

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 from a satellite galaxy or a globular cluster. We fit an orbit to the stream using single and multi-component potentials that best describe the stream orbit. We will use Grillmair Dionatos (GD-1) stream data obtained from SDSS photometry and Calar Alto spectroscopy. Once we have fitting parameters, we look at the likelihood- the probability of occurrence of the fitted orbital parameters. These include stream position, proper motion and its distance from centre of the Milky Way. We then 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. This is because the stars at the ends of the stream have larger frequency differences from the progenitor than that of the stars closer to the progenitor.

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, creating leading and trailing tails, respectively (Bowden et al. 2015). Understanding the physics of these stream orbits help us study the structure of the host galaxy, the shape of galactic halo and allows us to constrain galaxy's 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).

A number of these streams have been detected within our own Milky Way galaxy, which could help us constrain the potential of the Milky Way. The most famous example is the Sagittarius (Sgr) dwarf galaxy, discovered in 1994 (Ibata et al. 1994). The nucleus of Sgr has survived for many orbits around the Milky Way, while its tidal tails have now been detected over a full 360° on the sky and provides a strong constraint on the Milky Way's halo (Fellhauer et al. 2006). Some of the other detected streams in the Milky Way galaxy are GD-1 stream, Orphan stream and NGC5466 stream. These streams are derived from progenitors with lower mass than that of the Sgr stream (Bowden et al. 2015).

The difficulty in modelling the streams is that they do not follow a single orbit. 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 a single orbit to the streams (Bovy 2014). Koposov et al. (2010) mention 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 momenta, but Sanders & Binney (2013) found that this can lead to systematic biases in estimates of the potential parameters. This is due to the larger difference in frequencies of the stars at the end parts of the stream from their progenitor than that of the stars closer to the progenitor.

In this project, I will be using `galpy`, a Python package written by Jo Bovy (Bovy 2015) for galactic dynamics calculations. The `galpy` package fits for different galactic potentials using a variety of integration methods. The units in `galpy` are in natural units: 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 km s⁻¹, respectively in a model where the Sun is assumed to be at a distance 8.5 kpc from the Galactic centre and has the circular velocity of 220 km s⁻¹.

2. Data

GD-1, first detected by Grillmair & Dionatos (2006), is a cold thin stream that is 63° long on the sky. It is suggested that it was 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 ~ 8.5 kpc from the Sun radially and ~ 15 kpc from the Galactic centre and is moving perpendicular to the line of sight with the velocity of 220 km s⁻¹ (Koposov et al. 2010). We will be using data on the GD-1 stellar stream, which is a combination of the Sloan Digital Sky Survey (SDSS) photometry and Calar Alto spectroscopy. These data include position of the stream, radial velocity, proper motion and distance of the stream, given in the tables 1-4 in Koposov et al. (2010). The stream positions are given in stream coordinates ϕ_1 and ϕ_2 which is a rotated coordinate system approximately aligned with the stream. ϕ_1 and ϕ_2 represent the longitude and latitude in the stream, respectively. The proper motions are also given in stream coordinates which can easily be converted to Galactic coordinates.

3. Method

3.1. Orbit Fitting

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

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

where V_c represents the circular velocity and q_Φ is the flattening parameter.

We need the initial position and velocity components of the stream as well as the distance to the stream. Once we have the orbit initialized, we can integrate it to get the orbital properties such as the position of stream at any given time. 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 GD-1 stream given in Koposov et al. (2010) to predict its orbit at later times.

As mentioned before, fitting a single orbit cannot be very accurate for obtaining the potential of the Milky Way, since stars orbit on different paths from one another. In this case, stream models create a better understanding of the stream orbit.

3.2. Likelihood

Likelihood is 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), $V_{\text{rad}}(t)$ or $\mu(t)$ at a specific ϕ_1 given a model, which corresponds to $\mathcal{L} \propto P((\phi_2, d, V_{\text{rad}} \text{ or } \mu) \text{ at } \phi_1 | \text{model at time } t)$. The logarithmic likelihood for the case of ϕ_2 can be written as in equation (2), where an approximate form of it is followed in the next line. 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.

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

We can write the same expression as in equation (2) for d, V_{rad} and μ . This is shown for V_{rad} in equation (3):

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

In general we can write:

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

where i represents each of the data points and σ_i is the associated error. This means that we need to multiply the logarithmic likelihood value of each point to get a total likelihood value. An application of this is shown in Figure (1).

4. 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

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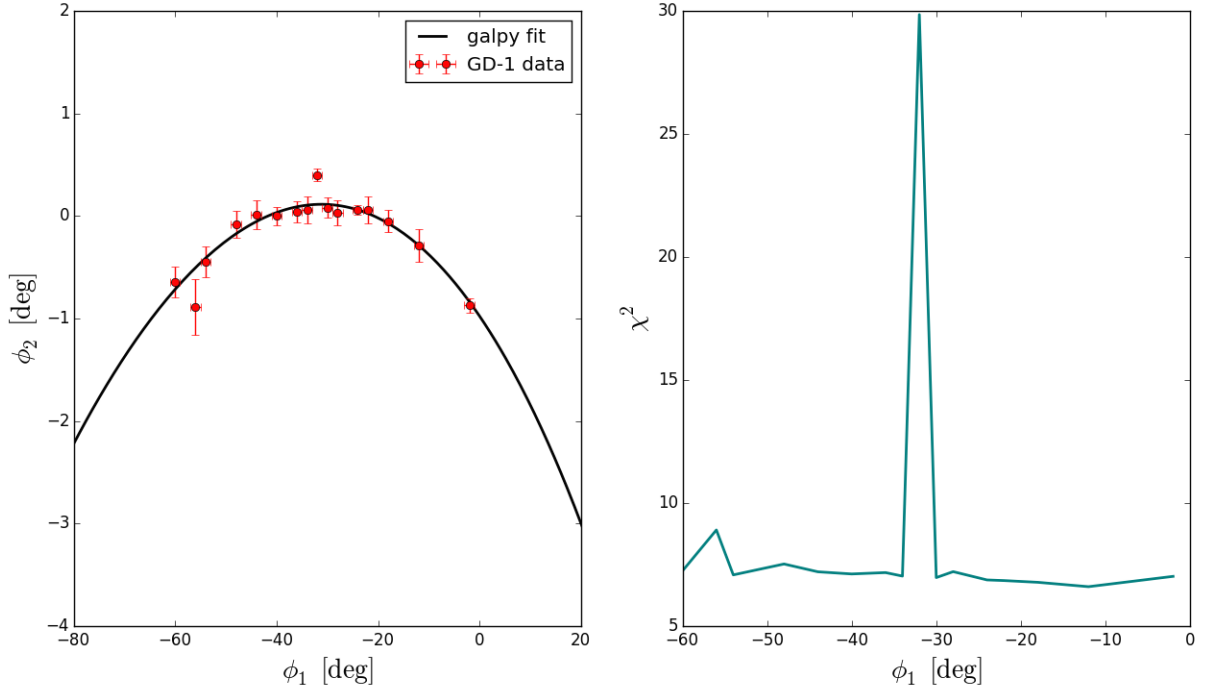


Fig. 1.— *Left:* Represents an application of orbit fitting explained in section 3 and it shows the values of ϕ_2 vs. ϕ_1 . The red dots represent the GD-1 stream data as in Koposov et al. (2010) tables along with the error bars on ϕ_2 . The error bars on the ϕ_1 values are all the same and 1° . The black curve is the fitted orbit to the stream using `galpy` and the stream initial conditions. *Right:* Represents the χ^2 value obtained from calculating the log-likelihood of the ϕ_2 and ϕ_1 values using equation (4).