A Ghost in Boötes: The Least-Luminous Disrupted Dwarf Galaxy

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Abstract

We report the discovery of Specter, a disrupted ultrafaint dwarf galaxy revealed by the H3 Spectroscopic Survey. We detected this structure via a pair of comoving metal-poor stars at a distance of 12.5 kpc, and further characterized it with Gaia astrometry and follow-up spectroscopy. Specter is a $25\times1$ stream of stars that is entirely invisible until strict kinematic cuts are applied to remove the Galactic foreground. The spectroscopic members suggest a stellar age $\tau \gtrsim 12$ Gyr and a mean metallicity $\langle\text{Fe/H}\rangle = -1.84 \pm 0.16$, with a significant intrinsic metallicity dispersion $\sigma_{\text{Fe/H}} = 0.37 \pm 0.13$. We therefore argue that Specter is the disrupted remnant of an ancient dwarf galaxy. With an integrated luminosity $M_V \approx -2.6$, Specter is by far the least-luminous dwarf galaxy stream known. We estimate that dozens of similar streams are lurking below the detection threshold of current search techniques, and conclude that spectroscopic surveys offer a novel means to identify extremely low surface brightness structures.

Unified Astronomy Thesaurus concepts: Dwarf galaxies (416); Low surface brightness galaxies (940); Stellar streams (2166)

1. Introduction

In the modern cosmological paradigm, galaxies form “bottom-up,” with smaller galaxies coalescing and merging over cosmic time to assemble larger galaxies (e.g., Press & Schechter 1974; White & Rees 1978; Bullock & Johnston 2005). Our own Milky Way continues growing to this day, as evidenced by its rich system of dwarf galaxy satellites (e.g., Mateo 1998; Simon 2019), and recent discoveries of phase-mixed accreted debris throughout the Galaxy (e.g., Belokurov et al. 2018; Helmi et al. 2018; Naidu et al. 2020; Malhan et al. 2022). Over the past several decades, deep photometric surveys have revealed a plethora of ultrafaint dwarf galaxies ($M_V \gtrsim -7.7$, hereafter “dwarfs”) surrounding the Milky Way (e.g., Willman et al. 2005a, 2005b; Belokurov et al. 2007b; Koposov et al. 2015; Simon 2019; Drlica-Wagner et al. 2020). These surveys have likewise unearthed a patchwork of ex situ stellar streams encircling the Galaxy, tidally stretched remnants of past satellites and their globular clusters (e.g., Majewski et al. 2003; Belokurov et al. 2007a; Grillmair 2009; Shipp et al. 2018; Bonaca et al. 2021). Although these emissaries are fascinating in their own right due to their extragalactic formation, they also teach us about the distribution of our own Galaxy’s stellar and dark matter (e.g., Murali & Dubinski 1999; Eyre & Binney 2011; Bonaca et al. 2014; Bovy et al. 2016; Bonaca & Hogg 2018; Malhan et al. 2021; Nibauer et al. 2022).

The key limitation of photometrically detecting nearby dwarfs and streams is the projected stellar surface density, since this sets the contrast between a given structure and the Milky Way foreground. While these systems are all resolved into individual stars, this is usually expressed in terms of the effective surface brightness (SB) of a given density of stars; there exists a well-known SB frontier of $\mu \sim 31$ mag arcsec$^{-2}$ for intact dwarfs found with deep surveys like the Sloan Digital Sky Survey and the Dark Energy Survey (Koposov et al. 2008; Walsh et al. 2009; Drlica-Wagner et al. 2020). It remains an open question whether the current SB frontier is purely an observational artifact, and if there exists a hidden population of “stealth” galaxies invisible to photometric star-counting searches (Tollerud et al. 2008; Bullock et al. 2010; Muñoz et al. 2018). These systems probe the lowest mass scales of galaxy formation, and are vital to our understanding of dark matter subhalos, structure formation, and even reionization (e.g., Klypin et al. 1999; Moore et al. 2006; Jethwa et al. 2018; Hayashi et al. 2022).

Recent works, armed with proper motions from Gaia (Brown et al. 2021; Lindegren et al. 2021), have pushed the SB frontier by employing kinematic filtering to peer through the Galactic foreground and detect more diffuse intact dwarfs (Torrealba et al. 2019). Incorporating kinematic information has likewise pushed the frontier to detect fainter and more diffuse stellar streams (e.g., Malhan & Ibata 2018; Ibata et al. 2019; Yuan et al. 2020; Oria et al. 2022; Tenachi et al. 2022). The best-characterized streams with dwarf progenitors have typical luminosities $M_V \sim -5.5$, whereas those with globular cluster (GC) progenitors tend to be narrower and have $M_V \sim -3.5$ (Shipp et al. 2018; Ji et al. 2020). Although width can roughly...
indicate whether a stream had a dwarf or GC progenitor, a more conclusive test is the detection of an intrinsic metallicity dispersion, indicative of multiple generations of star formation (Gilmore & Wyse 1991; Willman & Strader 2012).

Here we present the discovery of Specter, a diffuse stellar stream revealed by the H3 Survey (Conroy et al. 2019). We measure Specter’s structural and chemical properties, and argue that it is the faintest disrupted dwarf galaxy known to date. We suggest that Specter is representative of a large population of diffuse dwarf streams that are invisible to traditional search techniques. We describe our search for structures in the H3 Survey in Section 2, and characterize the morphology and stellar population of Specter in Section 3. Finally, we discuss the implications of our findings in Section 4.

2. Data and Discovery

2.1. Search for Structures in H3

The H3 Survey (Conroy et al. 2019) has been collecting high-resolution $R \approx 32,000$ spectra for parallax-selected halo stars since 2017, using the Hectochelle instrument on the MMT (Szentgyorgyi et al. 2011). To date, H3 has observed 240,000 stars with $r < 0.4$ mas and $15 < r < 18.5$, employing a sparse tiling strategy across the entire $|b| > 30^\circ$ (off-plane) and $\delta > -20^\circ$ (visible from the MMT) sky. H3 spectra cover the Mg $b$ triplet from 5150 to 5300 Å, and are analyzed with the full-spectrum MINESweeper pipeline to deliver radial velocities, spectrophotometric distances, metallicities, and $\alpha$-abundances (Cargile et al. 2020).

For the present study, our initial goal was to detect low-luminosity intact dwarfs, whose masses might be so low that only a few stars would be bright enough to appear in the combined Gaia and H3 catalogs. Such sparse populations would not normally pass a photometric detection threshold, but we expect the addition of chemistry and 3D kinematics to significantly enhance the likelihood of physical association. We emphasize the importance of H3’s $\approx 1$ km s$^{-1}$ radial velocity precision, which helps us isolate truly cold structures without being dominated by measurement noise. We thus performed a search for cospatial and comoving pairs of stars in the H3 data collected as of 2022 April, leveraging the power of Gaia DR3 (Gaia Collaboration 2018). For each pairwise combination of stars in this sample, we followed up for this work, and the red points are our final Specter members. We show the $\Omega_B = 0$ line that defines our great circle coordinate frame. In the top right CMD, we overlay an [Fe/H] = −1.8, 13 Gyr MIST isochrone, as well as the BHB ridgeline from Deason et al. (2011). Our members lie on the same isochrone, have near-identical proper motions and radial velocities, and are systematically metal-poor with spectroscopic [Fe/H] $< -1.5$. We also show the tentative LAMOST member described in Section 2.3.

![Figure 1](https://example.com/figure1.png)

Figure 1. Identification of spectroscopic members from H3 Survey data. The black points denote all H3 objects in the $10^\circ \times 10^\circ$ field of view shown in the top left panel, orange crosses denote PM-selected stars that were specifically followed up for this work, and the red points are our final Specter members. We retained dyads that significantly enhance the likelihood of physical association. We regard their status as uncertain. Group #1 and #2 could securely be associated with the Cetus stream based on their sky position and kinematics (Newberg et al. 2009; Yuan et al. 2022). Group #3 was likewise strongly associated with the Orphan stream (Belokurov et al. 2007a; Koposov et al. 2019). Groups #4 and #5 could not be immediately associated with known structures, but did not stand out as significant new structures either. Specifically, there was no strong spatial overdensity around these structures after kinematic and color–magnitude filtering was applied. Groups #4 and #5 may be associated with the Sagittarius stream since they are only $\approx 10^\circ$ off the Sagittarius orbital plane, and were perhaps missed by our angular momentum cuts to mask out Sagittarius. We regard their status as uncertain. Group #6 could not be associated with any known structures, and is the subject of this paper.

2.2. A Ghost in Boötes

Our search identified a pair of low-metallicity red giant branch (RGB) stars (Group #6 above) at $d \approx 12.5$ kpc that did not appear to be associated with any known structures, with near-identical proper motions and radial velocities. Motivated by this, we observed an additional 11 H3 fields around this pair, specifically targeting stars with similar proper motions that plausibly lie on the same isochrone. This yielded seven “member” stars within $2^\circ$ of each other that lie on the same isochrone and have exceptionally similar proper motions and radial velocities (Figure 1 and Table 1). As Figure 1 illustrates, several of the follow-up members would not have fallen in the standard H3 selection because they are outside the sparse on-sky footprint of the regular survey. We elaborate on the
Table 1
Spectra Members with Spectroscopy

| Gaia Source ID | R.A. (deg) | Decl. (deg) | PS g (mag) | S/N | \( v_\perp \) (km s\(^{-1}\)) | \( T_{\text{eff}} \) (K) | \( \log g \) | [Fe/H] | \([\alpha/Fe]\) |
|---------------|-----------|-------------|------------|-----|-----------------|-----------------|----------|--------|----------|
| 1492503132521811712 | 216.527 | 43.155 | 16.0 | 14.6 | -150.5 ± 1.1 | 8270 ± 70 | ... | ... | ... |
| 149167629977912064 | 217.162 | 42.568 | 16.8 | 13.8 | -139.4 ± 0.2 | 5150 ± 20 | 2.6 ± 0.1 | -1.51 ± 0.05 | 0.0 ± 0.1 |
| 149410587687711104 | 217.099 | 43.907 | 17.7 | 6.8 | -153.6 ± 0.3 | 5200 ± 30 | 2.8 ± 0.1 | -1.74 ± 0.08 | 0.3 ± 0.1 |
| 1491186908274561088 | 216.383 | 40.817 | 18.1 | 4.4 | -137.4 ± 0.5 | 5350 ± 30 | 3.2 ± 0.1 | -1.66 ± 0.12 | 0.3 ± 0.1 |
| 149173752831174912 | 217.978 | 42.729 | 18.7 | 2.4 | -147.5 ± 1.8 | 5520 ± 40 | 3.2 ± 0.1 | -2.11 ± 0.16 | 0.3 ± 0.2 |
| 1493316732469979136 | 218.035 | 43.452 | 18.6 | 3.7 | -147.2 ± 1.1 | 5670 ± 40 | 3.6 ± 0.1 | -1.72 ± 0.18 | 0.3 ± 0.2 |
| 14930776575413916 | 218.634 | 42.686 | 18.8 | 2.8 | -147.2 ± 1.1 | 5670 ± 40 | 3.6 ± 0.1 | -1.72 ± 0.18 | 0.3 ± 0.2 |

Notes. The first seven stars are from the H3 Survey, with stellar parameters estimated by MINESweeper. The last star is the tentative LAMOST member, with stellar parameters from Xiang et al. (2019). Listed uncertainties are statistical only. Since there are \( \approx 2 \) pixels per resolution element, the signal-to-noise ratio (S/N) per resolution element is \( \approx \sqrt{2} \) times larger than the values listed here.

The BHB is too hot to derive reliable parameters beyond temperature and radial velocity with the H3 spectrum, so we omit listing those parameters here.

Table 2
Measured Properties of Specter

| Parameter | Value | Unit |
|-----------|-------|------|
| Overview | | |
| \( d_\odot \) | 12.5 ± 0.5 | kpc |
| \( M_V \) | -2.6 ± 0.5 | mag |
| \( M_\odot \) | \( \approx 2000 \pm 500 \) | \( M_\odot \) |
| Length | \( \approx 5.5 \) | kpc |
| Width | \( \approx 200 \) | pc |
| H3 Members | | |
| \( \langle \mu_\alpha \rangle \) | -5.75 ± 0.02 | mas yr\(^{-1}\) |
| \( \langle \mu_\delta \rangle \) | -5.00 ± 0.13 | mas yr\(^{-1}\) |
| \( \langle v_{\text{LSR}} \rangle \) | -35.11 ± 0.13 | km s\(^{-1}\) |
| \( \sigma_{\text{LSR}} \) | 3.7 ± 0.9 | km s\(^{-1}\) |
| \( \langle [\text{Fe/H]} \rangle \) | -1.84 ± 0.16 | dex |
| \( \langle [\alpha/Fe] \rangle \) | 0.37 ± 0.21 | dex |
| \( r_\odot \) | 12 | Gyr |
| Orbit | | |
| \( r_{\text{Gal}} \) | 14.2 ± 0.4 | kpc |
| \( r_{\text{peri}} \) | 13.8 ± 0.5 | kpc |
| \( r_{\text{apo}} \) | 18.4 ± 0.9 | kpc |
| \( e \) | 0.14 ± 0.04 | |
| \( E_u \) | -0.98 ± 0.06 | 10\(^{-3}\) km\(^2\) s\(^{-2}\) |
| \( L_2 \) | 1.57 ± 0.11 | 10\(^3\) kpc km s\(^{-1}\) |

We use the member blue horizontal branch (BHB) star and the empirical ridgeline from Deason et al. (2011) to derive a distance \( d = 12.5 ± 0.5 \) kpc, adopting a 0.1 mag uncertainty in the BHB ridgeline. The other member stars have spectro-photometric distances from MINESweeper that are consistent with this value at the 1\( \sigma \) level, with an error-weighted mean distance \( \approx 13.3 ± 0.5 \) kpc, albeit with a larger systematic uncertainty. The parallax distribution of these stars is likewise consistent with this distance, with an error-weighted mean parallax corresponding to a distance \( \approx 15.5 ± 0.5 \) kpc after applying the zero-point correction (Lindegren et al. 2018).

To investigate if these stars are part of a larger structure like a dwarf galaxy or stellar stream, we queried Gaia DR3 for all stars in this region of the sky. We removed foreground contaminants with a stringent parallax selection of \( \pi < 0.2 \) mas and crossmatched our sample with photometry from Pan-STARRS (Chambers et al. 2016). We use Pan-STARRS optical photometry because it is deeper than Gaia, and Gaia \( G_{\text{BP}} \) colors are known to suffer from systematic issues for faint sources (Arenou et al. 2018). Our results are qualitatively unchanged if we instead use the Gaia \( G \), \( G_{\text{BP}} \), and \( G_{\text{RP}} \) photometric system, albeit the color–magnitude diagram (CMD) colors are noisier at the faint end. We dereddened the Pan-STARRS photometry using dust maps from Schlegel et al. (1998), renormalized by Schlafly & Finkbeiner (2011). Since we only desire stars with reliable proper motion measurements, we adopt a limiting magnitude of \( G = 20.5 \).

We compute the mean orbit of our H3 members with \texttt{galax} (Price-Whelan 2017; Price-Whelan et al. 2020), assuming the default MilkyWayPotential (Bovy 2015). We use this orbit to define a great circle coordinate system \((\phi_1, \phi_2)\) with a pole at \((\alpha, \delta) = (269.7^\circ, 33.5^\circ)\), and set the zero-point \((\phi_1, \phi_2) = (0, 0)\) at \((\alpha, \delta) = (217.5^\circ, 42.7^\circ)\). For each star in our Gaia sample, we assign a distance based on the nearest on-sky point on the orbit (e.g., Price-Whelan & Bonaca 2018; Bonaca et al. 2019). We transform the DR3 proper motions to the great circle frame and correct them for the solar reflex motion (Schönrich et al. 2010).

Figure 2 illustrates the transformed proper motion and color–magnitude spaces for a region close to our H3 members, and an equal-area background region. There is a clear overdensity of stars with proper motions similar to our spectroscopic members (top panel). Upon filtering for stars with these proper motions—shown by the \( \approx 1\) mas yr\(^{-1}\) red ellipse centered at \((\mu_\alpha^*, \mu_\delta^*) \approx (3.8, 0)\) mas yr\(^{-1}\)—a coherent stellar population reveals itself on the CMD (middle panel). Although the number of stars is small, the CMD overdensity is significant at the \( \approx 7\sigma \) level compared to the equal-area background region based on Poisson statistics. After further selecting stars that lie within 0.1 mag (in color) of a fiducial \([\text{Fe/H}] = -1.8, [\alpha/Fe] = 0.3\), 13 Gyr MIST isochrone (Choi et al. 2016; Dotter 2016), we illustrate their spatial density in the bottom panel of Figure 2. An elongated overdensity spanning \( \approx 25^\circ \) appears into view, surrounding our spectroscopic members and tracing their predicted orbit. This extended stellar system is clearly a disrupted stream, not a gravitationally bound dwarf galaxy. We name this...
information, the stellar population of Specter is drowned out by the Galactic foreground.

2.3. Search for Members in SEGUE and LAMOST

To investigate whether Specter has additional plausible members in existing spectroscopic data sets, we performed a search in the Sloan Extension for Galactic Understanding and Exploration (SEGUE; Yanny et al. 2009; Eisenstein et al. 2011; Alam et al. 2015) and Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST; Cui et al. 2012; Zhao et al. 2012) catalogs. After performing basic cleanliness cuts to remove bad fits and stars with [Fe/H] < -1, we crossmatched these catalogs to Gaia DR3 astrometry around Specter. We performed a coordinate transformation and reflex correction as described in Section 2.2, and applied the proper motion selection shown in Figure 2. As a function of the \( \phi_1 \) coordinate, we then selected stars that lie within \( \phi_2 \pm 3^\circ \) and \( \nu_r, h \pm 15 \) km s\(^{-1}\) of our predicted orbit for Specter. This search yielded zero stars in SEGUE and one star in LAMOST, which we display in Figure 1. Relaxing the kinematic selections by a factor of 2 does not produce more members that plausibly lie on the same isochrone as our H3 members.

Gaia DR3 1483861280364752512 lies at \((\phi_1, \phi_2) \approx (6.5, 0.1)\), and has a reported metallicity [Fe/H] = -1.83 ± 0.15 in the LAMOST catalog of Xiang et al. (2019). This star matches our mean metallicity for Specter and lies within the \( \phi_1 = \pm 10^\circ \) region in which we detect a significant overdensity of Specter stars in Gaia. We therefore tentatively assign it as a spectroscopic member of the stream and display it in Figure 1. We conservatively do not include this star in our detailed analysis of the stream (e.g., to derive the velocity and metallicity dispersion) and instead use the homogeneous set of seven H3 members.

Our search did not reveal more promising spectroscopic members out to \( \phi_1 \pm 50^\circ \) around Specter in either SEGUE or LAMOST. Beyond this, uncertainties in the orbit (due to measurement errors and systematic uncertainties in the Milky Way potential) likely make it challenging to confidently associate stars with Specter.

3. Specter

3.1. Structural Parameters

We estimate the spatial structure of Specter by fitting the \( \phi_2 \) distribution of stars in bins of \( \phi_1 \). We use the sample of stars shown in Figure 2 that pass our proper motion and isochrone selection. In each of 15 overlapping \( \phi_1 \) bins (8° wide and spaced 4° apart), we model the \( \phi_2 \) distribution as a mixture of a linear background and a Gaussian component for the stream (e.g., Bonaca et al. 2019). The free parameters are the mean and (log) width of the Gaussian component, the slope of the linear background, and the fraction of stars in the Gaussian component. There are 98–186 stars in each bin. We construct a likelihood and sample the parameter posterior distributions with emcee (Foreman-Mackey et al. 2013, 2019), assuming uniform priors on all parameters. Thirty-two walkers are used to sample each bin’s posterior for 1024 steps, discarding the first half as burn-in and taking the median estimate for each parameter.

Figure 3 summarizes our model fit across the stream. Specter is well constrained between \(-10^\circ \lesssim \phi_1 \lesssim 15^\circ\), beyond which the stellar density rapidly falls below our detection limits. The

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9 We follow the tradition of naming stellar streams after bodies of water, namely the Specter Rapids in Arizona, the state where the MMT is located.
width and median proper motion measurements are shown in the bottom panels of Figure 3 for the well-constrained stream region. In this range, the width (Gaussian $\sigma$) is $\approx 1^\circ$, or $\approx 200$ pc using the adopted distance. Both the predicted and observed proper motion gradients are quite shallow in this region of the stream.

3.2. Stellar Population

Our spatial model produces membership probabilities $P_{\text{mem}} = P_G/(P_{G} + P_{\text{bg}})$ where $P_G$ and $P_{\text{bg}}$ denote a star’s likelihood of being in the Gaussian or background components, respectively. Again, we only utilize stars that pass the CMD and proper motion (PM) cuts shown in Figure 2. The total number of stars above our limiting magnitude of $G = 20.5$ is approximately $\sum P_{\text{mem}} \approx 100$ in the inner $-10^\circ \lesssim \phi_1 \lesssim 15^\circ$ region. Using the formalism of Martin et al. (2008), adopting an [Fe/H] = −1.8, 13 Gyr MIST isochrone and a Kroupa (2001) IMF, this implies an integrated luminosity $M_V \approx -2.6 \pm 0.5$. If we simply add the fluxes of stars with $P_{\text{mem}} > 0.8$ and only use the Martin et al. (2008) formalism to integrate the unseen stellar flux, we derive a similar value $M_V \approx -2.6$. Summing the IMF-weighted MIST isochrone, the total stellar mass is consequently $M_* \approx 2000 \pm 500 M_\odot$ (log $M_*/M_\odot \sim 3.3$). Assuming that 68% of the luminosity is contained within the derived Gaussian width of the stream, the implied surface brightness of Specter is $\mu \sim 34$ mag arcsec$^{-2}$.

Figure 4 illustrates our H3 spectroscopic members in chemical space. Although the sample is small, metal-poor members are systematically $\alpha$-enhanced with an anticorrelation between [$\alpha$/Fe] and [Fe/H], suggesting an extended star formation history in Specter’s progenitor wherein the gas was gradually enriched by Type Ia supernovae (Gilmore 1989; Kirby et al. 2011). To further investigate the intrinsic metallicity distribution of Specter, we fit a Gaussian distribution to the metallicities using a maximum-likelihood approach (e.g., Walker et al. 2006). We sample the posterior distribution of the Gaussian parameters with emcee and assume a uniform prior for the log dispersion. Specter has a mean metallicity $\langle [\text{Fe/H}] \rangle = -1.84^{+0.16}_{-0.18}$ and an intrinsic metallicity dispersion $\sigma_{\text{fe/H}} = 0.37^{+0.21}_{-0.13}$ dex. By performing a similar fit to the [$\alpha$/Fe] measurements, we derive $\langle [\alpha$/Fe] $\rangle = +0.22_{-0.07}^{+0.07}$, with an unresolved intrinsic dispersion. The metallicity dispersion becomes unresolved if we exclude the most metal-poor star, but we have no reason to doubt its membership or metallicity. This star’s spectrum is discussed in more detail in Appendix B, and detailed validation of H3’s metallicity scale is presented in Cargile et al. (2020).

We perform a similar Gaussian fit to the radial velocities to resolve the line-of-sight velocity dispersion. Galactocentric radial velocities are used for this purpose, to remove any projection effects caused by the large spatial extent of the members. We add 0.5 km s$^{-1}$ in quadrature to the individual radial velocity errors to account for systematic uncertainties in the wavelength calibration. Specter has a velocity dispersion of $3.7^{+1.5}_{-0.9}$ km s$^{-1}$ in its central region. This is similar to the dispersion measured in other dwarf streams like Orphan, Indus, and Chenab (Li et al. 2022). Specter has $f = (r_{\text{Gal}} - r_{\text{peri}})/(r_{\text{apo}} - r_{\text{peri}}) \approx 0.1$, matching the observed trend from Li et al. (2022) that streams close to pericenter tend to have colder velocity dispersions, in contrast with theoretical predictions (Helmi & White 1999; Panithanpaisal et al. 2021). This discrepancy could be a selection effect, particularly in the case of
bias our result. We since models of BHB temperatures are quite uncertain, and will with a grid of MIST isochrones. The BHB member is excluded to compute the total prior. To further characterize the stellar population in Specter, although these ages are affected by a Galactic model-dependent photometric age of $\sim 12$ Gyr as reported by MINESweeper et al. 2008; Walsh et al. 2009; Drlica-Wagner et al. 2021. Specter has likely escaped detection thus far due to a combination of its low surface brightness (reducing its significance in photometric searches) and low star count (reducing its significance in 5D kinematic searches). Its detection required serendipitous H3 spectroscopy to identify the original comoving pair. The left panel of Figure 6 shows that Specter is almost an order of magnitude wider than known intact dwarfs at similar total luminosity. One interpretation is that Specter’s progenitor was structurally similar to Segue 1 or Willman 1, and the stream width has substantially broadened over time in the aspherical potential of the Milky Way. Specter is on a relatively polar orbit, a configuration that should promote rapid broadening of the stream (Erkal et al. 2016). However, past searches for intact dwarfs have been limited by a well-known surface brightness threshold of $\mu \sim 31$ mag arcsec$^{-2}$ (Koposov et al. 2008; Tollerud et al. 2008; Walsh et al. 2009; Drlica-Wagner et al. 2021), and the known population of intact dwarfs may not encompass all possible progenitors for Specter. For example, “stealth” galaxies inhabiting lower-mass dark matter halos could have escaped detection thus far, but could be plausible progenitors for Specter-like streams (Bullock et al. 2010).

The middle panel of Figure 6 shows that Specter lies above the luminosity–metallicity relation for intact dwarfs, joining Grus 1, Segue 2, and Willman 1 in this region of parameter space (Willman et al. 2011; Kirby et al. 2013; Walker et al. 2016). This could imply a higher progenitor mass for Specter than is presently observed, perhaps due to tidal stripping or additional stream components hiding behind the Galactic disk. Alternatively, these discrepant dwarfs could reflect a metallicity floor for galaxy formation, at least in some special formation environments (Simon & Geha 2007; Rafelski et al. 2012; Kirby et al. 2013).

3.3. Orbital Kinematics and Associations

Figure 7 compares several observed properties of Specter to a subset of known streams compiled by Mateu (2022). In these panels, there is an apparent association between Specter and Gaia-6 (Ibata et al. 2021). Gaia-6 is $\approx 7^\circ$ offset from Specter with a similar size and orientation, and comparable proper motions. However, the proper motion gradient in Gaia-6 is quite different than Specter, particularly in the stream-parallel component. Malhan et al. (2022) report a median metallicity for Gaia-6 of $[\text{Fe/H}] = -1.16$, which is more metal-rich than Specter, although the distribution of 10 member metallicities has a long tail toward the metal-poor end (K. Malhan 2022, private communication). Additionally, Martin et al. (2022) report a metallicity of $[\text{Fe/H}] = -1.50$ using narrowband photometry of 12 members from the Pristine survey.

Figure 6 places Specter in the broader context of stellar streams and intact stellar populations around the Milky Way, and Table 2 summarizes our measurements. Specter’s large metallicity spread is typical of dwarf galaxies around the Milky Way—as shown in the right panel of Figure 6—and argues against a globular cluster origin (Kirby et al. 2011; Willman & Strader 2012). The most striking feature of Specter is its low luminosity, even lower than the globular cluster streams presented in Shipp et al. (2018). Both the stream width and intrinsic metallicity spread of Specter suggest a dwarf galaxy origin for the stream. Our observations therefore indicate that Specter is a disrupted ultrafaint dwarf galaxy, comparable in stellar mass to Boötes 2, Carina 3, or Willman 1 (Willman et al. 2005a, 2011; Walsh et al. 2007; Martin et al. 2008). Specter has likely escaped detection thus far due to a combination of its low surface brightness (reducing its significance in photometric searches) and low star count (reducing its significance in 5D kinematic searches). Its detection required serendipitous H3 spectroscopy to identify the original comoving pair. The left panel of Figure 6 shows that Specter is almost an order of magnitude wider than known intact dwarfs at similar total luminosity. One interpretation is that Specter’s progenitor was structurally similar to Segue 1 or Willman 1, and the stream width has substantially broadened over time in the aspherical potential of the Milky Way. Specter is on a relatively polar orbit, a configuration that should promote rapid broadening of the stream (Erkal et al. 2016). However, past searches for intact dwarfs have been limited by a well-known surface brightness threshold of $\mu \sim 31$ mag arcsec$^{-2}$ (Koposov et al. 2008; Tollerud et al. 2008; Walsh et al. 2009; Drlica-Wagner et al. 2021), and the known population of intact dwarfs may not encompass all possible progenitors for Specter. For example, “stealth” galaxies inhabiting lower-mass dark matter halos could have escaped detection thus far, but could be plausible progenitors for Specter-like streams (Bullock et al. 2010).
in energy and angular momentum space. However, Specter is more metal-poor than the bulk of Sequoia stars, more metal-rich than I’itoi, and generally more circular than the bulk of retrograde debris in H3 (Naidu et al. 2020, 2022). We therefore note these associations, but do not find strong evidence that Specter is associated with any of these more massive disrupted dwarfs. We also verify that no globular clusters lie along Specter’s integrated orbit in 3D space, although this test is naturally sensitive to the assumed Galactic potential.

3.4. Detection Probability and Population

Given our detection of Specter in the H3 Survey, we can roughly estimate how many low-luminosity streams like Specter might exist at similar distances. In this case the “detection” signifies observing the original pair of comoving stars in the primary H3 sample. For a ~20000 $M_\odot$ stellar population at 12.5 kpc, a Kroupa (2001) IMF and our fiducial MIST isochrone predicts $\approx 13$ stars to fall within the H3 magnitude limits $15 < r < 18.5$. We perform a simple Monte Carlo test to estimate the probability of detecting a pair of stars from a theoretical Specter-like stellar population. We generate mock streams by randomly sampling pole coordinates uniformly on the sky, and create corresponding great circle coordinate frames. For each mock stream, we sample a Poisson distribution centered at $\langle N_{true} \rangle = 13$ and randomly place that number of stars on a $25^\circ \times 1^\circ$ region similar to Specter (distributed uniformly in $\phi_1$ and normally in $\phi_2$). Each mock stream is then “observed” by checking if any stars fall within the H3 tiles observed to date. If so, the stars are subjected to the sampling fraction (proportion of targets that get assigned fibers) for that tile. We repeat this mock stream generation and observation for 1000 trials, and use the fraction of trials in which at least two stars are “observed” as the probability of detecting a population with $N_{true}$ stars. By further repeating these trials for 1000 Poisson realizations of $N_{true}$, we get a distribution of representative detection probabilities. The median detection probability is $\approx 3\%$, which matches our naive expectation that the dominant contribution will be the $\approx 2.5\%$ survey footprint fraction of the sky. Put differently, since there are $\approx 13$ Specter stars within the H3 magnitude limit, there is a

Figure 4. Comparing the observed orbital track, distance, and proper motions of Specter to some nearby known streams in the galstreams library.

Figure 5. Comparing the observed orbital track, distance, and proper motions of Specter to some nearby known streams in the galstreams library.

Figure 6. Comparing the luminosity, size, and metallicity of Specter to known streams and intact structures. Left: stream widths (Gaussian $\sigma$) and luminosities for several dwarf and GC streams from Shipp et al. (2018). We overlay intact (gravitationally bound) dwarfs and GCs, using the half-light radius as a proxy for characteristic size (McConnachie 2012; Baumgardt et al. 2020; Vasiliev & Baumgardt 2021). Middle: luminosity–metallicity relation for Specter, alongside an updated sample of intact dwarfs from McConnachie (2012) and dwarf streams from Shipp et al. (2018). Right: mean metallicity and intrinsic metallicity spreads for streams from Ji et al. (2020). We overlay intact dwarfs and GCs compiled by Willman & Strader (2012), omitting error bars for clarity.
very high probability that a member pair will be observed if a field lands on the stream. Our Monte Carlo trial folds in the inherent stochasticity of the stellar population, as well as a more accurate model of the interaction between stream geometry, projected density, and the sparse survey footprint.

Based on these trials, and the fact that we detected one such stream in H3, the expected number of true streams (at similar distance) can be estimated as the inverse of the detection probability. Taking the 16th and 84th quantiles of our Monte Carlo trials as a 1σ interval, we estimate 20–50 undetected Specter-like streams lying between 10 and 20 kpc of the Sun. If we use this number to normalize a Navarro et al. (1997) number density profile and extrapolate to larger Galactocentric radii, we expect that hundreds of streams like Specter might be revealed by radial velocity measurements themselves, as well as additional discoveries of such galaxies depends on the efficiency of galaxy formation at the lowest mass scales, and future deep surveys and kinematic searches may reveal intact analogs of a “stealth” progenitor for Specter. If instead Specter’s progenitor was an ultrafaint dwarf like Segue 1 or Willman 1, then the stream’s large ≈200 pc width requires a dynamical explanation. Numerical simulations of the tidal disruption of various progenitor types may shed light on this problem—probing whether such a short and wide stream (with no discernible progenitor today) can be produced by a Segue I–like galaxy, or whether it suggests the gradual elongation of a more diffuse and stealthy progenitor.

A tantalizing possibility is that an intact dwarf analog to Specter’s progenitor has not yet been observed due to the current search techniques (e.g., Tollerud et al. 2008). In particular, Specter’s progenitor may have an extended “stealth” dwarf galaxy that inhabited a low-mass dark matter halo (Bullock et al. 2010). The existence of such galaxies depends on the efficiency of galaxy formation at the lowest mass scales, and future deep surveys and kinematic searches may reveal intact analogs of a “stealth” progenitor for Specter. If instead Specter’s progenitor was an ultrafaint dwarf like Segue I or Willman I, then the stream’s large ≈200 pc width requires a dynamical explanation. Numerical simulations of the tidal disruption of various progenitor types may shed light on this problem—probing whether such a short and wide stream (with no discernible progenitor today) can be produced by a Segue I–like galaxy, or whether it suggests the gradual elongation of a more diffuse and stealthy progenitor.

It is quite likely that Specter is the first known representative of a large class of disrupted dwarfs lurking below the detection threshold of current search techniques. Our simple Monte Carlo trial of the H3 selection function implies that dozens more Specter-like streams await detection in future spectroscopic surveys like SDSS-V (Kollmeier et al. 2017), DESI (DESI Collaboration et al. 2016; Allende Prieto et al. 2020), 4MOST (de Jong et al. 2019), and WEAVE (Dalton et al. 2020).

4. Discussion

We have presented the discovery and structural analysis of Specter, the least-luminous disrupted dwarf galaxy stream yet known in the Milky Way. It is remarkable that Specter was discovered using a single pair of metal-poor giants based on their proper motions and radial velocities, an otherwise blind spectroscopic survey. Specter joins a handful of objects that were detected as cold structures in spectroscopic surveys, a class originated by the Sagittarius dSph (Ibata et al. 1994). In fact, it is perhaps the first structure since Sagittarius to be revealed by radial velocity measurements themselves, as opposed to integrals of motion (e.g., Tenachi et al. 2022).

Naturally, the distinction of Specter being the least-luminous dwarf galaxy stream assumes that we have detected the majority of its spatial extent. As shown in Figure 2, below φ ≈ −25° our kinematic selection increasingly fails to filter out the rising density of disk contaminants at lower Galactic latitudes. This leaves open the possibility that Specter has hidden components behind the disk, which could help to reconcile Specter’s low luminosity for its metallicity (Figure 6, middle). However, the stellar density fits shown in Figure 3 exhibit a characteristic decrease in density on both sides of the stream, and our maps rule out a continued extent of the stream beyond φ ≈ 15°. Furthermore, Specter would be less luminous than the dwarf galaxy streams in Shipp et al. (2018) even if its star count was inflated by a factor of 5. For these reasons, we classify Specter as the least-luminous dwarf galaxy stream known and emphasize that the luminosity of its progenitor galaxy is relatively more uncertain.

A tantalizing possibility is that an intact dwarf analog to Specter’s progenitor has not yet been observed due to the current brightness limitations of current search techniques (e.g., Tollerud et al. 2008). In particular, Specter’s progenitor may have an extended “stealth” dwarf galaxy that inhabited a low-mass dark matter halo (Bullock et al. 2010). The existence of such galaxies depends on the efficiency of galaxy formation at the lowest mass scales, and future deep surveys and kinematic searches may reveal intact analogs of a “stealth” progenitor for Specter. If instead Specter’s progenitor was an ultrafaint dwarf like Segue I or Willman I, then the stream’s large ≈200 pc width requires a dynamical explanation. Numerical simulations of the tidal disruption of various progenitor types may shed light on this problem—probing whether such a short and wide stream (with no discernible progenitor today) can be produced by a Segue I–like galaxy, or whether it suggests the gradual elongation of a more diffuse and stealthy progenitor.

It is quite likely that Specter is the first known representative of a large class of disrupted dwarfs lurking below the detection threshold of current search techniques. Our simple Monte Carlo trial of the H3 selection function implies that dozens more diffuse systems like Specter could reside at similar distances, and hundreds more might lie undiscovered throughout the Galaxy. This is further supported by recent discoveries of extremely diffuse debris using 6D kinematics (Oria et al. 2022; Tenachi et al. 2022). Although most streams discovered by kinematic techniques do not have formal luminosity estimates, several are likely as ephemeral as Specter (e.g., Ibata et al. 2019; Ji et al. 2022; Malhan et al. 2022). Our work motivates follow-up spectroscopy of these streams to ascertain if they might have dwarf galaxy progenitors.

This work has demonstrated the power of spectroscopic surveys to detect extremely diffuse structures that would not form strong overdensities on the CMD or in 5D kinematics, but are revealed by their line-of-sight velocities. The detection of comoving pairs informs us about “where to look” in kinematic and chemical spaces, increasing the detection significance of otherwise subthreshold structures. Future searches similar to those presented here, performed with upcoming large-scale surveys like SDSS-V (Kollmeier et al. 2017), DESI (DESI Collaboration et al. 2016; Allende Prieto et al. 2020), 4MOST (de Jong et al. 2019), and WEAVE (Dalton et al. 2020).
spectroscopic surveys, are sure to unveil more hidden ghosts in the Galactic halo.

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Facilities: MMT, Gaia, PS1.
Software: numpy (Harris et al. 2020), scipy (Virtanen et al. 2020), astropy (Robitaille et al. 2013; Price-Whelan & Bonaca 2018), matplotlib (Hunter 2007), emcee (Foreman-Mackey et al. 2013, 2019), gala (Price-Whelan 2017; Price-Whelan et al. 2020).

Appendix A
Significance of Detection in H3

Our final sample of seven spectroscopic members from H3 has a nontrivial selection function, because two stars were observed in the regular survey, and five were subsequently followed up with PM-selected targeting. It is therefore prudent to ascertain whether targeting stars with a tight selection in PMs could spuriously produce a clustering in radial velocities. We perform a simple empirical test using H3 data for PMs could spuriously produce a clustering in radial velocities. to ascertain whether targeting stars with a tight selection in followed up with PM-selected targeting. It is therefore prudent observed in the regular survey, and

Figure 9. Demonstrating Specter’s significant RV signal in the H3 data set. Top: equatorial PMs of CMD-selected giants in H3 within 25° of Specter, with nine selection regions overlaid near Specter. Bottom: galactocentric RV distributions in each PM selection region. Specter stands out as a sharp spike in the RV distribution, and there are no similar spurious spikes in other PM-selected regions.

Gaia data set (Figure 2) confirm that we have identified a bona fide coherent stellar population, rather than a chance projection of field stars.

Appendix B
Spectra of H3 Members

We illustrate the $R \approx 32,000$ H3 spectra for our seven spectroscopic members in Figure 10, arranged in the same brightness ordering as Table 1. We display the best-fitting MINESweeper models and stellar parameters. The most metal-poor star in our sample, Gaia DR3 1493316732469979136 deserves further comment since its
metallicity is a key part of our argument for Specter’s dwarf galaxy origin (Section 3.2). This star has a relatively low signal-to-noise ratio (S/N) in our sample. However, by comparing it to the next faintest star in Specter (at similar S/N and stellar parameters; bottom panel of Figure 10), the lack of strong iron lines already suggests $[\text{Fe/Hi}] \lesssim -2$ for this star. We have verified that MINESweeper derives the correct RV for this star by rerunning the fit with a broader RV prior. The RV is well measured, with a sharp Gaussian posterior distribution. We also ran a MINESweeper fit excluding the H3 spectrum, utilizing only the parallax and broadband optical–IR photometry. This photometry-only fit returns $[\text{Fe/Hi}] = -3.0 \pm 0.5$, excluding the mean metallicity of Specter at $\sim 2.5\sigma$. Based on these lines of evidence, we argue that Gaia DR3 1493316732469979136 is indeed metal-poor.

Figure 10. Top: H3 spectra for seven members in Specter, with the best-fitting MINESweeper model overlaid in red. The topmost star is the BHB, for which a reliable metallicity cannot be estimated. A masked telluric region is shown in gray, and we indicate strong Fe I lines in blue. Bottom: comparison between H3 spectra for the most metal-poor member in Specter, and a reference star at higher metallicity selected from the H3 catalog to have similar temperature, surface gravity, and spectral signal-to-noise ratio. Both spectra are smoothed with a 5 pixel boxcar. Note in particular the Fe line at $\approx 5170$ Å that is much weaker in the Specter member than the reference star. We emphasize that the full-spectrum-fitting MINESweeper routine picks up on aggregate spectral details that are difficult to discern by eye. Regardless, this comparison reassures us about this member’s metallicity.

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