Metallicity Gradients In and Chemical Fingerprinting of The Milky Way's Halo Streams

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Abstract:

Stars have distinctive abundance patterns that reflect the unique chemical history of their parent system. In principle, therefore, "chemical fingerprinting" can help identify stars stripped from dwarf galaxies moving through the Galactic halo field. Several large tidal structures are known to be circling the Milky Way, including the Sagittarius (Sgr) stream and the Monoceros stream, also known as the Galactic anticenter stellar structure (GASS). The present work has focused on making the first test of the "chemical fingerprinting" concept by focusing on stars expected to be part of these, and possibly other, known streams.

Observations:

We have observed 80 M giant stars selected to be likely members of the Sgr tidal stream (see Fig. 1)or the GASS structure, and 4 stars in the TriAnd structure, using both spatial information from Majewski et al. (2003) and Rocha-Pinto et al. (2003; 2004) and velocities from Majewski et al. (2004) and Crane et al. (2003). These stars were observed on the SARG spectrograph (R=46000) on the TNG telescope, the Mayall 4-m echelle (R=35000) and the MIKE echelle spectrograph (R=19000) on the Clay 6.5-m telescope.

Abundance Analysis:

We adopt Houdashelt's color-calibrated effective temperature (Houdashelt et al. 2000) in the abundance analyses, and use the LTE stellar line analysis program MOOG (Sneden 1973) for the analysis of 11 Fe lines, and other elements discussed. The model atmospheres adopted here are generated by interpolation from Kurucz (1994) grids. We iterate the surface gravity (parameterized as log g, from Padova isochrones; Girardi et al. 2000), metallicity ([Fe/H]), and microturbulence until a consistent set of stellar and model atmosphere parameters is found. We use the spectral synthesis task in MOOG for determining λ7483Å La abundances including hyperfine splitting calculations, but use the *abfind* routine for other elements (λ7489Å and λ7496Å for Ti, λ7450Å for Y). Some stars that have night sky-line contamination in the La line are left out of our analysis.

Exploration of the Sgr Stream:

In our first chemical abundance study of a tidal stream (Chou et al. 2006), the Sgr stream metallicity distribution function (MDF) is found to evolve significantly from a median [Fe/H] ~ -0.4 in the Sgr core to ~ -1.2 dex over a Sgr leading arm length representing ~ 2.5-3.0 Gyr of dynamical (i.e. tidal stripping) age, based on echelle spectroscopy of candidate M giants at different points along the tidal stream of the Sgr dwarf spheroidal (dSph) galaxy (Fig.2). The majority of these stars are shown through ``chemical fingerprinting" to have been formed in Sgr, and not the Milky Way, on the basis of unusual titanium and/or s-process abundances (Fig. 3-6). The MDF evolution shows direct evidence that there can be significant chemical differences between current dSph satellites and the bulk of the stars they have contributed to the halo, and suggests that there is danger in making comparisons of halo stars to dSph stars of today. Our results also suggest that Sgr experienced a significant change in binding energy over the past several Gyr, which has substantially decreased its tidal boundary across a radial range over which there must have been a significant metallicity gradient in the progenitor galaxy. In this poster, we also analyze the MDF of a moving group of M giants we previously discovered towards the North Galactic Cap (NGC) having opposite radial velocities to the infalling Sgr leading arm stars there (Majewski et al. 2004) and conclude that most of these may represent Sgr *trailing arm* stars overlapping the Sgr leading arm in this part of the sky. This conclusion invoked "chemical fingerprinting" -- the NGC stars also have unusual Ti and s-process like the Sgr stream stars we found.

Exploration of the Galactic Anticenter Stellar Structure:

Clearly chemical abundances provide a means to identify member stars of halo streams. The origin of the recently identified GASS ``ring", a low latitude overdensity beyond the disk first discovered in Monoceros (Newberg et al. 2002) and spanning the second and third Galactic quadrants, remains controversial. Models include scenarios where GASS is a piece or warp of the Galactic disk (Momany et al. 2006) versus those where it represents tidal debris arms from the disruption of a Milky Way satellite galaxy (e.g., Rocha-Pinto et al. 2006). From preliminary analysis, the behavior of Ti and s-process abundances of GASS is more like that formed in a dSph like Sgr (Fig. 3-6), which suggests that GASS is more likely to be from a disrupted dwarf galaxy than to represent a structural component derived from the disk.

Exploration of the TriAnd overdensity:

The distant TriAnd overdensity has been little explored since its discovery (Rocha-Pinto et al. 2004, Majewski et al. 2004b), but has been proposed to be part of the Monoceros stream (Peñarrubia et al. 2005). If TriAnd is an old piece of GASS, and it follows the Sgr paradigm, then the position of the older piece should have lower mean [Fe/H]. However, from our preliminary analysis, the mean [Fe/H] of TriAnd is ~ -0.7 (Fig. 3-6), higher than the lowest GASS star we have observed ([Fe/H]~-1.0). The TriAnd stars also do not seem to have as extreme [Y/Fe] as GASS, though the sample is still small (4 stars). Overall, based on its higher [Fe/H] and different abundance patterns, it appears that TriAnd is not a piece of Monoceros.

Discussion and Future Plan:

Though it is now clear that accretion of dwarf galaxies likely played a prominent role in creating the Milky Way halo (Searle & Zinn 1978), the chemical abundance patterns of current Milky Way satellites are typically very different than those of typical halo field stars (e.g., Shetrone et al. 2003). Our study helps clarify the bridge from dwarf galaxy to halo star *directly* by exploring chemical trends along the tidal tails of disrupting dwarf galaxies. Our initial abundance analysis on debris from the Sgr dwarf galaxy has already revealed a significant [Fe/H] trend along the leading arm from the core to debris stripped some 2 Gyr ago from the satellite. This trend vividly demonstrates the origin of differences between current dwarf galaxies and the stars they contributed to the halo and presents a new method for mapping the star formation and dynamical histories of galaxies. We will improve our analysis of the Sgr stream by investigating the dynamically simpler *trailing arm* of Sgr. We also plan to repeat this analysis on the GASS system. Two locations within GASS have been proposed to contain the ``dwarf galaxy progenitor" of the stream: Canis Major (Martin et al. 2004) at *l* ~ 245° and Argo (Rocha-Pinto et al. 2006) at *l* ~ 290°. If GASS is a stream and follows the Sgr paradigm, then the position of the core should have the highest mean [Fe/H], and we can test whether this holds for Argo or Canis Major.

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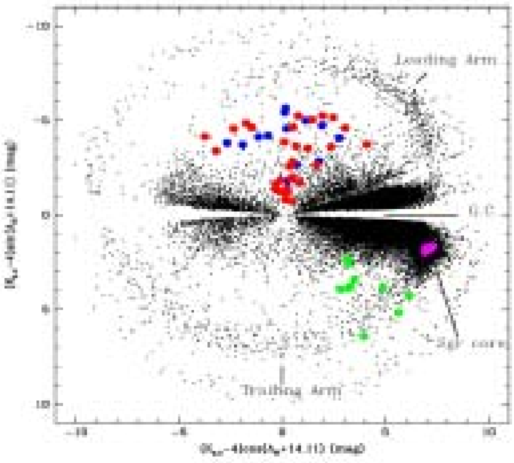

FIG. 1. Sgr orbital plane position of M giants lying within 10° of that nearly polar plane. Only stars with (J-Ks)o > 1.0 and E(B-V)<0.555 are shown. The Sun lies at the origin of the distribution and stars are positioned in a polar projection based on their dereddened 2MASS Ks magnitude (radial direction, after subtraction of 4 mag) and angle from the center of Sgr, increasing in the direction of the trailing arm (i.e. counterclockwise). Stars from the four subsamples for which we present new data here are represented by the large colored symbols: Sgr core (magenta), leading arm north (red), leading arm south (green) and the ``NGC" group of stars having positive GSR radial velocities off the main leading arm trend (blue).

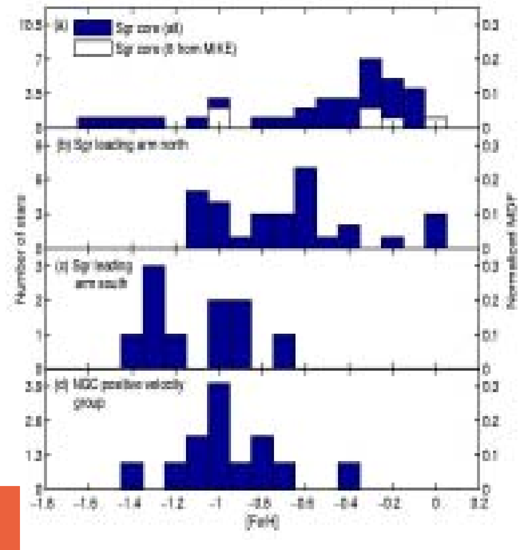

FIG. 2. MDF derived for stars in the (a) Sgr core (including all previous echelle data with our six newly observed stars shown in white), (b) leading arm north of the Sun, (c) leading arm south of the Sun, and (d) the positive-velocity, NGC moving group (blue circles in Fig. 1). The right hand axis shows the normalized number distribution for each group.

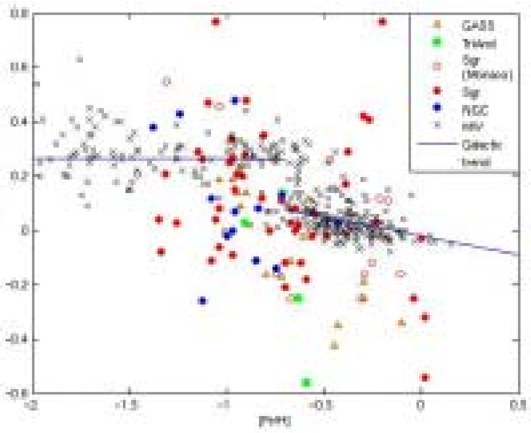

FIG. 3. [Ti/Fe] as a function of iron abundance. The red symbols are Sgr M giants from our observation and Monaco et al. (2005), blue circles are the ``NGC" group of stars having positive GSR radial velocities off the main leading arm trend, yellow triangles are the GASS stars, green squares are TriAnd stars, and the other black crosses are Galactic stars from Fulbright (2002), Johnson (2002), and Reddy et al. (2003). The solid line is a fit to the Galactic trend for halo and disk field stars.

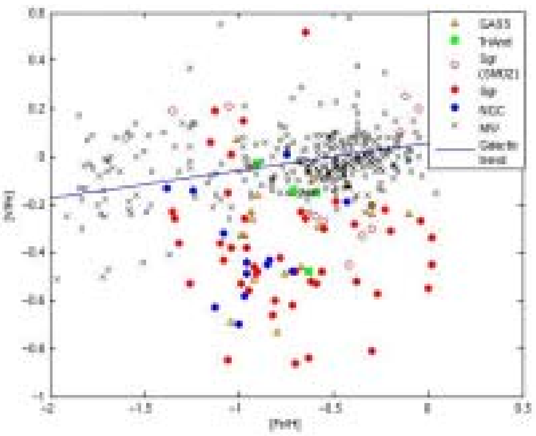

FIG. 4. [Y/Fe] as a function of iron abundance. Same symbols as Fig. 3, except red open circles are from Smecker-Hane et al. (2002, hereafter SM02), and we add Galactic stars from Gratton et al. (1994). Most of the Sgr and GASS stars have lower [Y/Fe], and this is the distinction between our sample stars and those in the standard Galactic populations.

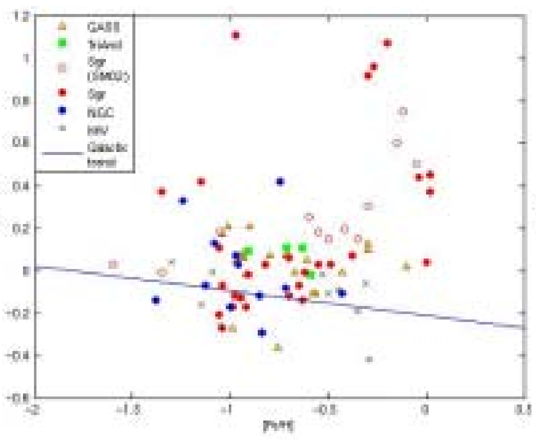

FIG. 5. [La/Fe] as a function of iron abundance. Same symbols as Fig. 4, except the Galactic stars are only from Gratton et al. (1994). [La/Fe] for most Sgr and GASS stars are higher than Galactic stars.

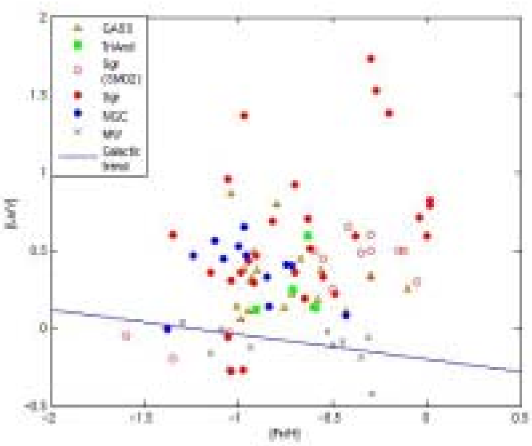

FIG. 6. [La/Y] as a function of iron abundance. Same symbols as Fig. 5. Most of our program stars have extreme [La/Y] in this plot.

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