The Spur and the Gap in GD-1: Dynamical Evidence for a Dark Substructure in the Milky Way Halo

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Received 2018 November 8; revised 2019 June 1; accepted 2019 June 6; published 2019 July 23

Abstract

We present a model for the interaction of the GD-1 stellar stream with a massive perturber that naturally explains many of the observed stream features, including a gap and an off-stream spur of stars. The model involves an impulse by a fast encounter, after which the stream grows a loop of stars at different orbital energies. At specific viewing angles, this loop appears offset from the stream track. A quantitative comparison of the spur-and-gap features prefers models where the perturber is in the mass range of $10^6-10^8 M_\odot$. Orbit integrations back in time show that the stream encounter could not have been caused by any known globular cluster or dwarf galaxy with a determined orbit, and mass, size, and impact parameter arguments show that it could not have been caused by a molecular cloud in the Milky Way disk. The most plausible explanation for the gap-and-spur structure is an encounter with a dark matter substructure, like those predicted to populate galactic halos in ΛCDM cosmology. However, the expected densities of ΛCDM subhalos in this mass range and in this part of the Milky Way are $2\sigma-3\sigma$ lower than the inferred density of the GD-1 perturber. This observation opens up the possibility that detailed observations of streams could measure the mass spectrum of dark matter substructures and even identify individual substructures and their orbits in the Galactic halo.

Key words: cosmology: observations – dark matter – Galaxy: halo – Galaxy: kinematics and dynamics – gravitation – stars: kinematics and dynamics

1. Introduction

In the currently preferred ΛCDM cosmological model of cold dark matter (CDM) with dark energy ($\Lambda$), dark matter forms clumps of very low masses (e.g., Springel et al. 2008). Through mergers, these clumps grow to become massive halos that include a number of distinct lower-mass clumps, or subhalos (e.g., White & Rees 1978). Baryons can only be retained in halos more massive than $\sim 10^9-10^{10} M_\odot$ (e.g., Efstathiou 1992; Bullock et al. 2000), which agrees well with the lowest-mass galaxies discovered around the Milky Way (e.g., Simon & Geha 2007; Martin et al. 2008). A critical prediction of the CDM paradigm is the existence of dark subhalos less massive than $\lesssim 10^6 M_\odot$.

Alternative cosmological models have been proposed that behave like ΛCDM on large scales but have less structure on small scales. In the case of warm dark matter (e.g., Bode et al. 2001), this is accomplished with a dark matter particle that is less massive ($m \sim k\text{eV}$) than the CDM particle ($m \gtrsim 10 \text{GeV}$) and thus streams out of the lowest-mass clumps. The fuzzy dark matter model (e.g., Hu et al. 2000) posits an ultralight dark matter particle ($m \sim 10^{-22} \text{eV}$) that exhibits quantum behavior on macroscopic scales, which prevents the collapse of halos less massive than $\sim 10^7 M_\odot$. Therefore, a ruling on the existence of low-mass ($\lesssim 10^7 M_\odot$) dark matter subhalos would place strong constraints on the nature of dark matter (e.g., Buckley & Peter 2017; Bullock & Boylan-Kolchin 2017), which can be further refined by measuring the minimum halo mass (e.g., Schmid et al. 1999; Hofmann et al. 2001; Loeb & Zaldarriaga 2005).

Albeit dark, low-mass subhalos should still exert gravitational influence; for example, fluctuations of the gravitational tidal field are sensitive to the presence of subhalos down to $10^{-3} M_\odot$ (Peñarrubia 2018). In a cosmological volume, however, gravitational lensing is our most sensitive method of detecting gravitational perturbations. And indeed, some strongly lensed galaxies require the presence of a subhalo in the lens plane to fully explain the distribution of light in the lensed system. To date, subhalos in the mass regime $10^6-10^9 M_\odot$ have been identified in a number of lenses (e.g., Vegetti et al. 2012; Hezaveh et al. 2016). However, these objects are expected to host stars (although at luminosities below the current detection threshold), so the search for lower-mass and truly dark subhalos continues, primarily by increasing the sample size of analyzed lenses.

In the local universe, dynamically cold stellar streams are promising devices for measuring detailed properties of the matter distribution (e.g., Johnston et al. 1999; Bonaca & Hogg 2018). Formed by stars escaping a disrupting globular cluster at slightly offset orbital energies, stellar streams are approximately one-dimensional structures in the 6D phase space. An encounter between a stellar stream and a dark matter subhalo would perturb the orderly structure of the stellar stream, produce a gap in the stream density (e.g., Ibata et al. 2002; Johnston et al. 2002; Carlberg 2012), and, depending on the impact geometry, possibly also fold a part of the stream (e.g., Yoon et al. 2011). More than 40 thin stellar streams have been discovered in the Milky Way halo (Grillmair & Carlin 2016), and the most prominent ones have already been searched for evidence of density variations. The abundance

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of dark matter subhalos down to $\sim10^6 M_\odot$ inferred from the power spectrum of density variations in streams is consistent with the ΛCDM predictions (e.g., Carlb erg & Grillmair 2013). In addition to dark matter subhalos, a number of physical processes and observational effects can alter stream morphology at this level (e.g., Küpper et al. 2008; Amorisco et al. 2016; Ibata et al. 2016). As a result, no stream has definitively established the presence of dark matter substructure.

So far, studies of stream gaps have been statistical in nature (e.g., Erkal et al. 2017), mainly because the data were not good enough to identify individual gaps at high confidence. However, thanks to the recently released Gaia data (Gaia Collaboration et al. 2018a), identification of stream member stars has become extremely efficient (e.g., Malhan et al. 2018). In turn, this has enabled the discovery of a perturbation site in the GD-1 stream (Price-Whelan & Bonaca 2018)—a prime candidate for dark matter influence on a stellar stream.

In this work, we follow up this initial discovery with the first in-depth analysis of a perturbed stellar stream. We first review the observed properties of GD-1 (Section 2) and then develop a fiducial model of a perturbed stream that qualitatively matches the GD-1 observations (Section 3.1). Next, we explore the range of impact parameters allowed by the spatial distribution of GD-1 (Section 3.2) and make predictions for its kinematics (Section 3.3). Finally, we discuss the limitations of the current modeling framework (Section 4.1) and the possible origin of the perturber (Section 4.2) and suggest strategies to distinguish between different origin scenarios (Section 4.3).

2. Observed Features of the GD-1 Stellar Stream

The GD-1 stellar stream is the longest ($>100^\circ$, 10 kpc) thin ($\sigma \approx 12^\prime, 30$ pc) stellar stream discovered in the Galactic halo (Grillmair & Dionatos 2006). Based on its width and length, GD-1 is expected to be extremely informative about the global distribution of matter in the Galaxy (Lux et al. 2013; Bonaca & Hogg 2018). Indeed, dynamical modeling of GD-1 individually and in concert with the tidal tails of the Palomar 5 globular cluster has already revealed that the inner dark matter halo is spherical (Koposov et al. 2010; Bowden et al. 2015; Bovy et al. 2016). The GD-1 data from the Sloan Digital Sky Survey (York et al. 2000) has been analyzed for signatures of density variations (Carlberg & Grillmair 2013), but the contamination from the foreground Milky Way stars was too high to unambiguously attribute detected gaps to the stream itself.

Recently, Price-Whelan & Bonaca (2018) used proper motions from the Gaia mission (Gaia Collaboration et al. 2018a) and photometry from PanSTARRS (Chambers et al. 2016) to confidently separate GD-1 stars from the Milky Way field stars. This contamination-free view of GD-1 enabled the first unambiguous detection of gaps in a stellar stream, which remain evident in deeper imaging (de Boer et al. 2018). Additionally, the combined astrometric and photometric selection reveals GD-1 stars offset from the main stream track: an extended spur at $(\phi_1, \phi_2) \approx (−33^\circ, 1^\circ)$ and a diffuse blob at $(\phi_1, \phi_2) \approx (−14^\circ, −1^\circ)$ in GD-1 coordinates (Figure 1, top). Patterns imparted by the complex selection function, confusion by background galaxies, and foreground dust do not coincide with these GD-1 features; instead, they are inherent properties of the stream itself (Price-Whelan & Bonaca 2018).

To highlight the complex structure of the GD-1 stream, we present the distribution of likely stream members in the top panel of Figure 1. As a first step in finding likely members, we followed Price-Whelan & Bonaca (2018) in selecting stars consistent with an old and metal-poor population at a distance of 8 kpc and moving retrograde with respect to the Galactic disk, with proper motions in the GD-1 reference frame $(\mu_\phi, \mu_\delta) \approx (−7, 0)$ mas yr$^{-1}$. The spatial distribution of these stars in the $\phi_2$ direction (i.e., perpendicular to the stream) is modeled as a combination of a constant background, a stream component at the location of the main stream track, and one additional Gaussian component on either side of the main stream to capture stream features beyond the main track. We solved for the normalization, position, and width of every component by exploring the parameter space with an ensemble MCMC sampler (Foreman-Mackey et al. 2013). We used 256 walkers that ran for a total of 1280 steps and kept the final 256 steps to generate posterior samples in these parameters. The above procedure is a full-stream generalization of the calculation in Price-Whelan & Bonaca (2018) that quantified the fraction of stars in the additional components at the locations of the spur and blob. Finally, we define a stream membership probability, $p_{\text{mem}}$, as the joint probability of a star belonging to either the main stream or the additional feature, evaluate these probabilities using MCMC samples, and apply them to every star. The top panel of Figure 1 shows stars with $p_{\text{mem}} > 0.5$, with larger and darker points representing stars with a higher membership probability.

Most likely GD-1 members trace a thin stream, whose width varies between $\sigma \approx 10^\prime$ and $30^\prime$. As noted by Price-Whelan & Bonaca (2018), the stellar density along the stream is not uniform, and there are two significant underdensities, or gaps, located at $\phi_1 \approx −40^\circ$ and $−20^\circ$, which we refer to as G-40 and G-20, respectively. The main focus of this work is the structures related to the G-40 gap, so if not specified, the gap refers to G-40. The additional feature components are above the background density in the spur region, $\phi_1 \approx −35^\circ$, and the blob region, $\phi_1 \approx −15^\circ$, and consistent with zero along the rest of the stream. In the following section, we present a model of GD-1 that simultaneously explains the gap in the stream and the spur extending from the stream.

3. Modeling the Perturbed GD-1 Stream

3.1. Setup and the Fiducial Model

Unlike the observed GD-1, a globular cluster disrupting on the GD-1 orbit in a simple—analytic and smooth—galaxy creates a stream that is also smooth (Price-Whelan & Bonaca 2018). This model follows stars as they leave the progenitor and accounts for their epicyclic motion relative to the progenitor’s orbit (Küpper et al. 2008, 2010; Fardal et al. 2015). The resulting pattern of over- and underdensities is much more uniform than the observed stream, so the full extent of density variations in GD-1 cannot be simply explained by the process of globular cluster disruption alone. As inhomogeneities can also be introduced into a stellar stream by adding a perturbation to the gravitational potential (e.g., Siegals-Kaskins & Valluri 2008), in this section, we present a model of the GD-1 stream that had a recent close encounter with a dense, massive object.

As a first step in creating a model of the GD-1 stream, we follow Price-Whelan & Bonaca (2018) in finding the orbit of the GD-1 progenitor by fitting the six-dimensional phase-space distribution of GD-1 stars. We assume a spherical logarithmic
potential with a circular velocity of $225 \text{ km s}^{-1}$ for orbit integration. This simple gravitational potential is very close to the best-fit model of GD-1 (Koposov et al. 2010; Bowden et al. 2015), and it also allows much faster force evaluations than the standard multicomponent model of the Milky Way. The present-day location of the GD-1 progenitor is not firmly established (e.g., Price-Whelan & Bonaca 2018; Webb & Bovy 2019), so we adopt a scenario in which the progenitor is completely dissolved because it qualitatively reproduces a number of global GD-1 features (see Price-Whelan & Bonaca 2018).

We assume that the GD-1 progenitor was a globular cluster of initial mass $7 \times 10^6 M_\odot$. In our model, it started losing stars through evaporation 3 Gyr ago and completely disrupted 300 Myr before the present day. We follow the progenitor’s dissolution by releasing test particles from its Lagrange points (the mean ejection radius is $\sim 150 \text{ pc}$ initially) and produce a model of the stream following Fardal et al. (2015). In this approach, the tidal radius from which the stars are being ejected is a function of the progenitor’s mass and position in the Galaxy. Although idealized, such models capture detailed properties of the more realistic N-body simulations of disrupting globular clusters (Küpper et al. 2012). The present-day distribution of test particles is shown in GD-1 coordinates in the bottom panel of Figure 1. Had the progenitor survived to the present, it would be located at $\phi_1 = -20^\circ$. Instead, this model has a gap at that location, which coincides with the G-20 gap observed in GD-1. The progenitor’s initial mass and time of disruption were chosen to reproduce the stream width and the morphology of the more depleted observed gap.

However, the observed GD-1 stream has two prominent gaps. To produce a model stream that also has a gap coinciding with the observed G-40 gap, our model also includes a massive and dense object on an orbit that crosses GD-1. The parameters of the encounter were chosen to reproduce the observed morphology of the gap-and-spur feature in GD-1. The perturber is represented by a Hernquist (1990) sphere of mass $5 \times 10^6 M_\odot$ and scale radius 10 pc. Its closest approach to GD-1 happened 495 Myr ago with a relative distance of 15 pc, which is smaller than the stream width. The perturber came closest to GD-1 stars that are presently at $\phi_1 \approx -38^\circ$. During the encounter, nearby stars received a velocity kick from the perturber and started moving toward the location of its closest approach. In case of a weaker perturbation, e.g., one produced by a more diffuse perturber, the most significant component of the velocity kick is along the stream, which changes the orbital period of the affected stars (Erkal & Belokurov 2015a). On one side of the perturber, the affected stars have shorter orbital periods and hence speed by the unaffected stars, while on the other side, they take longer to orbit the Galaxy and lag behind the unaffected stream stars. This creates a gap at the projected location of the closest approach, with a pileup of stars on either side of the gap creating a signature double-horned profile (Carlberg 2012). However, the perturber in our model is dense, so it imparts a significant velocity kick perpendicular to the stream, as well as along the stream. This leads to a loop of stars straying beyond the unperturbed stream track. At the present, this loop is viewed nearly edge-on and looks like the observed spur (Figure 1, bottom).

The stream model in the bottom panel of Figure 1 qualitatively matches many features in the observed GD-1 stream (Figure 1, top). Not only are both of the most prominent gaps reproduced at the right location and with the right size, but their density contrast is matched as well. The G-20 gap, modeled as a disrupted progenitor, is almost completely depleted, while the G-40 gap, the location of the impact, still retains some stars. Furthermore, the model features a spur of the correct offset from the main stream and correct length. It is not a perfect model; for example, the model stream extends past the observed extent of GD-1. Still, this model is a remarkably realistic rendition of the observed GD-1, so we next quantitatively explore the range of impact parameters that produce a good match to the observed stream.

### 3.2. Constraining the GD-1 Perturber

In our fiducial model of the GD-1 stellar stream (Section 3.1), the encounter with a perturber introduced a gap in the stream and ejected a spur of GD-1 stars beyond the main stream. In this section, we constrain the range in the perturber’s...
mass and size; its impact parameter, velocity, and time of perturbation that reproduce well the location and width of the gap; and the location and extent of the spur.

To efficiently explore the allowed parameter space, in this section, we assume that GD-1 stream stars share the orbit with their progenitor. This allows for even faster generation of a stream model, at the expense of less realistic density contrasts along the stream. In the third row of Figure 2, we show our fiducial model of perturbed GD-1 under this assumption. The perturber parameters have the same normalization as the streak-line model presented in the previous section, but the encounter velocity and impact parameter angles are different. This modification was necessary because in general, stream tracks are offset from their progenitors’ orbits (Sanders & Binney 2013). Despite this difference, modeling the GD-1 stream with a single orbit results in features similar to those seen in the streak-line model. This simpler model also features a loop of stars removed from their original orbit, which projects to the GD-1 spur location at $\phi_1 \approx -40^\circ$, opens a gap at $\phi_1 \approx -40^\circ$, and reconnects to the leading tail at $\phi_1 \approx -40^\circ$.

**Figure 2.** Stream response to different encounter parameters in columns from left: the time of impact and the perturber’s mass, impact parameter, velocity, and size. The value of the varied parameter (given in the top left corner of every panel) increases from top to bottom, while all other parameters are at their fiducial values (given in the third row). Signatures of perturbation become more prominent with an increase in time after the impact and mass of the perturber and with a decrease of its impact parameter, velocity, and size. The relative sizes of the gap and the loop and the loop orientation break some of these degeneracies.
With a method at hand to quickly generate stream models that reproduce the basic features observed in GD-1, we explore how the stream morphology depends on the impactor’s properties. We consider five parameters: the time of impact, $T$, and the perturber’s mass ($M$) and its impact parameter ($b$), velocity ($V$), and size ($r_f$). Each column of Figure 2 shows models where one of the parameters is changed, while the others are kept at their fiducial values. Parameter values increase from top to bottom (as labeled at the top left of every panel), with the fiducial values shown in the third row. Most of the presented models preserve the angle between the loop and the unperturbed stream, while the main differences are in the width of the gap and the extent of the loop.

As the mass of the perturber increases, the imparted velocity kicks to the stream stars are larger, and the resulting loop and gap size increases. Indeed, the bottom right panel of Figure 2 shows a model perturbed with an object where one of the parameters is changed, while the others are kept at their fiducial values. Parameter values increase from top to bottom (as labeled at the top left of every panel), with the fiducial values shown in the third row. Most of the presented models preserve the angle between the loop and the unperturbed stream, while the main differences are in the width of the gap and the extent of the loop.

The encounter model stars to the position of observed stars in the stream. The predictions of our stream models are testable against the observed stream parameters, and we provide posterior samples, but not the true encounter parameters. This method recovers the true encounter parameters.

First, we compare $\phi_2$ positions perpendicular to the stream of perturbed model stars to the position of observed stars in the spur, defined as a spline that goes through control points of the stream between $\phi_1 = -50^\circ$ and $-39^\circ$ and control points of the spur between $\phi_1 = -39^\circ$ and $-30^\circ$. The positions of likely GD-1 members and this spline are shown in the top left panel of Figure 3 as black points and a gray line, respectively. The positions of stars in the fiducial model (A) and two other models (B and C) are shown in the bottom rows, with darker colors marking stars with a significant change in energy due to the encounter (bracketed by the third percentile on the trailing end and the 92nd percentile of the energy difference on the leading end of the stream). Quantitatively, we define the spur $\chi^2$ factor:

$$\chi^2_{\text{spur}} = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{\phi_{2,i} - \phi_{2,\text{spline}}(\phi_{1,i})}{\sigma_{\text{spur}}} \right)^2,$$

for $N$ model stars with positions ($\phi_{1,i}, \phi_{2,i}$) and the adopted width of the spur as $\sigma_{\text{spur}} = 0.2^\circ$. To ensure that the model spur is long enough, we only consider models where at least one star has $\phi_1 > -32^\circ$ and $\phi_2 > 0.8^\circ$.

Next, we compare the location and width of the observed and model gaps. The observed gap profile is shown in the top panel of the middle column of Figure 3 (black points) and is well represented by a top-hat profile centered on $\phi_{1,\text{gap}} = -40.5^\circ$ and $w_{\text{gap}} = 8.5^\circ$ wide (gray line). The gap profiles of models A–C have similar positions and widths; however, the density contrast between the gap and the spur is much larger (bottom rows). As the predictions of our stream models regarding density are simplistic, we define the gap $\chi^2$ as

$$\chi^2_{\text{gap}} = \frac{1}{N_{\text{bin}}} \sum_{i=1}^{N_{\text{bin}}} \left( \frac{N_{\text{model}}(\phi_{1,i}) - N_{\text{obs}}(\phi_{1,i})}{\sigma_{\text{gap},i}} \right)^2,$$

where $i$ denotes $N_{\text{bin}} = 29$ bins in the range $-60^\circ < \phi_1 < -20^\circ$. Here $N_{\text{model}}(\phi_{1,i})$ is the number of model stars in bin $i$, and $\sigma_{\text{gap},i}$ is the associated Poisson uncertainty. Here $N_{\text{obs}}(\phi_{1,i}) \equiv N_{\text{obs}}(n_{\text{base}}, n_{\text{hat}}, \phi_{1,\text{gap}}, w_{\text{gap}})$ is the number of stars expected in bin $i$ from a top-hat distribution with the position $\phi_{1,\text{gap}}$ and width $w_{\text{gap}}$ adopted from the observed profile but with the base level, $n_{\text{base}}$, given by the median of the model profile outside of the gap ($-55^\circ < \phi_1 < -45^\circ$ and $-35^\circ < \phi_1 < -25^\circ$), and $n_{\text{hat}}$ is the median of the model profile in the gap ($-43^\circ < \phi_1 < -37^\circ$). We further require the density contrast $n_{\text{hat}}/n_{\text{base}}$ to be at least 0.5.

We combine the spur-and-gap contributions to the surrogate log likelihood as $\ln L = -\chi^2_{\text{spur}} - \chi^2_{\text{gap}}$. Even though this likelihood is an approximation to the formal likelihood, which would compare the positions of model stream stars to the observed ones, it is expected to favor models that reproduce well the features seen in the data (spur and gap). Therefore, we use an ensemble MCMC sampler (Foreman-Mackey et al. 2013) to find the allowed range in the parameters of interest—the perturber’s mass, size, velocity, impact parameter, and impact time—while marginalizing over the orientation angles and impact location. We started 200 walkers and advanced them for 5000 steps, keeping the last 2000 steps for analysis. In principle, the resulting chain provides posterior samples, but since this is a highly idealized search of the parameter space, we only provide plausible ranges of parameters, instead of showing their two-dimensional distributions. Specifically, in each panel of the corner plot (Figure 3), we show the two-dimensional convex hull of all models with a likelihood above the fifth percentile (gray shaded regions). Therefore, Figure 3 contains likelihood, rather than posterior, information. Applied to the fiducial model of GD-1 (presented in Figure 1), this method recovers the true encounter parameters.

High likelihood models of the GD-1 stream have encounter parameters expected from the stream’s sensitivity to different parameters (explored in Figure 2). Recent encounters are favored, with most of the models having been perturbed within the last 1 Gyr and none more than 2 Gyr ago. The perturbing
The object itself is massive \((5.5 \lesssim \log M/M_\odot \lesssim 8)\) and dense \((r_s \lesssim 20 \text{ pc})\). A range of velocities are allowed, as the data dismiss only the slowest-moving perturbers \((V \gtrsim 50 \text{ km s}^{-1})\). The closest approach was extremely close to the stream, with the impact parameter smaller than \(b \lesssim 50 \text{ pc}\).

Many of the inferred encounter parameters are correlated. For example, more massive perturbers allow for larger impact parameters and scale radii and older encounters. In addition, the current data place very weak constraints on the perturber’s velocity. This is hardly surprising given the similar effect these parameters have on the appearance of the spur and gap (Figure 2). In the next section, we discuss new observables that can further constrain the GD-1 perturber.

### 3.3. Predictions for the Kinematic Signatures of the Encounter in GD-1

The perturber properties presented in the previous section were constrained by the spatial distribution of the GD-1 debris alone. We now explore the kinematic signatures of the GD-1 encounter with such a perturber and discuss how to further constrain its properties with future kinematic observations.

In Figure 3, we introduce three models whose loops reproduce the observed spur-and-gap morphologies (left); consequently, their encounter parameters are in the allowed region of the parameter space (right). These particular models were selected to display the diversity in kinematic signatures of the loop allowed by the spatial data. To account for the velocity gradients present along the stream, in Figure 4, we show differences in velocity components between the perturbed and unperturbed stream for these three models. Each column displays velocity signatures of a single model, with radial velocity differences in the top row and the two proper-motion components in GD-1 coordinates in the next two rows. In all of the models, there are kinematic offsets between the loop and the unperturbed stream.

Radial velocity signatures exhibit the largest diversity, most prominently manifested as the velocity difference between the spur and the unperturbed stream at \(\phi_1 \approx -30^\circ\). Here model A predicts that the spur moves faster than the stream, and in model B, the stream moves faster than the spur, whereas there is no difference between the two in model C. The other side of the loop has the opposite behavior, so models A and B predict...
bimodal radial velocity measurements in the GD-1 stream at 
\(-50^\circ \lesssim \phi_1 \lesssim -45^\circ\). Models A, B, and C have rather similar 
parameters overall (Figure 3, right), but the perturber’s orbital 
plane is misaligned with that of GD-1 by 170°, 15°, and 50°, respectively. Therefore, future follow-up observations will not 
only further constrain all impact parameters but also provide 
the first strong constraints on the encounter geometry.

Velocity offsets in proper motions have the same direction 
across all models (Figure 4, bottom two rows). Focusing first 
on the (1) direction, this behavior stems from the fact that there 
is a gap in the stream and the stream moves in the negative (1) 
direction (i.e., \(\mu_1 > 0\)). As Erkal & Belokurov (2015a) 
showed, a velocity kick along the stream (the (1) direction) 
makes the affected stars on the leading side of the gap speed 
past the unperturbed stream. And indeed, loop stars at 
\(\phi_1 \lesssim -45^\circ\) have proper motion \(\mu_1\) more negative than the 
unperturbed stream at the same \(\phi_1\). The opposite behavior is 
expected, and seen, on the other side of the loop (\(\phi_1 \gtrsim 35^\circ\)), 
where the affected stars lag behind the stream at less negative 
\(\mu_1\). Details of the loop proper-motion offsets still depend on 
the perturber’s parameters, but the direction of offsets along the 
stream is universal in the encounter scenario.

Because the spur is at positive (2), its proper motion 
perpendicular to the stream (the (2) direction) should be faster 
than that of the unperturbed stream stars. As expected, 
\(\Delta \mu_2 > 0\) for all of the models at \(\phi_1 \gtrsim -35^\circ\). The other side 
of the loop is at most slightly offset from the main stream track, 
so \(\Delta \mu_2\) is very small at \(\phi_1 \lesssim -45^\circ\). Finally, the magnitude of 
kinematic offsets perpendicular to the stream \((\Delta \mu_2)\) is 
universally smaller than along the stream \((\Delta \mu_1)\). This is also 
expected because the gap is much wider than the distance 
between the stream and the spur.

The encounter model makes falsifiable predictions for 
proper-motion kinematics in the affected region of the GD-1 
stream: the spur, as a trailing part of the loop, should be moving 
slower than the adjacent stream stars in the (1) direction (along 
the stream). The predicted velocity offsets are small, but the 
proper motions of diffuse, cold streams have been measured at 
this precision with the Hubble Space Telescope (Sohn et al. 
2016), so future kinematic data will rule on the perturbative 
origin of GD-1 features. Furthermore, the expected offsets in 
radial velocity are on the order of a few \(\text{km s}^{-1}\), which is easily 
within reach of current spectroscopic facilities (e.g., Simon & 
Geha 2007). The baseline radial velocity in the perturbed part 
of the stream is \(\sim 100 \text{km s}^{-1}\) (Koposov et al. 2010), allowing 
for confident selection of GD-1 members out of the field Milky 
Way population. Should the encounter scenario be confirmed, 
these new data will make strong predictions on the orbit and 
present-day position of the perturber.

4. Discussion

In the previous section, we presented a model of the GD-1 
stream that experienced a recent encounter with a massive, 
dense object. This flyby imparted significant velocity kicks to 
the closest stars both along the stream, which produced a gap 
in the stream, and perpendicular to the stream, which launched 
a spur of stars outside of the main stream. The qualitative and 
quantitative agreement between the observed and modeled gap 
and spur suggests that these GD-1 structures are the first 
dynamical evidence for a halo substructure. Below, we discuss 
improvements for future modeling of GD-1 (Section 4.1), 
review possible origin scenarios of the observed features 
(Section 4.2), and outline strategies to distinguish these 
scenarios with additional observations (Section 4.3).

4.1. Limitations of the Current Modeling Setup

A number of simplifying assumptions were made to facilitate 
the initial modeling of complex features observed in the GD-1 
stream. While we expect these assumptions to still produce 
unbiased inference, there is additional information available in 
the present data that has yet to be employed. We will need 
better models to fully explain these observations, so in this 
section, we discuss areas for improvement in the modeling of 
the GD-1 system.

Our fiducial model of GD-1 is built from test particles 
released by the disrupting progenitor directly from the 
Lagrange points, instead of particles dynamically ejected from 
the globular cluster progenitor itself. Stream models generated 
under this assumption match the distribution of tidal debris 
(including the intrinsic density variations along the tidal tails) 
from direct N-body simulations while the progenitor persists 
(e.g., Küpper et al. 2012; Fardal et al. 2015). However, the 
method is yet to be tested when the progenitor is completely 
disrupted, such as in the case of GD-1 and most of the known 
halo streams. The last stages of tidal disruption can result in 
enhanced density variations, so to fully account for all 
structures observed in GD-1, we will need a full self-gravitating 
N-body model of the stream.

Of course, the reason we decided against employing self-
gravitating models in this work is that they are computationally 
expensive, prohibitively so for any kind of parameter space 
exploration. This is why we further focused only on the 
perturbed region of GD-1 when inferring the properties of its 
perturber and assumed that all stars are on the same orbit. 
Reassuringly, fiducial encounter parameters produce qualita-
atively similar features both in an idealized stream (Figure 1) 
and in stars along a single orbit (Figure 2). As discussed in 
Section 3.2, this choice limited us to only matching positions 
of stream features and disregarding density along the stream. 
Since the density profile of the gap is also expected to contain 
information about the perturber (Erkal & Belokurov 2015b), 
going forward, we will need to have a proper generative model 
of the stream.

Furthermore, our treatment of the GD-1 perturber is also 
simplistic. Although we explored perturbers of different masses 
and sizes, they all follow the Hernquist (1990) density profile. 
This profile reduces to the point mass case in the limit of 
vanishing scale size and is similar to the profile of Navarro– 
Frenk–White (NFW; Navarro et al. 1997) dark matter halos at 
small radii, although at larger radii, it falls off more steeply as 
\(r^{-3}\), compared to \(r^{-3}\) for NFW halos. While the inference of 
the perturber’s scale radius should be robust to the details of its 
outer density profile, future work should explore whether any 
observables can be traced to the perturber’s density structure, 
as it might hold additional clues to its origin.

In the absence of a realistic stream model, our inference of 
the GD-1 perturber was based on a set of high-level criteria 
instead of directly calculating the likelihood of the observed 
spatial distribution of tidal debris for a given set of model 
parameters (e.g., likelihood developed in Bonaca et al. 2014). 
Spot-checking of the accepted models suggests that we erred 
on the conservative side and accepted a wide range of models, 
some of which would likely be ruled out with the full
likelihood. For example, model B in Figure 3 has both sides of its loop appreciably offset from the stream track, instead of just the trailing side coinciding with the spur. Because of that, with the current approach, we only bound the allowed parameter space and remain agnostic to the relative likelihood of models within the bounds. This prohibits us from measuring probabilities associated with each model parameter. For example, in the following section, we qualitatively discuss the inferred constraints on the mass and size of the GD-1 perturber in the context of objects orbiting the Milky Way but are unable to quantify their relative probabilities. To find the preferred regions of the parameter space and recover the posterior density, future inferences will need to employ a more realistic model of GD-1 and a proper likelihood.

And finally, our search of the parameter space has not been exhaustive, so different islands may still be allowed (for example, at a lower perturber mass or older encounter). This is, of course, always true when sampling a parameter space (e.g., Hogg & Foreman-Mackey 2018). However, ours is sufficiently low-dimensional that future studies employing the formal likelihood should be able to perform a brute-force sweep of the entire parameter volume and identify all classes of perturber properties that explain GD-1 features.

4.2. Origin of GD-1 Structures

Many massive objects are known or expected to orbit the Galaxy, and if any should have encountered a cold stream, the perturbation would remain recorded in the stream’s density profile. So, the presence of perturbed features in GD-1 is not surprising, but their detailed structure is. In this section, we discuss what the observed structures suggest about their origin.

4.2.1. Nonimpact Scenarios

In this work, we assumed that GD-1 was perturbed because of inhomogeneities in its density profile. However, N-body simulations of disrupting globular clusters show that a certain level of structure in the resulting stream is intrinsic to the disruption process (e.g., Küpper et al. 2008, 2010). These simulations predict that stars escape a globular cluster on orbits that epicycle around the progenitor’s orbit. Seen in projection, these epicycles produce a regular pattern of over- and underdensities along the stream. Küpper et al. (2015) showed that some of density variations detected in the tidal tails of the Palomar 5 globular cluster can be attributed to epicycles.

However, none of the present-day globular clusters would intrinsically produce density variations as prominent as those observed in GD-1 (see Price-Whelan & Bonaca 2018). If the GD-1 progenitor had a more complex internal structure than the known globular clusters, this might propagate to the morphology of its tidal tails and account for the observed features.

Nontrivial morphologies in stellar streams can also be produced by chaotic dispersal (Price-Whelan et al. 2016a). For example, unexpectedly short lengths of the Ophiuchus and Palomar 5 streams have been attributed to chaos: in a chaotic potential featuring a rotating bar, large swaths of these streams can be dispersed to surface densities below our current detection threshold (Price-Whelan et al. 2016b; Pearson et al. 2017). On a retrograde orbit and with a larger pericenter than either of these streams, GD-1 is deemed less susceptible to the chaotic influence of the rotating bar (Banik & Bovy 2019). Furthermore, the gap-and-spur features in GD-1 are much more localized than the typical signatures of chaos in complex, time-dependent gravitational potentials, but there is still a lot of parameter space left to explore.

4.2.2. Luminous Objects as the GD-1 Perturber

While these noninteraction scenarios are still possible causes of structures seen in GD-1, we find the interaction scenario more plausible. The Milky Way is surrounded by ∼50 dwarf galaxies (McConnachie 2012) and ∼150 globular clusters (Harris 2010), most of which, like GD-1, reside in the Galactic halo. Thanks to the Gaia mission, a significant fraction of these satellites are now fully located in the 6D phase space (Gaia Collaboration et al. 2018b; Simon 2018; Baumgardt et al. 2019). To test whether any of these objects could have perturbed GD-1, we integrate their orbits in a fiducial Milky Way potential (Price-Whelan 2017) and show their relative distance from the GD-1 gap at φ = −40° during the past billion yr in Figure 5. Lines are shaded according to the object’s mass, with the classical dwarfs being the darkest, ultrafaints medium, and globular clusters lighter. All of them have kept at least 1 kpc away from GD-1. The relative distances shown in Figure 5 were calculated for fiducial present-day positions and velocities of satellites. Since the associated measurement uncertainties can be substantial, we also sampled the error distribution in satellite properties and measured in how many realizations any given satellite comes closer to GD-1 than the maximum permitted impact parameter of 57 pc (see Figure 3). Upon resampling the observational uncertainties, all satellites with known orbits are excluded as GD-1 perturbers at a 3σ level or higher. Orbital parameters are known for all but two globular clusters (GLIMPSE C02 and 2MASS-GC01; Baumgardt et al. 2019), both of which are faint objects located in the Galactic bulge (Bonatto & Bica 2008; Kurtev et al. 2008) and therefore unlikely GD-1 perturbers. Out of 49 dwarf galaxies present in the up-to-date catalog of McConnachie (2012), only 24 objects have their orbits determined. In summary, present data rule out all luminous satellites with known orbits as GD-1 perturbers, but follow-up spectroscopy is required to test the remaining 25 satellites.

As it orbits the Galaxy, GD-1 crosses the disk at timescales comparable to the inferred time of perturbation (the lightest line in Figure 5 is the distance from the Galactic plane). While
strong disk shocking can facilitate disruption of a diffuse globular cluster (Dehnen et al. 2004), GD-1 disk crossings are between 13 and 23 kpc from the Galactic center, where the disk density is too low to significantly impact the stream or produce sharp features such as the gap and spur. Still, giant molecular clouds (GMCs) that are orbiting in the disk plane can perturb cold stellar streams (Amorisco et al. 2016). To test whether GMCs are viable candidates for the GD-1 perturber, in Figure 6, we compare the inferred mass and size of the GD-1 perturber (light gray shaded region) to known objects in the Milky Way, including molecular clouds. Dwarf galaxies are shown as light squares (McConnachie 2012), globular clusters as medium triangles (Baumgardt & Hilker 2018), and outer-disk molecular clouds (beyond 10 kpc) as dark circles (Miville-Deschênes et al. 2017). This comparison is rather conceptual, as different classes of objects have different density profiles: for the GD-1 perturber, we show the mass and scale radius assuming a Hernquist profile; for dwarf galaxies and globular clusters, we show the total dynamical mass and half-light radius; and we show the total (high) mass and full size for molecular clouds. Keeping these caveats in mind, the most massive globular clusters and the most compact dwarf galaxies have masses and sizes comparable to the preferred values of the GD-1 perturber, but GMCs are in general too diffuse (at a given mass, their sizes are at least an order of magnitude larger than expected of the GD-1 perturber). To additionally test for an extremely dense, yet undiscovered, class of GMCs, we also created GD-1 models perturbed by a $10^7 M_\odot$ point mass moving on a circular disk orbit for the three most recent disk crossing times. These configurations result in a spur that is below the stream at $\phi_2 < 0$, rather than above at $\phi_2 > 0$, as observed in GD-1. Based on their low central density and expected orbits, we conclude that GMCs are unlikely to have perturbed GD-1. A dense GMC orbiting outside of the Milky Way disk at large galactocentric radii is still allowed by the data, and in Section 4.3 we discuss future tests to ascertain the nature of the GD-1 perturber.

The prospect of ruling out known luminous objects as GD-1 perturbers based on their orbits strongly depends on the accurate knowledge of the underlying gravitational potential. In this work, we assumed a smooth and static model for the Milky Way (Price-Whelan 2017) because it reproduces well the global 6D phase-space distribution of GD-1 (Price-Whelan & Bonaca 2018). This implies that, to first order, the assumed gravitational potential is close to the effective Milky Way potential over the last 3 Gyr (the dynamical age of GD-1 in our fiducial model). Future studies will explore whether GD-1 can distinguish between different choices for a static potential (e.g., Bovy 2015). Furthermore, the presence of two massive satellites within the Milky Way, the Large Magellanic Cloud (LMC) and Sagittarius, means the potential is more complex in detail. Dynamical considerations imply that the LMC is very massive ($\sim 10^{11} M_\odot$; e.g., Kallivayalil et al. 2013; Gómez et al. 2015; Peñarrubia et al. 2016) and has already been invoked to explain deviations from the expected stream tracks of the Tucana III and Orphan streams (Erkal et al. 2018, 2019, respectively). Sagittarius is likely less massive ($\sim 10^9 − 10^{11} M_\odot$; Jiang & Binney 2000) but still a significant perturber in the inner Galaxy (e.g., Laporte et al. 2019a, 2019b). These massive satellites may have affected the orbit of GD-1, as well as those of luminous satellites and any dark matter subhalos. To reaffirm that the GD-1 perturber is not a luminous satellite, future work should recalculate their relative distances in a more realistic gravitational potential that includes the LMC and Sagittarius (for example, as a time-dependent expansion of basis functions; Garavito-Camargo et al. 2019).

So far, we have estimated the influence of known objects on GD-1 by directly modeling individual bodies. An alternative approach may be to consider a statistical model for the distribution function of GMCs, globular clusters, and dwarf

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**Figure 6.** Comparison of inferred mass and scale radius of the GD-1 perturber (following a Hernquist profile; light gray shaded region) to the known dwarf galaxies (squares), globular clusters (triangles), and molecular clouds in the outer disk (circles). For dwarf galaxies and globular clusters, we show the total mass and half-light radius, while for molecular clouds, we show the total mass and scale radius. Molecular clouds are too diffuse to have caused features in the GD-1 stream, while orbital properties rule out globular clusters and dwarf galaxies. The dark gray shaded region shows the masses and scale radii of dark matter subhalos (following an NFW profile) and the expected $3 \sigma$ scatter (the inner and outer dotted lines denote the $1 \sigma$ and $2 \sigma$ scatter, respectively). The GD-1 perturber is on the dense, or high-concentration, end of the dark matter subhalos.
galaxies in our Galaxy. For example, Banik & Bovy (2019) compared the power spectra of gaps in the Palomar 5 stream expected from whole populations of GMCs and dark matter subhalos. A similar analysis of GD-1 could, in principle, estimate the likelihood of the GD-1 perturber being a member of these groups. However, unlike the gaps in Palomar 5, the gap detected in GD-1 is associated with an off-stream spur. A statistical treatment of both features is beyond the scope of this work, but the framework for simultaneous modeling of a gap-and-spur feature that we developed here should provide a good starting point for such population studies in the future.

4.2.3. Dark Perturbers

Having ruled out luminous objects with known orbits, we find that the most probable GD-1 perturber is a dark object in the Milky Way halo. As luminous satellites can have approximately the required masses and sizes, a low-luminosity unknown satellite might be the culprit. To avoid detection, it would have to be fortuitously hiding in the disk plane or moving very fast, as our best estimate is that the encounter was recent. Near-future and upcoming surveys of the plane (Schlafly et al. 2018) and halo (LSST Science Collaboration et al. 2009) should provide a complete census of objects in the Milky Way and find a perturber of low luminosity.

Alternatively, the GD-1 perturber could be completely dark. A dense perturber in the mass range $10^5-10^7 M_\odot$ is required, so we next discuss black holes—the densest dark objects in the universe. Baryonic black holes of similar masses typically reside in centers of galaxies (the mass of the Milky Way’s supermassive black hole, Sgr A*, is $\simeq 4 \times 10^6 M_\odot$; Boehte et al. 2016). A population of nonbaryonic primordial black holes is hypothesized to have formed in the early universe (Carr & Hawking 1974) and has sparked renewed interest as a dark matter candidate following the LIGO detections (Bird et al. 2016). Several lines of inquiry have limited the contribution of massive ($\gtrsim 10^5 M_\odot$) primordial black holes to the dark matter budget to less than $\lesssim 0.1\%$ (Carr et al. 2016, and references therein). So if GD-1 had encountered a primordial black hole, this would have been an extremely rare event, and we would not expect to see similar features in other streams upon a comparable amount of scrutiny.

On the other hand, $\Lambda$CDM cosmological simulations predict scores of dark matter subhalos orbiting Milky Way–like galaxies. Even after accounting for the destruction of subhalos due to the stellar disk (D’Onghia et al. 2010; Errani et al. 2017; Garrison-Kimmel et al. 2017), their density in the inner 20 kpc is high enough that a stream on a GD-1–like orbit is expected to have encountered at least one $10^9-10^9 M_\odot$ subhalo within the last $\sim 8$ Gyr (Erkal et al. 2016). Of the two prominent gaps in GD-1, our fiducial model ascribes one to the site of the progenitor’s disruption (G-20) and one to the encounter with a perturber (G-40). Thus, a dark matter subhalo is a plausible GD-1 perturber in terms of encounter rates expected in the $\Lambda$CDM universe.

The high inferred density of the GD-1 perturber makes it more resilient to disruption in the tidal field of the inner galaxy, but the preferred values are on the high end of the dark matter halo concentrations. For example, the $\Lambda$CDM concentration–mass relation for isolated dark matter halos predicts that a $10^8 M_\odot$ halo should have a scale radius of $\sim 50$ pc (Diemer & Joyce 2019), while the most diffuse GD-1 perturber of similar mass has a scale radius of $\sim 20$ pc. The scatter in the mass–concentration relation is small at high masses ($\sim 0.15$ dex), although it has not been quantified below $\lesssim 10^{10} M_\odot$, and there are some indications that the fraction of high-concentration halos increases at low masses (Diemer & Kravtsov 2015). On the other hand, subhalos surviving in dense environments are more concentrated than field halos of the same mass (e.g., Avila-Reese et al. 2005). The dark gray shaded band in Figure 6 shows the masses ($M_{\text{500}}$) and sizes (NFW scale radii, $r_s$) expected for dark matter subhalos orbiting in the GD-1 radial range (Molînè et al. 2017). The whole band encompasses the $3\sigma$ scatter in the concentration–mass relation, while the inner and outer dotted lines correspond to the $1\sigma$ and $2\sigma$ scatter, respectively. The properties of the $\Lambda$CDM subhalos are consistent with the inferred mass and size of the GD-1 perturber only at a $2\sigma$–$3\sigma$ level, and the current GD-1 analysis allows the perturber to be orders of magnitude denser than expected of $\Lambda$CDM dark matter subhalos.

Among the objects expected to orbit the Milky Way, globular clusters have the largest overlap with the inferred mass and size of the GD-1 perturber (Figure 6). Current dynamical data rule out all of the known globular clusters, but this overlap motivates a search for new globular clusters, which we discuss in the next section. Should future searches for luminous objects yield no plausible candidate for the GD-1 perturber, and a dark matter subhalo remains a viable option, the high inferred density might point to dark matter physics beyond CDM (e.g., Kahlhoefer et al. 2019).

4.3. Future Prospects

Constraining the number and properties of low-mass dark matter halos is essential for understanding the nature of dark matter (Bullock & Boylan-Kolchin 2017). Interpreting the gap-and-spur feature in the GD-1 stream as a signature of a perturbation provides us a really promising candidate for a dark halo substructure. With the follow-up work outlined below, we now have a great opportunity to detect and characterize a dark matter subhalo.

The best way to test whether GD-1 features are an outcome of an encounter with a massive perturber is to obtain detailed kinematics in the perturbed region of the stream. The encounter scenario predicts velocity offsets between the spur and the stream, and they can be used to falsify this model. The expected offsets are small but measurable with a modest investment of spectroscopic time to get the radial component of the velocity (the required precision is $\sim 1$ km s$^{-1}$) and a somewhat more significant astrometric commitment to measure the transverse motion precisely enough ($\sim 0.1$ mas yr$^{-1}$). The magnitude of these velocity offsets could already falsify other origin scenarios. For example, a velocity offset between the spur and the stream that is much larger than the velocity dispersion in a globular cluster would imply an input of energy to the system and thus rule out scenarios in which the spur is a consequence of substructure in the GD-1 progenitor. However, the ultimate test of the encounter scenario is a measurement of velocity offsets on both sides of the GD-1 gap. The offsets are predicted to monotonically increase along the loop, with the spur always lagging behind the stream in the component of the velocity along the stream (for details, see Section 3.3).

Should the encounter scenario be confirmed, details of the kinematic structure in the perturbed part of GD-1 will put very strong constraints on the orbit of the perturber (see Figure 4 for different possibilities). This would, in turn, allow the search for additional signatures of the perturber along its inferred orbit.
Recently, Van Tilburg et al. (2018) showed how a massive and dense object can be detected in the halo via time-dependent weak lensing of background stars. As the magnitude of the effect depends on the object’s density profile, we might directly measure the structural properties of the GD-1 perturber. Combined with a better theoretical understanding of dark matter subhalos and their density profiles, this measurement could also provide information about the particle nature of dark matter.

Ultimately, locating the perturber gravitationally would open up possibilities for electromagnetic follow-up. If the source is bright in X-rays, this might be a signature of an accreting black hole (e.g., Bailyn et al. 1995). Alternatively, a spatially coincident excess of gamma-rays might signal the annihilation of dark matter particles (similar to the results of searches at the locations of dwarf galaxies; e.g., Hooper & Linden 2015). Either way, an electromagnetic detection would better characterize the nature of the GD-1 perturber.

As discussed above, further study of the GD-1 gap-and-spur feature may provide the first opportunity to follow up an individual halo substructure. But most excitingly, these features demonstrate that cold stellar streams are extremely fine-tuned detectors, sensitive at a level that was only hoped for beforehand. In GD-1 alone, there are additional gaps that may be further evidence of gravitational perturbations (specifically, the G-20 gap is associated with a diffuse blob of GD-1 stars beyond the main stream). In addition to GD-1, there are over 40 known streams in the Milky Way halo (e.g., Grillmair & Carlin 2016; Shipp et al. 2018). In the era of Gaia, we now have both the incentive and the resources to study them all in detail. With the full network of streams, we could learn not only about individual halo substructures, but about the population as a whole.

We thank the referee for thorough comments that improved the manuscript. It is also a pleasure to thank Vasily Belokurov, Warren Brown, Will Dawson, Benedikt Diemer, Elena D’Onghia, Adrienne Erickcek, Douglas Finkbeiner, Lars Hernquist, Kathryn Johnston, Manoj Kaplinghat, Sergey Koposov, Doug Lin, Barry McKerman, Erica Nelson, Sarah Pearson, Hans-Walter Rix, Josh Speagle, and Tomer Yavetz for valuable discussions and input.

This project was developed in part at the 2018 NYC Gaia DR2 Workshop at the Center for Computational Astrophysics of the Flatiron Institute in New York City in 2018 April. This work was performed in part at the Aspen Center for Physics, which is supported by National Science Foundation grant PHY-1607611.

This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC; https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

Software: Astropy (Robitaille et al. 2013; Astropy Collaboration et al. 2018), colossus (Diemer & Joyce 2019), gala (Price-Whelan 2017), emcee (Foreman-Mackey et al. 2013), IPython (Pérez & Granger 2007), matplotlib (Hunter 2007), numpy (Van der Walt et al. 2011), scipy (Jones et al. 2001).

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