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Exploring the possible link between a recently discovered globular cluster and a low-latitude stellar stream in the Milky Way

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Abstract. The newly discovered globular cluster (GC) VVV-CL160 has kinematic properties distinct from almost all other known objects of the same classification in our Galaxy. Moreover, a link between the low-latitude Hríd stellar stream and this GC has been proposed due to their positions and corresponding kinematics and metallicities. If this connection becomes well established, Hríd might be associated with an ancient, as yet undiscovered, dwarf galaxy that would be going through accretion into the Milky Way (MW). This work aimed to investigate possible scenarios that would have led to the formation of Hríd, thus contributing to the development the hypothesis cited above. We have used the most recent observational data of VVV-CL160 and explored the space of parameters not yet well determined (its mean radial velocity) in order to construct plausible initial conditions for N-body models of this GC in the past. We have run and analyzed several simulations of these models in the presence of a realistic analytical potential of the MW. As a starting point, we constructed two King's profiles, both with a total mass of 2×10^4 $M_\odot$ (derived from an average mass-to-light ratio of approximately 2 for GCs in the Galaxy), one more and the other less initially concentrated: $W_0 = 3$ and $W_0 = 10$, respectively. We considered orbits of 150 Myr (the last pericentric passage for most cases), 600 Myr and 1 Gyr. Preliminary results suggest that indeed it seems unlikely that Hríd is a trail left by just VVV-CL160. Beyond that, the outputs point towards the idea that is conceivable that the histories of formation of these systems may be intertwined, hence motivating the search for radial velocity data of this globular cluster.

Resumo. O recém-descoberto aglomerado globular (GC) VVV-CL160 tem propriedades cinemáticas distintas de quase todos os outros objetos da mesma classificação conhecidos em nossa Galáxia. Além disso, uma ligação entre a corrente estelar de baixa latitude Hríd e o GC em questão foi proposta devido às suas posições e correspondentes cinemáticas e metalicidades. Se esta conexão se tornar bem estabelecida, Hríd poderia ser associada a uma hipotética galáxia anã, ainda não descoberta, que estaria sendo acretada à Via Láctea (MW). Este trabalho visa investigar cenários que poderiam ter levado à formação do Hríd, contribuindo assim para o desenvolvimento da hipótese acima citada. Usamos os dados observacionais mais recentes de VVV-CL160 e exploramos o espaço de parâmetros ainda não bem determinados (sua velocidade radial média) para construir condições iniciais plausíveis para modelos de N-corpos deste GC no passado. Executamos e analisamos várias simulações desses modelos na presença de um potencial analítico realista da MW. Como ponto de partida, construímos dois perfis de King, ambos com massa total de 2×10^4 $M_\odot$ (derivada de uma relação massa-luminosidade média de aproximadamente 2 para aglomerados globulares na Galáxia), um mais e outro menos concentrado inicialmente: $W_0 = 3$ e $W_0 = 10$, respectivamente. Consideramos órbitas de 150 milhões de anos (a última passagem pericêntrica para a maioria dos casos), 600 Myr e 1 Gyr. Os resultados preliminares sugerem que, de fato, parece improvável que Hríd seja um traçado gerado apenas por VVV-CL160. Além disso, os outputs apontam para a ideia de que é concebível que as histórias de formação desses sistemas podem estar entrelaçadas, assim motivando a busca por dados de velocidade radial deste aglomerado globular.

Keywords. globular cluster: individual: VVV-CL160 – Galaxy: kinematics and dynamics – Methods: numerical

1. Introduction

The Milky Way is the only galaxy we are able to study with an immense amount of detail, after all we are immersed in it. The search for the reconstruction of the history of formation and evolution of our galaxy has motivated efforts in several areas of knowledge, by better understanding the physical and chemical details behind the observed phenomena, it is possible to make afferences about problems at other scales: adding constraints to cosmological models, for example.

In this context, attention is focused on two types of structures present in the Milky Way: globular clusters of stars and stellar streams. Globular clusters contain the oldest stars in our galaxy and lie around along the disc or galactic halo. Stellar currents can be described as a beam of stars that have been or are being separated from another original structure (a cluster globular or a dwarf galaxy) due to the action of tidal forces. Then, a certain current stellar cluster may still be gravitationally connected to the cluster whose disruption originated it.

In particular, we are interested in two recently discovered systems: the VVV-CL160 globular cluster and the Hríd stellar stream. Their origins are unknown, however they have many similar characteristics Minniti (2021): positions in space, proper motion vectors and metallicities. Thus, it has been proposed that there is a very high chance of them being associated with each other Minniti (2021). Hríd's main properties are: it extends over approximately 63° in the galactic longitude, and its galactic latitude varies across $[10°, 25°]$, mean heliocentric distance of 3.3 kpc (8.0 kpc in galactocentric coordinates) and metallicity $[Fe/H] = -1.1$ Minniti (2021). In what regards VVV-CL160, its characteristics are shown in Table 1.

Once there are indeed many similarities between the two objects, the aim of this work is to study their dynamics, via semi-analytical N-body simulations, in order to better comprehend *how* this GC and this stream might have been interacting with each other. This way, we try to contribute in the exploration of questions such as "is Hríd the result of the disruption of VVV-CL160?".

α	18h 6m 57.1s
δ	$-20.015°$
r_{core}	0.44 pc
r_{tidal}	58 pc
[Fe/H]	-1.4
M_V	-5.5
D	6.8 kpc

Table 1. Angular positions in the sky, structural parameters, metallicity, absolute magnitude and heliocentric distance of VVV-CL160 Minniti (2021) Garro (2022).

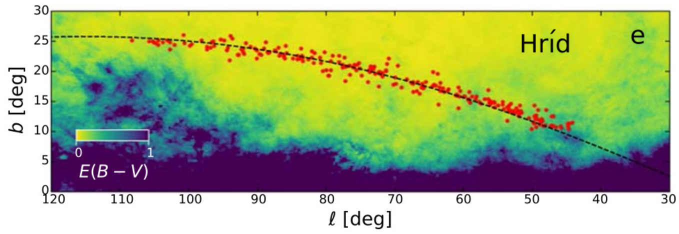

Figure 1. Visualization of stars belonging to Hríd's structure in galactic coordinates Ibata (2021).

2. Methods

As an overview, our aim was to create N-body systems that would represent some of VVV-CL160's possible dynamical states millions of years ago so that we can evolve them in time numerically so that we can compare the morphologies of the outputs with what is observed today. To acheive this, the plausible orbits of this cluster were studied and then we generated N-body distributions. This way, it was possible to create initial conditions and such models were evolved forward in time via semi-analytical N-body simulations to study the hypothetical correlation between the cluster and the Hríd stellar stream in the present time.

2.1. Software

Gala, an Astropy-affiliated Python package for Galactic Dynamics research, was used in order to integrate orbits under the influence of analytical potentials (in this case, to represent our Galaxy's potential realistically) Price-Whelan, A. M. (2022). Galstreams, a library of stellar streams of the Milky Way, was used to obtain Hríd's data. NEMO, a stellar dynamics toolbox, was was used to create N-body distributions according to King's model Teuben (1995). Furthermore, a Python code was written with the purpose of executing semi-analytical N-body simulations in such a way that it is easily possible to set which potentials (and their parameters) ought to be considered. In this code, the UNSIOTOOLS Python wrapper was used to implement the falcON algorithm, responsible for computing gravitational accelerations due to the particle interactions with one another Lambert (2014).

2.2. Possible orbits of VVV-CL160

The average radial velocity of this GC is its most relevant free parameter. Based on an exploration of plausible speeds in Minniti (2021), nine values were chosen from -200 km/s to 200 km/s, with a difference of 50 km/s between each. Thus, as the coordinates in the sky, the heliocentric distance, and the proper motions are known, we obtained nine positions in phase space, each one associated with a radial velocity value. Now, in the presence of a realistic gravitational potential of Via Milky Way, these nine points were integrated 300 Myr (last pericentric passage), 600 Myr and 1 Gyr backwards in time. For each orbital duration, nine sets of three-dimensional positions and velocities were obtained, they represent possible states of the GC's center of mass (CM) in the past.

2.3. N-body models

To generate distributions that vaguely resemble VVV-CL160, according to King's model, the structural parameters chosen were the same presented in the introduction. As described in Minniti (2021), such values for core radius and tidal radius were obtained by fitting a King profile to numerical surface density data of stars according to their positions in the sky. As for the total mass, a mean mass-to-luminosity ratio of approximately 2, for GCs in the Milky Way, was used:

$$\left\langle \frac{M}{L_V} \right\rangle \approx 2 \longrightarrow M \approx 2 \times 10^4 \, \text{M}_\odot \, . \tag{1}$$

Finally, we chosen two values for the central potential depth W_0, a dimensionless parameter which sets the concentration,

$$W_0 = \frac{\Psi(0)}{\sigma^2} \, , \tag{2}$$

where Ψ is the relative potential $\Psi = -\Phi + \Phi_0$ (the potential except for a constant Φ_0). That is, we considered two different models: $W_0 = 3$ (more concentraded) and $W_0 = 10$ (less concentraded). Moreover, both systems consist of 10^4 particles and we assumed no dark matter is present.

2.4. Initial conditions and simulations

At this point, we have the N-body models, the positions and velocities of the GC's centers of mass in various hypothetical, yet plasible, scenarios of the past. Therefore, it suffices to shift the coordinates of the particles in the distributions such that they are centralized in those CMs: those are the initial conditions to be ran. In total, 54 simulations, with softening length $\epsilon = 0.1$ pc, were executed and analyzed.

3. Results and discussions

By analyzing Fig. 2 and Fig. 3 it is possible to notice that going back 300 Myr, in both concentration options, is not enough to produce stellar streams of extensions comparable to that of Hríd. This fact motivated the study of simulations with a duration of 600 Myr and 1 Gyr; intuition points towards the idea that the longer the orbit lasts, the more significant the disruption on the cluster. Besides that, in the cases where $W_0 = 10$, the stars seem to be less uniformly distributed compared to the other initial concentrarion option.

Fig. 4 show that, in fact, the suspicion was confirmed: in these cases, longer orbits in duration generated more extensive stellar streams. However, this time, some results do not have the desired morphology (comparable to Fig. 1), some streams cross the galactic center ($V_R = 100$ km/s and $V_R = -200$ km/s) and/or are practically perpendicular to the disk, others show very different morphologies. Despite this, one case is to be highlighted: in Fig. 4, with $V_R = 150$ km/s. This stream presents an interesting correspondence with Hríd concerning the galactic latitudes. As for the longitudes, this output is not so long as to cover 63 degrees in the sky, but its trace is indeed very similar to that of Hríd

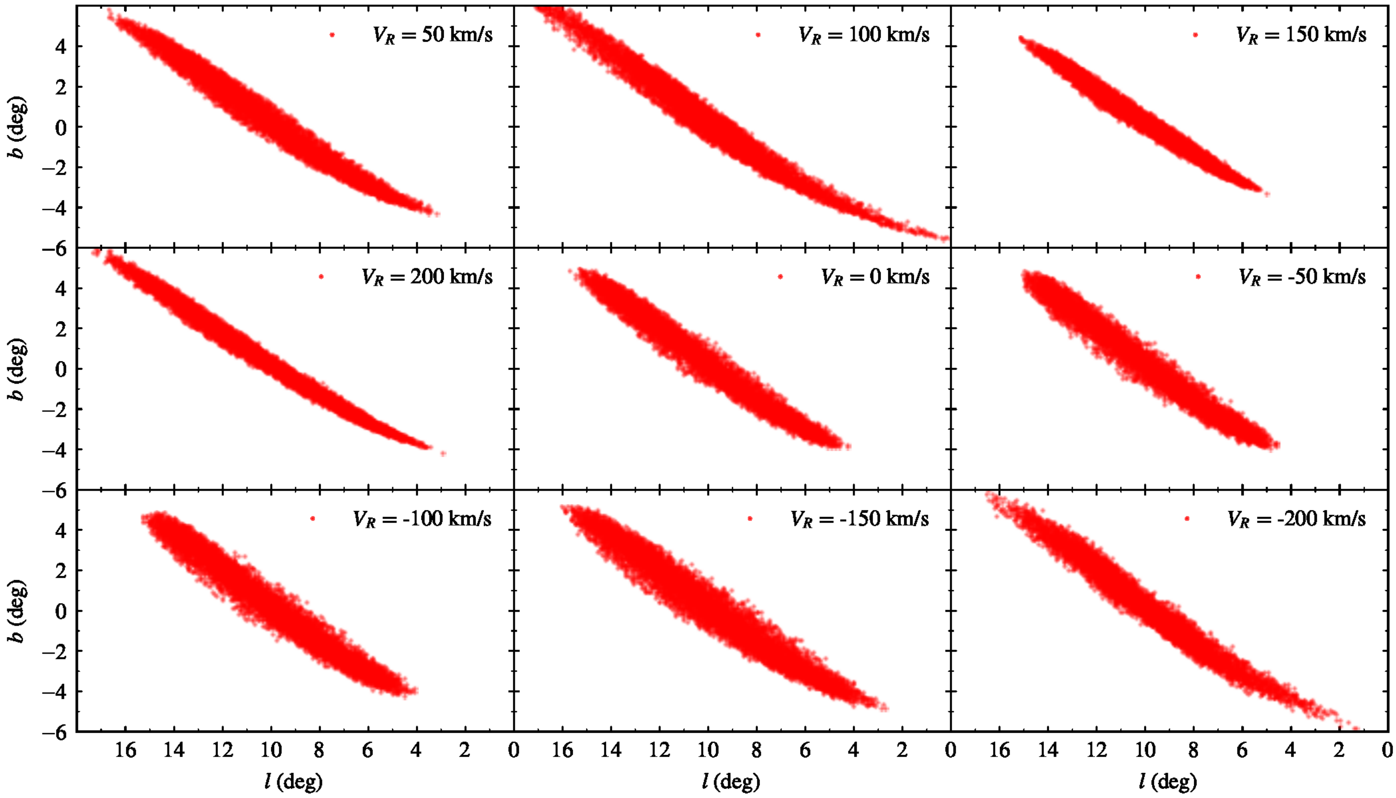

Figure 2. Particles from the model with $W_0 = 3$, in galactic coordinates, in the end of each simulation of 300 Myr.

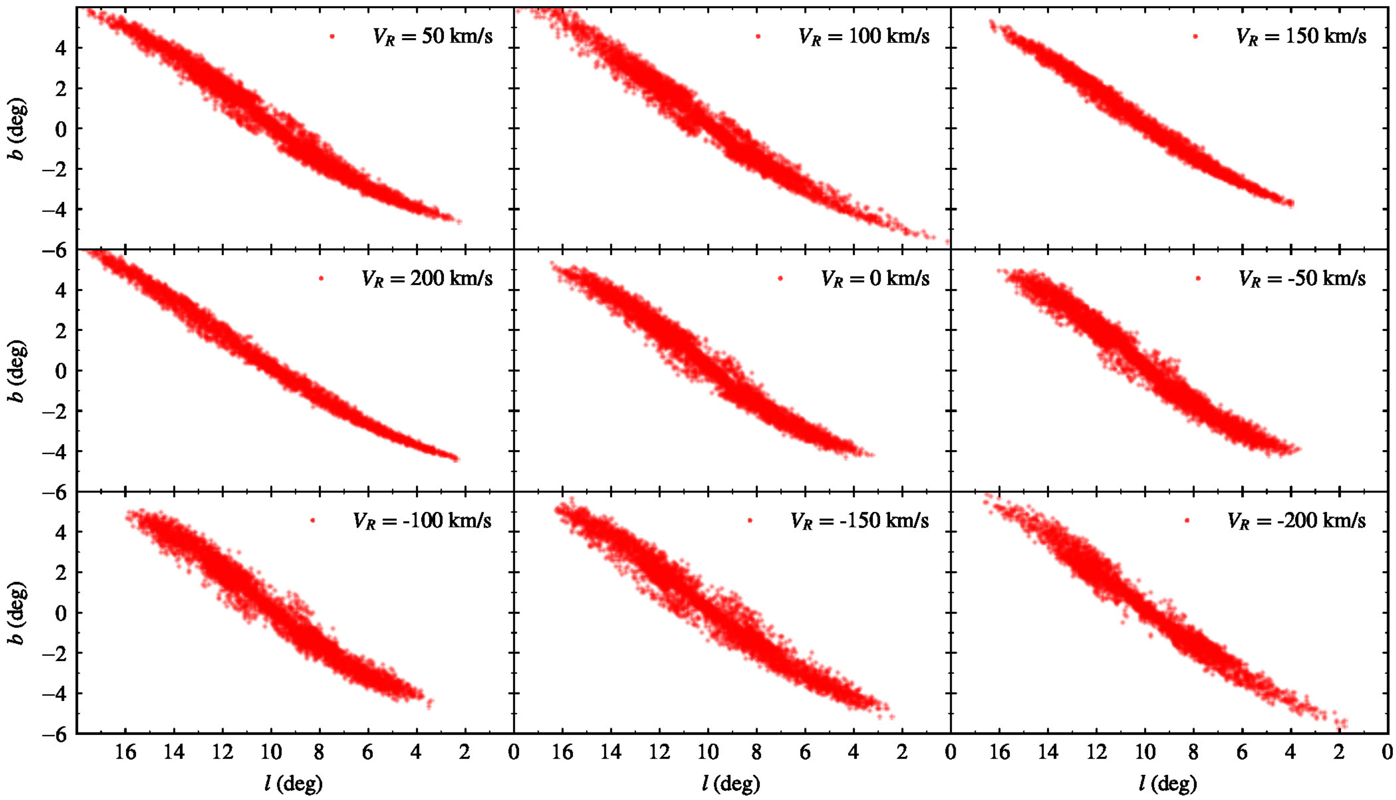

Figure 3. Particles from the model with $W_0 = 10$, in galactic coordinates, in the end of each simulation of 300 Myr.

in galactic coordinates, as shown in Fig. 5. Furthermore, all simulations that lasted 1 Gyr generated excessively long streams, such that they all crossed the center of the Milky Way by the end of the simulations.

Therefore, the interesting output mentioned above was investigated in more detail. From Fig. 6, it can be seen that the correspondence previously commented also reasonably occurs in the three possible spatial projections of cartesian coordinates. This was not necessarily expected, as visualizations in galactic coor-

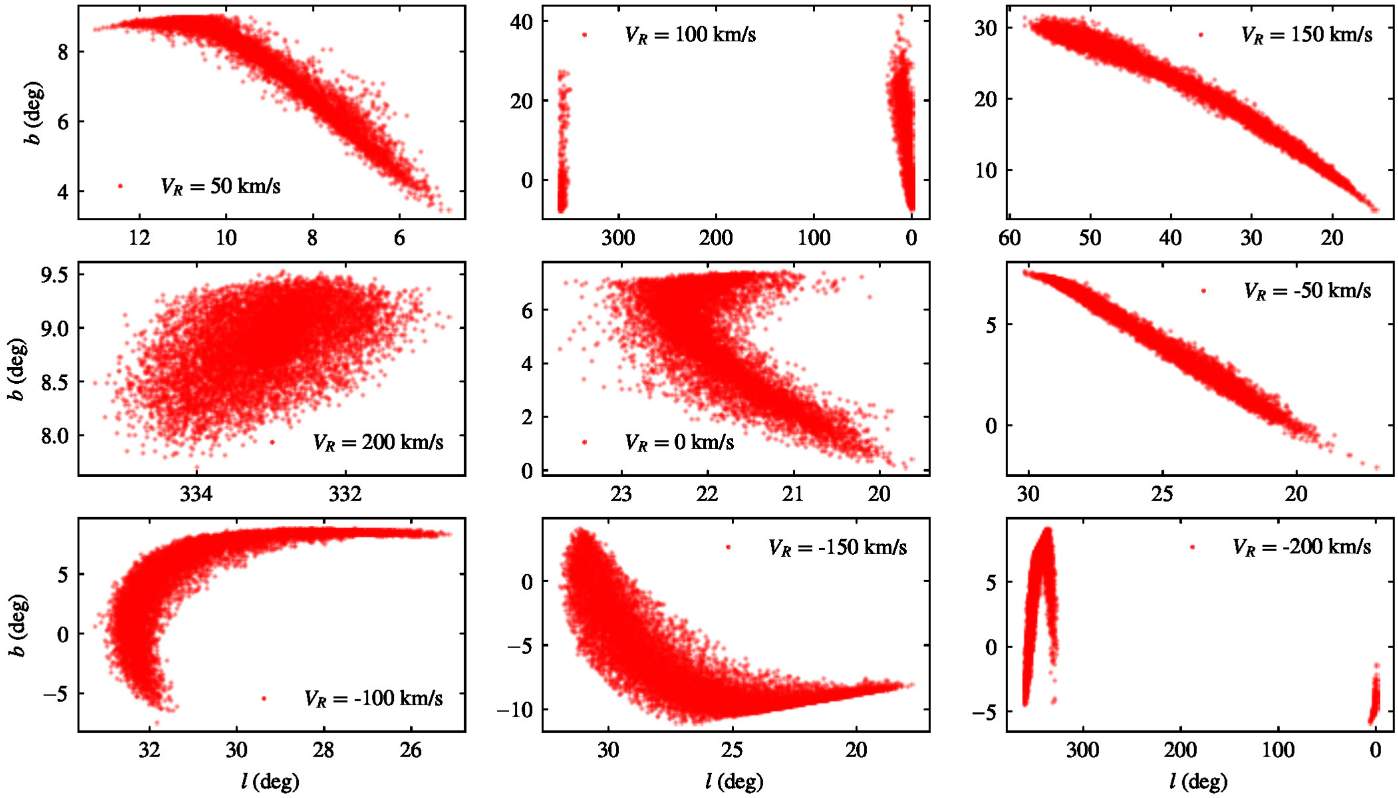

Figure 4. Particles from the model with $W_0 = 3$, in galactic coordinates, in the end of each simulation of 600 Myr.

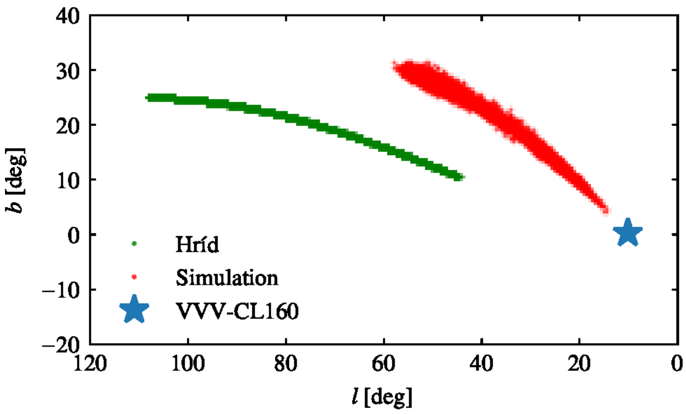

Figure 5. Visualization, in galactic coordinates, of the result of the 600 Myr simulation with $W_0 = 3$ and $V_R = 150$ km/s, of Hríd's trace and VVV-CL160 current position in the sky.

dinates omit one spatial dimension. In fact, a case similar to this one evidences a contrast: by varying only the initial concentration of the N-body system ($V_R = 150$ km/s and duration of 600 Myr were kept unchanged), a very relevant deviation in the final position of the resulting stream occured: it ended at the other side of the Galaxy when compared to the previous scenario, as shown in Fig. 7. 7.

The internal structures of the obtained streams were also analyzed. When plotting maps of particle density (Fig. 8 and Fig. 9), it was observed that the initially more concentrated cluster tended to have its core faded more quickly. In reality, this type of distribution lost its nuclei in practically all simulations. On the other hand, those less concentrated at the beginning showed more durable cores. It is not clear whether this apparent relationship between initial concentration and internal structure of the resulting stellar streams is directly generalizable or whether there are other dependencies (the general shape of the orbit, for example). In addition, it is important to highlight the fact that the analyzed models *did not* maintain their structures similar to that of VVV-CL160 nowadays. This can be seen as an indication that Hríd is not a tidal depri of this cluster's disruption. However, this was expected, after all, structural parameters currently observed were used to describe this system millions of years in the past: this was a first approximation. Nevertheless, the morphological similarities observed in Fig. 6 may indeed suggest a possible dynamical connection between the two systems: one was not necessarily generated by the other, however, it is conceivable that their evolution histories are intertwined.

4. Conclusions and perspectives

At the end of the simulations and analyses, it was possible to conclude that, despite not having an exact correspondence between simulation and observation, the result obtained may, in fact, point in favor of a possible dynamic connection between the structures of interest. The initial concentration appeared to be very impactful in the gravitational evolution of the cluster, we intend to explore this relationship and its possible generalization in future works. This also implied the argument that the origin of the Hríd stellar stream is probably not the disruption of the studied cluster. Therefore, the hypothesis proposed by Minniti (2021) (the association between Hríd, VVV-CL160, another cluster globular and a hypothetical ancient dwarf galaxy) has been lightly corroborated. Furthermore, the results further motivate measurements of VVV-CL160's radial velocity in order to make this problem more detailed and insightful.

References

Garro et al. (2022), A&A, 658, A120.

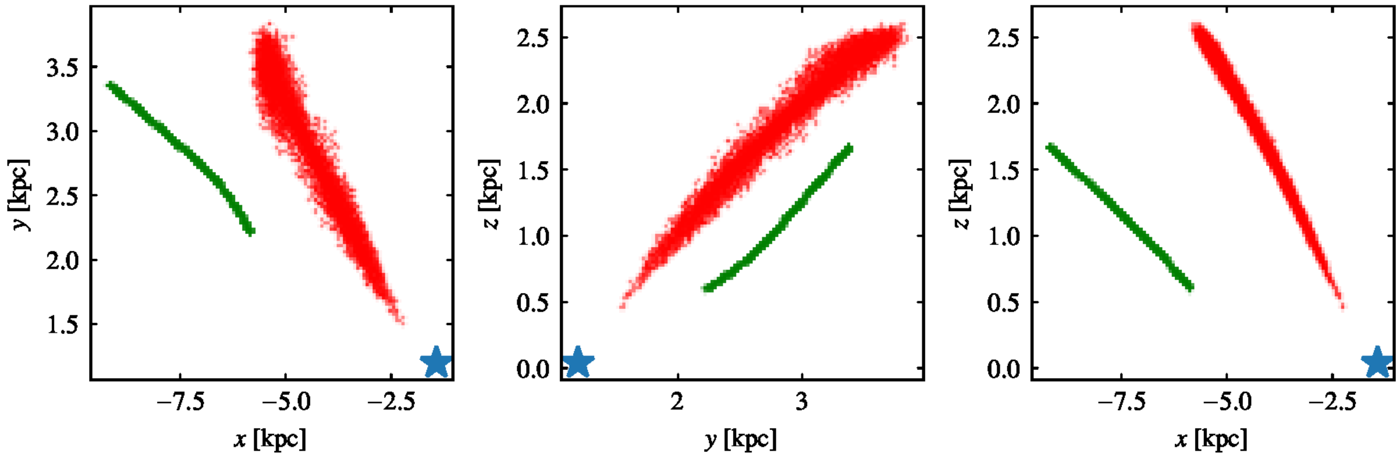

Figure 6. Visualization, in cartesian coordinates, of the result of the 600 Myr simulation with $W_0 = 3$ and $V_R = 150$ km/s, of Hríd's trace and VVV-CL160 current position in the sky.

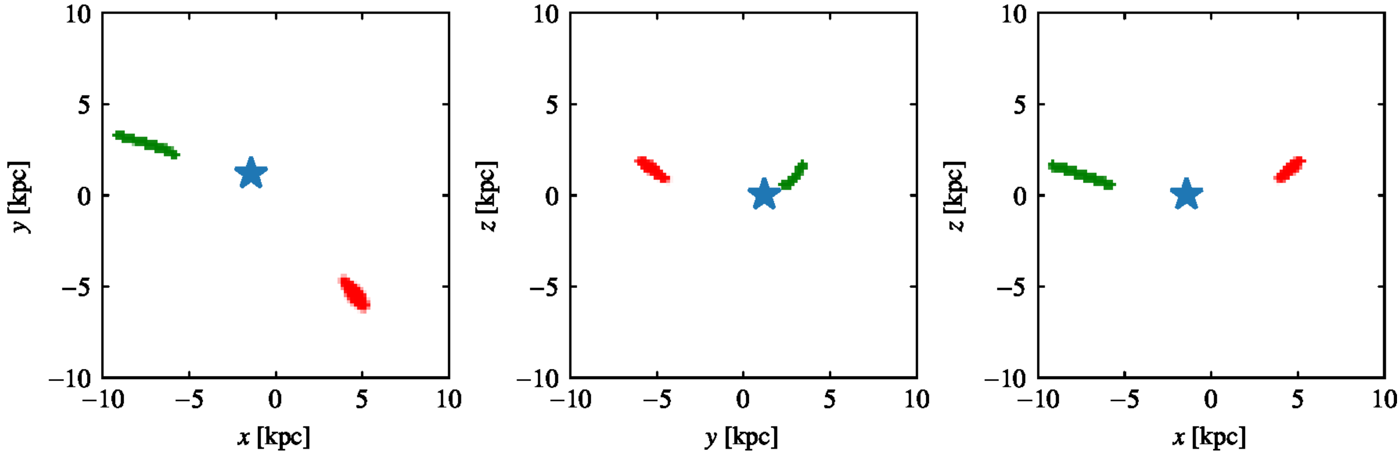

Figure 7. Visualization, in cartesian coordinates, of the result of the 600 Myr simulation with $W_0 = 10$ and $V_R = 150$ km/s, of Hríd's trace and VVV-CL160 current position in the sky.

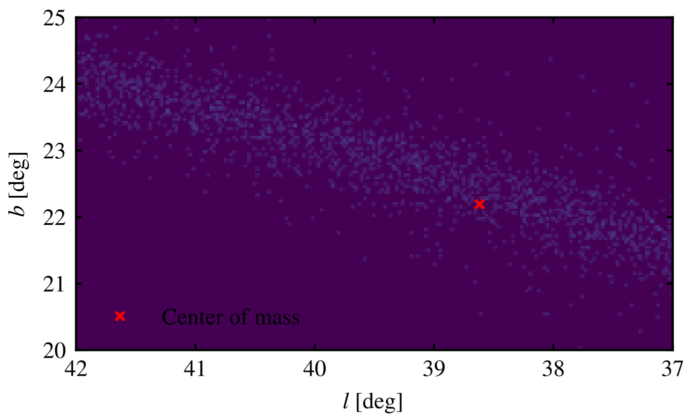

Figure 8. Visualization of the distribution of stars in the interior of the output stream from the simulation with 600 Myr, $W_0 = 3$ and $V_R = 150$ km/s.

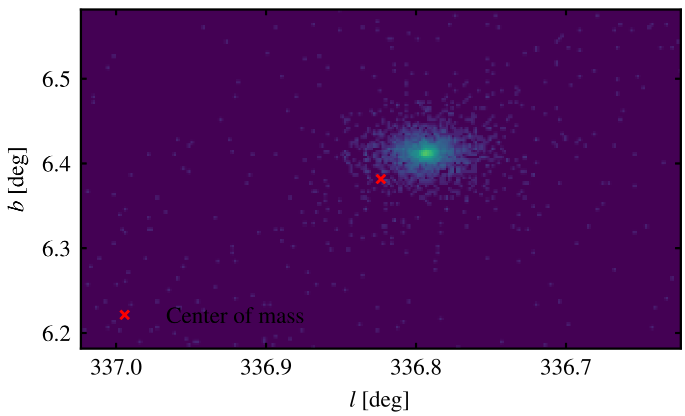

Figure 9. Visualization of the distribution of stars in the interior of the output stream from the simulation with 600 Myr, $W_0 = 10$ and $V_R = 150$ km/s.

Ibata et al. (2021), ApJ, 914, 123.
Lambert, J. C. (2014), in Astronomical Data Analysis Software and Systems XXIII, Manset, N. and Forshay, P., Astronomical Society of the Pacific Conference Series, 429.
Minniti et al. (2021), A&A, 650, L11.
Mateu, C. (2022), arXiv e-prints, arXiv:2204.10326.
Price-Whelan A. M. (2017), The Journal of Open Source Software, 2.
Teuben, P. (1995), in Astronomical Data Analysis Software and Systems IV, Shaw, R. A. and Payne, H. E. and Hayes, J. J. E., Astronomical Society of the Pacific Conference Series, 398.