Chemodynamical tracers for the formation of dSph. Leo I vs Simulations

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Resumen / Presentamos un análisis de la cinemática interna de la galaxia esferoidal enana Leo I usando BEACON a fin de encontrar patrones químicos-cinemáticos entre estrellas de distintas poblaciones estelares, empleando sus metalicidades y velocidades a lo largo de la linea de visión. Comparamos nuestros resultados con los diferentes escenarios propuestos para la formación de galaxias esferoidales enanas, especificamente el modelo de disolución de cumulos de estrellas y su principal predicción.

Abstract / We present an analysis of the internal kinematics of the Leo I dwarf spheroidal galaxy using BEACON to find chemo-kinematic patterns among stars of different stellar populations, using their metallicity and velocity along the line of sight. We compare our results with the different scenarios proposed for the formation of dwarf spheroidal galaxies, specifically the dissolving star cluster model and its main prediction.

Keywords / galaxies: dwarf — kinematics and dynamics — Local Group — structure

1. Introduction

Dwarf spheroidal galaxies (dSph) are the most common type of galaxies in the Universe, however, due to their low luminosity, their study has been very difficult. These systems have stellar masses of $10^5 - 10^7$ $M_\odot$, but their velocity dispersions of $\sim$10 km s^{-1} out to large radii imply dynamical masses 2 orders of magnitude larger (e.g. Simon & Geha, 2007; Koch et al., 2009; Kleyna et al., 2002, 2003; Muñoz et al., 2005, 2006; Simon & Geha, 2007; Walker et al., 2007). They are therefore thought to be the most dark matter dominated objects known in the Universe (e.g. Mateo, 1998; Walker et al., 2009).

In the standard hierarchical galaxy formation models, larger galaxies are formed from smaller objects like dwarf galaxies through major and/or minor mergers (Kauffmann et al., 1993; Cole et al., 1994). Thus, it is important to study these galaxies to understand the formation and evolution of normal sized galaxies.

There are different models that could explain the origin of dSph galaxies considering different mechanisms. Gnedin et al. (1999) and Mayer et al. (2007) proposed that dSph galaxies were formed from dwarf disc satellites of a larger galaxy, then their gas was removed by ram-pressure and additional tidal stirring changed their form.

D'Onghia et al. (2009) proposed that dSph galaxies were formed by encounters between two dwarf disc galaxies and resonant stripping destroyed the form of the galaxies, leaving the DM halo intact.

According to the dissolving star cluster scenario proposed by Assmann et al. (2013a,b); Alarcón Jara et al. (2018), a dSph galaxy is formed by the fusion and dissolution of several star clusters, formed within a DM halo. In order to corroborate those formation models it is necessary to understand the details of the star formation histories and the kinematics of dSphs. dSphs galaxies have been generally considered to be pressure-supported systems with little or no rotation. On the other hand, significant rotation signatures have been reported for some dSph galaxies in the literature (Battaglia et al. (2008); Lewis et al. (2007); Fraternali et al. (2009)). However, these works are based on V_{LOS} measurements of only a few tens of RGB stars in each galaxy, which may not be enough to derive conclusive results. Large spectroscopic data sets are needed to understand the internal kinematics of dSph galaxies. Recent work by del Pino et al. (2017) shows that the spherical shape of the Fornax dSph could be due to the superposition of many different stellar components with distinct kinematics, differentiated by their chemical composition. The main prediction of the dissolving star cluster model, is that stars formed in the same star cluster follow similar orbits while they dissolve. This motivates us to search for streaming motions or circular orbits of stars with similar chemical compositions (since they were formed in the same molecular gas cloud) in galaxies where large spectroscopic data sets are available.

2. Method: BEACON

Acquisition of large spectroscopic samples and proper motions of dwarf galaxies will allow us to disentangle the internal kinematic of dwarf galaxies. BEACON is a new software tool developed by del Pino et al. (2017). The code is optimized to find groups of stars with similar

chemo-kinematic properties in resolved stellar systems. Its development was motivated by the results of del Pino et al. (2015), which show that the Fornax dSph galaxy contains different stellar populations with different angular momentum. This prediction was corroborated using BEACON, see del Pino et al. (2017).
The code has been optimized for joining together groups of stars with similar positions, velocities and metallicities, then if the number of stars in the group is bigger than a minimum cluster size (MCS), the code classifies them as a one side stream (OSS). If at the opposite side of the center of mass exists another stream with similar chemical composition, but with opposite velocity, then the two groups are classified as a both side stream (BSS).

3. Results

3.1. BEACON & simulated data

In the thrashing scenario of a dwarf disc galaxy, one would expect to see some left-over/coherent rotation signal in the kinematics of the stars. But, most of the dwarf spheroidal galaxies do not show signals of rotation, and if they do, this signal is very weak. In the dissolving star cluster model proposed by Assmann et al. (2013a), stars sustain orbits similar to the ones held by their dissolved cluster. We would expect to see many "rotation" signals in randomly oriented directions.
In the left panels of Fig. 1 we present simulated examples of different streams formed by dissolved star clusters. According to this model, for a young star cluster which is not entirely dispersed within the dark matter halo, we shall see a one side stream like is seen in the first panel. Additionally, depending on the orbit of the star cluster within the dark matter halo, we shall see different rotating patterns as in the second and third panels, where the majority of the stars follow circular orbits. We apply BEACON to these streams and the results are shown in the right panels of Fig. 1. BEACON is able to detect one-side streams and both side streams, but it has problems detecting the stars close to the center, as they have lower velocities and positions out of the standard deviation of the recovered sample.

In a simulation we can give a certain metallicity to each star according to the age of the star cluster where it was formed: the older, the more metal-poor. We use data from a simulation in which we form 8 star clusters using a constant star formation history during 10 Gyr, this means that we formed one star cluster every 1.25 Gyr. For simplicity, the metallicities are given using a linear age to metallicity ratio. To mimic the data, we choose randomly 1000 stars of the simulation and we add the typical error values found in our Leo I catalog, ($\pm$ 2.5 km s^{-1} for the velocity and $\pm$ 0.2 Fe H^{-1} for the metallicity). Applying BEACON to this sample with the optimal parameters, we can recover approximately 70% of the stars from the same star cluster correctly.

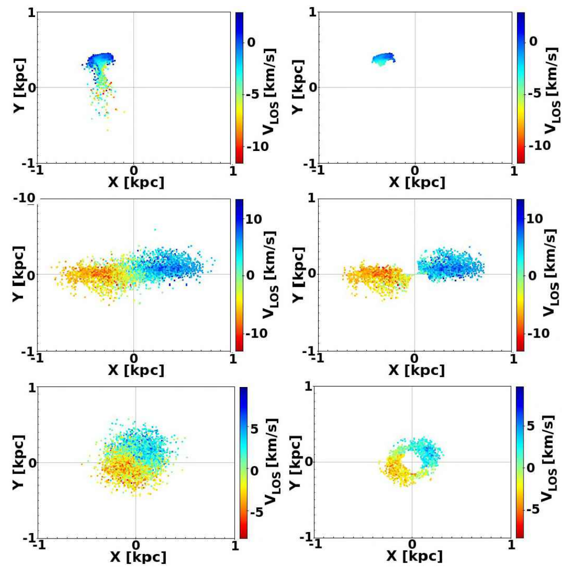

Figure 1: Dissolved star clusters in simulations. Left panels show the different kinds of streams that simulations of the dissolving star cluster model reproduce, and the right panels show the particles that BEACON is able to recover from those streams. We can see that BEACON is able to recover one side streams (first panel) and both side streams (second and third panels), but the stars in the center are more difficult to recover using this code.

3.2. BEACON in real data of Leo I

Leo I, a satellite of the Milky Way, is one of best candidates to test formation models because it is orbiting at 250 $\pm$ 20 kpc (Karachentsev & Kashibadze, 2006) from the Milky Way, so it has not recent tidal interactions with the Galaxy, it also formed stars at a relatively constant rate until $\sim$1 Gyr ago (Weisz et al., 2014). We use data from Leo I obtained from the Keck/DEIMOS instrument by Sohn et al. (2007); Kirby et al. (2010) and new data acquired with Magellan/IMACS in March 2018. We applied BEACON to the 943 stars combining these three samples.

We found 230 stars classified in 10 different rotating stream candidates that share similar metallicities. An example of one of these streams is given in Fig. 2, where we see a clear signal of rotation. We calculate the angular momentum and then normalize it by the number of stars in each group, representing the angular momentum per unit of stellar mass. Those 10 different streams show different angular momentum directions (Fig. 3 left panel) distributed randomly in the galaxy. This result is in favor of the dissolving star cluster scenario shown in Fig. 3 right panel.

4. Discussion and conclusions

Motivated by the predictions of the dissolving star cluster model we investigate the presence of stream motions using BEACON, to find chemo-kinematic patterns in stars of Leo I. We find multiple rotating populations in Leo I, similar to the results obtained for Fornax by del Pino et al. (2017). This could indicate that the overall

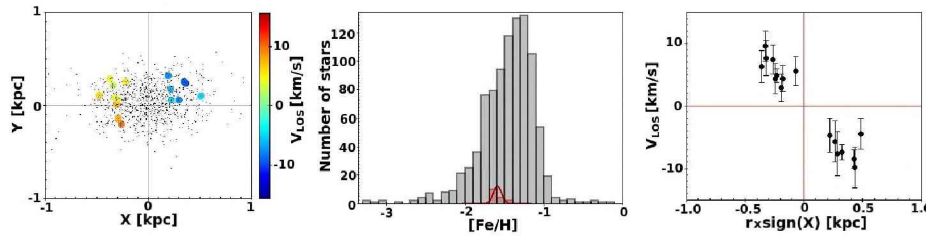

Figure 2: Example of a group of stars recovered by BEACON: The left panel shows the distribution of the stars in the galaxy with black dots, stars that are part of the same stream are coloured according to their velocity. Middle panel shows a histogram with the metallicity distribution from the stars of our sample, and in red the metallicity of the stars from the stream. The right panel shows the velocities of the stream versus the distance from the center.

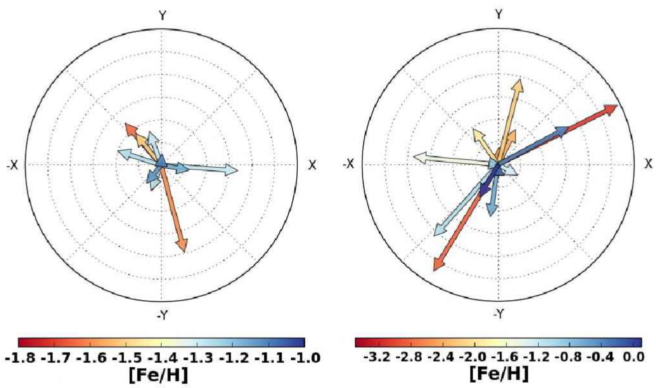

Figure 3: Angular momentum per unit of stellar mass for different streams: The left panel shows the different angular momentum patterns recovered by BEACON in the sample of 943 stars from Leo I according to their Fe to H ratio. Circles have radius from 0 to 3 $\times 10^{3}$ pc ^{2} s^{-1} with step of 0.5 $\times 10^{3}$ pc^{2} s^{-1} for each dotted concentric circle. The right panel shows the angular momentum for a simulation of the dissolving star cluster model with 16 star clusters dissolved. It is clear that there is no net rotation signal, in agreement with the predictions of the dissolving star cluster model.

structure of dSph galaxies is due to the superposition of different stellar populations with different orbits.
In the context of the dissolving star cluster model, these chemo-kinematic patterns are one of the main predictions and arise naturally with the model. However, the patterns found in Leo I and Fornax can be explained with other models assuming rotating progenitors as well. For example, the tidal stirring model explains the formation of dSphs as interactions between a dwarf disc galaxy and a Milky Way size galaxy. These interactions could be responsible for reshaping a disc galaxy into a dSph (Mayer et al., 2007). Simulations show that after a significant time, the final object conserves some signatures of this process and could have remnant rotation around the minor axis. In Leo I, the specific angular momentum of the stream candidates is randomly distributed around the galaxy as is predicted by the dissolving star cluster model.

Another option to explain this pattern implies that the evolution of dSph galaxies could involve several mergers between two or more galaxies. Two disc galaxies collide and as a result they could form a dSph. This idea has been studied before and shows that some of the orbits of the progenitors could remain after the collision and that some stars could still be on their initial orbits after the merging, presenting angular momentum vectors in different directions (Amorisco & Evans, 2012).
As the formation process of dSph galaxies is still unclear, it is necessary to apply BEACON to other dSphs with large and high quality data, when available, in order to search for chemo-dynamical substructures in those systems and obtain a better understanding of the origin of dSphs.

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