WAS THE ANDROMEDA STREAM PRODUCED BY A DISK GALAXY?
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Received 2008 March 24; accepted 2008 May 27; published 2008 July 3

ABSTRACT

The stellar halo of M31 exhibits a startling level of inhomogeneity, in which the “giant southern stream” stands out most prominently. Our previous analysis indicates that this stream, as well as several other observed features, are products of the tidal disruption of a single satellite galaxy with stellar mass \(\sim10^9 M_\odot\) less than 1 Gyr ago. Here we show that observed features of the stream and halo debris favor a cold, rotating, disklike progenitor over a dynamically hot, nonrotating one. These features include the asymmetric distribution of stars along the stream cross section and its metal-rich core/metal-poor sheath structure. We find that a disklike progenitor can also give rise to arclike features on the minor axis that resemble the recently discovered minor-axis “streams,” even reproducing their lower metallicity. Although interpreted initially as new, independent tidal streams, our analysis suggests that these minor-axis streams may arise from the progenitor of the giant stream. Overall, our study points the way to a more complete reconstruction of the stream progenitor and its merger with M31, based on the emerging picture that most of the major inhomogeneities observed in the M31 halo share a common origin with the giant stream.

Subject headings: galaxies: individual (M31) — galaxies: interactions — galaxies: kinematics and dynamics

1. INTRODUCTION

Our proximity to the Andromeda galaxy (M31) and our unobstructed view make it an excellent laboratory for studying the stellar halos of large galaxies. Resolved stellar maps have revealed highly complex inhomogeneities in M31’s halo, most strikingly the giant southern stream (GSS), extending \(\sim150\) kpc away from M31’s center in the southeast direction (Ibata et al. 2001; Ferguson et al. 2002; McConnachie et al. 2003; Ibata et al. 2007, hereafter I07) and falling toward M31’s center with relative radial velocities as high as \(\sim250\) km s\(^{-1}\) (Ibata et al. 2004; Guhathakurta et al. 2006; Kalirai et al. 2006). Other significant morphological and kinematic features in the M31 halo include stellar shelves (Ferguson et al. 2002; Fardal et al. 2007, hereafter F07; Gilbert et al. 2007, hereafter G07) and the recently discovered minor axis “streams” (I07). The GSS is especially notable because it offers an opportunity to precisely measure M31’s potential (Ibata et al. 2004; Fardal et al. 2006, hereafter F06) and provides a view into the most significant Local Group galaxy disruption in the last gigayear.

Models detailing the formation of the GSS agree remarkably well with most aspects of the observations and suggest the progenitor had a stellar mass of \(\sim2 \times 10^7 M_\odot\) (F06; F07; Font et al. 2006). Our kinematic analysis in F07 finds that seemingly unrelated features like the “northeast shelf” and less prominent “western shelf” are also the result of the same disruption process (F07), a conclusion supported by independent studies of their stellar populations (Ferguson et al. 2005; Richardson et al. 2008). The observed GSS’s most striking point of contrast with the models is its asymmetry in the transverse direction. As shown both with photometric samples (McConnachie et al. 2003) and spectroscopic surveys (G07), its stellar distribution is sharply truncated on the northeast side and falls off much more slowly on the southwest side. In addition, the current models do not address the observed stellar population gradients within the GSS (I07; Ferguson et al. 2002; McConnachie 2006).

In this Letter, we show that this structure in the GSS can be accounted for if the progenitor hosted a cold, rotating stellar disk, unlike the simple spherical progenitors used in previous simulations. Surprisingly, we find that the disruption of a disk galaxy can also give rise to features similar to the recently discovered arclike minor-axis “streams”; this suggests that most of the major inhomogeneities observed in the M31 halo are tidal debris from the same galaxy that caused the GSS. In \(\S\) 2, we describe our model for the progenitor and our \(N\)-body study of its tidal disruption. In \(\S\) 3, we show results from these simulations, focusing on the transverse density profile of the GSS, the metallicity gradient, and arclike structures that overlap the minor axis. Section 4 summarizes our conclusions.

2. SIMULATION METHOD

Our simulations use the methods worked out in our earlier papers: Geehan et al. (2006), F06, and F07. We use the orbit and potential from Table 1 of F07 and represent a nonrotating progenitor with the spherical Plummer model of F07. For runs with a disk progenitor, we use the same initial position and velocity but substitute a different initial structure of the satellite.

Briefly, our disk models assume the satellite is composed of a bulge and rotating disk of stars. For simplicity, we assume that the dark matter associated with the galaxy has been tidally stripped before the encounter modeled here. We use a hot exponential sech\(^2\) disk with mass \(1.8 \times 10^9 M_\odot\), radial scale length 0.8 kpc, and vertical scale height 0.4 kpc. We add to this a Hernquist bulge of mass \(4 \times 10^8 M_\odot\) and scale length 0.4 kpc. We initialize particle for these components with the package ZENO from J. Barnes. We evolve the satellite in M31’s potential starting from 12 evenly spaced orientations of the disk. From this, we select two models displaying particularly good agreement with observational features, referred to here as disks A and B. In a future paper, we will examine a larger sample of runs and quantify the debris structure in detail (M. A. Fardal et al. 2008, in preparation).
3. RESULTS

3.1. Stream Morphology

Figures 1b and 1d show surface density maps based on the disk A and Plummer models, respectively. Both models reproduce the main feature of a stream extending to the southeast. They also reproduce the observed line-of-sight distances and velocities along the GSS. However, the transverse distribution of GSS stars is strikingly different between the two models—disk A displays a much sharper northeast edge. The observed star-count maps (I07; Ferguson et al. 2002) are not directly comparable since they contain both non–GSS-related M31 components and non-M31 contaminants and are not explicitly calibrated to stellar surface density, but the morphology of the GSS in these maps appears much closer to our disk model.

In Figure 1d, the Plummer model displays many stars spilling over as far as the southeast minor axis, located to the northeast of the GSS. When G07 compared their Keck DEIMOS spectroscopic data near M31’s southeast minor axis to this model, they noted much less spillover from the GSS than predicted by the model. K. M. Gilbert et al. (2008, in preparation) have quantified this by dividing the number of stars moving with GSS-like velocities on the minor axis to those in the GSS core at the same projected radius \( R_{\text{proj}} \). For the nine innermost DEIMOS masks on the minor axis combined, this ratio \( R_{m} = 0.01 \pm 0.02 \); for the three outermost masks on the minor axis, \( R_{m} = 0.05 \pm 0.02 \); and for the mask f135 located somewhat nearer the GSS, \( R_{m} = 0.17 \pm 0.06 \).

In Figure 2a, we compare the density of GSS stars in all three N-body models to these results. We select “GSS” stars by computing the trend of radial velocity with \( v_{\text{R}} \) and taking \( v_{\text{proj}} \) stars that fall within \( \pm 80 \, \text{km s}^{-1} \) of this velocity in the given field, also restricting the stars to those actually in the GSS’s “shell.” We then repeat the procedure for a control field located at the peak of the GSS at the same \( v_{\text{proj}} \), using a smaller interval \( \pm 40 \, \text{km s}^{-1} \) as the GSS core has a sharper velocity distribution. Clearly, the two disk models are in better accord with the observations than the Plummer model.

The sharper northeast edge and smaller minor-axis contamination of the disk models thus imply that the progenitor was rapidly rotating. We will explore this argument in more detail in M. A. Fardal et al. (2008, in preparation).

3.2. Metallicity Pattern

The mean color of GSS red giant branch (RGB) stars is observed to vary in the transverse direction: the GSS is significantly broader in blue than in red stars (Ferguson et al. 2002; McConnachie 2006), probably due to a metallicity gra-
Fig. 2.—(a) Comparison of the minor-axis contamination to observations. The G07 DEIMOS masks (rectangles) are grouped into inner minor-axis masks, outer minor-axis masks, and a single mask (f135) offset from the minor axis. The inset plots for each group show the ratio of the strength of the GSS component to the peak of the GSS at the same position, $R_c$ is measured for our three runs as discussed in the text at $840$ Myr into the runs. Observational estimates and $\pm 2\sigma$ error bars from K. M. Gilbert et al. (2008, in preparation) are plotted as horizontal solid and dotted lines. Clearly, the Plummer model contributes too much debris on the minor axis. (b) Star particle metallicities in the original, predisrupted satellite (black dots) versus radius normalized by the disk scale length. For comparison, observed results for M33’s disk stars are plotted in red: Stephens & Frogel (2002; square); linear approximation to points of Kim et al. (2002; straight line); Galleti et al. (2004; diamonds); McConnell et al. (2006; crosses); Barker et al. (2007; triangles). The color bar translates [Fe/H] to the color scale of Figs. 1e and 1f. (c) Histogram of particle metallicity values in disk A within the core and cocoon regions marked in Fig. 1e. (d) Histogram of particle metallicity values in disk B within the core, cocoon, N arc, and S arc regions marked in Fig. 1f.

3.3. Minor-Axis Arcs

Using MegaCam photometry of M31’s halo, I07 found multiple “streams” or surface density ridges on the minor axis. Streams C and D (the two closest to M31) form two curving ridges at slightly different orientations, which appear to merge as they approach the survey boundary (see their Fig. 22). Stream C appears to be slightly broader than stream D and slightly more metal-rich, although not as metal-rich as the GSS core/cocoon. From Figure 33 in I07, we estimate the mean metallicity of streams C and D to be $-0.82$ and $-0.91$, respectively. Mori & Rich (2008) suggested these streams might be shell features from a satellite disruption, similar to the event that created the GSS but from a different progenitor. While studying our overall sample of runs based on 12 disk orientations, we noticed one (disk B) with two curious “arcs” crossing the minor axis. These are clearest at 680 Myr into the run shown (Fig. 1c). Morphologically, the arcs somewhat resemble streams C and D, with a fatter southern arc nearly merging into a thinner northern arc. Like the observed streams, neither arc crosses the GSS to the southwest. The simulated arcs are significantly farther from M31’s center than the observed arcs, however. As Figure 1f shows, the simulated arcs are significantly less rich in metals than the GSS. Using the same metallicity model as for disk A and the regions defined by boxes in this figure, the mean [Fe/H] is $-0.78$ for the southern arc and $-0.90$ for the northern arc. Thus, there is considerable evidence (although no proof) that these arcs are close analogs of the streams in I07.

In our model, these two arcs originate from the outer regions of the disk and are sharp mainly because of the relatively cold velocity field of the disk. Both arcs consist of material that takes a path around M31’s center nearly opposite to the bulk of the progenitor, explaining why they lie so far from the GSS.
The large size of our disk is thus crucial—a compact M32-like progenitor would be unable to produce similar arcs. The southern arc consists of a group of stars sharing nearly the same energy and coming from fairly far out in the progenitor’s disk. The northern arc consists of stars from even further out (explaining its lower average metallicity), which form a tidal tail during the interaction with M31.

We have not yet searched for these arclike features in the full parameter space of the collision. However, in a few additional runs where we modified the disk mass, radius, and orientation of disk B, we found the arcs were sensitive to the exact input parameters. Thus, we require more theoretical investigation as well as more observational constraints to determine whether the arcs explain some of the I07 minor-axis streams or are merely a fortuitous similarity. If the arcs are shown to be related to the GSS, they will be a very solid argument for the disk nature of the progenitor and will place strong constraints on the parameters of the collision.

4. CONCLUSIONS

In summary, several strands of observational evidence suggest that the GSS originated from a progenitor with a strong sense of rotation, such as a disk galaxy. The transverse density profile of the GSS is more easily produced by a rotating satellite. The observed decline in mean metallicity from the central core of the GSS to its cocoon to the southwest suggests that the progenitor had a strong radial metallicity gradient, like those found mainly in disk galaxies. Furthermore, several observed arcs lying across the minor axis in M31 have close analogs in one of our runs. If shown to be related to the GSS in the manner suggested by our model, these features would be clear confirmation of a disklike progenitor.

A disk galaxy progenitor is seemingly at odds with age measurements of the GSS, which suggest little star formation during the last 4 Gyr (Brown et al. 2006a, 2006b). As the fields used to infer this were placed in the GSS core, it is possible that these estimates were biased to older stars if the progenitor had an age gradient as well as a metallicity gradient. Age measurements in the GSS cocoon would therefore be interesting. It is also possible that the GSS progenitor was more similar to an S0 galaxy than a spiral, perhaps due to strangulation of its gas supply or ram pressure stripping of its gas reservoir.

Many papers have used metallicity to assess the relationship between various M31 disk and halo features. If, as we suggest, the GSS progenitor had a strong metallicity gradient, then metallicity is not a reliable fingerprint of origin, complicating the forensic reconstruction of M31’s merger history. Despite this, the growing database on M31 halo structure is a fascinating puzzle, offering unique insight into the life of a typical disk galaxy and the death of its unfortunate former companions.

We thank Tom Quinn and Joachim Stadel for PKDGRAV, Josh Barnes for ZENO, and Alan McConnachie, Roger Davies, and Evan Kirby for helpful discussions.

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