The southern leading and trailing wraps of the Sagittarius tidal stream around the globular cluster Whiting 1

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ABSTRACT
We present a study of the kinematics of 101 stars observed with VIMOS around Whiting 1, a globular cluster embedded in the Sagittarius tidal stream. The obtained velocity distribution shows the presence of two wraps of that halo substructure at the same heliocentric distance as that of the cluster and with well differentiated mean radial velocities. The most prominent velocity component seems to be associated with the trailing arm of Sagittarius with \( \langle v_r \rangle \sim -130 \, \text{km s}^{-1} \), which is consistent with the velocity of Whiting 1. This result supports that this globular cluster was formed in Sagittarius and recently accreted by the Milky Way. The second component with \( \langle v_r \rangle \sim 120 \, \text{km s}^{-1} \) might correspond to the leading arm of Sagittarius, which has been predicted by numerical simulations but with no conclusive observational evidence of its existence presented so far. This detection of the old leading wrap of Sagittarius in the southern hemisphere may be used to confirm and further constrain the models for its orbit and evolution.

Key words: (Galaxy): halo – formation – globular clusters: individual

1 INTRODUCTION
The accretion of massive satellites is believed to have contributed to the formation of a significant fraction of galaxy haloes by transferring a large amount of gas, stars and globular clusters (GC). Compelling evidence for the latter comes from the GC systems of nearby galaxies (e.g., M 31), where a large fraction of their globulars seem to align with tidal streams (Mackey et al. 2010, 2013; Huxor et al. 2014; Veljanoski et al. 2014). As for the Milky Way, the accretion of GCs in the hierarchical formation scheme has been long proposed because of the existence of at least two distinct subgroups in the Galactic halo (e.g. Searle & Zinn 1978; Zinn 1993; Marín-Franch et al. 2009; Forbes & Bridges 2010; Leaman et al. 2013; Zaritsky et al. 2016).

The most pronounced accretion event in the Galaxy is the one corresponding to the Sagittarius (Sgr; Ibata et al. 1994) dwarf spheroidal and its associated stellar structure, the so-called Sgr tidal stream (e.g. Martínez-Delgado et al. 2001; Newberg et al. 2002; Majewski et al. 2003; Belokurov et al. 2006; Koposov et al. 2012; Huxor & Grebel 2015). Given the spatial extent of that system, it seems likely that some of the Galactic GCs might have formed within Sgr and been later accreted by the Milky Way. Indeed, four GCs are immersed in the Sgr main body (M 54, Arp 2, Terzan 7 and Terzan 8; Da Costa & Armandroff 1995) and multiple Galactic halo GCs have been associated with the accreted galaxy (e.g. Dinescu et al. 2000; Bellazzini et al. 2002; Palma et al. 2002; Martínez-Delgado et al. 2002; Bellazzini et al. 2003; Carraro 2009; Forbes & Bridges 2010; Dotter et al. 2011; Sbordone et al. 2015). The total number of GCs likely associated with Sgr may reach \( \sim 20\% \) of the outer halo GC population at \( R_\odot > 10 \, \text{kpc} \) (Bellazzini et al. 2003), and Law & Majewski (2010a) found 9 globulars compatible with the...
2 OBSERVATIONS

For the selection of targets for spectroscopy, we have used in this work the photometric catalogs generated in a Megacam@CFHT and Megacam@Magellan survey of all outer Galactic halo satellites (R. R. Muñoz et al., in preparation). Figure 1 shows the Megacam CMD corresponding to Whiting 1 (left panel) and its surroundings (middle panel), where a well-populated main sequence (MS) in the plane of the Sgr orbit because of its lower surface brightness. A final conclusion about the extra-Galactic origin of these GCs requires the kinematic characterization both of the cluster and the underlying populations.

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3 RESULTS AND DISCUSSION

The derived radial velocity distribution of the 101 target stars is shown in Figure 2. The histogram is constructed using a bin size of 20 km s\(^{-1}\) and the observed morphology remains similar when the parameters used to generate it are changed or only one of the fields is considered. Three different components are clearly distinguished in the velocity distribution with approximate mean velocities of \(v_r = 130\) km s\(^{-1}\), \(0\) and \(120\) km s\(^{-1}\) in descending order of number of stars.

The inclusion of bright foreground stars as targets ensures the presence of Milky Way stars along that line-of-sight. We evaluate such a contribution by comparing our results with the velocity distribution predicted by the Besançon synthetic model (Robin et al. 2003). We performed 10 simulations using the default parameters for the position in the sky of Whiting 1 and for a solid angle of 1 deg\(^2\). We only considered those synthetic stars in the same color-magnitude range as our targets, and used the same step and window width. The comparison histogram results from the co-addition of the 10 synthetic distributions, and it was scaled to fit its maximum value to our results (see Figure 2). This procedure confirms that the bulk of stars at \(v_r \sim 0\) km s\(^{-1}\) is mostly composed of Milky Way stars, while the peaks at \(v_r = -130\) and \(120\) km s\(^{-1}\) represent excesses of stars not associated with any known Galactic population.

We derive velocity distributions from the (Peñarrubia et al. 2010, hereafter PR10) and LM10 models of the Sgr tidal stream along the line-of-sight of Whiting 1. We have selected in both cases all those model stars in an area of 2 deg \(\times\) 2 deg around the cluster position and generated a histogram using the same bin and window sizes used to build the previous ones. We then arbitrarily scaled the distributions and overplotted the results in Figure 2. Both PR10 and LM10 predict 2 components of Sgr in that area of the sky with mean velocities \(<v_r> \sim -130\) and \(\sim 115\) km s\(^{-1}\). The position of these peaks are compatible with the ones derived from the velocity distribution of the target stars. According to the classification provided by these models, the bulk of Sgr stars around \(v_r \sim -130\) km s\(^{-1}\) might belong to the trailing arm of that halo substructure while the less significant peak might correspond to the leading arm. The mean heliocentric distance predicted by PR10 for both wraps in this area of the sky is \(d_0 \sim 30\) kpc. On the other hand, LM10 predicts mean distances of \(d_0 \sim 21\) kpc and \(\sim 28\) kpc for the leading and trailing arms, respectively.

The expected two sections of the Sgr tidal stream along the line-of-sight to Whiting 1 are evident in our spectroscopic results but not in the CMD shown in Figure 1. We analyze the distribution of target stars belonging to the Sgr components as a function of \(g\) by counting stars associated with the leading \((160 < v_r < 100)\) and trailing \((90 < v_r < 150)\) arms with a bin size of \(\delta g = 0.1\). Figure 3 shows the normalized distribution obtained for both populations and we are not able to determine a shift in the \(g\) band between the subsamples of target stars. This might indicate that the leading and trailing arms of Sgr are spatially coincident or have slightly different distances, making it difficult to distinguish the populations in the CMD. Therefore, our results are in good agreement with the predictions made by the PR10 model both for the position and the kinematics of the leading and trailing components of the Sgr tidal stream around Whiting 1.

According to the PR10 classification, target stars with radial velocities around \(v_r \sim 120\) km s\(^{-1}\) might be associated with an old component of the leading arm of Sagittarius, accreted a long time ago (> 2 Gyr). While the northern and southern trailing arms have been well characterized using different tracers such as RR Lyrae, blue horizontal branch, sub-giant branch and red clump stars (e.g. Koposov et al. 2012; Belokurov et al. 2014), the southern leading arm predicted both by PR10 and LM10, has remained undetected. This might be due to the coincidence of its projected path with that of the trailing arm or to its lower surface-brightness. Only tentative detections have been reported using alternative tracers such as carbon stars, with distances...
Figure 3. Left: CMD for stars beyond 10 arcmin from the center of Whiting 1. The positions in the diagram of stars belonging to the Sgr trailing and leading wraps are indicated as orange stars and green triangles, respectively. The blue isochrone corresponds to a $t \sim 10$ Gyr and $[\text{Fe/H}] \sim -1.5$ population. Right: normalized distribution of stars belonging to both arms as a function of $g$ in the range $19 < g < 23.5$ and following the same color code as in the left panel.

and velocities consistent with our results along that line-of-sight (Huxor & Grebel 2015).

Alternatively, the group of stars with positive radial velocities might belong to a different halo substructure. The Cetus Polar stream (Newberg et al. 2009; Yam et al. 2013) is located at a compatible heliocentric distance of $d_{\odot} \sim 33$ kpc at its nearest point to Whiting 1. However, that substructure is crossing the sky at $\ell \sim 140^\circ$ and presents a very low density of member stars to become such an important contribution in our velocity distribution. Additional streams or overdensities have not been reported in this line-of-sight, and so the Sgr tidal stream remains as the likely underlying population. This first spectroscopic detection of the leading arm of that tidal stream confirms one of the predictions made by the available Sgr models and could be used in the future to better constrain the complex orbit of the stream.

Figure 4. Density map generated for an area of 1 deg $\times$ 1 deg centered in the coordinates of Whiting 1 [RA$_0$,Dec$_0$]=(30.73$^\circ$,-03.25$^\circ$]. Isodensity lines are drawn at levels of 3, 3.5, 4, 5, 7.5, 9, 10 and >12 times the mean background level. The solid line indicates the mean orbit of the Sgr tidal stream along that line-of-sight according to PR10, whereas the dashed line indicates the direction of the Milky Way center. The symbols indicating the position of target stars are color-coded according to the velocity ranges indicated in the legend.

Once we have established the nature of the underlying population around Whiting 1, we include in our analysis the radial velocity measured for this cluster, set at $v_r \sim -130.6 \pm 1.8$ km s$^{-1}$ (Carraro et al. 2007). The distance and velocity of the trailing arm of Sgr is compatible with that of Whiting 1 (see Figure 2). According to PR10 model, that wrap is composed of stars stripped away during the last $\sim 0.6$ Gyr, thus Whiting 1 was accreted by the Milky Way during the last passage of Sgr. Law & Majewski (2010a) proposed 5 GCs with a higher probability of belonging to the Sgr GC system (Arp 2, M 54, NGC 5634, Terzan 8 and Whiting 1) while other 4 clusters (Berkeley 29, NGC 5053, Pal 12 and Terzan 7) display a lower but still significative probability. Among the most likely members, only NGC 5634 and Whiting 1 are far away from the Sgr core and both are associated with the trailing arm in the LM10 model. Although no underlying population was found at a compatible distance around NGC 5634 in CB14, the abundances derived by Sbordone et al. (2015) for this cluster are consistent with those of the main body of Sgr. Law & Majewski (2010a) also show that Whiting 1 is the second closest GC to the plane containing the orbit of Sgr, after M 54. Our observations support the scenario in which Whiting 1 was formed in the Sgr dwarf spheroidal and later deposited in the Galactic halo.

The minimum distances of the target stars from the center of Whiting 1 are 10 and 13 arcmin in fields 1 and 2, respectively, which ensure a low probability of including cluster stars. This is confirmed by the distribution of trailing and leading arm stars shown in Figure 4, where none of the populations seem to be clustered around Whiting 1. We also investigate the structure of the cluster searching for the signature of tidal tails in the CFHT photometry. We perform a matched-filter analysis of the distribution of stars associated with Whiting 1 following the procedure described in Rockosi et al. (2002). The density contours derived for the GC are shown in Figure 4, where the position of the target stars are also overplotted. Given the relative position of spectroscopic targets and cluster, we discard the presence of cluster members in our sample as the origin of the two-peak distribution observed. Interestingly, the cluster has a hint of elongations in opposite directions suggesting that the cluster has suf-
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