

# Dynamics of Stellar Streams to constrain Milky Way potential

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## ABSTRACT

In this project, we will be looking at stellar streams generated by the tidal disruption of stars in a satellite galaxy or a cluster. We fit an orbit to the stream using single and multi-component potential that best describes the stream orbit. We will use GD-1 stream data obtained from SDSS and Calar Alto spectroscopy. Once we have fitting parameters, we look at the likelihood of the fitted orbital parameters including its position, proper motion and its distance from centre of the Milky Way and optimize the parameters to get the largest likelihood value. Previously it was assumed that if the stream is thin, an orbit can be fitted to the stream; however, this causes bias in constraining the potential using the stream, as this assumption is not very accurate.

## 1. Introduction

Stars in satellite galaxies and clusters get tidally disrupted by their host galaxy as they orbit around it. The orbit of the tidally disrupted stars is close to that of their progenitor, extending ahead and beyond, making a tail shape. (Bowden et al. 2015) Understanding the physics of these stream orbits help us study the structure of the host galaxy and the shape of galactic halo as well as to constrain its potential. Tidal streams can also give us information about the large- and small-scale structure of the Milky Way halo's density distribution. (Bovy 2014)

There are a number of streams detected within our Milky Way galaxy which could help us constrain the potential of the Milky Way. The most famous example of such case is Sagittarius (Sgr) dwarf galaxy that has been discovered in 1994. (Ibata et al. 1994) The nucleus of the Sgr has survived for many orbits around the Galaxy, while its tidal tails have now been detected over a full  $360^\circ$  on the sky and provides a strong constraint on the Galaxy's halo. (Fellhauer et al. 2006) Some of the other detected streams in Milky Way galaxy are Grillmair-Dionatos (GD-1) stream, Orphan stream and NGC5466 stream. These streams are derived from progenitors with lower mass than that of the Sgr stream so they will be easier to model. (Bowden et al. 2015)

The difficulty in modelling the streams is that they do not follow a single orbit and this makes it hard to know which fitting of orbits is the best. We can fit more than one single orbit to the streams but it would be computationally expensive which has led to the assumption of fitting one single orbit to the streams (Bovy 2014). Koposov et al. (2010) mentioned that if the stream is very thin, we can make the assumption that the stream stars move along the same orbit even though in general the stars have different energies and angular momentum, but Sanders & Binney (2013) found that assuming the stream lies along a single orbit can lead to systematic biases in estimates of the potential parameters.

In section 2, I will describe current tools we have and in section 3 the data we use. In section 4 I will discuss how the orbit fitting to the streams is done and in section 5 I will present the timeline for this project.

## 2. Current Tools

I will be using `galpy` which is a Python package written for galactic dynamics calculations. `galpy` includes a vast number of functions including different galactic potentials and integration methods. There are different types of potentials, single-component logarithmic being one.

The units in `galpy` are in natural units that ensures the circular velocity is one at a cylindrical radius of one and height of zero. (Bovy 2015) One needs to multiply the output by the actual values to convert to physical units. For instance, position and velocity should be multiplied by 8.5 kpc and 220 kms<sup>-1</sup>, respectively in a model where the Sun is assumed to be at 8.5 kpc from the Galactic centre and has the circular velocity of 220 kms<sup>-1</sup>.

## 3. Data

GD-1 that was first detected by Grillmair & Dionatos (2006), is a cold thin stream that is 63° long on the sky. It is suggested that it has been generated from a globular cluster since it is very thin, but there is no progenitor remnant to confirm this hypothesis (Sanders & Binney 2013). It is located at  $\sim 8.5$  kpc from the Sun and  $\sim 15$  kpc from the Galactic centre and is moving perpendicular to the line of sight with the velocity of 220 kms<sup>-1</sup>. (Koposov et al. 2010) We will be using the GD-1 stellar stream data which is a combination of the Sloan Digital Sky survey (SDSS) and Calar Alto spectroscopy and it includes position of the stream, radial velocity, proper motion and distance of the stream that is given in tables 1-4 in Koposov et al. (2010). The stream positions are given in stream coordinates  $\phi_1$  and  $\phi_2$  which is a rotated coordinate system where it is approximately aligned with the stream.  $\phi_1$  and  $\phi_2$  represent the longitude and latitude of the stream, respectively. The proper motions are also given in stream coordinate.

## 4. Method

### 4.1. Orbit Fitting

To begin, we assume a single-component potential known as flattened logarithmic potential for the Milky Way. This potential is given by equation (1):

$$\Phi(x, y, z) = \frac{V_c^2}{2} \ln \left( x^2 + y^2 + \left( \frac{z}{q_\Phi} \right)^2 \right), \quad (1)$$

where  $V_c$  represents the circular velocity and  $q_\Phi$  shows the flattening parameter.

For initializing the orbit, we need to have initial conditions which are the initial position and velocity components of the stream. We also need the distance to and the velocity of the stream. Once we have the orbit initialized, we can integrate it so get the orbital properties at any given time. These properties include the position, velocity, proper motion, distance, energy and a lot more.

An application of fitting an orbit to the GD-1 stream data is shown in Figure (1), where we have used initial conditions of the stream to predict the orbit at later times.

## 4.2. Likelihood

We can calculate the likelihood as the probability of getting a y-value at an x-value given a model. In our case, we will consider likelihood as the probability of getting  $\phi_2(t)$ , distance(t),  $V_{rad}(t)$  or  $\mu(t)$  at a specific  $\phi_1$  given a model, which corresponds to  $\mathcal{L} \propto P((\phi_2, d, V_{rad} \text{ or } \mu) \text{ at } \phi_1 | \text{model at time } t)$ . The log likelihood for the case of  $\phi_2$  can be written as:

$$\begin{aligned} \mathcal{L} &\propto \int \exp \frac{-(\phi_1(t) - \phi_1^{obs})^2}{2\sigma_1^2} + \frac{-(\phi_2(t) - \phi_2^{obs})^2}{2\sigma_2^2} dt \\ \mathcal{L} &\propto \sum_i \exp \frac{-(\phi_1(t) - \phi_1^{obs})^2}{2\sigma_1^2} + \frac{-(\phi_2(t) - \phi_2^{obs})^2}{2\sigma_2^2}. \end{aligned} \quad (2)$$

We need to integrate over time to get an average value since we do not know the time the data has been taken but since we do not have an infinite number of times, we will only take the sum. We can write the same expression as in equation (2) for  $d$ ,  $V_{rad}$  and  $\mu$ . This is shown for  $V_{rad}$  in equation (2):

$$\mathcal{L} \propto \sum_i \exp \frac{-(\phi_1(t) - \phi_1^{obs})^2}{2\sigma_1^2} + \frac{-(V_{rad}(t) - V_{rad}^{obs})^2}{2\sigma_2^2} \quad (3)$$

In general we can write:

$$\ln(\mathcal{L}) = -\frac{\chi^2}{2} = \prod_i \frac{(x_{model,i} - x_{data,i})^2}{2\sigma_i^2}, \quad (4)$$

where  $i$  represents each of the data points and  $\sigma_i$  is the associated error. This means that we need to multiply the log-likelihood value of each point to get a total likelihood value.

## 5. Timeline

- Fitting orbit to the GD-1 stream and calculating parameter likelihood by the end of November
- Fit stream model for fixed a potential by the end of December
- Fit stream model for a varying potential by the end of January
- Look at different potential families by the end of February
- Wrapping up and writing final report by the end of March

## REFERENCES

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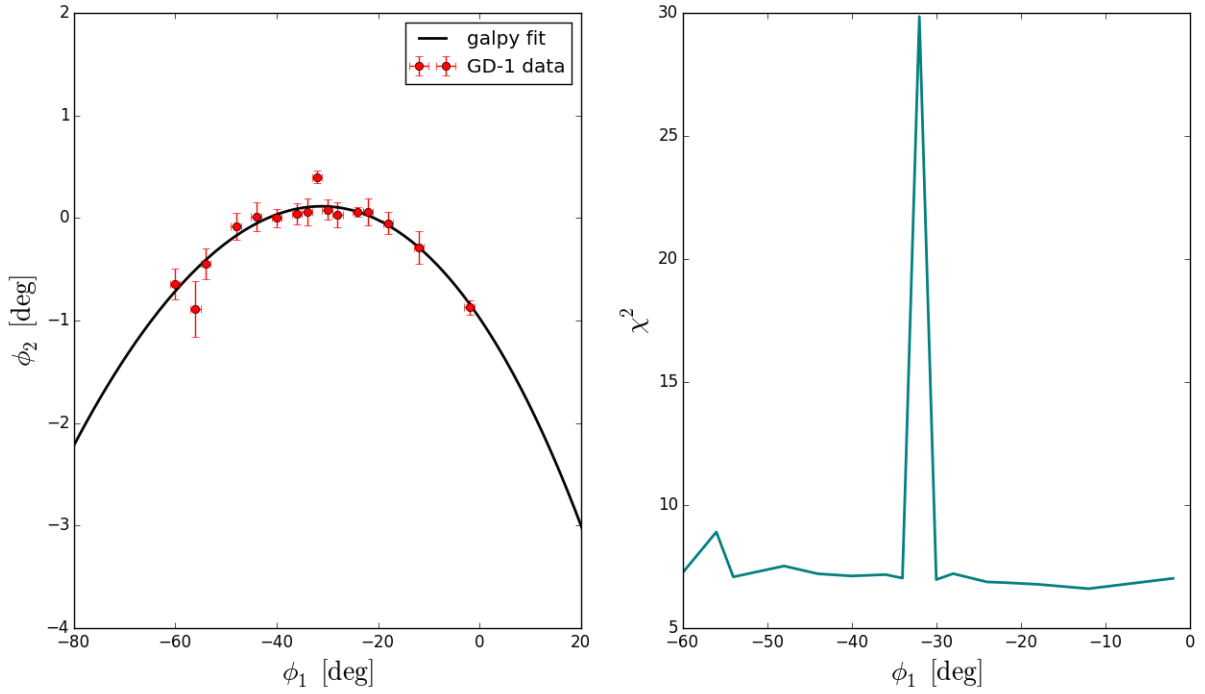


Fig. 1.— *Left:* This plot shows the values of  $\phi_2$  vs.  $\phi_1$ . The red dots represent the GD-1 stream data as in Koposov et al. (2010) tables along with the error bars on  $\phi_2$ . The error bars on the  $\phi_1$  values are all the same and  $1^\circ$ . The black curve is the fitted orbit to the stream using `galpy` and the stream initial conditions. *Right:* Represents the  $\chi^2$  value obtained from calculating the log-likelihood of the  $\phi_2$  and  $\phi_1$  values using equation (2).