The Orbital Distribution of Satellite Galaxies

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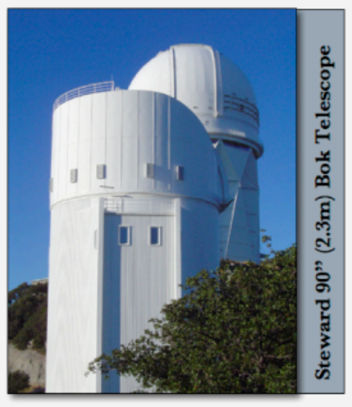
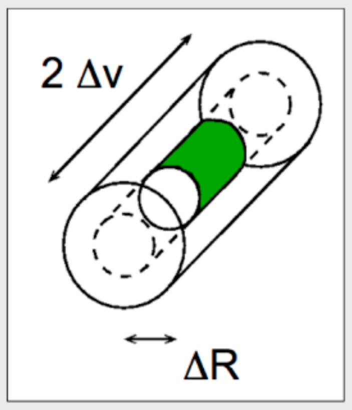


ABSTRACT

We measure the distribution of velocities for prograde and retrograde satellite galaxies using a combination of published data and new observations for 78 satellites of 63 extremely isolated disc galaxies (169 satellites total). We find that the velocity distribution is non-Gaussian (>99.9% confidence), but that it can be described as the sum of two Gaussians, one of which is broad (σ = 176 ± 15 km/s), has a mean prograde velocity of 86 ± 30 km/s, and contains ~55% of the satellites, while the other is slightly retrograde with a mean velocity of -21 ± 22 km/s and σ = 74 ± 18 km/s and contains ~45% of the satellites. Both of these components are present over all projected radii and found in the sample regardless of cuts on primary inclination or satellite disc angle. The double-Gaussian shape, however, becomes more pronounced among satellites of more luminous primaries. We remove the potential dependence of satellite velocity on primary luminosity using the Tully-Fisher relation and still find the velocity distribution to be asymmetric and even more significantly non-Gaussian. The asymmetric velocity distribution demonstrates a connection between the inner, visible disc galaxy and the kinematics of the outer, dark halo. The reach of this connection, extending even beyond the virial radii, suggests that it is imprinted by the satellite infall pattern and large-scale effects, rather than by higher-level dynamical processes in the formation of the central galaxy or late-term evolution of the satellites.

OUR PROJECT: Can we find an observational link between the rotation of satellites tracing the outer dark halo and the inner visible disk?

Simulations of galaxy formation and evolution (e.g. Okamoto et al. 2005, Governato et al. 2007) can predict realistic satellite properties and distributions within evolved galaxy halos. To constrain these models and test CDM, we observe real satellites of isolated primary disks. The difficulty is that for galaxies outside the Local Group, typically just one or two satellites are available for study. We therefore adopt the 'ensemble approach' (following Zaritsky et al. 1997, hereafter ZSFW) and stack the satellites of a 'typical' primary. This allows us to construct a statistically significant measure of the projected satellite rotational velocity distribution around their host, providing new aims for simulations of galactic halo substructure.



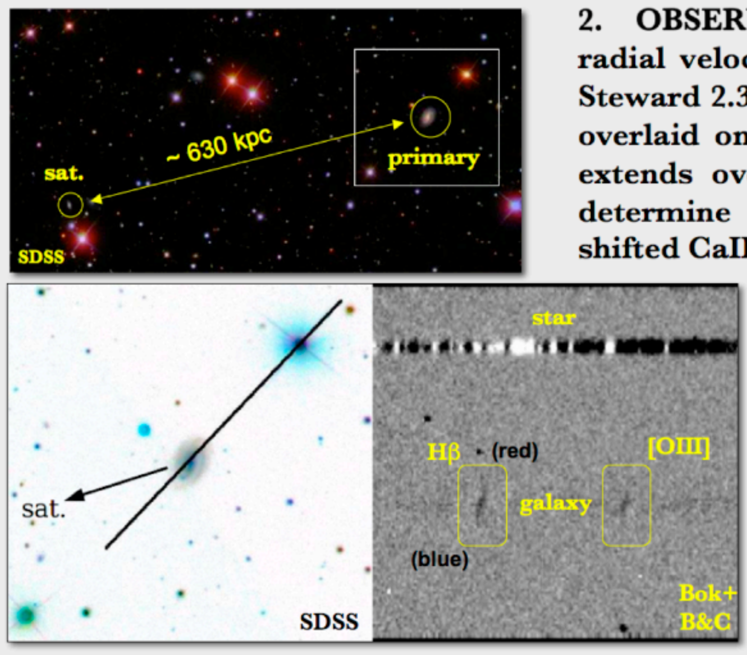
1. **SAMPLE SELECTION:** A well-defined, homogeneous primary galaxy sample is crucial for the ensemble approach. We select strictly isolated disk galaxies below z ~ 0.1 from SDSS-DR4, with criteria refined using mock catalogs from cosmological N-body simulations (see Bailin et al. 2008). The selection criteria applied are:

No bright galaxies in outer cylinder:
$\Delta v < 1800$ km/s
$\Delta r < 1$ Mpc/h
$\Delta m > 0.8$

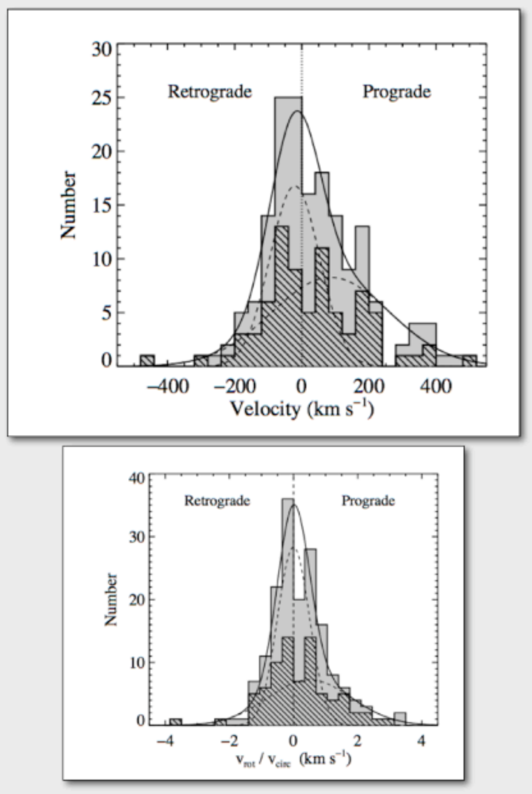
Satellites lie in green cylinder:
$\Delta v < 900$ km/s
$\Delta r < 500$ kpc/h
$\Delta m > 2.2$

(Length of green cylinder must be half length of dashed cylinder, otherwise one satellite can belong to multiple primaries).

With these criteria, we assume that any selected primary and its unseen halo dominates the local potential, and that any satellites nearby are not associated with any other primaries.

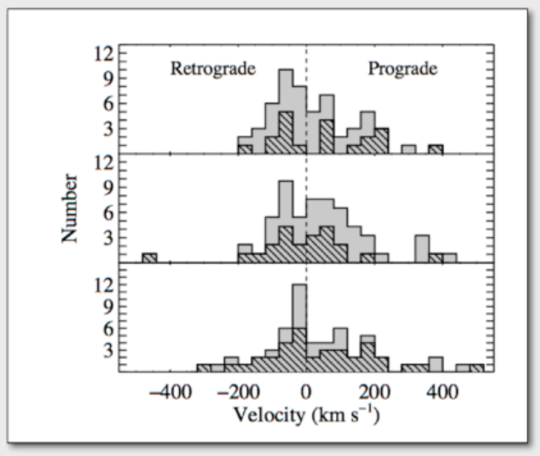


2. **OBSERVATIONS:** The SDSS provides the positions and relative radial velocities of the primaries and their satellites. We then use the Steward 2.3m Bok telescope and B&C single-slit spectrograph (slit image overlaid on SDSS negative image at lower left, which in this case also extends over a bright star and helps confirm slit/sky orientation) to determine the rotation direction of the primaries via red- and blue-shifted CaII H&K absorption, Hβ and [OIII] emission lines (spectrum shown at bottom right). This allows us to determine the projected orbital velocity of the satellite about its host. We then orient all primaries in the same direction and examine the ensemble cloud of satellites about a typical isolated disk galaxy. Any comparisons to simulations, however, must begin by matching our primary inclination distribution (see paper).

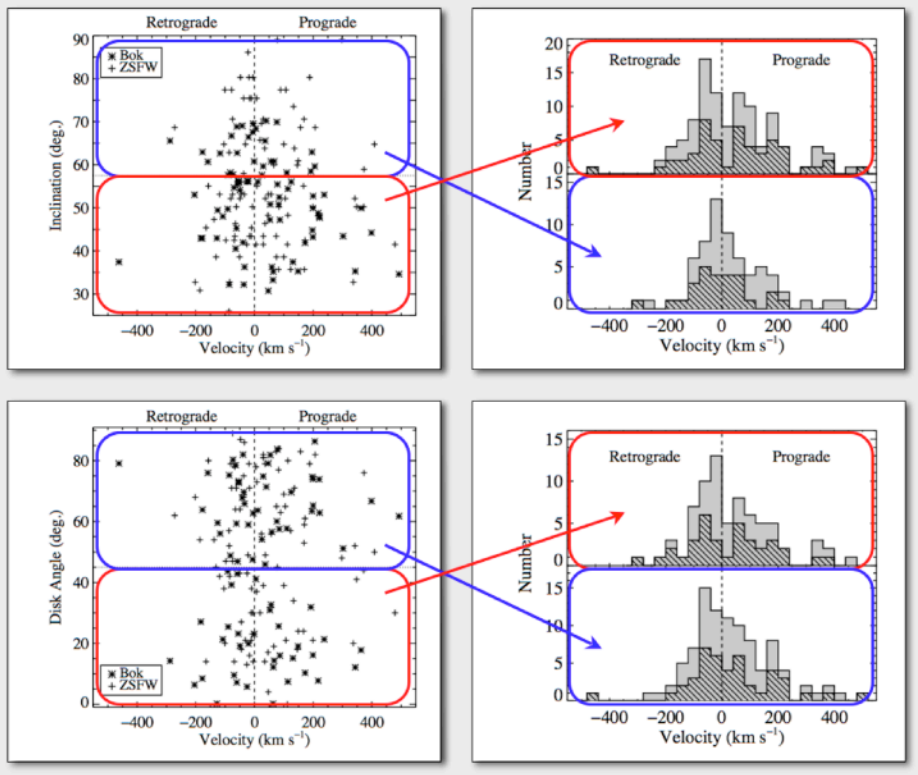


3. **Projected radial rotation velocity distribution in 40 km/s bins. Our new Bok sample is shown in hatched linestyle and the overall (Bok + ZSFW) sample is shaded. Positive values depict satellites rotating in the same sense as the disc, while negative values indicate counter-rotating satellites. These data are inconsistent with a normal distribution at the >99.9% CL. A double-Gaussian model provides an acceptable fit to the distribution (solid linestyle, with the individual Gaussian components in dashed linestyle; see abstract for values). The fit parameters were derived from the *unbinned* v_r distribution using a maximum likelihood approach. They are not a fit to the binned distribution shown here.**

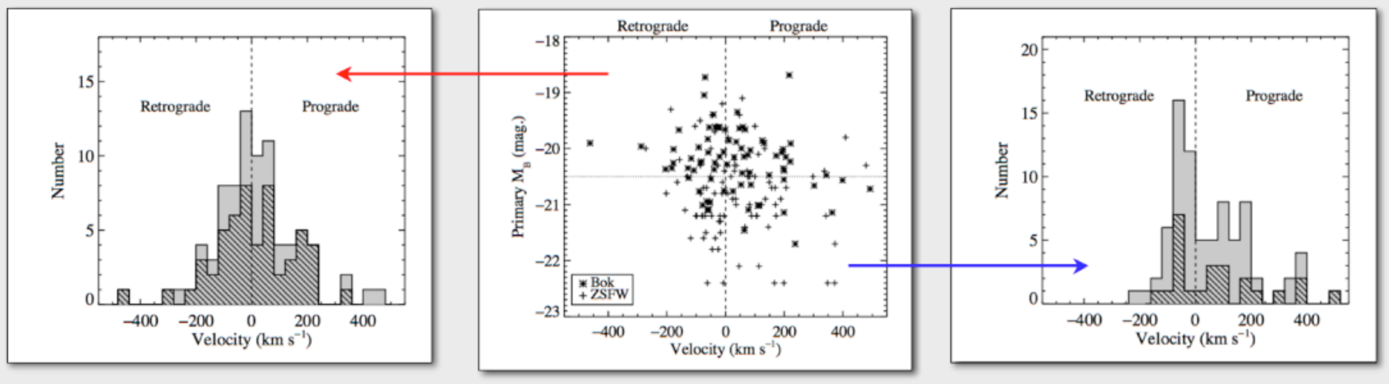
We remove the potential dependence of satellite velocity on primary luminosity using the Tully-Fisher relation and still find the velocity distribution to be asymmetric and even more significantly non-Gaussian (see figure at left.)



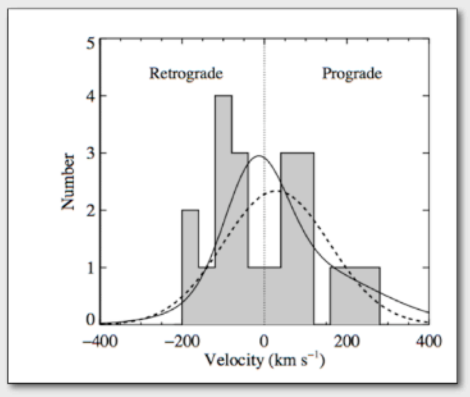
4. **Rotational velocity distributions in projected radii bins (from top) [0 - 162], [162 - 368], and [368 - 750] kpc, each containing 56, 56, and 57 satellites, respectively. The overall asymmetric distribution is apparent throughout the halo.**



5. **The asymmetric distribution is apparent across the range of primary inclinations and satellite disk angles.**



6. **Rotational velocity distributions of satellites around the 'faint' (left) and `bright' (right) primary subsamples, defined on either side of M_B = -20.5 mag (center figure). The narrow retrograde and broad prograde components are clearly distinguished in the bright subsample, yet the faint subsample remains inconsistent with a single Gaussian distribution at the >99% CL even though the binned plot shows little difference.**
These results may reflect a true physical difference among satellite orbits of bright and faint primary galaxies, or the ease with which one can distinctly separate the prograde component for the brighter primaries, which will be centered at larger mean velocity in the more luminous systems (see e.g. Guzik & Seljak 2002).



7. **Projected rotational velocity distribution for satellites around M31 (see paper for references). We would like to test whether or not the double-Gaussian shape may be due to two distinct *primary* galaxy populations, rather than two satellite populations. This requires having single primaries with enough satellites for good statistics. Here we make a first attempt using M31. The rescaled single- and double-Gaussian fits from the ensemble sample are overplotted in dashed and solid linestyle, respectively. The small sample size from the M31 satellites currently precludes any distinction between these two models.**

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