THE EXTENDED SHAPES OF GALACTIC SATELLITES

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We are exploring the extended stellar distributions of Galactic satellite galaxies and globular clusters. For seven objects studied thus far, the observed profile departs from a King function at large $r$, revealing a “break population” of stars. In our sample, the relative density of the “break” correlates to the inferred $M/L$ of these objects. We discuss opposing hypotheses for this trend: (1) Higher $M/L$ objects harbor more extended dark matter halos that support secondary, bound, stellar “halos”. (2) The extended populations around dwarf spheroidals (and some clusters) consist of unbound, extratidal debris from their parent objects, which are undergoing various degrees of tidal disruption. In this scenario, higher $M/L$ ratios reflect higher degrees of virial non-equilibrium in the parent objects, thus invalidating a precept underlying the use of core radial velocities to obtain masses.

1 Introduction

One of the more remarkable aspects of galactic dark matter (DM) is that the smallest galactic systems, the dwarf spheroidal galaxies (dSph), appear to have the largest mass-to-light ratios ($M/L$) – approaching 100 in some Milky Way dSphs. Even among the dSph galaxies it appears that intrinsic brightness is anticorrelated with $M/L$, which has prompted the suggestion that all dSph galaxies have about the same mass, they just vary in luminosity. Globular clusters, the next smallest stellar systems, seem not to have DM. It has long been recognized that a primary difference between dSphs and globular clusters lies in the concentrations of their radial profiles. Thus, it is reasonable to consider the structure of a stellar system somehow to be connected to the inferred $M/L$’s, although what the causal relationship may be is unclear: Could
the typical, fluffy profile of dSphs be a response to large DM contents, perhaps in the form of extended cold DM halos? Or do more extended stellar systems somehow produce the appearance of large $M/L$’s, even if artificially?

Deep HST imaging to derive the luminosity function of the Ursa Minor dSph has shown no difference with the luminosity function of the globular cluster M92 down to $0.45 \, M_\odot$, which establishes that the apparent stellar $M/L$ is the same for both low and high $M/L$ systems. Thus, it is not surprising that many attempts to eradicate the “high $M/L$ problem” have focused on potential problems with the methodology for dynamically inferring masses. Despite general differences in concentrations, and even shapes, between most globular clusters and dSphs, it is still commonplace to adopt King’s dynamical formalism derived for globular clusters to describe dSph galaxies. The assumptions implicit in this methodology are that the stellar system has an isotropic velocity distribution and a well-defined, flat core in its light profile (i.e., that King profiles fit the light), that $M/L$ is independent of radius, and that the system is in virial equilibrium. Concerns have been raised not only regarding the applicability of each of these assumptions to dSph systems, but also to whether the dynamics of dSphs are simply more complex than accounted for by King’s model. For example, several groups have studied the possibility that the central velocity dispersions, $\sigma_{v,c}$, are inflated due to superposed orbital motions from binary stars, but each concludes that binaries alone cannot account for the large inferred $M/L$’s. Improperly assuming velocity isotropy can also alter inferred $M/L$’s, although apparently by only factors of two or three, not by factors of $10^{-3}$ needed to “solve” the dSph $M/L$ “problem.”

Perhaps the most controversial assumption has been that of virial equilibrium. Hodge & Michie long ago proposed that Galactic tides may act to inflate $\sigma_{v,c}$. Later analyses found that perhaps some, but not all high $M/L$ measures for dSphs can be accounted for by tides, and that, rather than inflating $\sigma_{v,c}$, tides should produce ordered, shearing-like motions. Kuhn & Miller suggested the possibility that incited resonances between internal stellar orbits and the bulk Galactic orbit of a stellar system could also inflate $\sigma_{v,c}$, but Sellwood & Pryor counter that such oscillatory motions are not excited by motion in a logarithmic potential. The discovery of potential “extra-tidal” stars around some dSphs raises the specter that tidal disruption processes, long expected to be acting on some globular clusters, also affect the supposedly DM-dominated dSphs. Prodigious disruption, of course, would be inconsistent with an assumption of equilibrium. The Sagittarius (Sgr) galaxy provides an obvious demonstration that Galactic dwarf satellites can face substantial tidal disruption, and its derived $M/L$, in the range of $20-100$, might be considered a convenient illustration of potential problems with dynamical
masses. However, Sgr may be a red herring in the dSph DM argument because its present morphology is atypical of Galactic satellites, and it is not obvious that the Sgr progenitor would have been similar to “normal” dSphs (though it is likely that Sgr merely represents an extremely disturbed form of dSph). On the other hand, studies of the light profiles of “normal” dSphs also reveal signs of possible tidal effects in the form of radial profile “breaks” which are predicted as a manifestation of stripped stars in models of the tidal disruption of dSph galaxies in a Galactic potential.

The existence of these profile breaks puts interesting twists on the DM debate. If the break populations are truly unbound, the degree of dynamical equilibrium in dSphs is questionable. Note that Piatek & Pryor, show that one pericentric passage of a satellite is insufficient to perturb a satellite enough to raise the derived $M/L$. Nor does the presence of unbound stars inflate the measured $\sigma_v$ of their parent systems. However, Kroupa has commented that earlier disruption models utilized N-body codes too small to follow the evolution of a satellite to complete dissolution, and that larger N-body simulations of large satellites show that late stages of disruption can produce tidal debris that in places may converge into 1% stable remnants that resemble dSphs, but which contain no DM such a scenario echoes an earlier suggestion that “large $M/L$ dSphs” are simply coherent, unbound groups of stars on similar orbits, the remnants of tidal disruption. The notion of dSphs and some globular clusters being remnant nuggets floating in, and as, the debris of the disruption of larger progenitors was first postulated by Kunkel and Lynden-Bell and more recent analyses discuss the possibility of at least some “dynamical families” of daughter objects in the outer Galactic halo. But while Mayer et al. confirm that inflated $M/L$ can occur along preferred lines of sight to a disrupting system, apparently this might only account for a small number of the dSphs currently inferred to have high $M/L$.

However, if the break populations are bound, it suggests, in the least, that the structure of dSphs is more complicated than that of typical globular clusters. One prosaic explanation for the existence of bound break populations might be that they are a cloud of still bound retrograde rotating stars, the product of the dynamical imbalance in normal evaporative processes to preferentially strip prograde orbiting stars; such a model should lend itself to an easily recognizable observable kinematical signature at the tidal radius, $r_t$. Alternatively, the break populations may represent an extended, secondary “halo” component, still embedded in deep dSph DM halos. According to Burkert, dSphs need these large DM halos, since the cut-off radii of King profile fits to dSphs are too small to be the true $r_t$ if the inferred $M/L$ are correct.

Searching for and following these break populations to extremely large radii
is therefore critical, in order to (1) check on their ubiquity, particularly among
the large $M/L$ systems, (2) look for correlations in the properties of these
break populations as a function of the characteristics of the core of the system,
and (3) see if the break populations organize themselves, eventually, into the
expected tidal streamers. The existence of tidal tails and their association to
the break populations is a key discriminant to the various high $M/L$ models
discussed, since “even modest amounts of dark matter will be very effective at
containing visible stars and halting production of tidal tails”\textsuperscript{30}. We have set
out to explore the extended profiles of Galactic satellites (dSphs and clusters),
with these, and a number of other, rationale in mind.

2 Extended Profiles of Galactic Satellites

Our survey strategy is intended to go beyond merely obtaining a more accurate
rendering of the light profiles of satellites: We aim to identify stars widely sepa-
rated and dispersed from the cores of their parent systems, and from which
we may gather dynamical constraints. The technique we employ to work in
the low density, “needle in the haystack” regime of the outer profiles of stel-
lar systems is based on multifilter imaging, including use of the $DDO51$ filter
centered on the gravity-sensitive Mgb triplet and MgH lines at 5150 Å. The
Washington $M-T_2$ color provides a temperature index against which to com-
pare $M-DDO51$ colors, which gauge surface gravity (primarily) and [Fe/H]
(secondarily) in late G through early M stars\textsuperscript{7,25}. Thus, by imaging a stellar
system to magnitudes not much fainter than the red giant branch (RGB), we
can discriminate, with a high degree of confidence and relative ease, between
giants associated with that system and foreground disk dwarf stars. The latter
are a primary contaminating nuisance and the limiting factor in the effective
use of simple starcounting techniques to trace the extended structures of re-
solved stellar systems. The number of field giant contaminants (i.e., giants that
just happen to be at the same color and magnitude as the RGB of the parent
system) is relatively small (but is subtracted off from the derived density pro-
files in Figure 1 below). Removing virtually all field star “noise” enables us to
map these stellar systems to well past their King limiting radii, which is often
adopted as the tidal radius for a stellar system.

Hunting for individual far-flung stars that can be associated with a parent
stellar system allows one to explore the system to extraordinarily low effec-
tive surface brightnesses (some ten or more magnitudes below sky brightness).
We have demonstrated this technique in our study of the Carina\textsuperscript{26} and Ursa
Minor\textsuperscript{34} dSphs. The reality of our identified “candidate extratidal stars” has
been investigated in a variety of ways. An \textit{a posteriori} analysis of the poten-
tial contamination of the isolated RGB sample by photometric errors yields at most an 18% expected false detection rate within our Carina sample. This is much lower than the contamination rate implied by the analysis of our Carina data by Morrison et al.; however, we have enumerated a number of assumptions and other problems (foremost among them, utilization of a greatly inflated error distribution for our sample) with the Morrison et al. analysis that invalidates their conclusions. Our estimated low false detection rates are upheld by spectroscopy: (1) Of 50 spectroscopically studied candidate RGB giants in the Carina sample we find a false detection rate exactly as predicted above (18%), and we find nine members beyond the King cut-off radius. (2) For 155 stars in the Ursa Minor field with published spectroscopy, we are 100% accurate in classifying dwarfs and giants. The identified extended RGB population is mimicked by the distribution of Ursa Minor’s blue horizontal branch stars. (3) In similar studies of the And I and III dSphs, Keck spectroscopy of 54 of our giant candidates reveals a 100% identification accuracy.

We have now made “associated star” maps of a number of dwarf galaxy and globular cluster satellites of the Milky Way and M31 systems. Figure 1 shows preliminary results on five other satellites with published $M/L$: the Sculptor, Leo I and Leo II dSph galaxies, and the globulars NGC 288 and Palomar 13. For Sculptor, Leo I and NGC 288 we have employed the techniques discussed above. For Pal 13, we use a proper motion membership analysis to identify extratidal candidates, while to obtain the density profile of Leo II we have used the classical method of starcounts on very deep $UBV$ imaging.

3 Trend of Departure Density with $M/L$

All seven systems in Figure 1 show, with varying amplitudes, a break from their central King profile density distributions that heralds the onset of a second structural population with a shallower, more or less power law, fall-off. We define the “departure density” as the density, normalized to the core, at which the observed profile departs from the best fit King profile to the central parts. Among the ensemble in Figure 1 one sees a trend of higher departure density for higher $M/L$ objects (Figure 2). Interpretations at both extremes of the dSph DM debate can be postulated to account for this apparent trend: (1) dSph galaxies (and clusters) with DM can support secondary, but bound, “halo” populations of stars. Figure 2 implies that objects with larger $M/L$ have larger DM halos that can support more substantial stellar halos. (2) The extended populations around dSph galaxies (and some globular clusters) are not bound, but, rather, consist of extratidal debris from their parent objects, which are undergoing various degrees of tidal disruption. In the satellite dis-
Figure 1: Radial profiles (normalized to the King limiting radius, often adopted as $r_t$) of the core-normalized density of associated star candidates (minus the mean field background) (filled circles) for seven objects, shown in $M/L$ order. Solid lines show King profiles fit to the centers (all fits are similar to, or taken from, previously published fits). Typical values of $M/L$ and $r_t$ are given. Poissonian error bars are typically of order the size of the points.

ruption models of Johnston et al.\textsuperscript{15}, the departure density reflects the tidal mass loss rate. Thus, the apparent correlation suggests that higher inferred $M/L$'s correspond to higher mass loss rates, and this, in turn, suggests that the high $M/L$'s are \textit{not} a reflection of the DM contents, but, rather, higher degrees of virial non-equilibrium in the parent objects.

That Pal 13 partakes in the Figure 2 trend lends some support to the second scenario. An $M/L$ of 20 has just been reported for this very small globular cluster\textsuperscript{4} while we report elsewhere a number of reasons why this cluster must be undergoing severe tidal disruption (e.g., Pal 13 has large blue straggler fraction, a double subgiant branch, a break in its density profile, and a highly destructive orbit). In the context of the interpretations for the $M/L$-departure density trend given above, one must either accept that globular clusters, including very small ones (with only several thousand $M_\odot$ in stars), can have substantial dark matter contents along with their dSph counterparts, or that the masses inferred from $\sigma_{v,c}$ are being substantially inflated due to the effects of tidal disruption. Fortunately, the extreme interpretations discussed here can be discriminated by measuring radial velocity trends with radius: DM halos should produce\textsuperscript{18} declining $\sigma_v$ with $r$ while models of tidally disrupting systems show\textsuperscript{19} flat or rising $\sigma_v(r)$. Our survey, which identifies the
very “needle-in-the-haystack” targets one needs to do this experiment, has already allowed us to obtain confirmatory (∼ 15 km s−1 resolution) velocities to significantly larger r (to beyond the King cut-off radii) than previous surveys (which have been limited to the high density dSph cores). Our next challenge is to obtain velocities at a higher resolution capable of testing the physics. Models by Kleyna et al. predict that ≤ 20 quality spectra at ∼ 0.75r_t are needed to discriminate between models. These future data will hopefully bring us closer to understanding the mysteriously large M/L’s of dSph galaxies.

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