INVESTIGATION OF THE CONTAMINATION OF THE GOULD (2003) HALO SAMPLE

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ABSTRACT

A recent astroph posting argued that the Gould (2003a) halo sample is substantially contaminated with thick-disk stars, which would then "wash out" any signature of granularity in the halo velocity distribution due to streams. If correct, this would imply that the limits placed by Gould (2003b) on streams are not valid. Here I investigate such contamination using six different indicators:

1) morphology of the underlying reduced proper motion diagram used to select halo stars,
2) comparison of kinematic and parallax-based distance scales
3) comparison of derived halo parameters for the Gould (2003a) sample with other determinations
4) a precision color-color diagram for a random subsample
5) the 3-dimensional velocity distribution of a random subsample
6) metallicity distribution versus kinematic cuts on a random subsample

I estimate that the contamination is of order 2 percent. Thus, the upper limits on the density of nearby streams derived by Gould (2003b) remain valid. In particular, at 95% confidence, no more than 5% of local halo stars (within about 300pc) are in any one coherent stream. Determining whether or not this local measurement is consistent with CDM remains an outstanding question.

Subject headings: stars:halo – galaxies:substructure

1. INTRODUCTION

A critical test of the current picture of hierarchical structure formation, is measuring the "granularity" or substructure within the halo as a function of Galactocentric distance. Gould (2003b) determined that, contrary to naive expectation within this framework, the local Galactic halo is remarkably smooth, with only ~5% possible contribution from substructures. However, this conclusion is only as good as the underlying Gould (2003a) sample: significant contamination by thick-disk stars would tend to "wash out" any substructure signal (Kepley et al. 2007). Prompted by this concern, I demonstrate below through six different tests, that this sample is not in fact seriously contaminated and therefore that the current (still valid) limit of ~5% substructure must be understood by current models of Galaxy formation.

2. MORPHOLOGY OF THE RNLTT REDUCED PROPER MOTION DIAGRAM

The Gould (2003a) halo sample is derived from the revised New Luyten Two-Tenths (rNLTT) catalog of Gould & Salim (2003) and Salim & Gould (2003). The argument made by Kepley et al. (2007) for contamination of this sample is that Ryan & Norris (1991) found such contamination among the halo candidates that they had extracted from the underlying Luyten (1979, 1980) NLTT catalog.

Figures 1 and 2 (both taken from Salim & Gould 2002) show the reduced proper motion (RPM) diagrams for the NLTT and rNLTT, respectively. Halo stars are clearly separated from disk/thick-disk stars in rNLTT (used by Gould 2003a), but not NLTT (used by Ryan & Norris 1991).

Figures 3 and 4 further confirm the difficulty of extracting a clean sample of halo stars from NLTT. They show the distributions of main-sequence stars and subdwarfs in the color range 1.2 < V − J < 2.25

Subsequently, Salim & Gould (2003) introduced a further refinement of the optical/infrared RPM of Salim & Gould (2002) by defining a discriminator $\eta$ that depends on both RPM and Galactic latitude $b$:

$$\eta = V + 5 \log \mu - 3.1(V - J) - 1.47 \sin b - 2.73$$

where $\mu$ is the proper motion in arcsec per year. They identified halo stars as dominant in the range

$$0 < \eta < 5.15$$

Salim & Gould (2003) shows (in black) the distribution of $\eta$ in the color range 2.25 < V − J <
3. COMPARISON OF PARALLAX AND KINEMATIC DISTANCE SCALES

A second check comes by comparing the kinematic-based distance scale derived by Gould (2003a) with trigonometric parallaxes found in the literature. To establish distances, Gould (2003a) fit for the two parameters of a linear color-magnitude relation, while enforcing a mean motion of halo stars relative to Sun of $U_2 = -216.6\, \text{km\, s}^{-1}$, so as to force agreement with the determination of this parameter by Gould & Popowski (1998) based on halo RR Lyrae stars. Gould (2003a) then compared this with the color-magnitude relation derived from halo stars with trigonometric parallaxes from Monet et al. (1992) and Gizis (1997). As can be seen from Figure 5, these relations are virtually identical. If the sample were contaminated with thick-disk stars (whose mean motion $U_2$ motion relative to the Sun is of order 5 times smaller than halo stars) by even 10%, then this would cause an error in the distance scale of 0.80 × 10% = 8%, yielding an offset between the parallax and kinematic relations of about 0.17 mag. The offset is clearly much smaller than this.

4. COMPARISON OF HALO KINEMATICS

It is not only the asymmetric drift of the halo that is correctly reproduced by the Gould (2003a) analysis, but also the velocity dispersions. Gould (2003a) found dispersions in the radial, rotation, and vertical directions of $168 \pm 1, 113 \pm 2,$ and

$$1 < \eta < 4.15 \quad \text{[Gould (2003): secure halo stars]} \quad (3)$$
to avoid main-sequence stars at high $\eta$ and white dwarfs at low $\eta$. From Figure 5, one may estimate that this choice generates roughly 2% contamination.

While I will give several other independent arguments that the sample is not seriously contaminated, this one is the strongest and most quantitative.
5. Distribution of "population discriminator" $\eta$ for rNLTT stars with $2.25 < V-J < 3.25$. There are two clear peaks corresponding to main-sequence stars (red) and subdwarfs (green). In the overlap the bins have been divided by symmetrizing (see text). Adapted from Salim & Gould (2003).

6. CMD of stars with trigonometric parallaxes (Monet et al. 1992; Gizis 1997), separated into various classes using the Salim & Gould (2003) RPM-discriminator $\eta$. The solid line shows the best fit to the halo stars in the data while the dashed line shows the fit based on kinematic analysis of the Gould (2003a) sample. They are virtually identical. If there were serious contamination by thick disk stars, the dashed line would have been driven to brighter mags. From Gould (2003a).

5. PRECISION COLOR-COLOR DIAGRAM OF A RANDOM SUBSAMPLE

Marshall has obtained precise photometric data for 564 stars selected by applying the same $1 < \eta < 4.15$ criterion used by Gould (2003a). Her Figure 9 (reproduced here as Fig. 7) shows a very tight color-color relation for these stars, consistent with a metal-poor population. It is clear that the stars extracted by this criterion are not very heterogeneous, as would have been expected were they seriously contaminated.

6. 3-D VELOCITY DISTRIBUTION OF A RANDOM SUBSAMPLE

J. Marshall (private communication 2007) has also obtained radial velocities for 295 of the stars in her sample, which (together with her excellent photometry and the rNLTT proper motions) permit her to make 3-dimensional velocity estimates for each star. The results are shown in Figure 8. The distribution is not significantly contaminated by thick-disk stars, which would appear as an overdensity centered at $(U, V, W) \sim (0, 190, 0) \text{ kms}^{-1}$.

89 \pm 2 \text{ km s}^{-1}$, respectively. These values are quite compatible with other determinations. For example Gould & Popowski (1998) found $171 \pm 10$, $99 \pm 8$, and $90 \pm 7$ from a much smaller sample of halo RR Lyrae stars. Serious contamination by the kinematically much cooler population of thick-disk stars would have tended to drive down these dispersions (assuming the distance scale remained in agreement with the parallax stars of Fig. 6).
Fig. 8.— *U*W velocities (in Galactocentric frame) of 295 stars selected from rNLTT using the same *μ* < 4.15 criterion adopted by *Gould* (2003). There is no significant contamination by thick-disk stars. Kindly provided by J. Marshall in advance of publication.
which they showed that the halo candidates that they had selected from NLTT were heavily contaminated by thick-disk stars. Figure 9 is the direct analog of Figure 2 from Ryan & Norris (1991). It shows the metallicity for all 239 stars and also for a subsample of 194 “kinematically secure halo” stars defined as the union of stars with either \( v_\perp > 220 \text{ km s}^{-1} \) or velocity in the rotation direction \( V < -220 \text{ km s}^{-1} \). The first point to note is that 82% of the stars are “secure halo” by this definition. The second point is that the metallicity distributions of the two samples are essentially identical. By contrast, Ryan & Norris (1991) found a huge tail of higher-metallicity stars in their full sample, which disappeared when they implemented the same “secure halo star” cut. This brings the argument full circle.

8. CONCLUSION

Contamination of the original Gould (2003a) halo sample by thick-disk stars is likely to be of order 2%. This implies that the effect of streams is not “washed out” by thick-disk contamination. Hence, the limits on granularity found by Gould (2003b) in this sample imply corresponding limits on streams in the Galactic halo. In particular, at 95% confidence, no more than 5% of local halo stars (within about 300 pc) are in any one coherent stream.

I thank Juna Kollmeier for suggesting a number of improvements to the original manuscript. I am grateful to Jennifer Marshall for making available her plots of 3-D velocity (Fig. 8) and metallicity distribution (Fig. 9) in advance of publication. This work was supported in part by grant AST-042758 from the NSF.

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