FIRST ANALYSIS OF STARS IN THE TRIANGULUM–ANDROMEDA STAR CLOUD

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ABSTRACT

We undertake the first high-resolution spectroscopic study of the Triangulum–Andromeda (TriAnd) star cloud—an extended, mid-latitude Milky Way (MW) halo substructure about 20 kpc away in the second Galactic quadrant—through six M giant star candidates selected to be both spatially and dynamically associated with this system. The abundance patterns of [Ti/Fe], [Y/Fe], and [La/Fe] as a function of [Fe/H] for these stars support TriAnd as having an origin in a dwarf galaxy with a chemical enrichment history somewhat similar to that of the Sagittarius dwarf spheroidal galaxy. We also investigate the previously proposed hypothesis that TriAnd is an outlying, dynamically older piece of the Monoceros Stream (also known as the Galactic Anticenter Stellar Structure, “GASS”) under the assumption that both features come from the tidal disruption of the same accreted MW satellite and find that net differences in the above abundance patterns between the TriAnd and GASS stars studied suggest that these two systems are independent and unrelated.

Key words: galaxies: interactions – Galaxy: halo – Galaxy: structure – stars: abundances

Online-only material: color figures

1. INTRODUCTION

The Triangulum–Andromeda (TriAnd) star cloud was identified as a low-latitude overdensity of M giant stars in the Two Micron All-Sky Survey (2MASS) by Rocha-Pinto et al. (2004, hereafter RP04) and as a strong sequence of main-sequence turnoff (MSTO) stars by Majewski et al. (2004b, hereafter M04). RP04 and M04 found the structure to extend across at least 50' x 20' of the halo at a heliocentric distance of 15–30 kpc. The mean heliocentric radial velocity of the structure is ~−119±9.6 km s⁻¹, and its mean [Fe/H] is ~−1.2 dex based on calcium infrared triplet measurements by RP04. Though a subsequent MegaCam survey of MSTO stars in this sky region (Martin et al. 2007) confirmed a ~20 kpc distance for this stellar structure, to date little additional attention has been given to TriAnd, including determining its properties at any level of detail useful for ascertaining the origin of the structure.

In contrast, significantly more attention has been given to the Galactic Anticenter Stellar Structure (GASS), also called the “Monoceros Stream” or “Monoceros Ring,” which was discovered only two years before TriAnd as several overdensities of presumed MSTO stars (Newberg et al. 2002) in the same general region of the Galactic anticenter as TriAnd⁷, but at a closer mean ~11 kpc heliocentric distance. Subsequent study of this ring-like structure with the Isaac Newton Telescope Wide Field Camera (Ibata et al. 2003; Conn et al. 2005), Sloan Digital Sky Survey spectroscopy and photometry (Yanny et al. 2003, hereafter Y03), and as traced by 2MASS M giants (Crane et al. 2003, hereafter C03; Majewski et al. 2003, hereafter M03; Rocha-Pinto et al. 2003, hereafter RP03) has shown that the low-latitude GASS ring spans at least the second and third Galactic quadrants and has a wide metallicity spread, from [Fe/H] = −1.6 ± 0.3 (Y03) to −0.4 ± 0.3 (C03). Nevertheless, the origin of GASS remains controversial. Principal scenarios include those where GASS is a piece/warp of the Galactic disk (Momany et al. 2006; Kazantzidis et al. 2008; Younger et al. 2008) versus those where it represents tidal debris from the disruption of a Milky Way (MW) satellite galaxy (Ibata et al. 2003; Y03; C03; RP03; Helmi et al. 2003; Frinchaboy et al. 2004; Martin et al. 2004; Peñarrubia et al. 2005; Conn et al. 2005; Rocha-Pinto et al. 2006). A comparison of chemical patterns between the GASS and other dwarf spheroidal (dSph) galaxies has recently been made in Chou et al. (2010b, hereafter C10b). Their GASS sample reveals similar abundance patterns for Ti, Y, and La as in the Sagittarius (Sgr) dwarf+spheroid system and other satellite galaxies, which suggests that stars in GASS are likely formed in a dwarf galaxy-like environment. However, this chemical observation does not in itself conclusively resolve the debate over the dynamical origin of GASS because theoretical models show that galactic disks grow outward by accretion of dwarf galaxies (e.g., Abadi et al. 2003a; Yong et al. 2005), and whether GASS represents an intact tidal stream versus some other Galactic structure generated from a previously hierarchically formed, outer disk is not clarified by this chemistry.

The lack of a definitive origin model for GASS notwithstanding, soon after the TriAnd discovery it was proposed by Peñarrubia et al. (2005) that this structure may simply be an outlying piece of GASS/Mon, which these authors hypothesized to be a structure formed from the dissolution of an MW satellite galaxy. Both structures are at similar Galactic latitudes, and Peñarrubia et al. were able to find an N-body simulation that could incorporate TriAnd as a dynamically older, earlier-stripped piece from the putative Mon progenitor galaxy, under the assumption that the position of this progenitor is in Canis
Major (the latter aspect motivated by the claim of a Canis Major
eroverdensity interpreted as the core of a disrupting dSph by
Martin et al. 2004—itself a greatly debated issue; see
Rocha-Pinto et al. 2006; Mateu et al. 2009, and references
therein). If TriAnd and GASS/Mon are parts of the same dwarf
galaxy system, then the stars in these two structures share a
common chemical enrichment history and should in principle
show similar enrichment patterns—e.g., those seen by C10b for
GASS/Mon. In effect, one could apply “chemical fingerprint-
ing” to determine whether the stars in TriAnd belong to the
GASS/Mon system.

This technique was recently applied by Chou et al. (2010a,
hereafter C10a) to show that a group of M giant stars in the North
Galactic Hemisphere (the “NGC moving group”) are likely older
pieces of the Sagittarius tidal stream. A comparison to the Sgr
system is quite apropos in the study of Mon and TriAnd, since
Sgr exhibits many similar properties to both, including a rela-
tively high metallicity with the presence of M giant stars in all
three cases (M03; RP03; RP04) that suggest the progenitor sys-
tems of all three substructures may have been somewhat similar.

Therefore, following the above precedents from our previous
chemical studies of halo substructure, in this Letter we make the
first high-resolution spectroscopic assessment of the chemical
abundance patterns in the TriAnd system and use these abun-
dance measurements to investigate the hypothesized connection
between the TriAnd and GASS/Mon systems.

2. OBSERVATIONS AND ANALYSIS

Our analysis of TriAnd stars is identical to that used for
Sgr and GASS M giants described in Chou et al. (2007,
hereafter C07), C10a, and C10b. We use spectra from echelle
spectrographs mounted on the Apache Point Observatory 3.5 m
Telescope9 and Kitt Peak National Observatory 4 m telescope,
with resolutions $R = 32,000$ and 35,000, respectively. We
measure equivalent widths (EWs) of eleven Fe I lines, two Ti I
lines, and one Y II line, and use spectral synthesis for one La II
line in the spectral region 7440–7590 Å previously studied by
Smith & Lambert (1985, 1986, 1990). We use the LTE code
MOOG (Sneden 1973) to derive abundances of these elements,
following the same procedures as in C07, C10a, and C10b,
and adopt the same model atmospheres generated by linear
interpolation from the grids of ATLAS9 models in Castelli &
Kurucz (2003).10 Our analysis used their ODFNEW models
without convective overshooting.

We observed six TriAnd M giants selected to have the
photometric parallax and radial velocity of that system from the
sample described in RP04. Observed GASS stars range from
7.8 < $K_s$ < 10.1, while the TriAnd stars span a narrower, 10.5 < $K_s$ < 11.2 range. Nevertheless, both samples have the
same $J-K_s = 1.0$ blue limit and about the same intrinsic red
giant branch (RGB) luminosity, as evidenced by a comparison
to the fitted isochrones (see Section 3). The primary difference
is that the GASS sample includes more very red, presumably
asymptotic giant branch (AGB) stars so that the red limits are
$J- K_s = 1.10$ for TriAnd and $(J - K_s)_{0} < 1.25$ for GASS;
this yields mean ($J - K_s$)$_0$ colors of 1.05 and 1.09 dex for
the full TriAnd and GASS samples, respectively. The apparent $K_s$
magnitudes and dereddened ($J-K_s$)$_0$ colors (Schlegel et al.
1998) for our target TriAnd stars are listed in Table 1. The same
information for GASS stars is found in C10b.

The derived abundances are also summarized in Table 1;
columns give the derived effective temperature using the
Houdashelt et al. (2000) color–temperature relation applied to
the 2MASS ($J-K_s$)$_0$ color, and the derived values of the sur-
ficial gravity ($\xi$), abundance $A(X)$, and abundance ratios [Fe/H] or [X/H] for each element X as well
as the standard deviation in the abundance determinations. The
latter represent the line-to-line scatter (for Fe, Ti, and Y) for
the EW measures, or different continuum level adjustments (for
La), as discussed in C07 and C10a.

Uncertainties in abundance ratios are derived as in C10b.
Briefly, we account for both uncertainties in measured EWs
as well as propagated uncertainties from the adopted stellar
parameters. The latter mainly come from the color-calibrated
effective temperatures and imprecise knowledge of the proper
isochrones to use for each star. The net uncertainties are
estimated to be 0.14, 0.20, 0.19, and 0.16 for [Fe/H], [Ti/Fe],
[Y/Fe], and [La/Fe], respectively.

3. RESULTS

Figure 1 shows color–magnitude diagrams (CMDs) of the
TriAnd and GASS M giant candidates. Based on our derived

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Table 1: Stellar Parameters and Chemical Abundances for the Program Stars

| Star No. | $K_{s,0}$ | $(J - K_s)_0$ | $T_{eff}$ (K) | log $g$ | $\xi$ | $A$(Fe$^b$) | $[Fe/H]^b$ | $A$(Ti) | $[Ti/Fe]^b$ | $A$(Y) | $[Y/Fe]^b$ | $A$(La) | $[La/Fe]^b$ |
|----------|----------|----------------|-----------|--------|-------|----------------|--------------|--------|----------------|------|--------------|--------|--------------|
| Sun      | ...      | ...             | ...       | ...    | ...   | ...             | ...          | ...    | ...             | ...  | ...          | ...    | ...          |
| TriAnd   | J01214158+3655505 | 10.65          | 1.06      | 3750   | 0.4   | 1.71            | 6.86         | -0.59  | 0.11            | 3.83 | -0.48/0.13    | 1.47   | -0.15/0.05    | 0.30   | -0.24/0.09  |
| J01425641+3851201 | 10.73          | 1.07          | 3750   | 0.3   | 1.74  | 6.47          | -0.71/0.09  | 4.33   | 0.14/0.05       | 1.36  | -0.14/...c    | 0.32   | -0.10/0.02   |
| J02044137+4059528 | 11.11          | 1.00          | 3850   | 0.4   | 1.74  | 6.54          | -0.91/0.11  | 4.02   | 0.03/0.02       | 1.27  | -0.03/...c    | 0.21d  | -0.01/0.02   |
| J23333344+3909235 | 10.60          | 1.07          | 3750   | 0.4   | 1.66  | 6.62          | -0.63/0.11  | 3.94   | -0.33/0.01      | 1.33  | -0.25/0.21    | ...    | ...          | ...    |
| J23490540+4057312 | 11.11          | 1.02          | 3850   | 0.9   | 1.53  | 7.12          | -0.33/0.14  | 4.35   | -0.22/0.20      | 1.69  | -0.19/0.12    | 0.82   | 0.02/0.09    |
| J23534927+3659173 | 11.02          | 1.07          | 3750   | 0.4   | 1.65  | 6.81          | -0.64/0.11  | 3.85   | -0.41/0.13      | 1.61  | 0.04/0.12     | 0.15   | -0.34/0.03   |

Notes:

$^a$ The effective temperature as derived from the Houdashelt et al. (2000) color–temperature relation.
$^b$ Abundances are shown with the standard deviation in measurements.
$^c$ Only one Y II line measurable in two adjacent orders.
$^d$ Measurement uncertain due to spectrum defect on the blue edge of the observed La line.
$^e$ Lines unmeasurable due to cosmic rays or other defects.

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9 From http://kurucz.harvard.edu/grids.html.
[Fe/H] for each star (indicated by the color scale), we roughly matched these distributions with a set of Marigo et al. (2008) isochrones for 8 Gyr, [α/Fe] = 0, RGB/AGB stars. The choice of 8 Gyr matches the approximate age of Sgr stars of [Fe/H] ~ −0.7 (Siegel et al. 2007); analogy with Sgr is the only information available to inform such a decision for the systems of interest here. The corresponding isochrone distances are ~12 kpc (GASS) and ~22 kpc (TriAnd); these are consistent with previous estimates of the distances to these structures. However, due to the age-metallicity degeneracy of RGB isochrones, other combinations of age and metallicity also fit reasonably well—e.g., 5 Gyr old isochrones at 25 kpc and 14 kpc also fit the TriAnd and GASS distributions, respectively. The wider CMD spread of GASS stars having similar metallicities to each other (e.g., [Fe/H] ~ −1) suggests a potentially larger relative distance spread (~11–22 kpc) for GASS stars compared to TriAnd if we assume tight, monotonic age-metallicity relations in the two systems.

Figure 2 compares derived distributions of [Ti/Fe], [Y/Fe], and [La/Fe] as a function of [Fe/H] for our TriAnd, GASS/Mon (from C10b), and Sgr stars (from C07, C10a). A strength of the following comparison of TriAnd, GASS/Mon, and Sgr stars is that not only are our abundances for all three systems derived homogeneously using the same methodology (same lines, same model atmospheres, same derivation of stellar parameters, etc.), but the stars selected for comparison span a very narrow range of stellar atmospheric parameters (~350 K in temperature and ~1.0 dex in log g) so that the lines under study are forming under similar atmospheric conditions. Linear fits to the MW distributions (see C10a) are also shown in Figure 2. In contrast to the general chemical similarity of GASS and Sgr (except for [La/Fe] at the highest metallicities; see C10b), we note some larger differences between TriAnd and these other two systems (Figure 2). While the mean trend of [Ti/Fe] versus [Fe/H] for the TriAnd stars is somewhat similar to the mean trends for Sgr and GASS (though the three of six sampled TriAnd stars at [Fe/H] ~ −0.6 fall well below stars of similar metallicity in Sgr and GASS), the s-process element patterns reveal more obvious differences. The mean level of [Y/Fe] (middle panel) for TriAnd stars is about 0.2 dex higher (or about 2.5 times the error in the mean for TriAnd) than that for either Sgr or GASS stars at the same [Fe/H], and almost at the solar enrichment level and near the mean for MW stars. And while the [La/Fe] pattern of TriAnd stars closely resembles that of Sgr stars (including one star at [Fe/H] = −0.3 with enhanced [La/Fe], hinting at a possible upturn at high metallicity), it is less similar to, and slightly enhanced compared to, the GASS pattern, at least in the mean.

To put this comparison on a more quantitative footing, we apply the statistical method of bootstrap sampling (e.g., Efron 1979; Efron & Tibshirani 1993) to judge the differences between TriAnd and GASS. For a more conservative test, we combine the 6 + 21 data points of TriAnd+GASS stars for [Ti/Fe] and [Y/Fe], and 5 + 19 for [La/Fe] as if all stars are from one dSph system. We then randomly pick six stars from the 27 TriAnd+GASS star sample, and compute and compare the mean values for [Ti/Fe], [Y/Fe], and [La/Fe] for the six selected and 21 non-selected stars (or, in the case of [La/Fe], five from 24 stars). This process is repeated with 10,000 random selections of six (five) stars. The derived distributions of the bootstrap samplings for Ti, Y, and La are approximately normally distributed, and we find that there are only ~4.5% with mean [Ti/Fe] less than...
the mean value of TriAnd stars in the 10,000 bootstrap samples, and \(\sim 3.3\%\) with mean \([\text{Y/Fe}]\) and \(\sim 2.5\%\) with mean \([\text{La/Fe}]\) more than those in TriAnd stars. If the bootstrap sampling is repeated with the same procedure as above but for only GASS stars, we find only \(\sim 0.95\%\) with mean \([\text{Ti/Fe}]\) less than TriAnd in the 10,000 bootstrap samples, and only \(\sim 1.1\%\) with mean \([\text{Y/Fe}]\) and 0 with mean \([\text{La/Fe}]\) more than TriAnd.

If we restrict the GASS stars to the same color range spanned by the TriAnd stars (1.00 \(\leq [J - K_s]_o \leq 1.07\)) to minimize metallicity selection biases, we find the mean \([\text{Fe/H}]\) for eight GASS stars to be \(-0.52 \pm 0.09\) dex with a dispersion (standard deviation) of 0.26 dex, compared with a mean \([\text{Fe/H}]\) of \(-0.64\pm0.08\) dex with a dispersion of 0.19 dex for the six TriAnd stars. Applying the bootstrap method for the more conservative test we described above, we find that there are only \(\sim 22.0\%\) with mean \([\text{Ti/Fe}]\) less than the mean value of TriAnd stars in the 10,000 bootstrap samples, and \(\sim 4.9\%\) with mean \([\text{Y/Fe}]\) and \(\sim 10.0\%\) with mean \([\text{La/Fe}]\) more than those in TriAnd stars for the combination of 6 + 8 data points of TriAnd+GASS stars for \([\text{Ti/Fe}]\) and \([\text{Y/Fe}]\), and 5 + 7 for \([\text{La/Fe}]\). If we repeat the bootstrap sampling for the eight GASS stars only and compare results with the mean values in TriAnd, we find only \(\sim 4.4\%\) with mean \([\text{Ti/Fe}]\) less than TriAnd in the 10,000 bootstrap samples, and 0 with mean \([\text{Y/Fe}]\) and \([\text{La/Fe}]\) more than TriAnd, respectively.

Given the marked degree to which the mean values of all three of the \([\text{Ti/Fe}]\), \([\text{Y/Fe}]\), and \([\text{La/Fe}]\) ratios for TriAnd stars are different from corresponding means for the various bootstrap samples, we conclude that there might be significant chemical differences between the two systems, sufficient to suggest that TriAnd is not likely a part of the GASS system.

4. DISCUSSION

As discussed in C10a, distinctive abundance patterns in stars reflect the unique enrichment history of their parent system, and therefore, “chemical fingerprinting” can help identify tidally stripped and captured stars in the Galactic field. The chemical patterns of \(\alpha\)-elements (e.g., Ti and \(s\)-process elements (e.g., Y and La) may indicate differences in the (early) star formation rate (SFR) between the progenitors of the TriAnd, Sgr, and GASS systems, as well as the MW. For example, \(\alpha\)-elements are mainly produced from Type II supernovae (SNe II) while iron is synthesized largely by Type Ia supernovae (SNe Ia). So [\(\alpha/\text{Fe}\)] is high in the early enrichment of a stellar system until SNe Ia occur after the first \(\sim 1\) Gyr. A shift to a lower [\(\alpha/\text{Fe}\)] trend compared to the MW at some particular [\(\text{Fe/H}\)] indicates a relatively slower initial SFR in that system, a feature seen in many dSph galaxies as well as in the LMC (e.g., Smith et al. 2002; Shetrone et al. 2003; Tolstoy et al. 2003; Venn et al. 2004; Geisler et al. 2005; Pompéia et al. 2008; C10a). TriAnd follows the same \(s\) trends as dSph galaxies, consistent with an origin in a dwarf galaxy-like environment and, like other MW satellites, a low early SFR compared to the MW.

The \(s\)-process elements are primarily generated in low-mass AGB stars. In more metal-poor environments AGB stars
produce heavier s-process elements like La more efficiently than lighter species such as Y (see review by Busso et al. 1999). C10a found underabundant trends in [Y/Fe] for all Sgr stars compared to the MW, and an upturn in [La/Fe] for Sgr at [Fe/H] > −0.5. The latter trend can also be seen in McWilliam & Smecker-Hane (2005) and is an indication of a slow enrichment history, so that the yields from low-metallicity AGB stars have enough time to contaminate the interstellar medium and leave their signature on the metal-rich populations (Venn et al. 2004; Pompeia et al. 2008). The [Y/Fe] trends in TriAnd stars are slightly higher than those in either Sgr and GASS and somewhat closer to MW trends, whereas TriAnd shows a slightly lower [La/Fe] pattern compared to Sgr. This suggests that AGB stars in the TriAnd progenitor produced heavy s-process elements less efficiently than in Sgr—i.e., that low-metallicity AGB progenitors in TriAnd contributed relatively less heavy s-process enrichment than those in Sgr. This may also indicate that the TriAnd progenitor was more metal-rich than the Sgr progenitor. On the other hand, the TriAnd star with [Fe/H] > −0.5 shows slightly supersolar [La/Fe] (like the Sgr [La/Fe] pattern, only less extreme), but above the GASS [La/Fe] pattern at these metallicities. This may suggest that the TriAnd system enriched more slowly than the progenitor(s) that generated the GASS stars, but more similar in rate to the Sgr dSph, to allow expression of the high La yields from those relatively fewer low-metallicity AGB stars that it did contain, but this conclusion must be regarded as quite tentative, given the errors on individual abundances and that this is based on only a single high-metallicity TriAnd star.

The N-body simulations from Peñarrubia et al. (2005) suggest that TriAnd may be an older piece of the Mon tidal stream. According to the Sgr paradigm, older debris should be more metal-poor than younger debris, but share the same chemical pattern trends if from the same parent system. Indeed, Peñarrubia et al. associate older model stream wraps with lower metallicity stars, but these data derive from lower resolution spectroscopic measures of Ca ii line indices for GASS and TriAnd stars (C03; RP04). Though our study here has focused on better precision, high-resolution abundance determinations, including [Fe/H] derived from eleven individual Fe line measures, unfortunately the sample of stars is still too small to make definitive conclusions about the relative metallicity of the two systems. On the other hand, the sample of TriAnd and GASS stars in hand does offer tantalizing evidence that, at least on the metallicity that were sampled, TriAnd does not reveal the same chemical pattern trends as GASS and that therefore the TriAnd star cloud is not part of an extended GASS system. 11 That said, larger samples of GASS and TriAnd stars having precisely determined metallicities and chemical abundance patterns would certainly provide a more conclusive chemical test of the possible connection between these two systems, as well as more insight into the origin and evolution of their respective progenitors.

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