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Relics of the hierarchical assembly of the Milky Way

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Abstract. I briefly review the more recent observational results about the search of stellar relics of the process of formation of the Milky Way galaxy. The stellar tidal stream of the Sagittarius dwarf galaxy is now traced all over the sky providing direct evidence of the last phases of the hyerarchical assembly of the Galactic Halo. The Monoceros ring, and the likely related Canis Major relic, seem to indicate that also the disky components of our Galaxy may have a hyerachical origin, at least in part.

Key words. Galactic structure – Dwarf galaxies –

1. Introduction

The process of hierarchical merging (White & Rees 1978; White & Frenk 1991) is generally accepted as the driving mechanism of the formation of giant galaxies. The study of the local (e.g. Galactic or in the Local Group) relics of such process may provide an unprecedentedly detailed insight of the current cosmological model as well as a formidable testbed for theories of galaxy formation.

The first clear observational evidence of the very *existence* of such relics dates back just a decade, e.g. the discovery of the Sagittarius dwarf spheroidal galaxy (Sgr-dSph) Ibata et al. (1994, 1997). The morphology of Sgr suggests that the dwarf galaxy is currently disrupting under the strain of the Galactic tidal field. The discovery of Sgr opened a new epoch in the study of the formation and evolution of our own Galaxy and triggered the interest of several scientists. New analysis began to appear at an increasing rate since year 2000, when the results of large surveys (2MASS, SDSS) revolutionized the approach to the field and changed our view of the Milky Way. The best way to have a direct idea of this change of perspective is to look at Fig. 1 of Newberg et al. (2002). The slice of Galaxy probed out to $R_{GC} \sim 50$ kpc by F stars from the SDSS shows that the Halo is far from being homogeneous, but, in fact, is rich of clumps and filaments that are the fingerprints of the recent accretion events that contributed to its construction.

The (successful) search for relic substructures has extended to M 31 (Ibata et al. 2001b; McConnachie et al. 2003; Merret et al. 2003), to nearby dwarfs (Coleman et al. 2004; Kleyna et al. 2003), and to galaxies outside the Local Group (Forbes et al. 2003; Peng et al. 2002; Pohlen et al. 2003), but it has to be recalled that the variety of detected structures shouldn't necessarily be ascribed to the same origin. Here I try to give a brief account of the most recent results concerning the substructures of the Milky Way.

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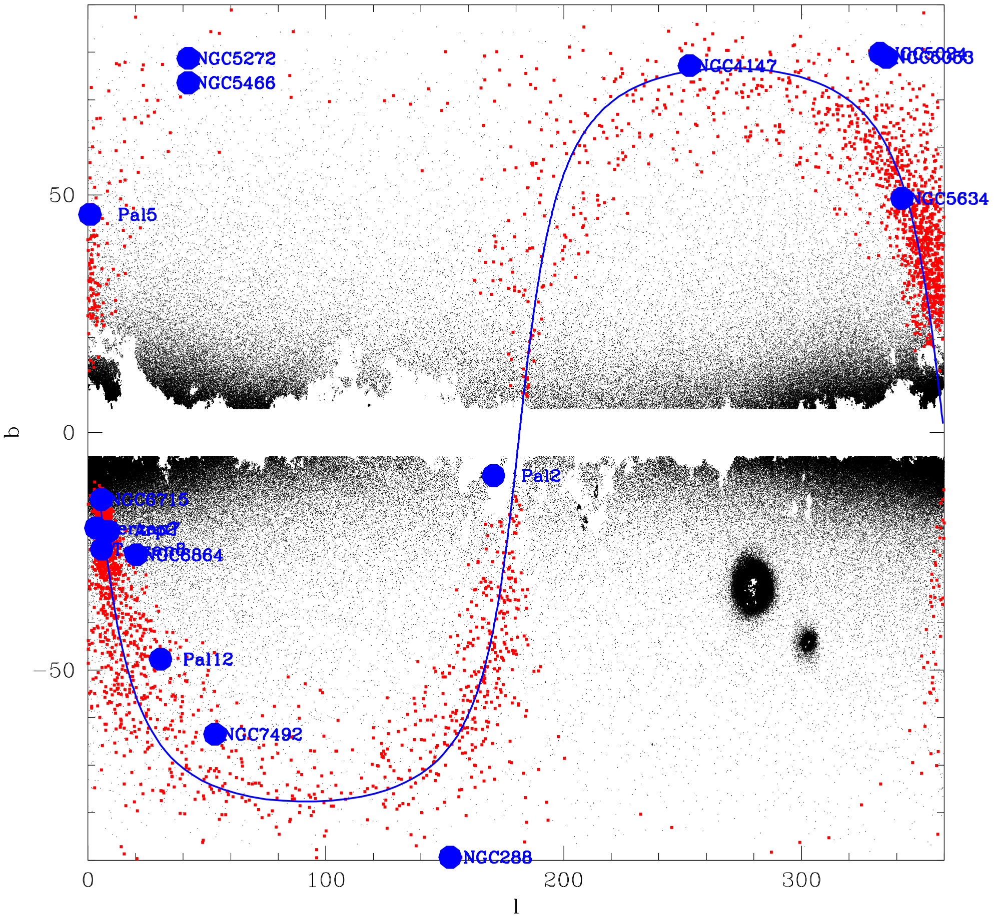

Fig. 1. Galactic coordinates distribution of the M giants from 2MASS, selected according to Majewski et al. (2003). The thicker points are the Sgr Stream members selected in the Y-Z plane (Galactocentric Cartesian coordinates). The position of some globular clusters possibly related with the Stream are also reported. The two blobs around $b \sim -40°$ and $l \sim 290°$ are the Magellanic Clouds. The stars affected by large extinction, near the Galactic plane, have been removed from the sample.

2. The Sagittarius galaxy and its Stream

The lucky occurrence that Sgr is dominated by an intermediate-age ($\sim 5-6$ gyr) metal-rich ($[M/H] \sim -0.5$) population (Layden & Sarajedini 2000; Monaco et al. 2002) is the key characteristic that make it possible to trace the Sgr Stream all over the sky (see Fig. 1). The brightest Red Giant Branch (RGB) stars of Sgr are of spectral type M, i.e. much redder than the typical Halo stars. The M-giants can be easily selected from their color in the All Sky catalogue of 2MASS. At galactic latitudes larger than $|l| \sim 20°$, e.g. where the contribution by

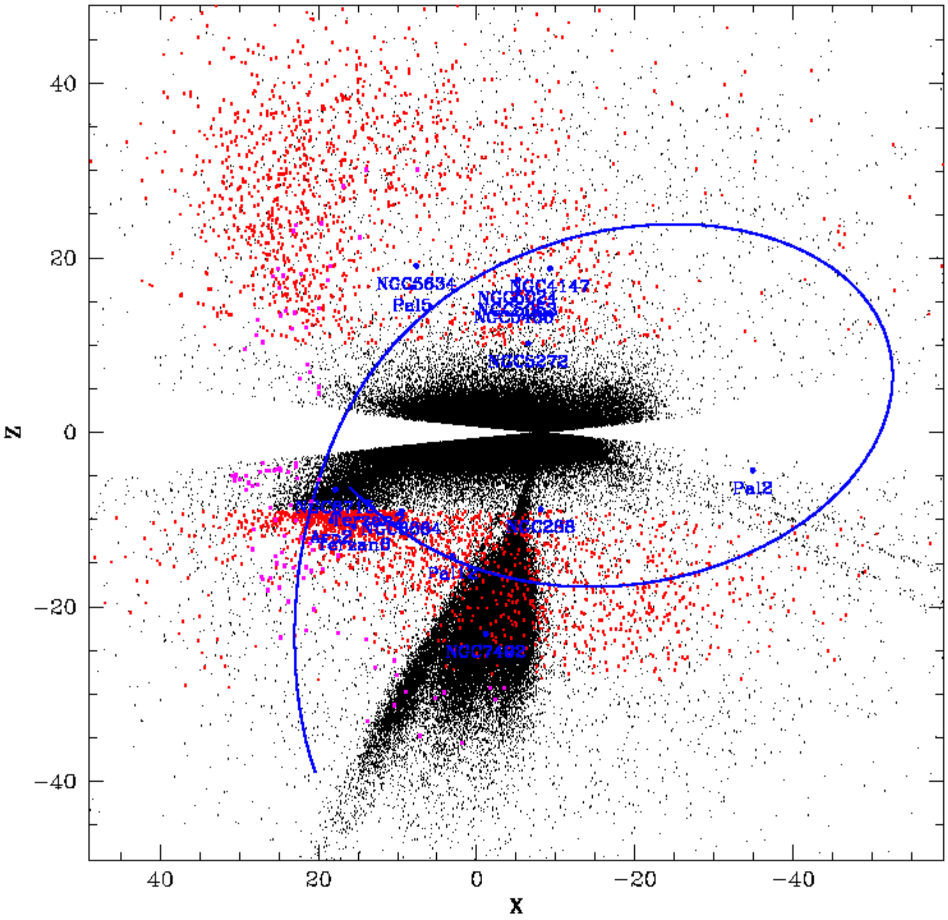

Fig. 2. Galactocentric X-Z distribution of 2Mass M-giants. The Stream stars, selected as in Fig. 1, clearly traces two lobes of the rosette orbit of Sgr. The model orbit by Ibata et al. (2001a) is also reported for comparison.

disc M stars is negligible, the Sgr Stream appear clearly as the major substructure of the outer halo, tracing the polar rosette orbit of the parent galaxy (Majewski et al. 2003), as clearly shown in Fig. 2. It is now observationally established that the disruption of Sgr is providing a sizeable contribution to the assembly of the Halo in terms of stars of various ages (from carbon stars to RR Lyrae, from A-F Main sequence stars to Blue Horizontal Branch stars, see Ibata et al. 2001a; Ibata et al. 2002; Ivezic et al. 2000; Newberg et al. 2002; Yanny et al. 2003; Martínez-Delgado et al. 2001; Mateo, Olszewski & Morrison 1998, and references therein), and of globular clusters (Bellazzini, Ferraro & Ibata 2003a; Bellazzini et al. 2003b; Bellazzini, Ibata & Ferraro 2003c; Martínez-Delgado et al. 2002), and, presumably, Cold Dark Matter.

While the search for the traces of previous passages of Sgr is going on (Newberg et al. 2003), various groups are collecting huge amounts of radial velocities of Stream stars. The kynematics of a coherent structure sampling the Galactic Halo from $R_{GC} \simeq 16$ kpc to $R_{GC} \simeq 50$ kpc may hidden a treasure of information about the shape, the mass and the degree of lumpiness of the CDM halo that hosts the Milky Way. Significant constraints on the shape of the Galactic potential, that appears quite spheric, have been already obtained by Ibata et al. (2001a) and by Majewski et al. (2004). The fact that the stars of the Sgr Stream are currently *raining* on the solar neightbourhood (Majewski et al. 2004) may also imply phase-space lumpiness in the local distribution of Dark Matter, possibly with relevant consequences on the experiments for the detection of its constituent particles (neutralinos, see Helmi et al. 2002; Freese et al. 2004, and references therein).

3. The Monoceros Ring and the Canis Major relic

An even more interesting case is provided by the recently discovered Monoceros Ring structure (hereafter the Ring, for brevity, Newberg et al. 2002; Yanny et al. 2003; Ibata et al. 2003; Majewski et al. 2003; Rocha-Pinto et al. 2003), near the Galactic plane. The more recent observational results (Crane 2003; Martin et al. 2004) suggests that the Ring is the stream remnant of an in-plane accretion that may be contributing to the build-up of the thick disk (see also Helmi et al. 2003; Abadi et al. 2003).

In particular Martin et al. (2004), while tracing the whole extent of the Ring using M-giants from the 2MASS database discovered a large overdensity of "Ring-like" M-giants in the Canis Major constellation. The elliptical shape, the overall structure of this overdensity and its coincidence with a noticeable grouping of globular (and open) clusters led Martin et al. (2004) to the conclusion that it is the relic of the dwarf galaxy whose disruption generated the Ring. The discovered relic is approximately centered at galactic coordinates (l,b)$\sim$ $(240^o, -7^o)$, it has a FWHM extension in the sky of $\sim 12°$ in the latitude direction and it is located at $\sim$ 7 kpc from the Sun (i.e., $(m - M)_0 \sim 14.25$), as obtained from the photometric parallax to M-giants introduced by Majewski et al. (2003). The mass, luminosity and characteristic dimensions of Canis Major appear quite similar to those of the Sgr dSph. The similarity with Sgr extends to other relevant characteristics: the two objects seem to host a similar grouping of globular clusters, and the upper RGB of both galaxies is dominated by stars of similar colour (M-giants), which are present in similar numbers in both galaxies.

The kinematic coherence of the Ring and its association with several clusters has been also confirmed by Rocha-Pinto et al. (2003); Frinchaboy et al. (2004); Forbes, Strader & Brodie (2004). Rocha-Pinto et al. (2004) report on a new overdensity of M giants covering the constellations of Andromeda and Triangulum. The kynematics of the member stars leave open the possibility that this structure is also associated with the Ring.

4. Other structures

The examples reported above concern large scale structures that can be identified and followed all over the Galaxy. The solar neighbourhood offers the opportunity to search a very small spot of Galaxy with the full 6-D information, i.e. position and 3-D velocity. The local relics of an ancient disruption event were found by Helmi et al. (1999) as an anomalous phase-space clump of metal poor stars. The conclusions of their analysis is that "...about ten per cent of the metal-poor stars in the halo of the Milky Way, outside the radius of the Sun's orbit, come from a single coherent structure that was disrupted during or soon after the Galaxy's formation. This object had a highly inclined orbit about the Milky Way at a maximum distance of 16kpc, and it probably resembled the Fornax and Sagittarius dwarf spheroidal galaxies". A similar case has been recently reported by Navarro et al. (2004), that showed that also a familiar star as Arcturus may have an "extragalctic" origin.

Gilmore et al. (2002) found an unexpected kynematical signal in a radial velocity survey performed with the 2dF spectrograph and interpreted it as the signature of a past accretion event. Mizutani et al. (2003) have suggested that Gilmore et al.'s anomalous stars may be related to the disruption of the parent galaxy of ω Centauri, an interesting object by itself in the perspective of the present review (see Ferraro et al. 2002; Tsuchiya et al. 2003; Bekki & Freeman 2003, and references therein).

5. Final Considerations

The present review cannot be considered neither exhaustive nor complete and I apologize in advance with the authors that cannot find their work reported here. Moreover I largely neglected theoretical studies, focusing only on the observational side. For a more complete approach to the topic see the volume by Martínez-Delgado & Prada (2004) that is expected to present a global picture as of September 2003. On the other hand new results appear nearly every day on the astro-ph and the matter cannot be succesfully cristallized in a long living review at the present time.

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References

Abadi M.G., et al., 2003, ApJ, 597, 21
Bekki K., Freeman K.C., 2003, MNRAS, 346, L11
Bellazzini M., Ferraro F.R., Ibata R., 2002, AJ, 124, 915
Bellazzini M., Ferraro F.R., Ibata R., 2003a, AJ, 125, 188
Bellazzini M., et al., 2003b, A&A, 405, 577
Bellazzini M., Ibata R., Ferraro F.R., 2003c, in Satellites and Tidal Tails, D. Martinez-Delgado and F. Prada Eds., S. Francisco, ASP, ASP Conf. Series, in press (astro-ph/0304502)
Coleman M., et al., 2004, AJ, 127, 832
Crane J.D., et al., 2003, ApJ, 594, L119
Ferraro F.R., et al., 2002, ApJ, 573, L89
Forbes D.A., et al., 2003, Science, 301, 1217
Forbes D.A., Strader J., Brodie J.P., 2004, AJ, in press (astro-ph/403136)
Freese K., et al., 2004, Physical Review Letters, 92, 111301
Frinchaboy P.M., et al., 2004, ApJ, 602, L21
Gilmore G., et al., 2002, ApJ, 574, L39
Helmi A., et al., 1999, Nature, 407, 53
Helmi A., et al., 2002, Physical Review D, 66, 063502
Helmi A., et al., 2003, ApJ, 592, L25
Kleyna J., et al., 2003, ApJ, 588, L21
Ibata, R.A., Irwin, M.J., Gilmore, G., 1994, Nature, 370, 194
Ibata, R.A., et al., 1997, AJ, 113, 634
Ibata R., et al., 2001a, ApJ, 551, 294
Ibata R., et al., 2001b, Nature, 412, 49
Ibata R., Lewis G., Irwin M., Cambrésy L., 2002, MNRAS, 332, 921
Ibata R., et al., 2003, MNRAS, 340, L21
Ivezic, Z., et al., 2000, AJ, 120, 963
Layden A.C., Sarajedini A., 2000, AJ, 119, 1760
Majewski S., et al., 2003, ApJ, 599, 1082
Majewski S., et al., 2003, AJ, in press, astro-ph/0403701
Martínez-Delgado, D., et al., 2001, ApJ, 549, L199
Martínez-Delgado, D., et al., 2002, ApJ, 537, L19
Martinez-Delgado D., Prada F., 2004, Satellites and Tidal Tails, ASP Conf. Series, in press
Martin N., et al., 2004, MNRAS, 348, 12 (Pap-I)
Mateo, M., Olszewski, E.W. & Morrison, H.L., 1998, ApJ, 508, L55
McConnachie A.W., et al., 2003, MNRAS, 343, 1335
Merret H.R., et al., 2003, MNRAS, 346, L62
Mizutani A., et al., 2003, ApJ, 589, L89
Monaco, L., et al., 2002, ApJ, 578, L47
Navarro J., et al., 2004, ApJ, 601, L34
Newberg H., et al., 2002, ApJ, 569, 245
Newberg H., et al., 2003, ApJ, 596, L191
Peng E.W., et al., 2002, AJ, 124, 3144
Pohlen M., et al., 2003, in Satellites and Tidal Tails D. Martinez-delgado and F. Prada Eds.,

S. Francisco, ASP, ASP Conf. Series, in press (astro-ph/0308142)

Rocha-Pinto H., et al., 2003, ApJ, 594, L115

Rocha-Pinto H., et al., 2004, AJ, submitted, astro-ph/0405437

Tsuchiya T., et al., 2003, ApJ, 589, L29

White S., Rees M., 1978, MNRAS, 183, 341

White S., Frenk C., 1991, ApJ, 379, 52

Yanny B., et al., 2003, ApJ 588, 824