Kinematic transitions and streams in galaxy halos

A.J. Romanowsky,1,2 J.A. Arnold,2 J.P. Brodie2, C. Foster3, D.A. Forbes4, H. Lux5, D. Martínez-Delgado6, J. Strader7, S. Zibetti8, and the SLUGGS team

1Dept. Physics & Astronomy, San José State Univ., San Jose, CA 95192, USA
2Univ. of California Observatories, Santa Cruz, CA 95064, USA
3Australian Astronomical Observatory, North Ryde, NSW 1670, Australia
4Centre Astrophysics & Supercomputing, Swinburne Univ., Australia
5School of Physics & Astronomy, University of Nottingham, NG7 2RD, UK
6Astronomisches Rechen-Institut, Heidelberg, Germany
7Dept. Physics & Astronomy, Michigan State Univ., East Lansing, MI, USA
8INAF - Osservatorio Astrofisico di Arcetri, I-50125 Firenze, Italy

Abstract. The chemo-dynamics of galaxy halos beyond the Local Group may now be mapped out through the use of globular clusters and planetary nebulae as bright tracer objects, along with deep multi-slit spectroscopy of the integrated stellar light. We present results from surveying nearby early-type galaxies, including evidence for kinematically distinct halos that may reflect two-phase galaxy assembly. We also demonstrate the utility of the tracer approach in measuring the kinematics of stellar substructures around the Umbrella Galaxy, which allow us to reconstruct the progenitor properties and stream orbit.

1. Stellar halos beyond the Local Group

Galaxies may generically consist of two basic components: an inner region that hosts in-situ star formation, and an outer accretion zone where satellite galaxies fall in and disrupt into halo streams and substructures. These components are reflected observationally by regions of distinct stellar densities, kinematics, dynamics, and chemical abundances. Thus these distinctions provide key information about the assembly histories of galaxies, while dynamical analyses of coherent halo substructures supply unique tests of the gravitational potential.

The Milky Way is a natural focal point for studying halo transitions, substructures, and satellites, and for testing predictions from hierarchical galaxy formation theory (e.g., Carollo et al. 2007, Law & Majewski 2010, Kroupa et al. 2010, McCarthy et al. 2012). However, there are limitations to such comparisons owing to the expected stochasticity of galaxy assembly (Cooper et al. 2010). Indeed, the wealth of emerging information about the nearby galaxy M31 has revealed remarkable differences in the stellar halo properties of these two galaxies (e.g., Font et al. 2006, Deason et al. 2013). This variation highlights the need to extend detailed halo chemo-dynamical studies be-
Beyond one or two local spiral galaxies, to galaxies of all types and environments, in order to obtain a robust understanding of structure formation in the universe.

Observing more distant stellar halos and substructures is very challenging, owing to the faintness of the starlight. Progress has been made with imaging of stellar halos, (e.g., Mouhcine et al. 2010; Martínez-Delgado et al. 2012), but direct spectroscopy remains more elusive, with success so far only in the inner halos (out to tens of kpc; e.g., Coccato et al. 2010; Murphy et al. 2011). For the outer halos, an effective solution was presaged by the discovery of the chaotic nature of the Milky Way halo (Searle & Zinn 1978): through the exploitation of bright tracer objects such as globular clusters (GCs) and planetary nebulae (PNe). Current instrumentation permits the study of halo kinematics out to distances of ≃ 50–100 Mpc (Gerhard et al. 2005; Misgeld et al. 2011).

GCs and PNe are not only mere kinematical tracers but also provide additional clues to galaxy formation by tracing multiple underlying stellar populations. The PNe and metal-rich GCs trace the metal-rich field stars – with the PNe possibly biased toward intermediate-age populations – while the metal-poor GCs trace the underlying classical metal-poor stellar halos which are otherwise very difficult to observe directly (cf. Park & Lee 2013). The potential of this method is demonstrated by the kinematical differences detected among these subpopulations within single galaxies (Coccato et al. 2013), and by expectations for galaxy merger remnants to host dynamical subcomponents that are traceable to distinct parts of their progenitors (Hoffman et al. 2010).

2. Early-type galaxies

Some giant early-type galaxies (ellipticals and lenticulars) host kinematically decoupled or distinct cores (KDCs), with strong rotational transitions on scales of ≃ 0.5 kpc (Krajnović et al. 2011). These features may be residues of central starbursts, and are relatively rare, while one could expect transitions to be more common at larger radii, reflecting generic two-phase assembly histories. The accreted component is predicted to be substantial outside of a few kpc, and to increase in importance with galaxy mass (Oser et al. 2012; Lackner et al. 2012).

Halo kinematic transitions in early-types are now being explored through two major surveys: one using the PN.Spectrograph (Coccato et al. 2009), and the other called SLUGGS (Brodie et al., in preparation). The latter is based on GCs (Pota et al. 2013), along with a novel multi-slit technique for mapping out integrated stellar spectroscopy in two dimensions to ≃ 3 effective radii ($R_e$; Proctor et al. 2009).

These surveys have revealed a remarkable variety of rotation profiles and kinematic twists in the galaxy halos that deviate from the patterns found in their inner regions. Some cases resemble giant KDCs, and may be considered kinematically distinct halos (KDHSs; Foster et al. 2013; Figure 1). In a similar vein, Hi disks and rings around early-type galaxies appear to be frequently decoupled from their central regions (Serra et al. 2014), while large-radius transitions in density and stellar populations have also been found (e.g., Forbes et al. 2011; Huang et al. 2013; Petty et al. 2013) – all of which may support the two-phase paradigm.

Interpreting the large-radius kinematical data will require detailed dynamical modeling, and comparisons to simulations of galaxy formation. Such simulations in a cosmological context have shown kinematic diversity in their outer parts (Wu et al. 2014), with further work needed to connect these variations to specific assembly histories.
Figure 1. Smoothed wide-field stellar velocity maps of two nearby early-type galaxies from the SLUGGS survey (Arnold et al. 2014). The X axes are aligned with the photometric major axes. NGC 4365 has a well-known KDC embedded in a “rolling” minor-axis rotation pattern, which is now seen to extend to large radii. This galaxy may be a major-merger remnant, with the rolling rotation tracing a faded polar ring that originated in progenitor disk spin (Hoffman et al. 2010). NGC 4473 has an abrupt kinematic change at $\sim 1R_e$ to a kinematically distinct halo, which shows simultaneous major and minor axis rotation (see also Foster et al. 2013).

3. Stellar streams

While kinematic transitions in galaxy halos may reflect the jumbled debris from multiple accretion events spanning a Hubble time, the cases of visible stellar streams are valuable in order to study the dynamics of accretion. Such streams may be more common than the canonical massive, gas-rich polar rings owing to the lower satellite masses and to the morphology–density relation which implies that ongoing accretion events will generally be gas poor. This presents again the observational obstacle of low surface brightness, with bright tracers as the escape clause, along with a new technique for using blends to extend individual-star spectroscopy out to $\sim 5$ Mpc (Theakanath et al. 2014). The tracers approach with PNe was demonstrated for the Giant Southern Stream in M31 (Merrett et al. 2003), and has been applied with GCs to streams at $\sim 20$ Mpc distances (Romanowsky et al. 2012; Blom et al. 2014).

For maximal stream constraints, a combination of GCs and PNe should be used, as recently done in the Umbrella Galaxy, NGC 4651 (Foster et al., in preparation; Figure 2). Here a handful of velocities in the shell-and-stream structure were sufficient to delineate its trajectory in phase-space and to enable a fit with a simple orbit model. The substructure photometry and dynamics indicate a disrupted gas-poor nucleated dwarf galaxy on a very eccentric, fairly polar orbit, analogous to the Giant Southern and Sgr streams in the Local Group. More detailed modeling of the host galaxy disk perturbation (cf. Purcell et al. 2011), and of the stream dynamics, could provide constraints on the dark matter distributions of both the satellite and its host.

References

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Figure 2. The Umbrella Galaxy, NGC 4651. Left: A color image combining Subaru/Suprime-Cam with amateur telescope data. A narrow stream terminates in an arc to the left, with several plumes and shells to the right of the galaxy. These features, in combination with kinematics measured from GC and PN tracers, have allowed a reconstruction of the stream progenitor and orbit. Right: Position–velocity phase-space of tracers, where green star symbols are associated with the umbrella feature. The curves show a model of the shell caustics (Sanderson & Helmi 2013).