbit model fitted to the photometric data. The upper panel traces the shape of the orbit projected on the photometric data, with the thickness of the line indicating its distance along the line of sight, and the numbered arrows showing the suggested direction of motion along the stream. The side panels show the projection of this orbit in line-of-sight velocity with respect to M31 versus distance along the principal axes, superimposed on the PNe data, with the friendless PNe highlighted. These panels show 21 of the friendless PNe; the remaining two are at $v_{\rm los} < -500\,{\rm km\,s^{-1}}$, so are presumably not associated with M31. The dotted lines at $\pm 250\,{\rm km\,s^{-1}}$ show the adopted circular speed. The location of M32 is shown as a circle in each panel.

plane. Whether M32 lies behind or in front of M31 is currently an open question (Mateo 1998), with some indications that it may lie in front (Ford, Jacoby & Jenner 1978); a better relative distance measure would provide a further important check on this model.

It is also worth noting that the direction of motion along the stream is not, as yet, very tightly constrained. If the stars were travelling in the opposite direction, from the Southern Stream toward the Northern Spur, then the only difference in Figure 2 would be that the orbit in the lower panel would be reflected about $v_{\rm los} = 0$. Since the shape of the orbit in this projection is approximately symmetric about $v_{\rm los} = 0$, the difference in the quality of fit is rather slight, so this possibility cannot be ruled out. One significant difference in this configuration is that M32 is no longer simultaneously coincident with the stream both spatially and kinematically, so it is still possible that the stream is the remnant of another satellite altogether. The recently discovered satellite And VIII which Morrison et al. (2003) identified from a concentration of PNe, faint HI clouds, and globular clusters with radial velocity with respect to M31 near $-204\mathrm{km\,s^{-1}}$ would be a candidate: this tidally stretched satellite occupies the region $X = 0-1$, $Y \sim -0.5$ (just beyond the edge of the PN.S survey), near M32 and the point where the Southern Stream meets the disk of M31.

5 CONCLUSIONS

We have demonstrated that the star stream to the south of M31 and the spur to the north of the system can be modeled as parts of a single coherent merger stream stretching over some hundreds of kiloparsecs. As well as explaining where the Southern Stream goes after disappearing into M31, this model also eliminates the awkward need to invoke the most extreme stellar warp known as an explanation for the Northern Spur. This is not to say that the stream is unrelated to the gaseous warp, however, as such a merger event could well play a role in exciting the warp (Quinn, Hernquist & Fullager 1993).

The model also makes a prediction as to where one might be able to detect the stream kinematically, and observations of the PNe in the disk of M31 show that there are stars at exactly the velocities that one would expect. These data trace the stream in the bright disk region where there is no chance of detecting it photometrically, and provide a direct link between the two photometric features at larger radii.

It is at present unclear whether the satellite whose debris makes up the Stream is still present or not. Both M32 and And VIII are possible parents, though they imply different orbit solutions. Direct measurements of the radial velocity of the Southern Stream will be required to distinguish between the possibilities.

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