Statistical detection of the tidal streams of the globular clusters using Gaia data

Carles Garcia Palau

Advisor: Jordi Miralda Escudé

Gaia DR2 Meeting - Barcelona

Institut de Ciències del Cosmos, Universitat de Barcelona (ICC-UB)

May 29, 2018

UNIVERSITAT DE BARCELONA

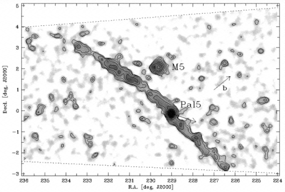
ICCUB

Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

EXCELENCIA MARÍA DE MAEZTU

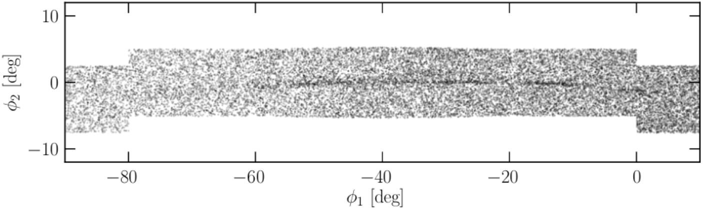
Introduction

- Tidal streams are stripped stars from a globular cluster due to the galaxy's tidal force.
- The escaped stars approximately follow the progenitor's orbit.
- The streams are useful to constrain the shape of the dark halo.
- Gaia-DR2 catalogue may be used to identify streams.



Surface density of Pal 5 (Odenkirchen et al. - 2003)

- A statistical method is designed to search new streams directly in the 6 dimensional phase-space and to infer the Milky Way's dark halo properties.



GD-1 in Gaia DR2 (Price-Whelan et al. - 2018)

Description of the statistical method

- The existence of a stream implies an over-density respect to the expected star density of the Milky Way which can be detected statistically.

- Given a star of the Gaia catalogue:
  - The phase-space mean position: w
  - The measurements uncertainties: Σ

- It can be computed for each star:
  - Probability to be a member of the stellar stream: P_S
  - Probability to be a member of the Milky Way: P_{MW}

- A likelihood function is the probability of obtaining a given data for a certain values of a characteristic parameters θ.

$$L(\alpha,\theta) \equiv \prod_{n=1}^{N} \alpha \cdot P_S(w_n, \Sigma_n|\theta) + (1-\alpha) \cdot P_{MW}(w_n, \Sigma_n|\theta)$$

  - Fraction of stars in the catalogue that form the stellar stream: α

- The Likelihood function L tends to the highest value near the true value of the parameters α, θ.

$$\bar{\alpha}, \bar{\theta} = \text{argmax}(L(\alpha, \theta))$$

- Hypothesis test:

$$\text{Hypothesis:} \begin{cases} H_0 : & \alpha = 0 & \theta \in \Theta \\ H_1 : & \alpha \in (0, 1] & \theta \in \Theta \end{cases}$$

- Likelihood ratio test:

$$\Lambda \equiv -2 \ln \left(\frac{L(0, \bar{\theta})}{L(\bar{\alpha}, \bar{\theta})} \right) > k \sim \chi^2_n \longrightarrow H_0 \text{ has to be rejected} \longrightarrow \text{There is a stream}$$

- Summary:
  1. Given a catalog of N stars, compute P_S, P_{MW} and L.
  2. Repeat this computation for a different values of the parameters.
  3. Figure out the values that maximise the likelihood.
  4. Compute the ratio test.

Calculation of the probability function P_{MW}

- The probability that a star belongs to the Milky Way P_{MW} depends on:
  - Phase-space position of a star assuming gaussian errors: $S(w, \Sigma)$
  - Luminosity function: $\mathcal{L} \propto r_{\odot}$
  - Phase-space density model of the Milky Way: $f(w|\theta_{st})$

- Phase-space density model of the Milky Way is made of the stellar components:
  - Thin and Thick disc
  - Bulge
  - Stellar Halo

$$f(w|\theta_{st}) = \sum \frac{1}{M} \cdot \rho(w|\theta_{st}) \cdot f_v(w|\theta_{st})$$

- The probability is defined as follows:

$$P_{MW}(w, \Sigma|\theta_{st}) \equiv \int S(w, \Sigma) \cdot \mathcal{L}(r_{\odot}) \cdot f(w|\theta_{st})\, d^6 w$$

Calculation of the probability function P_s

- The probability that a star belongs to the tidal stream P_s depends on:
  - Phase-space position of a star assuming gaussian errors: $S(w, \Sigma)$
  - Luminosity function: $\mathcal{L} \propto r_\odot$
  - Phase-space density model of the tidal stream: $f_s(w, \Sigma|\theta_{gc}, \theta_{st}, \theta_{dh})$
- The potential of the Milky Way is made up by the addition of the mass components:
  - Thin and Thick disc
  - Bulge
  - Dark Halo
- The Dark Halo is a axisymmetric NFW profile with $\gamma = 1$ and free parameters: $\theta_{dh} = \{\rho_0, a_1, a_3, \beta\}$

$$\rho_{dh}(x, y, z) = \rho_0 \left(M'\right)^{\frac{-\gamma}{2}} \left[1 + \sqrt{M'}\right]^{\gamma-\beta} \qquad M' \equiv \left(\frac{x^2}{a_1^2} + \frac{y^2}{a_1^2} + \frac{z^2}{a_3^2}\right)$$

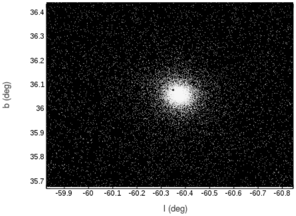
- The probability is defined as follows:

$$P_s(w, \Sigma|\theta_{gc}, \theta_{st}, \theta_{dh}) \equiv \int S(w, \Sigma) \cdot \mathcal{L}(r_\odot) \cdot f_s(w, \Sigma|\theta_{gc}, \theta_{st}, \theta_{dh})\, d^6 w$$

Simulation of the tidal stream

- The simulation of a tidal stream is performed following the next steps:
  1. Compute backwards in time the orbit of the globular cluster (10 Gyr).
  2. Spread out stars around the globular cluster following a phase-space density function (Plummer model).
  3. Compute forward the orbits of the stars within the potential of the galaxy and the potential of the globular cluster.
  4. Use the escaped stars to create a density model of the stellar stream.

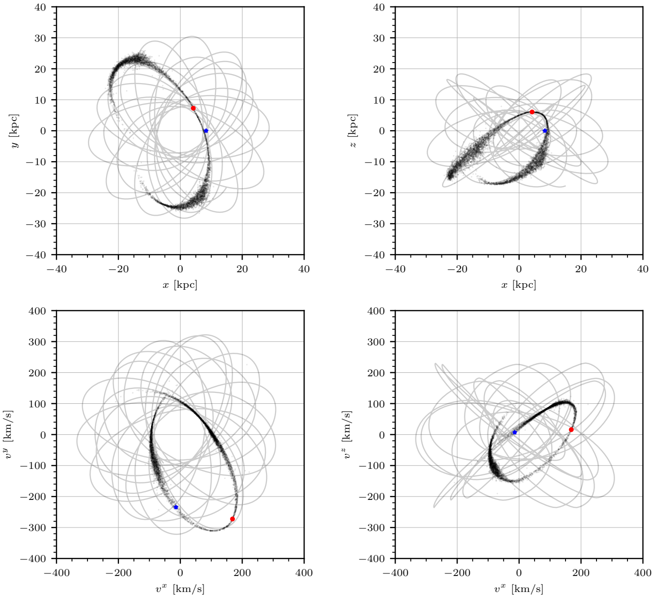
- The case of M68 (NGC4590) globular cluster as an example:



Current position, velocity and properties of the M68 (NGC4590) globular cluster.

Properties			Ref.
r	[kpc]	10.45 ± 0.1	[1]
α	[deg]	189.8651	[1]
δ	[deg]	-26.7454	[1]
v^r	[km/s]	-95.0 ± 0.3	[1]
μ_δ	[mas/yr]	-0.5 ± 0.59	[2]
μ_α	[mas/yr]	-8.95 ± 0.76	[2]
M_{gc}	[$M_\odot$]	$(0.57 \pm 0.27) \cdot 10^5$	[3]
a_{gc}	[pc]	6.4 ± 2	[3]

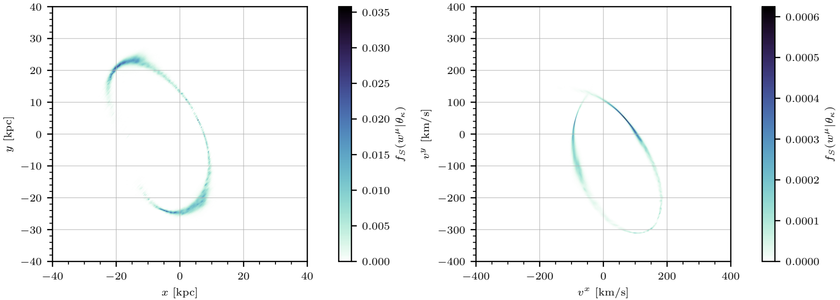
[1]: Dambis (2006)
[2]: Dinescu et al. (1999)
[3]: Lane et al. (2010)



The orbit of M68 from 10 Gyr ago to the present time and its simulated tidal streams.

- The phase-space density function is constructed using a Kernel Density Estimation choosing a gaussian distribution as a kernel.

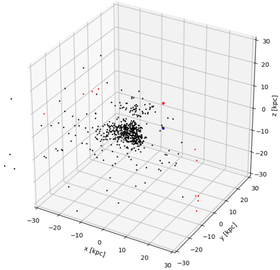
$$f_S(w, \Sigma|\theta_{gc}, \theta_{st}, \theta_{dh}) \equiv \frac{1}{E}\sum_{e=1}^{E} N(w|\bar{w}_e, \Sigma_e)$$

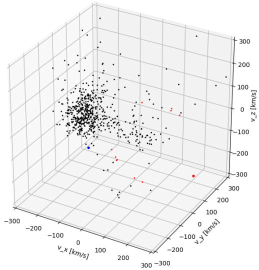


Density model of the tidal stream of the M68 globular cluster.

Validation of the Statistical Method

- The model has been validated with Gaia mock data:
  - Besançon galaxy model (Object catalogue)
  - Gaia Object Generator (Gaia errors)
- Using the stars with radial velocity ($\sim$ 7M).
- The parameters of the Dark Halo have been fixed.
- A stellar stream has been simulated and mixed with the mock Gaia data ($\sim$ 10 stars).
- A pre-selection cut chooses about $\sim$ 1000 stars in the region where the stellar stream is expected to be (stars with highest probability).





Recover the stream stars and the Dark Halo parameters

- Free parameters:

Stream stars fraction: α			
Globular Cluster:			
r	v^r	μ_α	μ_δ
Dark Halo:			
ρ_0	a_1	a_3	β

- Algorithm:

Given a initial conditions:

[1] Simulate a stellar stream.

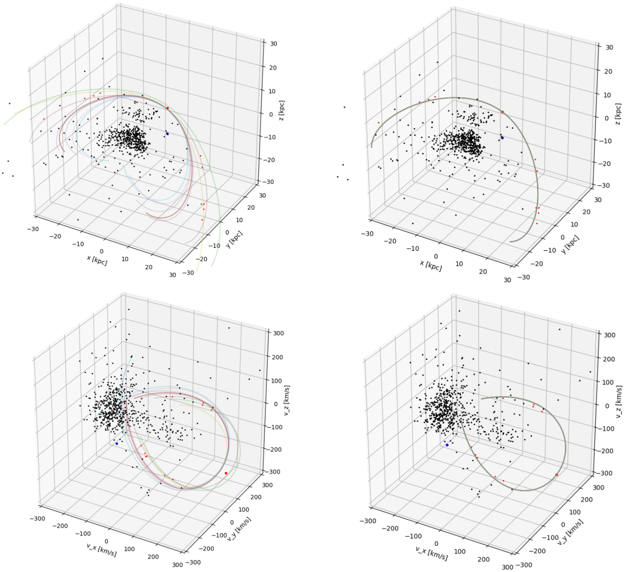
[2] Compute P_{MW}, P_s and L.

[3] Change the parameters following a Simplex optimisation algorithm.

- Result:

$\bar{\theta} = \text{argmax}(L(\theta))$

$\Lambda = -2 \ln\left(\frac{L(\bar{\theta}^0)}{L(\bar{\theta}^1)}\right)$



Conclusions

- The statistical method has recovered the values of the parameters:

Properties		Real	Recovered
α		0.011	0.006
r	[kpc]	10.45 ± 0.1	10.58
v^r	[km/s]	-95.0 ± 0.3	-94.97
μ_δ	[mas/yr]	-0.50 ± 0.59	-0.48
μ_α	[mas/yr]	-8.95 ± 0.76	-8.83
ρ_0	[$M_\odot/kpc^3$]	$7.11 \cdot 10^8$	$6.97 \cdot 10^8$
a_1	[kpc]	3.83	3.79
a_3	[kpc]	3.064	2.871
β		2.96	2.90

$$\Lambda \equiv -2 \ln \left(\frac{L(\bar{\theta}^0)}{L(\bar{\theta}^1)} \right) = 56.044 > k = 6.63$$

- It has found out a stellar stream with ~ 10 stars in a sample of $\sim 7M$.
- Next step: Use Gaia-DR2 to identify known streams (GD-1) and search for new ones.