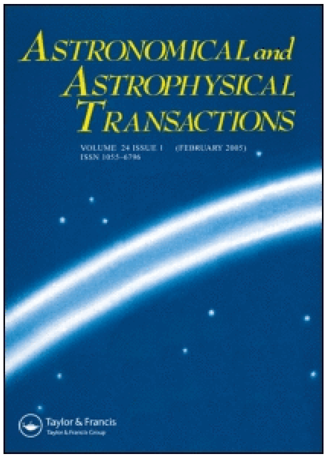

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Magnesium abundance in the Galactic halo stars and subsystem formation history

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Data from our compiled catalogue of spectroscopically determined magnesium abundances in dwarfs and subgiants with accurate parallaxes are used to select Galactic halo stars according to kinematic criteria and to identify presumably accreted stars among them. We analyse the relations between the relative magnesium abundances, metallicities and Galactic orbital elements for accreted halo stars.

Keywords: Galaxy (Milky Way); Stellar chemical composition; Halo disc; Galactic evolution

We justify the choice of the residual stellar velocity relative to the local standard of rest, $V_{\mathrm{res}} = 175\,\mathrm{km\,s^{-1}}$, as a criterion for separating the thick-disc and halo stars. We optimize the specific value of this criterion by minimizing the number of metal-rich ([Fe/H] > -1.0 dex) stars of our sample in the identified halo subsystem and metal-poor stars in the thick disc.

In identifying the stars of extragalactic origin, we have assumed that the stars born in a monotonically collapsing single protogalactic cloud could not be in retrograde orbits. Also we included all the stars with the same high residual velocities as those for the retrograde velocities, *i.e.* $V_{\mathrm{res}} > 240\,\mathrm{km\,s^{-1}}$, in the group of presumably accreted stars. As we see from figure 1(a), accreted stars constitute the majority in the Galactic halo. They came into the Galaxy from disrupted dwarf satellite galaxies. It can be seen from figure 1(b) that the relative magnesium abundances in the early Galactic halo stars are virtually independent of metallicity and lie within a fairly narrow range. This behaviour of early Galactic halo stars suggests that the interstellar matter in the early Galaxy mixed well at the halo formation phase. The appreciably increasing number of genetically related stars with metallicity suggests that more active star formation in the early Galaxy began slightly later when the mean metallicity of the interstellar medium reached [Fe/H] ≈ -1.0 dex, while the 'accreted' objects subsequently formed the bulk of the Galactic halo. It is seen also that presumably accreted stars demonstrate a large spread in relative magnesium abundances up to negative [Mg/Fe]. Since the relatively low [Mg/Fe] can arise from both the young age of stars and the small masses of the supernovae

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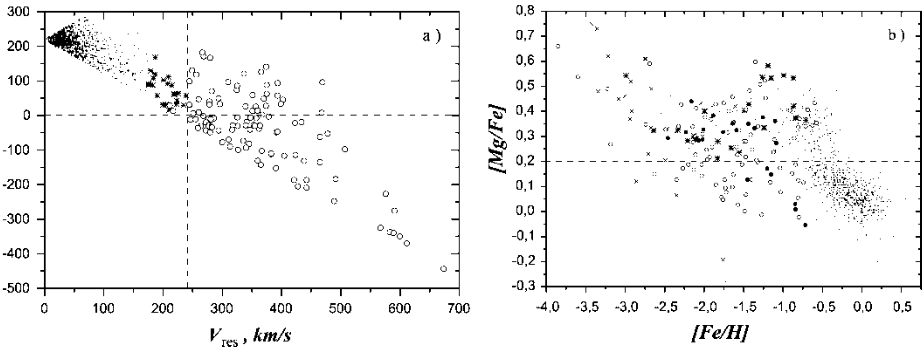

Figure 1. (a) Residual stellar velocities with respect to the local standard of rest versus azimuthal velocities and (b) metallicity versus relative magnesium abundance: crosses, thin-disc and thick-disc stars; asterisks, early Galactic halo stars; open circles, presumably accreted stars; full circles, the members of the Centaurus moving group among the accreted stars.

type II (SN II) in the protosystem cloud, it is interesting to try to identify genetically related stars in the accreted halo.

Based on angular momentum, we identify stars that were lost by the dwarf galaxy whose centre was the cluster ω Cen by the azimuthal and vertical velocities in the ranges $-50\,\mathrm{km\,s^{-1}} \leqslant \Theta \leqslant 0\,\mathrm{km\,s^{-1}}$. All these stars (as seen from figure 1(b)) lie along a narrow strip that exhibits a relative magnesium abundance that decreases sharply to negative values starting from $[\mathrm{Fe/H}] \leqslant -1.3$ dex. The considerably lower metallicity of the knee point than that in the Galaxy suggests that the stars of the Centaurus moving group were formed from matter in which the star formation rate was considerably lower than that in the early Galaxy. Hence, at least in this presumably initially massive ($M \approx 10^9 M_{\varepsilon}$) disrupted satellite galaxy the mean masses of the SN II progenitor stars were the same as those in our Galaxy.

Figure 2 shows that the lower limit for the relative magnesium abundance in accreted stars is almost independent of their azimuthal velocity. Since the right and left upper corners of figures 2(a) and (b) are totally devoid of stars, the upper envelope of these diagrams is naturally described by two inclined lines.

In other words the upper limit for the [Mg/Fe] ratio in accreted stars systematically decreases with increasing absolute value of the azimuthal velocity and the orbital inclination. As a result, we see that accreted stars with high relative magnesium abundances tend to have low orbital velocities around the Galactic centre at the solar Galactocentric distance. At the same time, stars with low [Mg/Fe] ratios are distributed more uniformly in all permitted values. Thus the stars with orbits lying near the Galactic plane are found, firstly, to constitute the majority of accreted stars and, secondly, to exhibit a wider range of relative magnesium abundances in both directions.

Simultaneously (see figures 2(c) and (d)), the two gradients in relative magnesium abundances were found to be negative rather than positive, as for all the genetically related stars in the Galaxy and non-zero above the 2.5σ level. The detected gradients are not related to the evolution of the Galaxy but only reflect the sizes of the orbits of the satellite galaxies; because of this, they lose their stars under the Galactic tidal forces. The sizes of the orbits for accreted stars and, hence, for their disrupted parent galaxies are found to increase, on average, with decreasing relative magnesium abundance in them.

In figure 3, the stars of the genetically related subsystems (the thin and thick discs and the early Galactic halo) form clearly traceable sequences. The sequences that intersect with the sequences of genetically related stars at a certain angle can also be traced for accretion. Stars of different geneses are grouped in the opposite parts of the diagrams; exactly one half of the

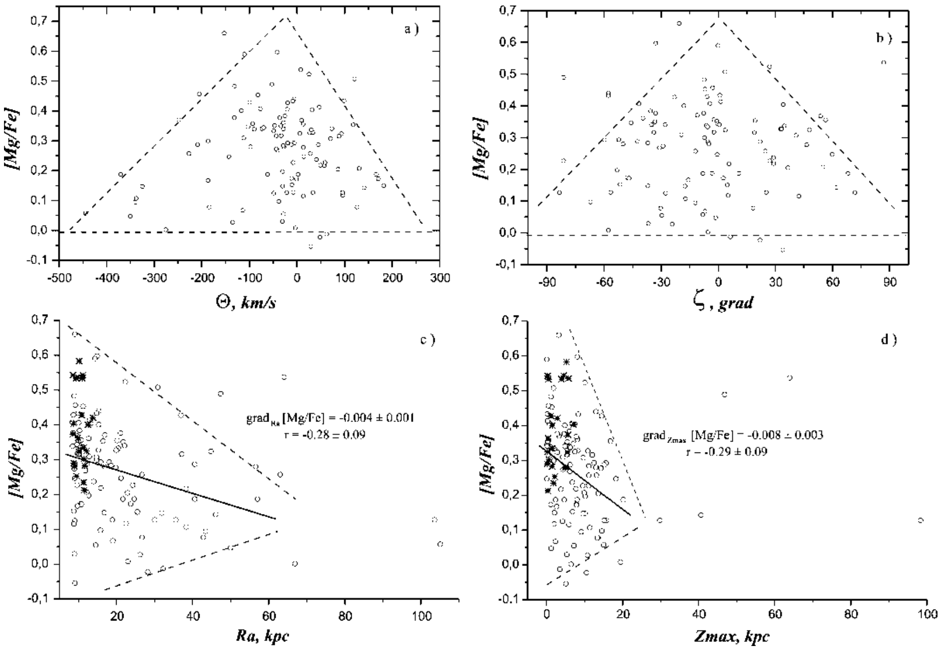

Figure 2. Relative magnesium abundances in accreted stars versus (a) their azimuthal velocities, (b) the Galactic orbital inclinations, (c) the maximum distance of the orbital points from the Galactic centre and (d) the maximum distance of the orbital points from the Galactic plane: dashed lines, envelopes of the points in the diagrams drawn by eye.

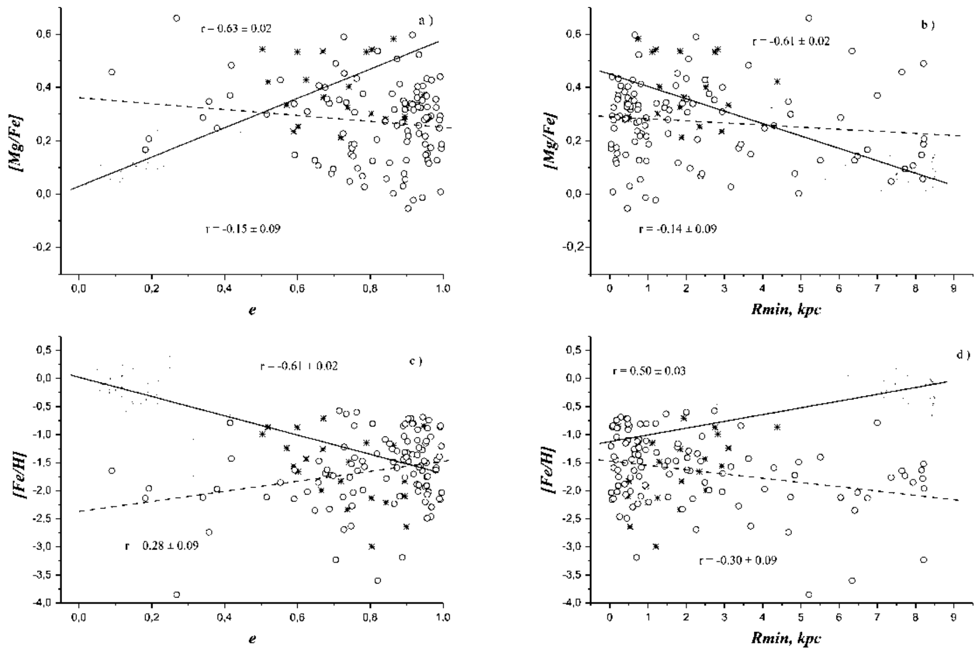

Figure 3. (a), (b) The relative magnesium abundances and (c), (d) the metallicities in the stars of our catalogue versus (a), (c) the eccentricities and (c), (d) the perigalactic radii of their orbits: solid lines, regression lines for genetically related stars; dashed lines, regression lines for presumably accreted stars. The correlation coeffcients for genetically related stars and presumably accreted stars are given at the top and the bottom respectively of each diagram.

accreted stars have very high eccentricities, $e > 0.9$, and small perigalactic radii of their orbits, $R_{\mathrm{p}} < 1$ kpc. The mean apogalactic radii of their orbits are also small (16 ± 1 kpc). The stars of the Centaurus moving group that came into our Galaxy from a disrupted, fairly massive dwarf galaxy have precisely such orbital elements. This is understandable; more massive disrupted systems leave a more distinct trace among the Galactic field stars.

Based on the above properties of accreted stars and our additional arguments, we surmise that, as the masses of dwarf galaxies decrease, the maximum SN II masses and hence the yield of α elements in them also decrease. In this case, the relation between the [Mg/Fe] ratios and the inclinations and sizes of the orbits of accreted stars is in complete agreement with numerical simulations of dynamic processes during the interaction of galaxies. Thus the behaviour of the magnesium abundance in accreted stars suggests that the satellite galaxies are disrupted and lose their stars *en masse* only after dynamic friction reduces significantly the sizes of their orbits and drags them into the Galactic plane.

Less massive satellite galaxies are disrupted even before their orbits change appreciably under tidal forces.

A full description of this investigation has been be published in [1].

References

[1] V.A. Marsakov and T.V. Borkova, Pis'ma Astron. Zh. **32** 604 (2006) (Engl. Transl. Astron. Lett. **32** 545 (2006)).