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Using ground based data as a precursor for *Gaia* in getting proper motions of satellites

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Abstract. We present our effort to measure the proper motions of satellites in the halo of the Milky Way with mainly ground based telescopes as a precursor on what is possible with Gaia. For our first study, we used wide field optical data from the LBT combined with a first epoch of SDSS observations, on the globular cluster Palomar 5 (Pal 5). Since Pal 5 is associated with a tidal stream it is very useful to constrain the shape of the potential of the Milky Way. The motion and other properties of the Pal 5 system constrain the inner halo of the Milky Way to be rather spherical. Further, we combined adaptive optics and HST to get an absolute proper motion of the globular cluster Pyxis. Using the proper motion and the line-of-sight velocity we find that the orbit of Pyxis is rather eccentric with its apocenter at more than 100 kpc and its pericenter at about 30 kpc. The dynamics excludes an association with the ATLAS stream, the Magellanic clouds, and all satellites of the Milky Way at least down to the mass of Leo II. However, the properties of Pyxis, like metallicity and age, point to an origin from a dwarf of at least the mass of Leo II. We therefore propose that Pyxis originated from an unknown relatively massive dwarf galaxy, which is likely today fully disrupted. Assuming that Pyxis is bound to the Milky Way we derive a 68% lower limit on the mass of the Milky Way of 9.5×10^{11} $M_\odot$.

Keywords. astrometry, globular clusters: individual (Palomar 5, Pyxis), Galaxy: halo, kinematics and dynamic

1. Introduction

The properties of the dark halo of our galaxy are some of the most poorly-constrained properties of the Milky Way, see e.g., Bland-Hawthorn & Gerhard (2016) for a review. Even its mass is uncertain, as different measurements obtain inconsistent values (e.g. Gibbons *et al.* (2014) and Boylan-Kolchin *et al.* 2013). This is problematic because many key properties of galaxies at about the mass of the Milky Way (like the number of faint satellites and characterization of the stellar halo) can be best observed in the Milky Way. Additionally, there are several potential problems for ΛCDM in near field cosmology, like for example 'Too big to fail' (Zavala *et al.* (2009), Boylan-Kolchin *et al.* 2011) and the missing satellites problem (Klypin *et al.* 1999). Whether these are really a problem depends on the exact mass of the Milky Way (Wang *et al.* 2012). To avoid error by extrapolation the mass is best measured at a large distance from the center.

The shape of the halo is another property where there might be a conflict between ΛCDM and observations. Law & Majewski (2010) obtained from detailed modeling of Sagittarius stream that the halo is triaxial. That would not be so surprising on its own, but the most minor axis of this nearly oblate halo is misaligned with the minor axis of the Galactic disc by nearly 90°. This configuration is surprising because it is unstable to torques (Debattista *et al.* 2013). Confirmation of this shape is necessary, and best done with measurements from new targeted observations of Milky Way halo objects.

Here we present proper motions and interpretation for two globular clusters. Firstly, the inner halo globular cluster Palomar 5 (Pal 5) (D≈20 kpc) which is especially interesting because it has a thin tidal stream (Odenkirchen *et al.* 2001). Secondly, we concentrate on the proper motion of a more distant cluster, Pyxis (d≈ 40 kpc, Da Costa 2000).

2. Measurements

Our proper motion measurement procedures for Pal 5 (using SDSS and LBC at LBT) and Pyxis (using HST and GeMS/GSAOI at Gemini South) are explained in detail in Fritz & Kallivayalil (2015) and Fritz *et al.* (2017). Here we summarize the method. Most procedures are similar in both cases although there are differences in the details. We work on single images not coadds of images, because stacks are difficult to correct for distortion. The distortion correction relies mainly on the fact that the distortion of one of the two data sets (i.e. either SDSS or HST) has a well known distortion solution. The object positions are corrected for differential chromatic refraction when it is relevant compared to the errors. The target stars are mainly selected photometrically, and in the case of Pal 5, the distance to the cluster center is also used. For Pyxis we also used the relative proper motions of stars to identify cluster members. The proper motions are measured relative to faint background galaxies. They are chosen as references because they can be found in all images. Their low SNR is the main error source of these measurements.

For Pal 5 we measure motions of $\mu_\alpha = -2.296 \pm 0.186$ mas/yr and $\mu_\delta = -2.257 \pm 0.181$ mas/yr, and for Pyxis, motions of $\mu_\alpha = 1.09 \pm 0.31$ mas/yr, $\mu_\delta = 0.68 \pm 0.29$ mas/yr.

3. Halo shape

Since Pal 5 is at most 20 kpc from the Galactic Center, it is not useful to obtain the full mass of the Milky Way. In contrast, Pal 5's associated stream is very useful to constrain the shape of the halo at the current distance of the cluster. Pearson *et al.* (2015) used the spatial properties and radial velocities of the Pal 5 cluster and stream to predict the expected proper motion for two different halos. For a spherical halo -2.35 mas/yr in both components is expected, and for the triaxial halo of Law & Majewski (2010), μ_α/μ_δ =-5.0/-3.7 mas/yr is expected. Our proper motion measurement better supports the spherical model. Further, Pearson *et al.* (2015) find that the L&M halo model would produce a fanned out stream, different from the observed stream of Pal 5. Combined, this suggests that if the halo is non-spherical, the symmetry plane lies in the Galactic plane, at least at the radial range probed by Pal 5 (≈20 kpc). However, Pearson *et al.* (2015) only test one non-spherical model, which leaves the elongation of the third axis unconstrained with prolate, oblate, or indeed spherical shapes all possible.

We investigate this uncertainty further in Bovy *et al.* (2016). To model proper disruption of the globular cluster we use *galpy* (Bovy 2015). We also allow the other potential parameters to vary within the observational uncertainties. The fit obtains a halo axis ratio of $c/a = 0.9 \pm 0.2$. There is no relevant degeneracy with any other potential parameters. We then fit, in addition, the GD-1 stream measurements from Koposov *et al.* (2010). Our combined fit obtains $c/a = 1.05 \pm 0.14$, strictly seen prolate but consistent with spherical. A halo so close to spherical is in slight tension with the prediction of numerical cosmological simulations, where c/a is 0.7 to 0.8 (e.g., Kazantzidis *et al.* 2010), and likely 0.8 for the Milky Way as its disk is close to maximal (e.g., Bovy & Rix 2013).

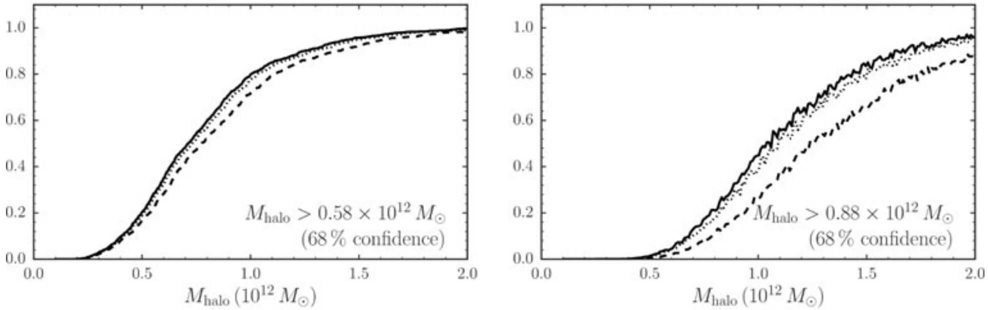

Figure 1. Lower limit constrain on the mass of the halo of the Milky Way. The left plots assumes that Pyxis is bound, the right assumes in addition also that Pyxis had a peripassage in the past. The three curves stand for different concentrations, the solid one uses $c = 15.3$, the short dashed one $c = 12$, the long one $c = 6$. The values are for the solid curves.

4. Origin of Pyxis

The proper motion of Pyxis and its radial velocity (Palma *et al.* 2000) results in a rather eccentric orbit. The pericenter is at about 30 kpc and the apocenter at more than 100 kpc. The apocenter is not well constrained because it is very sensitive to the total mass of the halo. Koposov *et al.* (2014) suggested that Pyxis could be the progenitor of the ATLAS stream. Our proper motion shows clearly that the two cannot be associated. Because Pyxis is somewhat younger (11.5±1 Gyrs) than other globular clusters of its metallicity ([Fe/H]= -1.45 ± 0.1) it is considered a young halo cluster (Irwin *et al.* 1995). These clusters (Zinn 1993) did not form in situ, and instead were once satellites of dwarf galaxies. Newer data as well as our orbit strengthen this classification. The mass of the former host dwarf galaxy can be estimated from metallicity and age. Assuming globulars are at most as metal rich as the host leads to a host of at least the mass of Leo II. Matching the age and metallicity of Pyxis with the age-metallicity relations of star clusters in different dwarf galaxies leads to an LMC like galaxy.

The Large Magellanic Cloud (LMC) was already proposed as a possible host by Irwin *et al.* (1995), also because Pyxis lies on the continuation of the Magellanic stream. We test this hypothesis using our proper motion and an LMC analog from a cosmological simulation (Sales *et al.* 2017), which is matched to the observed proper motion of the LMC (Kallivayalil *et al.* 2013). We find that while the tangential velocity of Pyxis matches, the radial velocity of formally bound particles at the position of Pyxis on the sky differ by more than 300 km/s from the measured velocity. Further, all other dwarf galaxies with known proper motions do not match the orbit of Pyxis. Since this includes all galaxies from Leo I mass upwards, the former host of Pyxis is not known. Because the host is rather massive, we assume that it would be detectable today, when it would be star forming, as usual for galaxies on first approach. Thus, we can conclude that Pyxis is not on first approach. Its former host is maybe hiding in second approach behind the Galactic Plane, or more likely was already disrupted, probably to a shell since the orbit of Pyxis is very eccentric.

5. Halo Mass

Since nearly all subhalos in simulations (Boylan-Kolchin *et al.* 2013) are bound to their halos, satellites of subhalos are bound to their subhalos. Thus, we can use the fact that Pyxis is very likely bound to the Milky Way to constrain the mass of the Galaxy.

When we require that Pyxis is 'just' bound we obtain that the halo mass of the Milky Way is to 68% probability larger than 0.58×10^{12} $M_\odot$ (Fig. 1). When we additionally require that Pyxis had a pericenter approach in the past, we obtain a halo mass which is to 68% probability larger than 0.88×10^{12} $M_\odot$. This mass depends only weakly on the concentration of the halo, in contrast to most mass estimates. Adding in the mass of disk and bulge, we get a total Milky Way mass which is with 68% probability larger than 0.95×10^{12} $M_\odot$.

6. Conclusion

As we have shown, proper motions of satellites can be great tools for constraining the properties of the halo of the Milky Way. With *Gaia* similar measurements will be easily possible for many targets with very high precision, although the precision is lower in DR2 since proper motions profit with $t^{1.5}$ from longer time baselines. However, there is a horizon of *Gaia*, beyond which its precision drops. There, measurements with other instruments are important and also require longer baselines, like with HST, see for example HST GO14734 (Kallivayalil *et al.* 2015) for an ongoing effort. At the distance of M31 old stellar populations are not detectable with *Gaia*, and thus proper motion measurements with other instruments are essential.

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