THE HIERARCHICAL FORMATION OF THE
GALACTIC DISK

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Abstract

I review the results of recent cosmological simulations of galaxy formation that highlight the importance of satellite accretion in the formation of galactic disks. Tidal debris of disrupted satellites may contribute to the disk component if they are compact enough to survive the decay and circularization of the orbit as dynamical friction brings the satellite into the disk plane. This process may add a small but non-negligible fraction of stars to the thin and thick disks, and reconcile the presence of very old stars with the protracted merging history expected in a hierarchically clustering universe. I discuss various lines of evidence which suggest that this process may have been important during the formation of the Galactic disk.

Keywords: Milky Way, galaxy formation, hierarchical clustering, cosmology, dark matter.

1. Introduction

Stellar disks are traditionally viewed as ensembles of stars on nearly circular orbits, dynamically fragile to fluctuations in the gravitational potential brought about by accretion events and mergers. Indeed, it is common to use the oldest stars in the Milky Way disk to date the time of its last major merger. Indications that star formation in the solar neighbourhood has been ongoing for most of the age of the Universe, coupled with the presence of metal-poor, old stars on disk-like orbits in the vicinity of the Sun, suggest that the Galaxy has suffered few, if any, important accretion events in the past ~ 10 Gyr. This relatively peaceful evolution is at odds with the rather hectic merging activity expected in hierarchically clustering structure formation models (see, e.g., Steinmetz & Navarro 2000).

Recent numerical simulations (Abadi et al 2003a,b) suggest one way of reconciling the flurry of early mergers expected in a ΛCDM universe—the current paradigm of structure formation models—with the presence of an old disk component in the Milky Way. These simulations show that satellite accretion events may contribute stars not only to the spheroid, but also to the disk com-
ponent of a galaxy. These stars make up the core of satellites whose orbits are eroded, circularized, and brought into the plane of the galaxy before being disrupted. Such events contribute upwards of $\sim 10\%$ of stars in the disk, and the majority of old disk stars.

In this contribution I describe several lines of evidence that suggest that, indeed, the Milky Way disk may contain a number of stars which originate in the tidal debris of disrupted satellites. If confirmed by further scrutiny, this evidence would demonstrate that mergers and accretion events have been responsible for shaping the disk of the Milky Way, as well as its spheroid, and would provide strong support to the hierarchical mode of galaxy assembly envisioned in the $\Lambda$CDM scenario.

2. Tidal debris in the disk of the Milky Way

Since the bulk of the thin disk of the Galaxy is made up of stars that formed in situ following the collapse of a gaseous, dissipative component, left-over debris from past accretion events is most easily identified in samples of stars that minimize contamination by the thin disk. Thus, tidal debris should show more prominently in metal-deficient star samples, since these are likely to contain stars that formed before the merging activity abated, as well as in samples collected above, below, or in the outskirts of, the Galactic plane.

One prime example of this is the discovery by the SDSS team of a “ring-like” structure in the direction of the anti-galactic center (Yanny et al. 2003). Further studies have confirmed that this is a dynamically coherent structure that spans a large arc on the plane of the Galaxy located at roughly 18 kpc from the Galactic center. Numerical simulations show that these “tidal arcs” occur naturally during the disruption of satellites on orbits coplanar with the disk (Helmi et al. 2003), and have identified features that distinguish this accretion interpretation from other competing scenarios, such as spiral arms or the resonant response of the disk to the influence of the Magellanic Clouds or of the bar in the Galactic bulge.

One example of “tidal arcs” found in the simulation of Abadi et al. (2003a,b) is shown in Figure 1. (Details may be found in Helmi et al. 2003.) The arc circumscribed azimuthally between $\phi = 100^\circ$ and $\phi = 210^\circ$ is caused by the apocentric “wrapping” of the inner tidal arm stripped from the satellite after a recent pericentric passage. The arc is fed by a continuous stream of particles escaping the satellite. There is a clear gradient in the energies of particles in the arc; the most bound are most advanced along the arc (i.e. larger $\phi$), which is reflected in a clear velocity gradient across the arc, shown in the middle panel of Figure 1.

This arc is a short-lived transient feature that weakens as particles of different energy phase mix throughout the disk. Thus, if this interpretation is correct,
Figure 1. Snapshot of the disruption of a satellite on an orbit roughly coplanar to the disk, taken from the simulation of Abadi et al. (2003a,b). Left panel shows a “face on” projection of the debris shortly after the first pericentric passage. The main galaxy is at the center of coordinates, but only the stars in the satellite are shown for clarity. Middle panel shows, in a cylindrical coordinate system, the (galactocentric) radial velocity versus azimuthal angle $\phi$ for particles in the arc. Right hand panel shows radial velocity and distance for all satellite particles. Curves in this panel indicate the loci of particles with three different values of the binding energy, $E$, and angular momentum equal to the average of particles in the arc. See Helmi et al (2003) for details.

one the SDSS “ring” to be dynamically “young”, and that the parent (disrupting) satellite may be still lurking somewhere in the Galactic disk. Recently, there have been intriguing suggestions that oddities in the distribution of disk stars in the direction of Canis Major may be due to the core of a disrupting dwarf rather than to the presence of a warp in the outer Galactic disk (Martin et al 2004). I conclude that the evidence in favour of interpreting the SDSS “ring” as debris from a (probably ongoing) accretion event is, if not conclusive, at least very compelling.

Are there other examples of this process? We have begun to scrutinize dynamically coherent structures in samples of stars that favour metal-deficient stars, in particular the compilations of Beers et al (2000, B00) and Gratton et al (2003, GCCLB). Figure 2a shows the distribution of specific angular momentum of stars in the B00 and GCCLB samples. These compilations favour metal-poor stars, and therefore contain mainly stars in the solar neighbourhood that belong to the traditional spheroid and thick disk components. As one can see in Figure 2a, the $J_z$-distribution is not smooth, and is punctuated by a number of local “peaks”, even when only stars with orbits confined to the plane are considered.

These ensembles of stars with common rotation speeds are reminiscent of the dynamical substructures that Eggen (1986 and references therein) identified as “moving groups” in the solar neighbourhood. Eggen proposed that these
groups were the late stages in the disruption of open clusters, recognizable locally as ensembles of stars with negligible dispersion in their rotation speed. Unfortunately, the lack of accurate distances for most candidates complicated the analysis and prevented proper assessment of his hypothesis. We (Navarro, Helmi & Freeman 2003) have reanalyzed Eggen’s hypothesis for the case of the “Arcturus group”.

Arcturus, the fourth brightest star in the night sky, is a Population II giant whose odd kinematics has been documented for centuries. It is very close to the Sun (hence its apparent brightness), and moves on an orbit confined to the Galactic plane, yet its rotation speed is only half that of the Sun. The vertical line labelled “Arcturus” in Figure 2a shows that there is a significant excess (over a smooth distribution) of stars of similar angular momentum as Arcturus in the B00 and GCCLB compilations.

Although there is a peak in the \( J_z \) distribution of stars in the B00 compilation that coincides with Arcturus, further inspection shows that these stars span a wide range of metallicities, casting doubt on Eggen’s interpretation of this group as a disrupting star cluster. Furthermore, the dispersion in rotation speed of the group far exceeds the \( \sim 0.5 \) km s\(^{-1}\) that would be characteristic of a disrupting cluster. The metal abundances of stars in the group, however, show a distinct pattern, as shown in Figure 2b. This figure shows the enrichment in \( \alpha \) elements ([\( \alpha/Fe \)]) as a function of iron abundance, in solar units ([Fe/H]), for all stars in the GCCLB compilation (open circles). (\( \alpha \) element abundances are not available for stars in the B00 catalog.)

The solid circles in Figure 2b correspond to those stars in the bin labelled “Arcturus” in Figure 2a. The trend defined by these stars is distinct from that traced by all GCCLB stars. The Arcturus group candidates define a narrow path in the [\( \alpha/Fe \)] vs [Fe/H] plane well approximated by one of the simple closed-box self-enrichment models of Matteucci & Francois (1989, see solid line in Figure 2b). Thus, GCCLB stars with \( J_z \) comparable to Arcturus form a dynamically and chemically coherent group of stars which might be naturally identified with debris from a disrupted satellite galaxy. Further corroborating evidence is provided by the discovery by Gilmore, Wyse & Norris (2002) of a population of stars above and below the plane of the Galaxy with angular momentum similar to Arcturus, which they interpret as the debris of a tidally disrupted satellite.

The discovery of evidence for past (and perhaps ongoing) accretion onto the disk of the Milky Way suggests a reassessment of the traditional scenarios for the assembly and enrichment of stars in the solar neighbourhood. Extrapolating boldly, one may even argue that most metal-deficient stars (disk and spheroid) in the solar neighbourhood have been contributed by various accretion events throughout the life of the Galaxy. Confirming such assertion would clarify the role of mergers and accretion events in the formation of the Galactic
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Figure 2.  (a) Angular momentum distribution of stars in the Beers et al (2000, B00) catalog (top two histograms); in the Gratton et al (2003, GCCLB) compilation (solid histogram), as well as that of stars identified as “Arcturus group” candidates by Eggen (1986, shaded histogram). (b) $\alpha$-enhancement ($[\alpha/Fe]$) vs iron abundance ($[Fe/H]$) for all stars in the GCCLB compilation. Stars with angular momentum similar to Arcturus are shown as solid circles, and compared to a simple closed-box self-enrichment model (Matteucci & Francois 1989).

disk and would lend strong support to hierarchical theories of galaxy formation.

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