Dwarf Galaxies: From the Deep Universe to the Present
Proceedings IAU Symposium No. 344, 2019
K. B. W. McQuinn & S. Stierwalt, eds.
© International Astronomical Union 2019
doi:10.1017/S1743921318007111

FOSSILs in the Galactic Halo

Carl J. Grillmair

IPAC, Mail Code 314-6, Caltech, 1200 E. California Blvd., Pasadena, CA 91125, U.S.A.
email: carl@ipac.caltech.edu

Abstract. We use a matched filter to detect compact groups of old, metal-poor stars that we term FOSSILs (Fragments of Old Stellar Systems in Limbo). With size scales on the order of 10 arcminutes, distances ranging from 2 to 200 kpc, and memberships ranging from a handful to several dozen stars, these FOSSILs stand out from the surrounding field and are presumably signatures of, or debris from, ancient star clusters and dwarf galaxies. They may be localized concentrations of stars within more extensive tidal streams, and in some cases may be the signatures of extant but heretofore undetected ultrafaint galaxies. Using magnitudes and colors from the Pan-STARRs survey, we detect ~ 70 such FOSSILs at 5σ or greater in a 2200 square degree region in the vicinity of the north Galactic pole. A subsample of more populous FOSSILs that could be candidate ultrafaint dwarf galaxies suggests a total population of 200 such objects within 200 kpc of the Galactic center. Spectroscopic and astrometric follow-up of these FOSSILs will be required to determine the nature of these structures, deepen our understanding of the make-up and accretion history of the Galactic halo, and perhaps alleviate the missing satellites problem.

Keywords. Galaxy: halo, galaxies: dwarf

1. Analysis

Matched filters, designed to optimally highlight specific stellar populations within a sea of mixed populations (noise), have been used to detect dozens of tidal streams in the Galactic halo at surface brightnesses as low as 37 mag/arcsec^2 (Grillmair & Carlin 2016; Grillmair 2017; Shipp *et al.* 2018). In addition to streams, many more compact features are also seen. Here we analyze a 2200 square degree portion of the PS-1 catalog (Chambers *et al.* 2016) using a filter designed to highlight structures with Z = 0.0001 ([Fe/H] ≈ -2.2) and an age of 13.2 Gyrs. The region was selected to avoid strong or variable extinction, and to overlap with the Sloan Digital Sky Survey. We include all stars with $g_{P1} < 21.7$ and successively shift the filter by 0.2 mag to select objects at distances ranging from 2 to 200 kpc. Using a filter response image such as the one shown in Figure 1, we background-subtract each 12×12 arcmin pixel and plot its filter response as a function of distance modulus. To improve centroiding we create filter response maps shifted over a 4×4 grid with a spacing of 3 arcmin in each dimension and then choose the pixel-center coordinates from the map that yields the strongest signal. While Gaia proper motions do not go deep enough to be useful in this filtering, we do remove brighter stars with measured proper motions if the inferred tangential velocities at any given distance exceed the escape velocity of the Galaxy (taken here to be 533 km s^{-1} (Piffl *et al.* 2014)).

Figure 1 is dominated by Poisson noise. To determine which enhancements are statistically significant we randomly scramble the sky coordinates of all stars in the sample and filter the results in exactly the same manner as above. Using 100 such realizations, we compute the standard deviations among the peak signals found at each distance modulus. We then select only those detections that exceed the mean peak signal at each distance modulus by at least 5σ.

https://doi.org/10.1017/S1743921318007111 Published online by Cambridge University Press

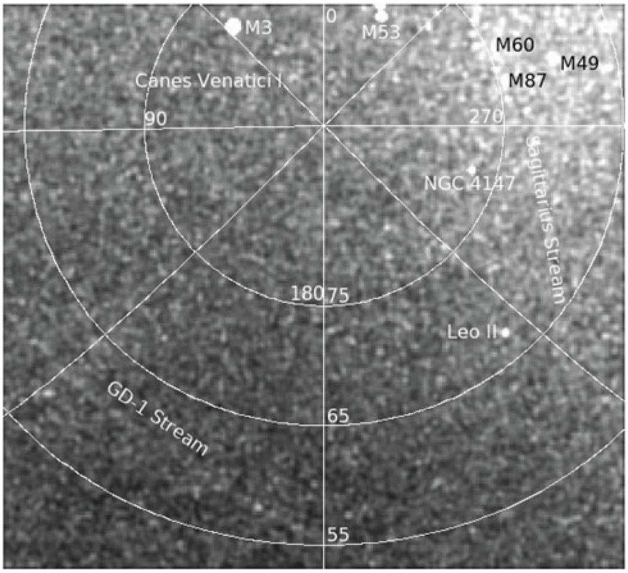

Figure 1. PS-1 field area chosen for analysis, with Galactic coordinates indicated. Stars have been filtered using a color-magnitude locus with Z=0.0001, an age of 13.2 Gyrs, a powerlaw luminosity function with $N \propto g^{0.3}$, and a distance of 8 kpc. The stars have been binned using pixels 12×12 pixels on a side. Globular cluster systems around Virgo cluster galaxies are labeled in black, while local globular clusters, dwarf galaxies, and streams are labeled in white. The Sagittarius stream appears relatively muted here as the portion of the stream in this field has a heliocentric distance of more than 20 kpc.

Sixteen known objects are excised from our final list, along with any detections within half a degree of these objects. These include several globular cluster systems around galaxies in the Virgo cluster (which have colors and magnitudes consistent with red giant stars in our own halo) as well as several Milky Way globular clusters and ultrafaint dwarfs.

2. Results

Known globular clusters and dwarf galaxies are detected at the tens or hundreds of σ level. The weakest of these (Coma Berenices) is detected at the 8σ level. By comparison, the strongest portions of the GD-1 stream (Grillmair & Dionatos 2006) are detected at $< 1\sigma$. The individual pixel peaks for GD-1 are evidently not significant compared with the distribution we would expect for a purely random distribution of stars and the stream was discovered only because the peaks form such a well-collimated stream.

Another 70 sources are found at $> 5\sigma$ significance. Figure 2 shows filter responses, color-magnitude diagrams, and sky positions of contributing stars (those lying within 3σ of the theoretical $Z = 0.0001$ locus) for two fairly typical detections. These detections have peak-signal distances of 17 and 105 kpc, respectively. Given the low surface density and concentration of the more distant detection, this may well be a candidate ultrafaint galaxy.

In virtually every case, the contributing stars appear to be distributed randomly with little evidence for clustering. Surface density profiles have powerlaw slopes clustering around zero, with only a handful having slopes steeper than -1.5. We note, however, that Coma Berenices and Canes Venatici II show color-magnitude sampling very similar to Figure 2, and have surface density slopes of -1.4 and -0.4, respectively.

https://doi.org/10.1017/S1743921318007111 Published online by Cambridge University Press

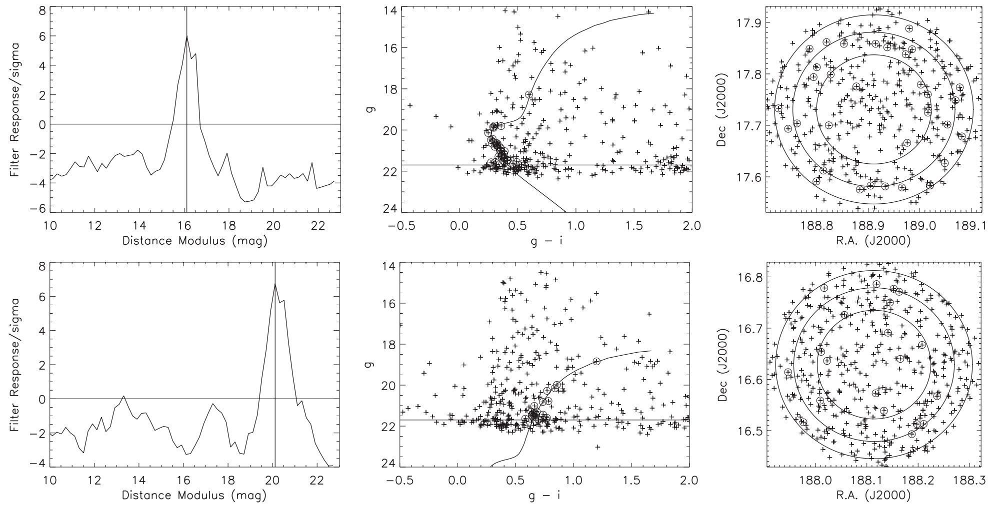

Figure 2. Filter response profiles, PS-1 color-magnitude diagrams, and sky positions of stars for two of our 70 detections. The signal strengths are given in units of the standard devications of peak signals in purley random distributions at each distance modulus, and in these cases indicate distances of 17 and 105 kpc, respectively. Circled crosses in the color-magnitude diagrams and sky positions indicate stars lying within 3σ of the theoretical $Z = 0.0001$ isochrone and which would have contributed to the observed signals in the left hand panels.

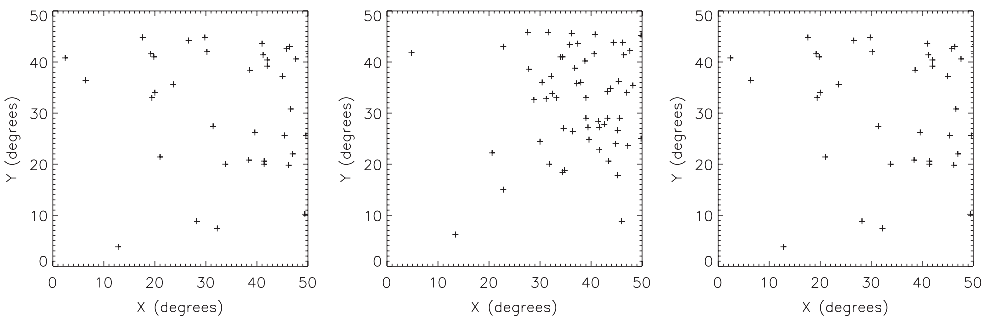

Figure 3. Sky positions of our $> 5\sigma$ detections in the same coordinate projection as in Figure 1. The left panel shows the distribution of FOSSILs with $1 < d < 10$ kpc, the center panels with $10 < d < 60$ kpc, and the right-hand panel shows FOSSILs with $60 < d < 200$ kpc.

Figure 3 shows the distribution of our detections on the sky. For FOSSILs with distances between 10 and 60 kpc there is a clear concentration along the Sagittarius stream. For FOSSILs at less than 10 kpc or more than 50 kpc, the distributions are more uniform, though there is a moderate concentration towards the Galactic center.

Completeness calculations using artificial clusters inserted into the field reveal that our results are complete to 20 kpc for clusters with total populations of > 1000 stars, to 80 kpc for populations with $N > 10,000$, and to 300 kpc for $N > 100,000$. As observed, the volume density of FOSSILs falls with Galactocentric radius as $N = R^{-3.6}$, though completeness corrections would presumably reduce this gradient significantly.

If we consider only detections in the left half of Figure 1 (with $0° < l < 180°$ and therefor clear of the Sagittarius stream) we find ten FOSSILs with $d > 10$ kpc and suggestively populated sequences that could potentially be ultrafaint dwarf galaxies. Estimating total stellar populations from a relation between signal strength and distance modulus (derived

https://doi.org/10.1017/S1743921318007111 Published online by Cambridge University Press

from analyzing the artificial clusters used for completeness calculations), we find that for our UFD candidates $400 < N < 30000$. If indeed these are UFDs, and if we extrapolate our results to the whole sky, we would predict a total population of ≈ 200 such objects within 200 kpc. If follow-up spectroscopy confirms that these are indeed UFDs, then the "missing satellites" problem (Klypin *et al.* 1999; Moore *et al.* 1999) would essentially be resolved.

References

Chambers, K, Magnier, E. A., Metcalfe, N. *et al.* 2016, arXiv:1612.05560
Grillmair, C. J., & Dionatos, O. 2006 *ApJ*, 643, L17
Grillmair, C. J., & Carlin, J. L. 2016, in: H. J. Newberg & J. L. Carlin (eds.), *Tidal Streams in the Local Group and Beyond* (Switzerland: Springer), p. 87
Grillmair, C. J. 2017, *ApJ*, 834, 98
Klypin, A., Kravtsom, A. V., Valenzuela, O., & Prada, F. 1999, *ApJ*, 522, 82
Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J., & Tozzi, P., 1999 *ApJ*, 524, L19
Piffl, T., Scannapieco, C., Binney, J., *et al.* 2014, *Astr. Ap.*, 562, 91
Shipp, N., Drlica-Wagner, A., Balbinot, E. *et al.* 2018, *ApJ*, 862, 114

https://doi.org/10.1017/S1743921318007111 Published online by Cambridge University Press