Asymmetric Warfare: M31 and its Satellites

Mark A. Fardal

Dept. of Astronomy, University of Massachusetts, Amherst, MA 01003

Abstract. Photometric surveys of M31’s halo vividly illustrate the wreckage caused by hierarchical galaxy formation. Several of M31’s satellites are being disrupted by M31’s tidal field, among them M33 and And I, while other tidal structures are the corpses of satellites already destroyed. The extent to which M31’s satellites have left battle scars upon it is unknown; to answer this we need accurate orbits and masses of the perturbers. I focus here on M31’s 150-kpc-long Giant Southern Stream (GSS) as an example of how these can be determined even in the absence of a visible progenitor. Comparing N-body models to photometric and spectroscopic data, I find this stream resulted from the disruption of a large satellite galaxy by a close passage about 750 Myr ago. The GSS is connected to several other debris structures in M31’s halo. Bayesian sampling of the simulations estimates the progenitor’s initial mass as $M_\star = 10^{9.5 \pm 0.2} M_\odot$, showing it was one of the most massive Local Group galaxies until quite recently. The stream model constrains M31’s halo mass to be $(1.8 \pm 0.5) \times 10^{12} M_\odot$. While these small uncertainties neglect several important degrees of freedom, they are likely to remain good even with a more complete model. Future work on M31’s satellites and streams will provide independent constraints on M31’s mass, and reveal the shared history of M31 and its halo components.

1 Introduction

Despite the term “Local Group”, M31 has never interacted with the Milky Way and the two galaxy virial radii are far from touching. So M31 is really just an isolated spiral galaxy that happens to be close enough to study in great detail. Of course even “isolated” galaxies have their satellites; M31 has two nearby ones at around 1% of its own stellar mass (M32 and NGC 205), while the spiral M33 has around 10% of M31’s mass but at such large distance that it is unclear whether it is truly a bound satellite. M31’s disk is far from regular: it is significantly warped, and star formation indicators show a fairly well-defined 10 kpc ring that dominates the total star formation rate. Various authors have attributed features within M31 to the impact of satellites including M32 and NGC 205 (Gordon et al. 2006). In fact, Block et al. (2006) assigned the entire 10 kpc ring to a Cartwheel-like expanding wave, requiring a collision 250 Myr ago which they attribute to M32. However, none of the satellite orbits are currently known, so all of these scenarios are highly speculative.

Photometric surveys of M31’s halo have discovered a great deal of stellar debris, some likely from M31’s disk and some tracing past or ongoing mergers. The recent PAndAS survey (McConnachie et al. 2009, Figure 1) extends to M33 and will eventually fill in a 150 kpc circle around M31, down to stellar magnitudes of $i_{AB} = 24.5$ at $S/N = 10$. Visible in Figure 1 are the Giant Southern Stream...
Figure 1. A 20 × 14 degree view of M31 (272 × 191 kpc assuming a distance of 780 kpc) from the PAndAS survey (McConnachie et al. 2009, maps by A. McConnachie and N. Martin). The inner map shows RGB branch color while the outer map shows false-color density. An inset shows M33 on the same scale. The image is made from matched-filter maps on a tangent plane projection which are sensitive to RGB stars at the distance of M31. Each individual field is 1 degree across. Visible rectangular artifacts are consequences of chip gaps and variations in field quality. The GSS and the NE and W shelves are all metal-rich features as indicated by the red color of their red giant branch. Metal-poor features include several dSph galaxies, the tangential arc to the E connecting to the dSph And I (dot in the middle of the GSS), and a radial stream along the NW edge of the survey at the upper right.

Stream (Ibata et al. 2001), as well as newly discovered tangential and radial streams to the E and NW respectively. Ledges or “shelves” on the NE and W sides are also apparent. These faint features, only made apparent by counting individual stars, are beginning to illuminate the orbits of objects in M31’s halo.

2 The Giant Southern Stream

2.1 Observations

I now focus on the GSS as the best-studied of the tidal features. Metallicity estimates of [Fe/H] ∼ −0.5 suggest the stream originates from a disrupted dwarf galaxy of stellar mass $M_{\text{sat}} \sim 10^9 M_{\odot}$ (Font et al. 2006). From HST photometry that reaches the main sequence, Brown et al. (2006a,b) infer a mean age of 8 Gyr and a total lack of stars younger than 4 Gyr. Distances from the RGB tip magnitude show the stream’s southern end lies far beyond M31 (McConnachie et al.)
Spectroscopic surveys measure the rate at which stream stars speed up as they fall back into M31’s (Ibata et al. 2004; Guhathakurta et al. 2006; Kalirai et al. 2006). The increasing surface brightness as the stream approaches M31 center strongly suggests the main body of the stream’s progenitor lies further ahead in the orbit, but where is it? Early suggestions included M32 (Ibata et al. 2001, but the stream velocities rule out a simple connection), the NE Shelf (Ferguson et al. 2002), or a stream evident in planetary nebulae (Merrett et al. 2003).

2.2 Modeling

The earliest modeling work on the GSS concentrated on fitting orbits through the stream. However, our initial work combining orbits with N-body simulations demonstrated that the stream does not follow the orbit. The stream consists of stars lifted to much higher orbital energies than that of the GSS progenitor, increasingly so as the radius increases, and the progenitor typically will have apocenter at half of the stream’s current length. In our first modeling attempt (Fardal et al. 2006) we provided an approximation connecting the stream and the orbit, and used this to show the stream must continue somewhere to the NE of M31’s center. Later (Fardal et al. 2007) we provided a scenario in which the subsequent loops of the stream create both the NE and W shelves (Figure 2). This model also explains the velocity trend and spatial location of the PNe “stream”, and shows this “stream” is simply a subset of the NE shelf debris with coherent velocities resulting from a caustic feature in observed phase space. This model has since been strengthened by the strikingly similar color-magnitude diagrams within the stream and shelf regions (Richardson et al. 2008), and the apparent detection of the stream’s fourth orbital wrap (Gilbert et al. 2007).
The model can be refined by adding rotation to the progenitor, which improves agreement with the transverse profile of the stream (Fardal et al. 2008).

Our modeling work takes the progenitor to be mostly stellar and starts the collision half an orbit before disruption, neglecting the question of how the satellite gets to that state. In tests with live halos, it seems plausible for the satellite to be dragged in by means of dynamical friction as it loses its halo to tidal stripping. Alternatively, an interaction with a perturber such as M33 may be responsible for putting it on a highly destructive orbit.

2.3 Parameter Sampling

Our model of the GSS appears to meet multiple tests; can we be more quantitative about its implications? We have begun a program of Bayesian sampling of parameter space, within the scenario just outlined. We use around 30,000 N-body simulations to sample a likelihood function formed from the stream’s position, distance, and velocity, plus the brightness of several bins within the GSS proper and the W shelf. The brightness ratio of the GSS and W shelf turns out to be quite sensitive to orbital phase, which puts strong constraints on the model. We run Markov chains in parallel until they converge to equilibrium. The satellites are simple Plummer-model progenitors disrupting within the best-fit M31 potential family of Geehan et al. (2006). That model contains large, quantified uncertainty in the halo mass; the new constraints from the GSS reduce this uncertainty significantly.

At this stage we use a restricted parameter space, eliminating five of the six orbital parameters by fixing them to their best-fit values as a function of orbital phase. We then sample from the dimensions of orbital phase, halo mass, and progenitor satellite mass. These parameters are very well constrained, with orbital phase $t/P = 1.25 \pm 0.15$ periods past disruption at pericenter $760 \pm 20$ Myr ago, virial mass $M_{100} = 10^{12.26 \pm 0.12} M_\odot$ (within $R_{100}$ which encloses 100 times the closure density), and GSS progenitor mass $M_{\text{sat}} = 10^{9.56 \pm 0.22} M_\odot$. Figure 3 shows these distributions. The eliminated orbital degrees of freedom were already well constrained at a given orbital phase, so we do not expect their restoration to widen the error bars dramatically. We have not yet estimated systematic errors, from M31’s distance, radial halo profile, or halo shape for example, but even so it is clear the GSS puts useful constraints on M31’s properties.

2.4 Implications

This modeling work has a number of implications:

- The GSS is due to a previously unknown satellite of M31, not any of the currently intact ones such as M32.

- Its disruption took place 760 Myr ago, small in cosmological terms. This is long after the last recorded star formation in the progenitor, but is far too early to induce the expanding star-forming wave envisioned by Block et al. (2006). (Indeed it is unclear whether the ring is expanding, it may be a static feature).

- The GSS progenitor’s stellar mass of $10^{9.5} M_\odot$, which is in good agreement with the measured stream metallicity, puts it just behind the LMC in the
Figure 3. Left: contours of halo mass $M_{100}$ versus the progenitor's current orbital phase, from our Bayesian sampling. Right: histogram of the progenitor mass, which is taken to be purely stellar.

catalogue of Local Group galaxies. Limits on the heating of M31's disk (Mori & Rich 2008) imply any dark halo in the progenitor was quite minor at the time of disruption.

- We measure M31’s halo mass at $M(r_{100}) = (1.8 \pm 0.5) \times 10^{12} M_\odot$. This mass implies that M33 is very likely to be a bound satellite. Our estimated mass is larger than the most likely values $7-10 \times 10^{11} M_\odot$ from kinematics of M31’s satellites (Evans et al. 2000), but smaller than the value $2.8 \times 10^{12} M_\odot$ inferred from the timing argument (Li & White 2008), and lower than expected from comparisons of the (observed) stellar and (theoretical) halo cosmic mass functions (Yang et al. 2008).

- More generally, N-body simulations can be used effectively to sample the entire parameter distribution in an automated way, at least if the problem has a single well-constrained mode as seems the case here. This shows one can obtain well-specified parameter estimates, errors, and covariances, even in cases where simulations are necessary to estimate the observables.

3 Other Satellites

M33’s tidal disturbances in HI have been long known, but similar disturbances in the stars are detected for the first time in PAndAS (Figure 1). Their presence suggests the material is not falling in for the first time but results from a prior interaction with M31 (McConnachie et al. 2009, Dubinski et al. in prep.). Our recent paper outlines a scenario suitable for exciting disturbances of the observed size scale in M33. M33 is placed on an orbit with orbital period 1.7 Gyr. After one pass through pericenter at 53 kpc, M33 then passes through apocenter at 264 kpc and arrives at its present-day position with tidal distortions comparable in size to those seen in the data. Interestingly, despite the large pericenter, M31’s disk shows some warping and other disturbances from M33’s passage.
A tidal stream that seems to emanate from And I is also prominent in Figure 1. Our eventual goal is to generate reliable orbital scenarios for each of the tidal structures visible in Figure 1, using a combination of photometric and kinematic data. Use of a Bayesian formalism as in Section 2.3 will then result in well-understood uncertainties and multiple independent determinations of M31’s halo mass. As the understanding of the star formation pattern and history within M31’s disk improves, we will be able to correlate this with the orbits and determine the extent to which M31’s satellites have left marks upon it.

Acknowledgments. I thank my collaborators on the work described here, including Arif Babul, Raja Guhathakurta, Alan McConnachie, Mike Irwin, Martin Weinberg, John Dubinski, Larry Widrow, and the other members of the SPLASH and PAndAS collaborations.

References

Block, D. L., et al. 2006, Nat, 443, 832
Brown, T. M., Smith, E., Guhathakurta, P., Rich, R. M., Ferguson, H. C., Renzini, A., Sweigart, A. V., & Kimble, R. A. 2006a, ApJ, 636, L89
Brown, T. M., Smith, E., Ferguson, H. C., Guhathakurta, P., Renzini, A., Sweigart, A. V., & Kimble, R. A. 2006b, ApJ, 652, 323
Evans, N. W., Wilkinson, M. I., Guhathakurta, P., Grebel, E. K., & Vogt, S. S. 2000, ApJ, 540, L9
Fardal, M. A., Babul, A., Geehan, J. J., & Guhathakurta, P. 2006, MNRAS, 366, 1012
Fardal, M. A., Guhathakurta, P., Babul, A., & McConnachie, A. W. 2007, MNRAS, 380, 15
Fardal, M. A., Babul, A., Guhathakurta, P., Gilbert, K. M., & Dodge, C. 2008, ApJ, 682, L33
Ferguson, A. M. N., Irwin, M. J., Ibata, R. A., Lewis, G. F., & Tanvir, N. R. 2002, AJ, 124, 1452
Font, A. S., Johnston, K. V., Guhathakurta, P., Majewski, S. R., & Rich, R. M. 2006, AJ, 131, 1436
Geehan, J. J., Fardal, M. A., Babul, A., Guhathakurta, P. 2006, MNRAS, 366, 996
Gilbert, K. M., et al. 2007, ApJ, 668, 245
Gordon, K. D., et al. 2006, ApJ, 638, L87
Guhathakurta, P., Rich, R. M., Reitzel, D. B., Cooper, M. C., Gilbert, K., Majewski, S. R., Ostheimer, J. C., Geha, M. C., Johnston, K. V., & Patterson, R. J. 2006, AJ, 131, 2497
Ibata, R., Irwin, M. J., Ferguson, A. M. N., Lewis, G., & Tanvir, N. 2001, Nature, 412, 49
Ibata, R., Chapman, S., Ferguson, A. M. N., Irwin, M., Lewis, G., & McConnachie, A. 2004, MNRAS, 351, 117
Kalirai, J. S., Guhathakurta, P., Gilbert, K. M., Reitzel, D. B., Majewski, S. R., Rich, R. M., & Cooper, M. C. 2006, ApJ, 641, 268
Li, Y.-S., & White, S. D. M. 2008, MNRAS, 384, 1459
McConnachie, A. W., Irwin, M. J., Ibata, R. A., Ferguson, A. M. N., Lewis, G. F., & Tanvir, N. 2003, MNRAS, 343, 1335
McConnachie, A. W., et al. 2009, Nat, 461, 66
Merrett, H. R., et al. 2003, MNRAS, 346, L62
Mori, M., & Rich, R. M. 2008, ApJ, 674, L77
Richardson, J. C., et al. 2008, AJ, 135, 1998
Yang, X., Mo, H. J., & van den Bosch, F. C. 2008, ApJ, 676, 248