Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **474,** 4766–4771 (2018) doi:10.1093/mnras/stx3001
Advance Access publication 2017 November 23

# The globular cluster NGC 7492 and the Sagittarius tidal stream: together but unmixed

J. A. Carballo-Bello,[1,2]⋆ J. M. Corral-Santana,[3] M. Catelan,[1,2] D. Martínez-Delgado,[4] R. R. Muñoz,[5] A. Sollima,[6] C. Navarrete,[1,2] S. Duffau,[7] P. Côté[8] and M. D. Mora[1]

[1]Instituto de Astrofísica, Facultad de Física, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna, 4860, 782-0436, Macul, Santiago, Chile
[2]Millenium Institute of Astrophysics, Santiago, Chile
[3]European Southern Observatory, Alonso de Córdova 3107, Vitacura, Santiago, Chile
[4]Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Mönchhofstr. 12-14, D-69120 Heidelberg, Germany
[5]Departamento de Astronomía, Universidad de Chile, Camino El Observatorio 1515, Las Condes, Santiago, Chile
[6]INAF Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 Bologna, Italy
[7]Departamento de Ciencias Físicas, Universidad Andrés Bello, Fernández Concha 700, Las Condes, Santiago, Chile
[8]National Research Council of Canada, Herzberg Astronomy and Astrophysics, Victoria, BC V9E 2E7, Canada

Accepted 2017 November 20. Received 2017 October 31; in original form 2017 September 6

## ABSTRACT

We have derived from VIMOS spectroscopy the radial velocities for a sample of 71 stars selected from CFHT/Megacam photometry around the Galactic globular cluster NGC 7492. In the resulting velocity distribution, it is possible to distinguish two relevant non-Galactic kinematic components along the same line of sight: a group of stars at $\langle v_r \rangle \sim 125\,\mathrm{km\,s^{-1}}$ which is compatible with the velocity of the old leading arm of the Sagittarius tidal stream, and a larger number of objects at $\langle v_r \rangle \sim -110\,\mathrm{km\,s^{-1}}$ that might be identified as members of the trailing wrap of the same stream. The systemic velocity of NGC 7492 set at $v_r \sim -177\,\mathrm{km\,s^{-1}}$ differs significantly from that of both components, thus our results confirm that this cluster is not one of the globular clusters deposited by the Sagittarius dwarf spheroidal in the Galactic halo, even if it is immersed in the stream. A group of stars with $\langle v_r \rangle \sim -180\,\mathrm{km\,s^{-1}}$ might be comprised of cluster members along one of the tidal tails of NGC 7492.

**Key words:** Galaxy: formation – globular clusters: individual – Galaxy: halo –.

## 1 INTRODUCTION

The accretion of the Sagittarius (Sgr) dwarf galaxy (Ibata, Gilmore & Irwin 1994) and the stellar tidal stream that its disruption has generated around the Milky Way (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; Navarrete et al. 2017) represent one of the best examples of ongoing accretion of satellite galaxies in the Local Universe. Such events contribute to the host galaxy halo not only with stars but also with globular clusters (GCs; e.g. Leaman, VandenBerg & Mendel 2013; Zaritsky, Crnojević & Sand 2016).

Indeed, substantial evidence of the accretion of GCs in the Milky Way has been gathered in recent years. In the case of Sgr, at least four globulars are found in its main body (M 54, Arp 2, Terzan 7 and Terzan 8; Da Costa & Armandroff 1995) and a few halo GCs have been associated with the stream across the sky (e.g. Dinescu et al. 2000; Bellazzini, Ferraro & Ibata 2002; Palma, Majewski & Johnston 2002; Martínez-Delgado et al. 2002; Bellazzini, Ferraro & Ibata 2003; Carraro 2009; Forbes & Bridges 2010; Dotter, Sarajedini & Anderson 2011; Sbordone et al. 2015). Bellazzini et al. (2003) estimated that ∼20 per cent of halo GCs beyond $R_G = 10$ kpc might be clusters formed in the interior of Sgr and later accreted by our Galaxy, while Law & Majewski (2010b, hereafter LM10b) proposed a list of nine of these systems spatially and kinematically compatible with the predicted path of the stream (Law & Majewski 2010a, hereafter LM10a).

NGC 7492 is a poorly studied halo GC located at a heliocentric distance of $d_\odot = 26.2$ kpc (Côté, Richer & Fahlman 1991), with Galactic coordinates $(\ell, b) = (53.39^\circ, -63.48^\circ)$. Although its projected position and distance seem to be compatible with that of the LM10a model along the same line of sight, this cluster has a low probability of being associated with the Sgr tidal stream, because on the predicted differences in angular separation, heliocentric distance and radial velocity (LM10b). Carballo-Bello et al. (2014) unveiled an underlying system at the same heliocentric distance as of the cluster with wide-field photometry and suggested that at least a fraction of those stars belong to Sgr (see also Muñoz et al. 2017a). However, the stellar overdensities reported around NGC 7492 (Leon, Meylan & Combes 2000; Lee et al. 2004) and, more importantly, the tidal tails unveiled by Navarrete, Belokurov & Koposov (2017, hereafter

⋆ E-mail: jcarballo@astro.puc.cl

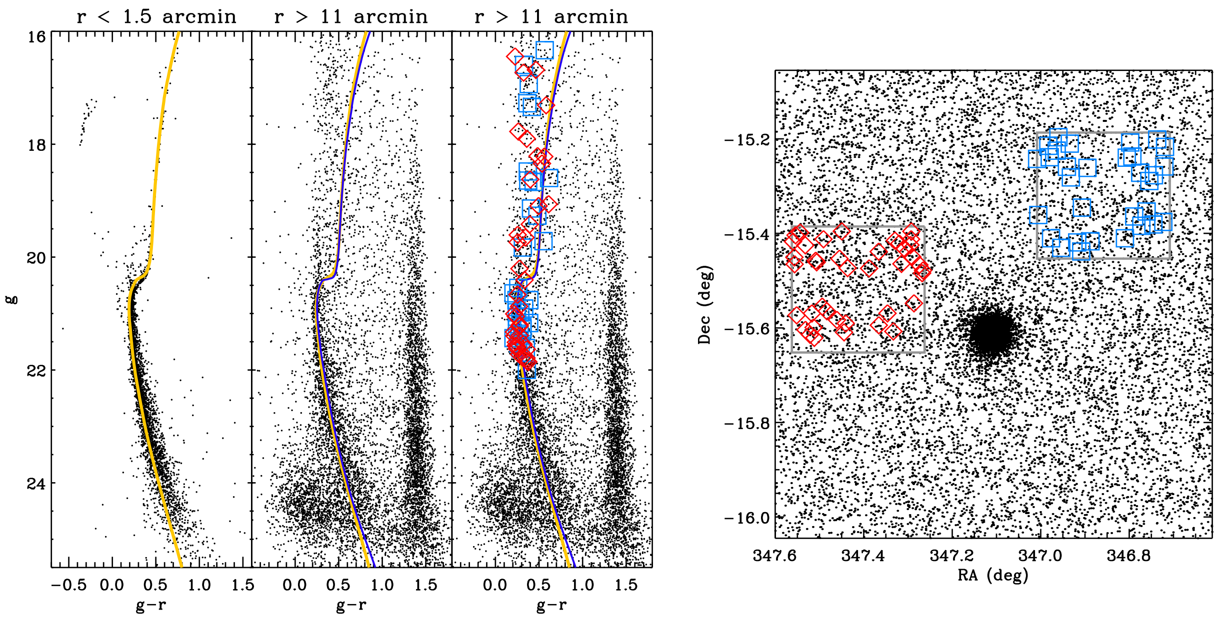


**Figure 1.** First and second panels from the left: Megacam CMDs corresponding to the stars in the catalogue at distances $r < 1.5$ arcmin and $r > 11$ arcmin from the centre of NGC 7492, respectively. The isochrone fitting shows that the underlying main-sequence observed in the second panel seems to be associated with a stellar system at $d_\odot \sim 26$ kpc. The yellow solid line corresponds to a $t \sim 12$ Gyr and [Fe/H] $\sim -1.8$ population while the blue one corresponds to $t \sim 10$ Gyr and [Fe/H] $\sim -1.5$. Third panel from the left: same CMD for stars with $r > 11$ arcmin, where the target stars in Fields 1 and 2 are overplotted as blue squares and red diamonds, respectively. Right-hand panel: distribution of the target stars around NGC 7492 using the same colour code to identify the fields observed. The approximate field of view of VIMOS has been overplotted as reference.

N17) in Pan-STARRS 1 survey data, may complicate the analysis of the underlying stellar system.

In this paper, we derive kinematic information for a sample of stars in the surroundings of NGC 7492 to assess whether this GC may have formed in Sgr and subsequently been accreted by the Milky Way.

## 2 OBSERVATIONS AND METHODOLOGY

Our targets for spectroscopy have been selected from the photometric catalogues generated in a Megacam@CFHT and Megacam@Magellan survey of all outer Galactic halo satellites (Muñoz et al. 2017a). The colour–magnitude diagram (CMD) for NGC 7492 and those objects beyond 1.2 times the King tidal radius ($r_t$) of the cluster are shown in Fig. 1. We use a value of $r_t$ as derived by Carballo-Bello et al. (2012; $r_t = 9.2$ arcmin). As pointed out by Carballo-Bello et al. (2014), a remarkable population of stars is found surrounding the cluster at large distances from its centre with a main-sequence (MS) morphology similar to that of the GC, in the range $20 < g < 24$ and $0.2 < g - r < 0.9$. However, the small area covered around the cluster in that study prevented them from reaching a conclusion about the nature of the underlying system. We selected targets in a box with $0.2 < g - r < 0.65$ and $16 < g < 22$ for stars with angular distances greater than 11 arcmin from the centre of NGC 7492, including as well turn-off (TO) stars of the underlying population and fore/background Milky Way objects. Two fields containing 71 stars were selected for targeting, with a total number of 31 and 40 stars observed in the fields 1 and 2, respectively (see Fig. 1).

Spectroscopic observations have been performed in service mode using the VIsible MultiObject Spectrograph (VIMOS) mounted at the 8.2 m Very Large Telescope (Cerro Paranal, Chile) with the same set-up used by Carballo-Bello et al. (2017). The mid-resolution grism and the filter GG475 allowed a spectral coverage from 5000 to 8000 Å with a resolution $R = 580$. Spectra are the result of a single exposure of 1740 s with an average signal-to-noise ratio of 34, which have been extracted using the ESO REFLEX pipeline for VIMOS. We estimated the instrumental flexure by performing a second-order correction of the wavelength calibration based on the position of several sky lines. The resulting offsets were removed from the individual spectra. We repeated this process iteratively until the shifts were negligible.

Radial velocities were derived by cross-correlating our normalized spectra with a list of templates smoothed to the resolution of our results. The sample of templates used was compiled by Pickles (1998) and we only considered MS or subgiant stars ranging from O to M spectral types in this procedure. The final radial velocity value was adopted from the template providing the best correlation coefficient. Radial velocities have been then corrected for the Earth motion relative to the heliocentric rest frame by using the IRAF task RVCORRECT and their errors have been estimated from the amplitude of the cross-correlation peak, using the prescriptions of Tonry & Davis (1979). A mean error value of $\langle \sigma_{v_r} \rangle \sim 45\,\mathrm{km\,s^{-1}}$ was found.

## 3 RESULTS AND DISCUSSION

We have visually matched the cluster CMD shown in Fig. 1 with a Dotter et al. (2008) isochrone with $t = 12$ and [Fe/H] $= -1.8$, as appropriate to NGC 7492 (Côté et al. 1991; Cohen & Melendez 2005; Forbes & Bridges 2010). The adopted Galactic extinction values are $A_g = 0.12$ and $A_r = 0.08$, as derived from the Schlafly & Finkbeiner (2011) extinction maps. The resulting heliocentric distance of NGC 7492 is $d_\odot = 26.5 \pm 1.5$ kpc, which is in good agreement with the estimate found for this cluster by Côté et al. (1991) and with the one derived by Figuera Jaimes et al. (2013) within the errors. As for the hypothetical underlying system

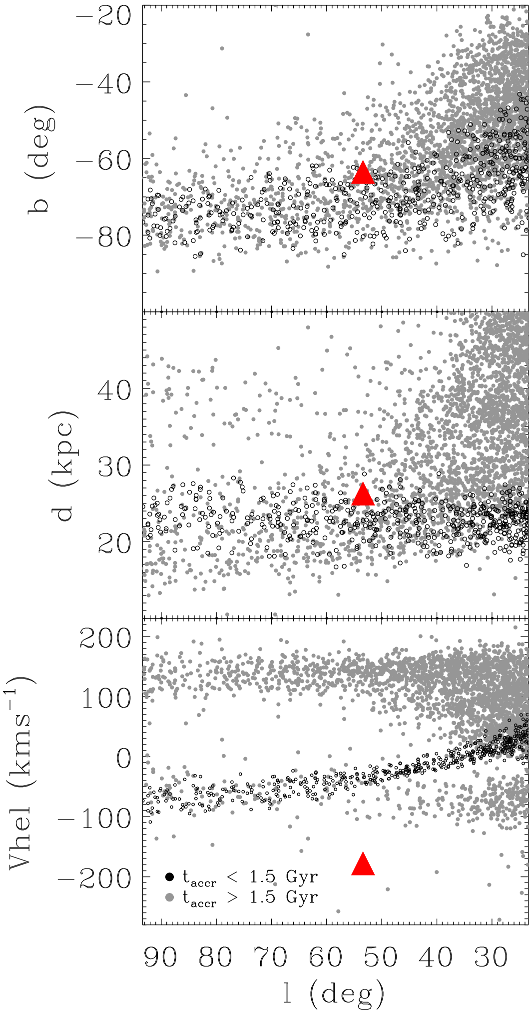


**Figure 2.** Projected path of the Sgr stream (up), heliocentric distance (middle) and radial velocity (bottom panel) as predicted by the LM10a model for $d_{\odot} < 50$ kpc. The grey and black points are model particles corresponding to those stars accreted before (leading) and during the last (trailing) 1.5 Gyr, respectively. The red triangle represents the position of NGC 7492 on those planes.

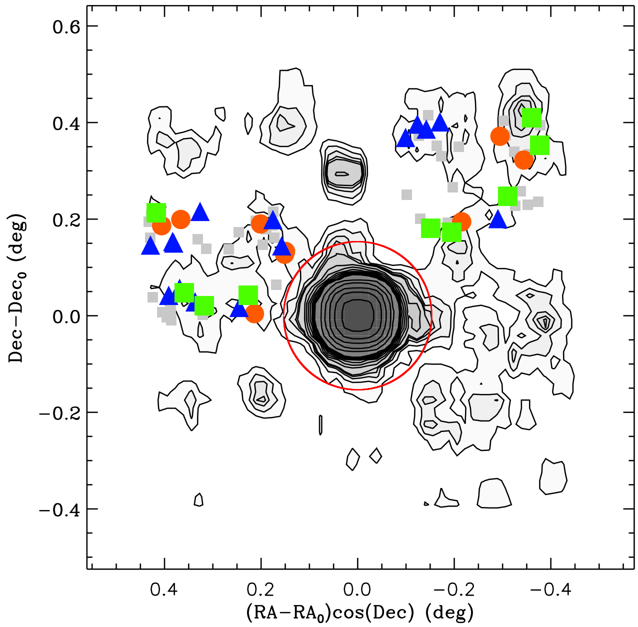


**Figure 3.** Density map of NGC 7492 stars as derived from the matched filter analysis, where North is up and East is to the left. The density contours displayed correspond to the number of standard deviations $\sigma = [1, 1.5, 2, 3, 5, 10, 20, 30, 50, >50]$ above the mean background level. The target stars are overplotted as orange circles ($v_r < -160\,\mathrm{km\,s^{-1}}$), blue triangles ($-150 < v_r\,[\mathrm{km\,s^{-1}}] < -90$), green squares ($80 < v_r\,[\mathrm{km\,s^{-1}}] < 150$) and small grey squares (rest of stars). The red line indicates the King tidal radius of NGC 7492.

beyond $r = 11$ arcmin from the GC centre, it presents an MSTO-magnitude similar to that of the cluster, which suggests that this stellar system and the cluster lie at the same heliocentric distance. Together with extra-tidal cluster members, the Sgr tidal stream is the main suspect of being responsible for the presence of those stars around NGC 7492, as proposed by the numerical simulations obtained by LM10a and Peñarrubia et al. (2010, hereafter P10). In Fig. 2, we show the projected position, heliocentric distance and expected radial velocity for that stream, according to the LM10a model for Sgr orbiting in a triaxial Galactic potential. Indeed, different sections of the stream seem to cross the area of the sky where NGC 7492 is located. This would indicate that both cluster and tidal stream are spatially coincident. We fitted the CMD with the same isochrone used by Carballo-Bello et al. (2014) for Sgr ($t = 10$ Gyr, [Fe/H] $= -1.5$) and obtained a distance of $d_{\odot} \sim 26.8 \pm 1.7$ kpc. We thus confirm that NGC 7492 is immersed in the Sgr tidal stream.

In order to check whether some of our target stars could lie on a tidal feature originating from NGC 7492, we generated two-dimensional density maps to search for tidal structures. We performed a matched filter analysis following the description introduced by Rockosi et al. (2002) and widely used for the detection of extratidal features in Galactic GCs (e.g. Grillmair & Johnson 2006; Balbinot et al. 2011, N17). The central 1 arcmin of NGC 7492 were considered to derive the number density of stars in the CMD, while those stars beyond $r = 25$ arcmin from the cluster centre were used to sample the fore/background stellar populations. The CMD bin sizes used to compute those number densities were $\delta g = 0.1$ and $\delta(g - r) = 0.05$ mag.

NGC 7492 is a member of the group of 'tidally affected' GCs, according to the classification by Carballo-Bello et al. (2012), so this cluster might be importantly distorted by its interaction with the Milky Way. We now focus on the density map generated using the procedure described above (see Fig. 3). Most of NGC 7492's stars seem to be contained within the King tidal radius, which is almost fully filled by cluster members. Our density contours also show the presence of minor overdensities beyond $r_t$, with a significance between $1\sigma$ and $2\sigma$ above the median background density. The orientation of these elongations, tentative tidal tails emerging from the cluster, is similar to that of the tails unveiled by N17 in Pan-STARRS1 survey data for NGC 7492. Moreover, their density contours for NGC 7492 show that this cluster would populate most of the Megacam field of view, with stars likely associated with the cluster found up to distances of 0.5 deg from its centre. Given our relatively small field of view, it is difficult to obtain a proper estimate of the contribution of fore/background populations to our density maps so we are not able to reproduce Navarrete's results with the same level of confidence. Even so, our NGC 7492 isopleths may be used as a reference to establish the nature of the stars observed with VIMOS for this work.

We have overplotted the position of the spectroscopic targets in the resulting density map shown in Fig. 3. Both groups of stars

**Table 1.** ID, Field, position, radial velocities and signal-to-noise ratio of the spectra obtained for the stars included in this sample. A full version of this table is included as supplementary material in electronic format.

| Star ID | Field | R.A. (hh:mm:ss) | Dec (dd:mm:ss) | $v_r$ (km s$^{-1}$) | $\sigma_{v_r}$ (km s$^{-1}$) | S/N |
|---|---|---|---|---|---|---|
| 1 | F1 | 23:07:43.6 | −15:16:53.7 | 71 | 60 | 37 |
| 2 | F1 | 23:07:38.0 | −15:26:18.0 | 136 | 53 | 33 |
| 3 | F1 | 23:07:54.4 | −15:24:37.3 | − 87 | 38 | 49 |
| 4 | F1 | 23:07:34.6 | −15:15:41.2 | 0 | 52 | 16 |
| 5 | F1 | 23:08:01.3 | −15:21:39.9 | 15 | 39 | 55 |
| 6 | F1 | 23:07:01.0 | −15:17:21.2 | − 306 | 39 | 9 |
| 7 | F1 | 23:07:33.0 | −15:25:00.8 | − 219 | 47 | 8 |
| 8 | F1 | 23:07:40.2 | −15:25:09.0 | 44 | 56 | 16 |
| 9 | F1 | 23:06:58.5 | −15:16:37.1 | 3 | 53 | 13 |
| 10 | F1 | 23:07:02.5 | −15:21:13.0 | 12 | 54 | 38 |

(fields 1 and 2) are coincident in projected position with the stellar overdensities revealed by the matched filter technique. In particular, field 2 lies along the stellar arm unveiled by N17, so a contribution of cluster stars in our results is expected. However, even if stars belonging to NGC 7492 are observed, the presence of the multiple wraps of Sgr predicted by the numerical simulations around this GC should be reflected in our radial velocity distribution.

The derived radial velocities are shown in Table 1. The histogram of velocities for the target stars was constructed using a bin size of 20 km s$^{-1}$ and was then smoothed with a boxcar average with a width of three bins. The result is shown in Fig. 4. It is possible to distinguish at least three components in the heliocentric radial velocity distribution, with peaks with approximate mean velocities of $v_r = -110$, 0 and 125 km s$^{-1}$, in descending order of number of stars. In order to identify the group of stars likely associated with the Milky Way stellar populations, we compare our results with the distribution obtained using the Besançon synthetic model (Robin et al. 2003). We performed 100 simulations using the default parameters for the position in the sky of NGC 7492 and using a solid angle equivalent to 2 deg$^2$. We randomly modified the velocities by adding values consistent with our mean observational error. The velocity distribution was derived by only including those synthetic stars in the same colour–magnitude range as of the target stars and using the same bin size. The distribution predicted for Milky Way stars along this line of sight is arbitrarily scaled and overplotted in Fig. 4 and confirms that the central group of stars around $v_r \sim 0$ km s$^{-1}$ is composed of target objects that are likely members of the Galactic disc and halo.

As for the remaining kinematic components, we derive the distribution of velocities for particles in the P10 and LM10a models for the Sgr tidal stream in an area of 2 deg × 2 deg around the cluster position. The predicted signature of the stream along this line of sight is overplotted in Fig. 4. Both numerical simulations predict a concentration of stars around $v_r \sim$ 110–130 km s$^{-1}$ belonging to the leading arm of the stream (according to the LM10a classification). This wrap of Sgr is predicted to be composed of stars with accretion times $t_{acc} > 1.5$ Gyr and might be connected with the same wrap detected in the surroundings of Whiting 1 by Carballo-Bello et al. (2017). We thus confirm the detection of an old leading arm in the Sgr tidal stream, which is still detectable via multi-object spectroscopy over a wide field of view and located at $d_\odot \sim 26$ kpc.

The peak observed at $v_r \sim -110$ km s$^{-1}$ may be associated with the second component of Sgr predicted in this region of the

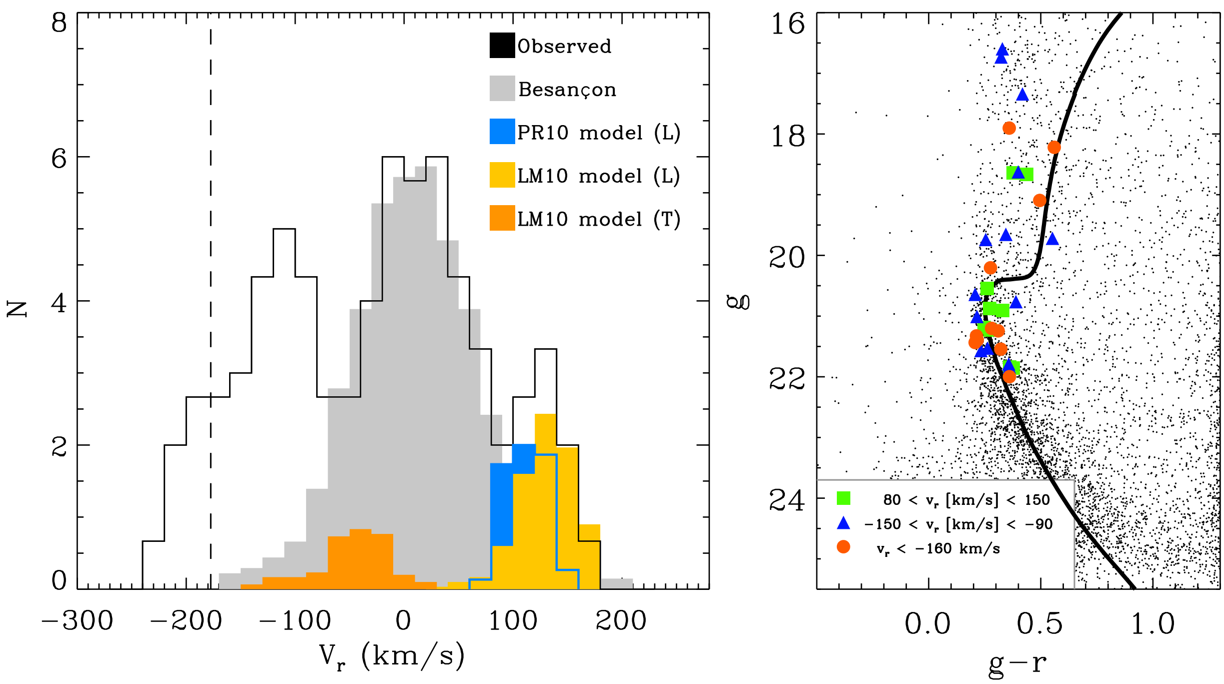


**Figure 4.** Left: radial velocity distribution obtained for the sample of stars around NGC 7492 (black solid line). The blue area represents the velocities for Sgr stars according to P10, while the yellow and orange areas correspond to the leading and trailing arms of Sagitarius, respectively, as proposed by the LM10a model. The grey area corresponds to the expected velocity distribution of Milky Way stars along the same line of sight as NGC 7492, as predicted by the Besançon model. Grey, blue and orange areas have been arbitrarily scaled for better visualization. The dashed vertical line indicates the radial velocity of the GC measured by (Cohen & Melendez 2005). Right: Megacam CMD corresponding to stars beyond 11 arcmin from the centre of NGC 7492. The black solid line represents the isochrone for a stellar population with $t \sim 10$ Gyr and [Fe/H] $\sim -1.5$ at the same heliocentric distance that NGC 7492. Stars satisfying $v_r < -160$, $-150 < v_r < -90$ and $80 < v_r < 150$ km s$^{-1}$, are overplotted as orange circles, blue triangles and green squares, respectively.

sky. Following the nomenclature used by LM10a, a more recently accreted ($t_{acc} < 0.5$ Gyr) trailing arm section of the stream should be found around NGC 7492 at a similar heliocentric distance but with $\langle v_r \rangle \sim -50\,\mathrm{km\,s^{-1}}$. Therefore, an important difference is found between our detection of the trailing arm of Sgr and the prediction made by the LM10a model. Given that no other halo substructure has been reported in this region, our results could be used to better constrain the orbital path (and kinematics) of the stream. The projected position in the sky for the stars found in both velocity peaks suggests that the stellar populations that we have identified as leading and trailing arms are found in both fields with no significant differences in their distribution (see Fig. 3). Although the model predicted more leading arm stars in this region of the sky, our histogram shows that the contribution of Sgr trailing arm stars is comparatively more important in our sample.

We also confirm that NGC 7492's radial velocity ($v_r = -176.9\,\mathrm{km\,s^{-1}}$; Cohen & Melendez 2005) differs significantly from that of the Sgr tidal streams along this line of sight as previously predicted by LM10b. This indicates that NGC 7492 is immersed in the Sgr tidal remnants but with a radial velocity that implies independent origins for both stellar systems. A few stars are found in our velocity distribution around the Cohen's velocity for the cluster, which was derived from the high-resolution spectra of four red-giant branch stars and is the measurement of reference in the literature for the kinematics of this globular. The position in the sky of the observed stars with $v_r < -160\,\mathrm{km\,s^{-1}}$ in the CMD is consistent with that of the isochrone corresponding to NGC 7492 (see Fig. 4). Moreover, those stars seem to be concentrated in field 2, which is located along the stellar arm unveiled by N17. Therefore, our results may confirm the findings of N17 about the presence of tidal tails in the field around this cluster. However, given the uncertainties of our velocities arising from the chosen instrumental set-up, it is not possible to either unequivocally associate those stars with NGC 7492 or estimate the number of cluster stars that are contributing the peak corresponding to the Sgr trailing arm.

## 4 CONCLUSIONS

We have derived radial velocities for a sample of 71 stars around the GC NGC 7492 and distributed among two VIMOS fields. Our velocity distribution shows three peaks: Milky Way stars, Sgr leading and trailing arms members. These halo substructures seem to be located at the same heliocentric distance as that of NGC 7492.

The Sgr streams are found at $\langle v_r \rangle \sim -110$ and $125\,\mathrm{km\,s^{-1}}$, with predicted accretion times $t_{acc} < 0.5$ and $>2$ Gyr, respectively. According to the LM10a model, the latter represents a new detection of the old leading arm previously reported in a similar study with the same instrumental set-up. As for the detection at negative velocities, it could correspond to a section accreted during the last 0.5 Gyr according to the numerical simulations available for the stream. Both components present a kinematical signature different from that of the GC, which may support an independent origin for NGC 7492, even when it is immersed in Sgr. A small number of stars at $v_r \sim -180\,\mathrm{km\,s^{-1}}$ in our results seems to be associated with NGC 7492 members located along the tidal tail recently discovered, which is also revealed by our Megacam photometry.

## ACKNOWLEDGEMENTS

JAC-B acknowledges financial support from CONICYT-Chile FONDECYT Postdoctoral Fellowship #3160502. JAC-B, MC and CN received support from the Ministry for the Economy, Development, and Tourism's Programa Iniciativa Científica Milenio through grant IC120009, awarded to the Millennium Institute of Astrophysics (MAS) and from CONICYT's PCI program through grant DPI20140066. MC acknowledges additional support by Proyecto Basal PFB-06/2007 and FONDECYT grant #1171273. CN acknowledges support from CONICYT-PCHA grant Doctorado Nacional 2015-21151643. DMD acknowledges funding from Sonderforschungsbereich SFB 881 'The Milky Way System' (subproject A2) of the German Research Foundation (DFG). RRM acknowledges partial support from CONICYT Anillo project ACT-1122 and project BASAL PFB-06 as well as FONDECYT project N° 1170364. SD acknowledges support from Comité Mixto ESO-GOBIERNO DE CHILE. MDM is supported by CONICYT, Programa de astronomía, Fondo GEMINI, posición Postdoctoral. Based on data products from observations made with ESO Telescopes at the La Silla Paranal Observatory under ESO programme ID 091.D-0446(D). Partially based on observations obtained at the CFHT, which is operated by the National Research Council of Canada, the Institut National des Sciences de l' Univers of the Centre National de la Recherche Scientifique of France, and the University of Hawaii.

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