Angular Information Entropy Evolution of the Milky Way–Andromeda Halo

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Abstract

The Milky Way (MW) and Andromeda (M31) galaxies are predicted to undergo a major merger in approximately four billion years. Using a series of N-body simulations of this interaction, the evolution of the *angular information entropy* of the combined MW–M31 halo has been computed. This statistic quantifies the degree of angular isotropy in logarithmically spaced radial shells and provides a complementary diagnostic to traditional halo shape analyses. The results indicate that early-time angular distributions retain strong anisotropy corresponding to the progenitor halos, while transient minima in entropy correspond to close passages and tidal interactions. Angular mixing proceeds from the outer halo inward, and by late times, the system approaches near-maximal entropy, indicating substantial coarse-grained angular isotropization. This diagnostic robustly captures merger-driven tidal features and relaxation without assumptions regarding halo shape or mass distribution.

1 Introduction

The future collision between the Milky Way and Andromeda galaxies has been extensively studied using proper motion measurements obtained by the Hubble Space Telescope (van der Marel et al., 2012; Sohn et al., 2012; Besla et al., 2012). Observations indicate that M31 is on a nearly head-on trajectory toward the MW, with a predicted first pericentric passage occurring ~ 4 Gyr in the future. Subsequent dynamical evolution is expected to form a single elliptical remnant over the following several billion years.

Galaxy mergers are known to induce tidal distortions, redistribute angular momentum, and produce long-lived tidal streams (Hopkins et al., 2009; Bullock and Johnston, 2005). While inertia-tensor analyses have been traditionally employed to quantify halo shape evolution, they are insensitive to detailed angular structure, particularly in the outer halo, and do not capture the degree of coarse-grained phase-space mixing.

In this work, a mass-weighted *angular information entropy* is employed to quantify the evolution of angular anisotropy in the MW–M31 halo throughout the merger. Unlike shape diagnostics, this method is independent of assumptions regarding ellipsoidal symmetry or total mass and provides a direct measure of information loss associated with angular phase-space mixing.

2 Methodology

Simulations of the MW–M31 merger were conducted using collisionless N-body realizations of each halo. Particles representing the dark matter and stellar components of both galaxies were combined at each snapshot, and the MW center of mass was computed iteratively to remove bulk motion while preserving merger-induced asymmetries.

The angular entropy, S, was computed in logarithmically spaced radial shells between $r = 0.1$ and $r = 400$ kpc, subdivided into $n_\theta = 12$ polar and $n_\phi = 24$ azimuthal bins. For each shell, particle positions (x, y, z) were transformed into spherical coordinates (r, θ, ϕ), and a mass-weighted histogram of angular positions was constructed. The Shannon entropy of this histogram was normalized to the maximum possible entropy, $S_{\max} = \log(n_\theta n_\phi)$:

$$S_{\text{norm}} = -\frac{1}{\log(n_\theta n_\phi)} \sum_i p_i \log p_i \tag{1}$$

where p_i is the mass fraction in angular bin i. Radial shells containing fewer than 50 particles were omitted to suppress shot noise. This procedure was applied to all 802 snapshots spanning the merger, providing a time-resolved measure of angular phase-space structure across the halo.

3 Results

The evolution of normalized angular entropy is illustrated in Figure 1. At early times, entropy values are systematically below unity, indicating that the halos retain distinct angular structures inherited from their progenitors. Lower entropy in the outer halo reflects coherent infall directions and tidal asymmetries, while the inner halo exhibits comparatively higher entropy consistent with shorter dynamical timescales and more rapid phase mixing.

Transient, V-shaped minima in the entropy occur during major dynamical events, corresponding to close passages and periods of strong tidal interaction. These features arise from the formation of coherent streams and merger-induced wakes, which temporarily concentrate mass into narrow angular bins and reduce entropy. This demonstrates that violent relaxation in angular phase space is not monotonic, but rather involves alternating ordering and disordering phases.

A notable characteristic of the entropy evolution is the radial propagation of these features. Disturbances first appear in the outer halo and progress inward, consistent with the weaker gravitational binding and longer orbital periods at larger radii. This outside-in progression highlights the radius-dependent nature of angular mixing and the persistence of coherent tidal features in the halo outskirts.

At late times, entropy approaches unity across all well-sampled radii, indicating near-complete angular isotropization. The outer halo retains modest residual anisotropy longer than the inner regions, reflecting the slower phase mixing timescale at large radii. The results indicate that the halo achieves coarse-grained angular equilibrium well before the final density and shape relaxation is complete, highlighting the diagnostic's ability to capture subtle merger-driven processes invisible to inertia-tensor analyses.

4 Discussion

Angular information entropy offers a complementary perspective on halo relaxation. It quantifies phase-space information loss rather than geometric deformation, allowing the identification of coherent tidal features and merger-induced ordering that would be invisible in traditional shape analyses. The persistence of low-entropy structures at large radii provides insight into the survival of tidal debris, and the eventual convergence to maximal entropy demonstrates the effectiveness of angular mixing in erasing directional memory.

The methodology is broadly applicable to other galaxy mergers and cosmological simulations. By combining mass weighting, angular binning, and shell-based analysis, this approach provides a robust, assumption-free diagnostic for studying halo relaxation, tidal structure, and merger-induced angular reorganization.

5 Conclusions

The MW–M31 merger proceeds through a sequence of angular phases: initial anisotropy from progenitor halos, transient angular ordering during tidal interactions, outside-in angular mixing, and eventual isotropization. The angular information entropy diagnostic captures these phenomena quantitatively and provides a robust tool for studying merger-driven relaxation in galactic halos. This method complements traditional shape analyses and enables detailed tracking of tidal features and angular phase-space evolution.

Acknowledgments

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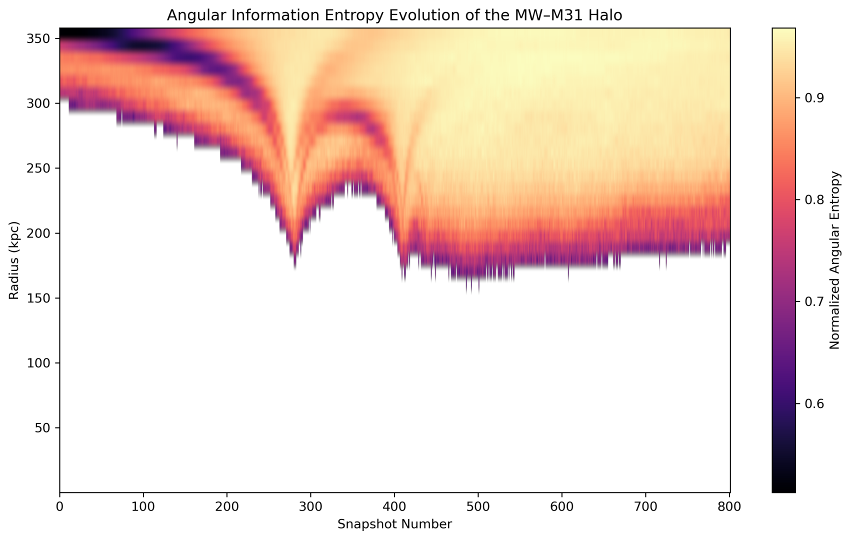

Figure 1: Time–radius evolution of normalized angular entropy in the MW–M31 merger simulation. Each snapshot corresponds to a recombined MW–M31 particle distribution recentered on the MW center of mass. Lower values indicate coherent angular structures such as tidal streams and merger wakes; higher values approach isotropy. Radial shells with fewer than 50 particles are masked. The V-shaped minima correspond to close passages and strong tidal interactions.

References

Besla, G., Kallivayalil, N., Hernquist, L., van der Marel, R. P., Cox, T. J., and Kereš, D. (2012). The role of dwarf galaxy mergers in the formation of the magellanic stream. *Monthly Notices of the Royal Astronomical Society*, 421:2109.

Bullock, J. S. and Johnston, K. V. (2005). Tracing galaxy formation with stellar halos. i. methods. *Astrophysical Journal*, 635:931.

Hopkins, P. F., Cox, T. J., Younger, J. D., and Hernquist, L. (2009). How do disks survive mergers? *Monthly Notices of the Royal Astronomical Society*, 397:802.

Sohn, S. T., Anderson, J., and van der Marel, R. P. (2012). The proper motion of m31: Space motion and orbit of the andromeda galaxy. *Astrophysical Journal*, 753:7.

van der Marel, R. P., Fardal, M. A., Besla, G., Beaton, R. L., Sohn, S. T., Anderson, J., Brown, T. M., and Guhathakurta, P. (2012). The m31 velocity vector. iii. future milky way-m31-m33 orbital evolution, merging, and fate of the sun. *Astrophysical Journal*, 753:8.