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ON THE NATURE OF FOSSIL STREAMS IN THE SOLAR NEIGHBOURHOOD OF THE MILKY WAY IN THE GAIA ERA

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Abstract. We seek signatures from the epoch of Galaxy formation, to provide insights about the chemodynamical processes that took place at the time of Milky Way formation. We produced a new kinematic survey based on spectro-photometric data from the Sloan Digital Sky Survey (SDSS) and high-quality proper motions derived from multi-epoch positions from the Guide Star Catalog II (GSC-II) data base, and used this survey to explore the solar neighbourhood of the Milky Way. We selected samples of subdwarfs within a few kpc of the Sun as tracers of the halo system. We find statistical evidence for discrete kinematic overdensities, possible accretion remnants, and compare this result to high-resolution N-body numerical simulations of the interaction between four dwarf galaxies and the Milky Way. The angular momentum distribution reveals that these imprints are possible fossil streams from low inclination retrograde and high inclination orbiting satellites. As the Gaia mission era is fast approaching, this knowledge will set the basis for future studies, and provide significant clues to constrain suggested scenarios for the formation and evolution of the Milky Way.

Keywords: Galaxy: formation, kinematics and dynamics, halo

1 Introduction

The formation and evolution of galaxies is one of the outstanding problems in astrophysics. In the context of hierachical structure formation, galaxies such as our own Milky Way grow by mergers and accretion of smaller sistems as dwarf galaxies: these satellite galaxies -torn apart by the tidal gravitational field of the parent galaxy - are progressively disrupted, giving rise to trails of stars along their orbit. After the accretion era ends, a spheroidal halo-like component may result in a more massive host galaxy.

Of all the Galactic components, the stellar halo offers the best opportunity for probing details of the merging history of the Milky Way. There is a real possibility to identify groups of halo stars that originate from common progenitor satellites (Eggen 1977; Ibata et al. 1994; Helmi et al. 1999; Harding et al. 2001; Morrison et al. 2009; Smith et al. 2009; Klement et al. 2009). However, recovering fossil structures in the solar neighborhood is considerably more difficult, as strong phase-mixing takes place.

This degeneracy can only be broken with 6-D (phase-space) or 7-D (including abundances) information achievable only by integrating astrometry, photometry, and spectroscopy. The SDSS and GSC-II Kinematic Survey is produced to serve this task (e.g., Spagna et al. 2010; Abazajian et al. 2009; Lasker et al. 2008). It provides accurate spectroscopic parameters (effective temperature, surface gravity, metallicity, and radial velocity), proper motions, and photometric distance estimates for about 27 000 FGK subdwarfs.

2 Methodology

Fossil signatures of galaxy formation can be found in the properties of high velocity stars in the inner regions of the halo, within a few kpcs from the Sun (Re Fiorentin et al. 2005). In what follows, we explore the solar neighbourhood with a stellar sample and with high resolution N-body numerical simulations of minor mergers, in order to detect and characterize such imprints.

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2.1 Fossil streams in the stellar halo

Among the sample of FGK subdwarfs from the SDSS-GSC-II Catalog, we selected samples of tracers of the Galactic halo population in the inner regions, and analyzed their full 7-D phase-space (kinematics and metallicity) distribution.

The left panel of Fig. 1 shows the kinematic distribution (velocity projections U versus W by way of illustration) of a sample of 2709 halo stars with [Fe/H] < -1.5 within 3 kpc from the Sun. Because of the strong phase-mixing that takes place in the inner halo, this distribution is relatively smooth; however, the kinematics of the highest velocity stars (highlighted as small red circles) already appears more clumped.

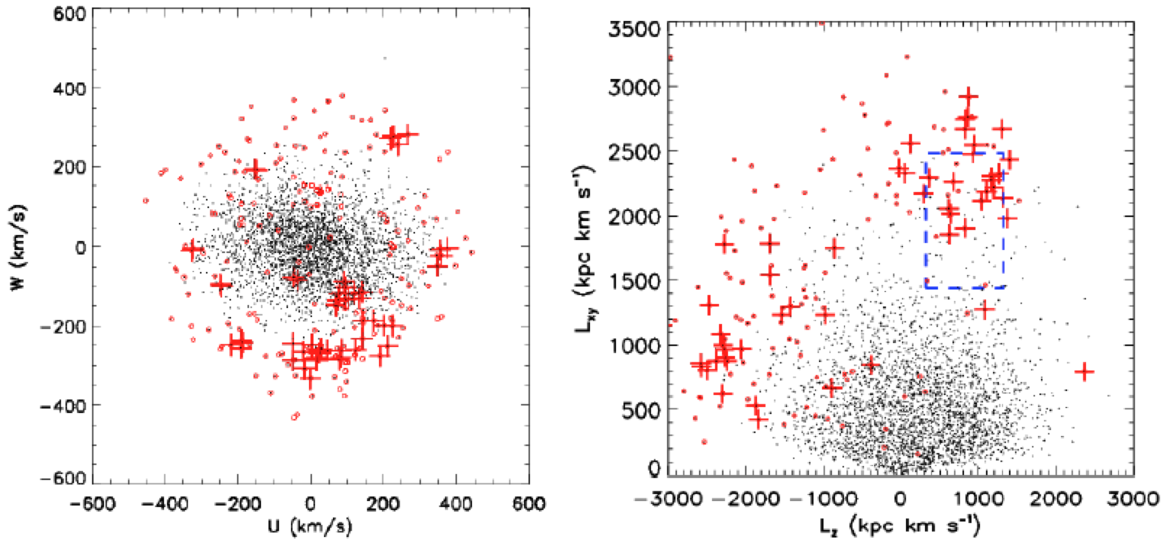

Fig. 1. Distribution of the selected halo stars (sample of 2709 elements with [Fe/H] < -1.5 and $d < 3$ kpc). The 5% fastest are highlighted (small circles). Among them, the crosses identify groups with velocity difference less than 42 km/s. **Left:** Velocity projection U vs. W. **Right:** Angular momentum components L_z vs. $L_{xy} = \sqrt{L_x^2 + L_y^2}$. As in Re Fiorentin et al. (2005), the box shows the locus of the halo stream discovered by Helmi et al. (1999).

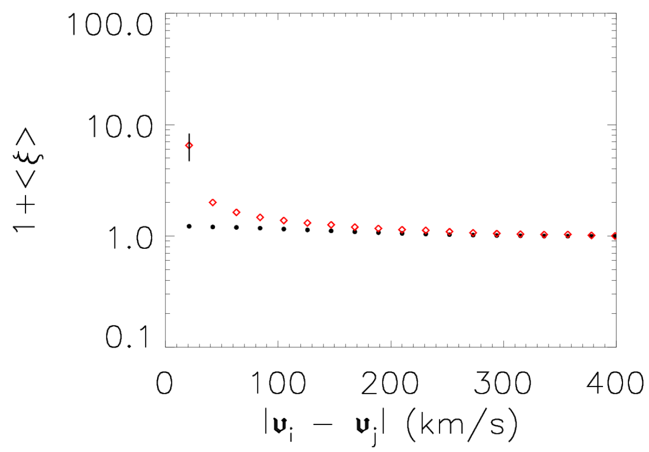

Fig. 2. Velocity correlation function for the full sample of halo stars (dots), and the 5% fastest-moving subset (diamonds) shown in Fig. 1.

The amount of kinematic substructures that remain in this volume is quantified by means of the two-point correlation function $\xi(\mathbf{v})$ on the pair velocity difference $|\mathbf{v}_i - \mathbf{v}_j|$, which measures the excess in the number of star pairs moving with a given velocity difference when compared to a representative random (smooth) sample (see Re Fiorentin et al. 2005, for more details). Stars with small velocity differences indicate the presence of clumps/streams as objects with coherent kinematics (see Fig. 2). Among the subset of the 5% fastest stars, this signal is indeed very strong, and we find it is due to moving groups formed by those stars indicated by the crosses in Fig. 1.

This result is confirmed also in angular momentum space (see the right panel of Fig. 1), where the initial clumping of satellites should be present even after the system has phase-mixed completely.

2.2 Fossil streams in the simulations

In order to better understand these findings, and to study the formation of the Milky Way stellar halo system through accretion events, we use a set of high-resolution numerical N-body simulations which simulate minor mergers of prograde and retrograde orbiting satellite halos within a dark matter main halo (Murante et al. 2010).

For both the prograde mergers, in which the satellite co-rotates with the spin of the disk, and the retrograde mergers, with a counter-rotating satellite, we consider two orbits: a low-inclination orbit with a 10 degree tilt with respect to the disk plane, and a high-inclination orbit with a 60 degree tilt.

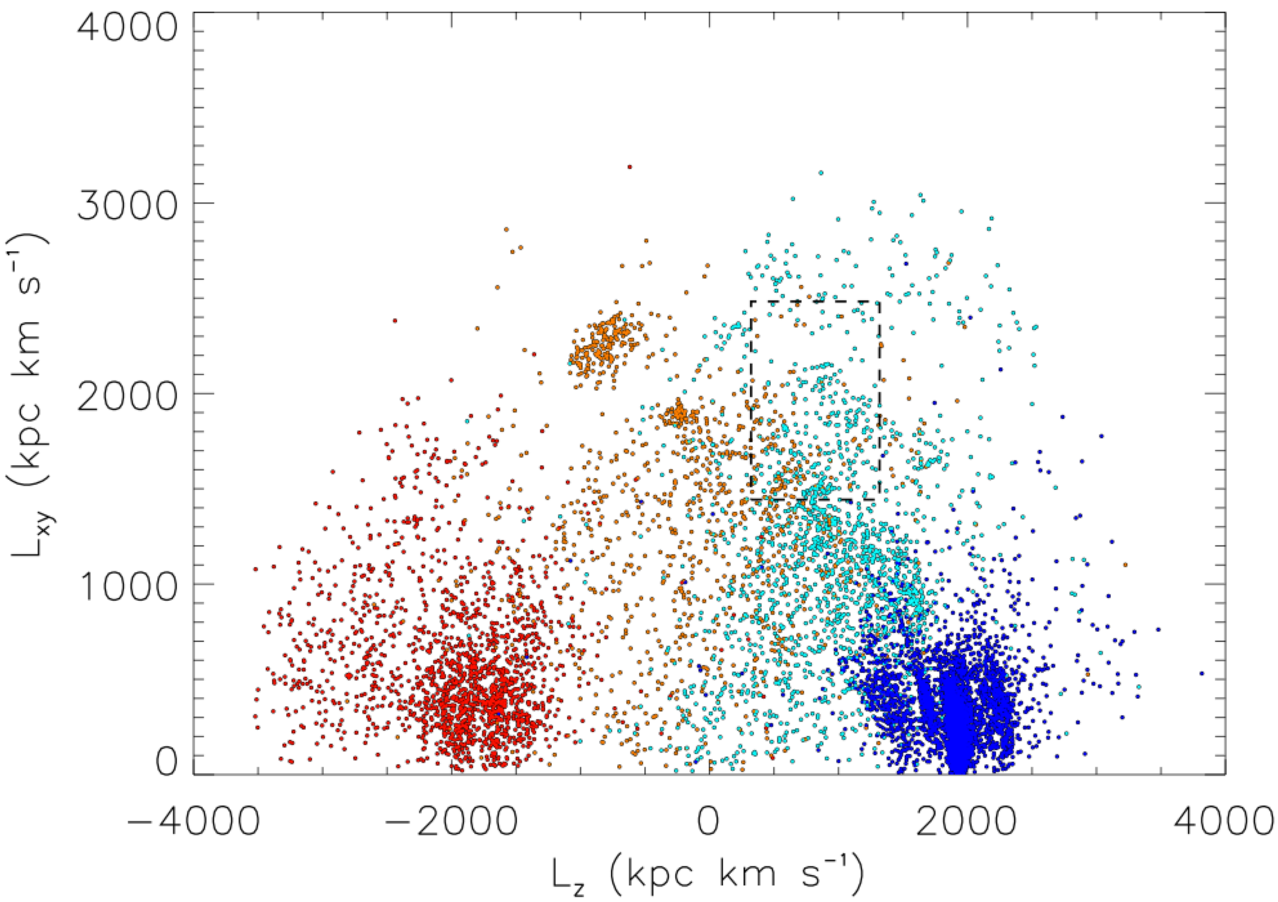

Fig. 3. Angular momentum distribution of the simulated Milky Way halo within 3 kpc of the Sun. Shown are 9471 particles accreted from four dwarf galaxies: 60 degree retrograde/prograde (orange/cyan), 10 degree retrograde/prograde (red/blue) satellites after interaction with the simulated Milky Way. The box has the same meaning as in Fig. 1.

After 4.63 Gyr (about 16 dynamical timescales of the main halo), once the four satellites have completed their merging with the primary halo, we select particles in a sphere of 3 kpc radius of the Sun, i.e. at 8 kpc from the Galaxy center, and analyze the signal left by the satellite stars.

Figure 3 shows how the debris of our four satellites are distributed in the angular momentum plane. The different colors indicate different progenitors: low-/high-inclination retrograde (red/orange), high-/low-inclination (cyan/blue) prograde satellites. Clearly, despite the chaotic build up of the parent halo, objects from accreted satellites remain strongly clumped in this space.

Any satellite is slowed down by dynamical friction exerted on it by disk and halo particles. In consideration of the drag force relation by Chandrasekar (1943), retrograde satellites are expected to suffer weaker dynamical friction with respect to prograde ones, since in the first case the velocity of the satellite is opposite to that of the disk and to the rotational velocities of the main halo particles. As a consequence, prograde orbits decay faster. This effect is even more evident for low-inclination orbits, and especially among the subsample of 5% fastest objects.

The regions of high inclination and low inclination counter-rotating mergers are well populated, consistent with observations (see again the right panel of Fig. 2), indicating that dynamical friction plays a significant role in the accretion events.

Future work will take into account how the current (e.g., SDSS-GSC-II) observations and Gaia-like observations will affect the distributions of debris of our four satellites (Re Fiorentin et al., in preparation). In the Gaia era we should indeed be able to retrieve the details of the various structures, allowing us to establish the number, as well as the characteristics, of the progenitors of the stellar halo.

3 Conclusions

We have found statistical evidence of substructure in the space motions of the fastest moving stars, due to a small number of moving groups that are strongly clustered in the angular momentum phase space. Investigation of the group members by their intrinsic properties (e.g., chemical abundance and orbits) suggest that they are possible fossil remnants of merging satellites with high inclination and low inclination retrograde orbits (cfr. Helmi et al. 1999; Klement et al. 2009, and Re Fiorentin et al. in preparation).

We have compared this result to high-resolution N-body numerical simulations of (four) minor mergers of orbiting dwarf galaxies: these satellites do appear very coherent in the local halo velocity distribution and angular momentum phase space. Among the subsample of the fastest objects, the regions of high inclination and low inclination retrograde orbits are well populated, consistent with the observations, and suggestive of the strong role played by dynamical friction in this process.

The solar neighborhood presents potentially a very large number of kinematic groups which are related to the various building blocks of the stellar halo. This implies that the merger history of the Galaxy may be unmasked in the very near future with surveys such as Gaia (e. g., Perryman et al. 2001; Turon et al. 2005; Gilmore et al. 2012, and for the latest news on the mission see `http://www.rssd.esa.int/Gaia/`), which will collect samples for millions of stars with very accurate positions and kinematics, and dramatically improve the reliability of such conclusions.

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