EVIDENCE THAT HYDRA I IS A TIDALLY DISRUPTING MILKY WAY DWARF GALAXY


1 Haverford College, Department of Astronomy, 370 Lancaster Avenue, Haverford, PA 19041, USA
2 LSST and Steward Observatory, 933 North Cherry Avenue, Tucson, AZ 85721, USA
3 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
4 McWilliams Center for Cosmology, Department of Physics, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA
5 Michigan State University, Department of Physics and Astronomy, East Lansing, MI 48824, USA
6 Texas Tech University, Physics Department, Box 41051, Lubbock, TX 79409-1051, USA
7 Spitzer Science Center, 1200 E. California Blvd., Pasadena, CA 91125, USA
8 University of California Santa Barbara, Department of Physics, Santa Barbara, CA, 93106, USA

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ABSTRACT

The Eastern Banded Structure (EBS) and Hydra I halo overdensities are very nearby (d ~ 10 kpc) objects discovered in Sloan Digital Sky Survey (SDSS) data. Previous studies of the region have shown that EBS and Hydra I are spatially coincident, cold structures at the same distance, suggesting that Hydra I may be the EBS’s progenitor. We combine new wide-field Dark Energy Camera (DECam) imaging and MMT/Hectochelle spectroscopic observations of Hydra I with SDSS archival spectroscopic observations to quantify Hydra I’s present-day chemodynamical properties, and to infer whether it originated as a star cluster or dwarf galaxy. While previous work using shallow SDSS imaging assumed a standard old, metal-poor stellar population, our deeper DECam imaging reveals that Hydra I has a thin, well-defined main sequence turnoff of intermediate age (~5–6 Gyr) and metallicity ([Fe/H] = −0.9 dex). We measure statistically significant spreads in both the iron and alpha-element abundances of σ_{Fe/H} = 0.13 ± 0.02 dex and σ_{[α/Fe]} = 0.09 ± 0.03 dex, respectively, and place upper limits on both the rotation and its proper motion. Hydra I’s intermediate age and [Fe/H]—as well as its low [α/Fe], apparent [Fe/H] spread, and present-day low luminosity—suggest that its progenitor was a dwarf galaxy, which has subsequently lost more than 99.99% of its stellar mass.

Key words: galaxies: dwarf – Galaxy: halo – Galaxy: structure

Supporting material: machine-readable tables

1. INTRODUCTION

The stellar tidal streams and substructure of the Milky Way (MW) provides an important observational window into the assembly of the Galaxy in a universe dominated by dark energy and dark matter. In the standard ΛCDM model, numerical simulations show that massive galaxies like the MW grow hierarchically, that is, from the continuous accretion and tidal destruction of smaller systems such as dwarf galaxies and globular clusters (e.g., Bullock & Johnston 2005; Johnston et al. 2008; Cooper et al. 2010). Observations of the Galaxy’s halo support this picture; in addition to the ~40 known dwarf galaxy satellites of the MW (McConnachie 2012; Bechtol et al. 2015; Drlica-Wagner et al. 2015; Koposov et al. 2015), a total of 21 stellar streams have been discovered to-date in wide-field optical imaging surveys such as the Sloan Digital Sky Survey (SDSS; e.g., Belokurov et al. 2006), PAndAS (Martin et al. 2014), Pan-STARRS (Bernard et al. 2014), ATLAS (Koposov et al. 2014), and DES (Balbinot et al. 2015).

Despite the growing number of stream discoveries, only four stellar streams have known progenitors: the globular clusters Pal 5, NGC 5466, NGC 288, and the Sagittarius dwarf spheroidal. Developing a detailed picture of the origin of the Galaxy’s halo requires understanding the relative contribution of tidally destroyed globular clusters and dwarf galaxies. Searching for and quantifying the ages, metallicities, and kinematics of likely stream progenitors is therefore an important step toward a more complete picture of the hierarchical assembly of the MW’s halo in a cosmological context.

The Eastern Banded Structure (EBS) stream (Figure 1) is an ideal target for such a study, as it is relatively nearby (d ~ 10 kpc; Grillmair 2011) and therefore may be close enough for proper motion measurements. Grillmair (2006) discovered the EBS in SDSS imaging data as a relatively broad stellar stream near the Monoceros Ring stellar overdensity. Grillmair (2011) identified an extended double-lobed, ~2 sq. degree feature along the stream—called Hydra I—which has a surface density larger than any other overdensity along the stream (white boxed region in Figure 1). Based on its morphology and prominence, Grillmair (2011) suggested that Hydra I may be the progenitor of the EBS stream. Using SDSS/SEGUE spectroscopic observations that are spatially coincident with Hydra I, Schlaufman et al. (2009) demonstrated the presence of a kinematically cold population of stars, with V_{helio} ~ 85 km s^{-1} and the colors and magnitudes expected for an old, metal-poor population at the distance of the EBS.

The origin and nature of the EBS/Hydra I features are complicated by their proximity to (and possible association with) a number of Galactic anti-center structures, including the Monoceros Ring (Li et al. 2012; Slater et al. 2014; Xu et al. 2015), the Anti-Center Stream (Grillmair et al. 2008; Carlin et al. 2010), and the Triangulum Andromeda substructures (Sheffield et al. 2014 and references therein). The origin and relationship between these features remains intensely debated (see Xu et al. 2015 for a recent review).
For example, it is currently unclear whether the Monoceros Ring is tidal debris from an accreted dwarf galaxy (Peñarrubia et al. 2005) or has its origin in the Galactic disk—as either a normal warp/flare (Momany et al. 2006) or as the result of kicked-up stars from disk oscillations occurring from an encounter with a massive satellite (Kazantzidis et al. 2008; Price-Whelan et al. 2015; Xu et al. 2015). We consider our results in the context of these Galactic anti-center structures in our discussion (Section 5.3).

Hydra I presents a unique opportunity to study an MW satellite undergoing active disruption. In this work we determine Hydra I’s stellar population, chemical, and kinematic properties with the aim of exploring whether the object is a disrupting dwarf galaxy or star cluster. Previous studies of Hydra I region were limited by a small number candidate member stars (with large velocity uncertainties), prohibiting detailed tests of Hydra I’s nature. In this work, we combine higher precision photometric and spectroscopic data of Hydra I—from the Dark Energy Camera (DECam; Flaugher et al. 2015) and MMT/Hectochelle spectrograph (Szentgyorgyi et al. 2011)—with archival SDSS data to study Hydra I using a large sample of candidate stars.

This paper is organized as follows. In Section 2 we describe our observational data sets. In Section 3 we discuss the selection of candidate member stars, and in Section 4 we present the results of our analysis and the derived properties of Hydra I. We discuss possible scenarios concerning the nature of Hydra I in Section 5, and present our conclusions in Section 6.

2. PHOTOMETRIC AND SPECTROSCOPIC DATA

2.1. DECam Photometry

Observations of Hydra I were obtained on 2014 March 20–23 using the DECam imager installed on the CTIO Blanco 4 m telescope. The DECam imager consists of sixty-two 2048 × 4096 imaging CCDs (chip gaps of ∼50″) arranged in a circular layout in the focal plane. On the Blanco telescope, this layout provides imaging over a 2.1 diameter, resulting in a 3 square degree imaging area with 0″26 pixels.

We imaged Hydra I using the ugr filters, but to facilitate comparisons with other studies of Hydra I/EBs and the Galactic anti-center region, we only present the gr imaging in this work. We used a series of 6 × 180 s exposures in each of the g and r filters and dithered between exposures to fill in the chip gaps. Figure 1 shows the resulting footprint of the DECam imaging (∼9 deg$^2$) on the Hydra I field. All imaging was obtained under photometric or near-photometric conditions. The mean FWHM of the image point-spread functions for the exposures ranged from 0″9 to 1″2.

The data were reduced using the NOAO Community Pipeline (CP; Valdes et al. 2014) and downloaded from the NOAO Science Archive. The CP performs both a standard instrumental calibration of the raw images (bias, overscan, cross-talk corrections; fringing corrections; dome flat and sky flat field corrections) and corrects for geometric distortions by reprojecting the images onto a common spatial scale.

We performed photometry on each DECam exposure by separately analyzing each of the 62 reduced, reprojected chips using the DAOPHOTII/ALLSTAR software suite (Stetson 1987, 1994). We derive a catalog of point sources using cuts on the DAOPHOT CHI and SHARP parameters which vary as a function of magnitude depth. To ensure a robust characterization of sources, we require that object must be point-like in each of the gri images.

The Hydra I/EBs region is located in the SDSS footprint, and so we derive calibrated magnitudes by matching directly to SDSS Data Release 8 (SDSS DR8; Aihara et al. 2011). We derived a photometric solution for each individual DECam exposure separately, after correcting the instrumental magnitudes for atmospheric extinction. We derived zero points and linear color terms using the maximum likelihood approach.
Table 1
DECam Photometry

<table>
<thead>
<tr>
<th>R.A. (degree)</th>
<th>Decl. (degree)</th>
<th>g0 (mag)</th>
<th>(\sigma_{g0}) (mag)</th>
<th>r0 (mag)</th>
<th>(\sigma_{r0}) (mag)</th>
<th>(E(B-V)) (mag)</th>
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</thead>
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<td>18.187</td>
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<td>3.340060</td>
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<td>0.0339</td>
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<td>3.363441</td>
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<td>0.033</td>
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<td>132.351990</td>
<td>3.397592</td>
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<td>0.038</td>
<td>0.0340</td>
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<td>132.352598</td>
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<td>0.012</td>
<td>18.727</td>
<td>0.009</td>
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<tr>
<td>132.352717</td>
<td>3.150096</td>
<td>22.082</td>
<td>0.037</td>
<td>22.058</td>
<td>0.050</td>
<td>0.0319</td>
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<td>132.354884</td>
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<td>132.355516</td>
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<td>132.358492</td>
<td>3.395449</td>
<td>23.487</td>
<td>0.106</td>
<td>22.591</td>
<td>0.070</td>
<td>0.0341</td>
</tr>
</tbody>
</table>

Note. DECam photometric point-source catalog of the EBS/Hydra I region (see footprint in Figure 1). The photometric data have been corrected for Galactic extinction (see Section 2.1) using the listed values of \(E(B-V)\). We provide photometry only for stars with \(g - r < 1\) due to the photometric calibration method employed in this study. Point-source selection was performed using the DAOPHOT CHI and SHARP parameters. (This table is available in its entirety in machine-readable form.)

We model the Hectochelle spectra using the procedure introduced by Walker et al. (2015, hereafter W15) to model sky-subtracted Hectochelle spectra. The spectral model is given.
Table 2
Hectochelle/MMT Spectroscopy

<table>
<thead>
<tr>
<th>R.A. (degree)</th>
<th>Decl. (degree)</th>
<th>V_r (km s(^{-1}))</th>
<th>(\sigma_{V_r}) (km s(^{-1}))</th>
<th>(g_0) (mag)</th>
<th>(\sigma_{g_0}) (mag)</th>
<th>(r_0) (mag)</th>
<th>(\sigma_{r_0}) (mag)</th>
<th>(E(B-V)) (mag)</th>
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<td>16.744</td>
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<td>18.182</td>
<td>0.002</td>
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<td>134.257034</td>
<td>4.086879</td>
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<td>1.10</td>
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<td>0.004</td>
<td>19.146</td>
<td>0.004</td>
<td>0.0512</td>
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<td>134.276366</td>
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<td>0.44</td>
<td>17.330</td>
<td>0.004</td>
<td>16.867</td>
<td>0.003</td>
<td>0.0510</td>
</tr>
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<td>97.81</td>
<td>0.44</td>
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<td>0.005</td>
<td>15.140</td>
<td>0.003</td>
<td>0.0505</td>
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<td>3.871296</td>
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<td>18.335</td>
<td>0.004</td>
<td>17.905</td>
<td>0.003</td>
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<td>134.117737</td>
<td>3.833826</td>
<td>31.85</td>
<td>1.47</td>
<td>20.291</td>
<td>0.006</td>
<td>19.858</td>
<td>0.004</td>
<td>0.0501</td>
</tr>
<tr>
<td>134.071915</td>
<td>3.766812</td>
<td>85.44</td>
<td>0.97</td>
<td>19.602</td>
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<td>19.375</td>
<td>0.003</td>
<td>0.0486</td>
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<td>134.084824</td>
<td>3.745721</td>
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<td>17.330</td>
<td>0.003</td>
<td>0.0475</td>
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<td>134.113266</td>
<td>3.739799</td>
<td>20.37</td>
<td>0.46</td>
<td>17.905</td>
<td>0.004</td>
<td>17.449</td>
<td>0.003</td>
<td>0.0464</td>
</tr>
</tbody>
</table>

Note. Hectochelle/MMT catalog of all 411 stars passing the spectroscopic quality control cuts and located within the SDSS CMD filter shown in Figure 2(a). Only a subset of these spectra were used in our analysis of Hydra I (see Section 3.1). Heliocentric radial velocities \(V_r\) and 1σ uncertainties were derived using the method described in Section 2.2. The DECam photometry has been corrected for Galactic extinction (see Section 2.1) using the listed values of \(E(B-V)\).

(This table is available in its entirety in machine-readable form.)

Figure 2. SDSS (left) and DECam (right) color–magnitude-number density (Hess) diagrams for stars within a 9 sq. deg region centered on Hydra I. The diagrams have been slightly smoothed with a Gaussian filter to enhance low density features. The dashed white lines denote the CMD filter used to select candidates for spectroscopic follow-up with MMT/Hectochelle. The isochrone (solid white line, Dotter et al. 2008) has an [Fe/H] = −1.8, age = 13 Gyr and shifted to a distance of 9.7 kpc (Grillmair 2011). The median color and magnitude uncertainties are shown as white points. The higher precision DECam photometry clearly shows the detection of a blue MSTO at \(g - r \sim 0.18\) not apparent in the SDSS data.

as

\[
M(\lambda) = P_1(\lambda) T\left[1 + \frac{Q_m(\lambda) + v_{los}}{c}\right].
\]

(1)

where \(c\) is the speed of light and \(P_1(\lambda)\) specifies the stellar continuum using an order-1 polynomial of the form

\[
P_1(\lambda) \equiv p_0 + p_1 \left[\frac{\lambda - \lambda_0}{\lambda_x}\right] + p_2 \left[\frac{(\lambda - \lambda_0)^2}{\lambda_x}\right] + \ldots + p_l \left[\frac{(\lambda - \lambda_0)^l}{\lambda_x}\right].
\]

(2)

The factor of \(T\left(1 + (Q_m(\lambda) + v_{los})/c\right)\) is a continuum-normalized template spectrum that is redshifted according to the line of sight velocity \(v_{los}\) and an order-\(m\) polynomial of the form

\[
Q_m(\lambda) \equiv q_0 + q_1 \left[\frac{\lambda - \lambda_0}{\lambda_x}\right] + q_2 \left[\frac{(\lambda - \lambda_0)^2}{\lambda_x}\right] + \ldots + q_m \left[\frac{(\lambda - \lambda_0)^m}{\lambda_x}\right].
\]

(3)

that compensates for systematic differences between wavelength functions of target and template spectra (see W15 for details). Following W15, we choose \(m = 2\), providing sufficient flexibility to fit the observed continuum shape and to apply low-order corrections to the wavelength solution. We adopt scale parameters \(\lambda_0 = 5220\) Å and \(\lambda_x = 60\) Å, such that \(-1 \leq (\lambda - \lambda_0)/\lambda_x \leq +1\) over the entire range (5160–5280 Å) considered in the fits.

Again following W15, we generate template spectra \(T\) using the synthetic library that was used for SEGUE Stellar
### Table 3
SDSS/SEGUE Spectroscopy

<table>
<thead>
<tr>
<th>R.A. (degree)</th>
<th>Decl. (degree)</th>
<th>( V_\text{rot} ) (km s(^{-1}))</th>
<th>( \sigma_{V_\text{rot}} ) (km s(^{-1}))</th>
<th>([\text{Fe}/\text{H}]) (dex)</th>
<th>( \sigma_{\text{[Fe/H]}} ) (dex)</th>
<th>( [\alpha/\text{Fe}] ) (dex)</th>
<th>( \sigma_{\alpha/\text{Fe}} ) (dex)</th>
<th>( R_0 ) (mag)</th>
<th>( \sigma_{R_0} ) (mag)</th>
<th>( \ell_0 ) (mag)</th>
<th>( \sigma_{\ell_0} ) (mag)</th>
<th>( E(B-V) ) (mag)</th>
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</thead>
<tbody>
<tr>
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<td>16.636</td>
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<td>0.008</td>
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<td>0.005</td>
<td>16.118</td>
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<td>0.0339</td>
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</table>

Note. SDSS/SEGUE catalog of all 292 stars located in the Hydra I region and within the SDSS CMD filter shown in Figure 2(a). All spectroscopic parameters were taken from the SSPP pipeline. Only a subset of these spectra were used in our analysis of Hydra I (see Section 3.1). The DECam photometry has been corrected for Galactic extinction (see Section 2.1) using the listed values of \( E(B-V) \). (This table is available in its entirety in machine-readable form.)

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Parameter Pipeline (SSPP) parameter estimation (Lee et al. 2008a, 2008b). The SSPP library contains rest-frame, continuum-normalized, stellar spectra computed over a grid of atmospheric parameters spanning 4000 \( \leq T_{\text{eff}}/K \leq 10,000 \) in effective temperature (with spacing \( \Delta T_{\text{eff}}/K = 250 \)), \( 0 \leq \log_{10}([\text{Fe}/\text{H}])/[\text{cm}/\text{s}^2] \) \( \leq 5 \) in surface gravity (\( \Delta \log_{10}([\text{Fe}/\text{H}])/[\text{cm}/\text{s}^2] \) = 0.25 dex) and \( -5 \leq [\text{Fe}/\text{H}] \leq +1 \) in metallicity (\( \Delta [\text{Fe}/\text{H}] \) = 0.25 dex). The library spectra are calculated for a range in \( [\alpha/\text{Fe}] \); however, this ratio depends on metallicity. The library has \( [\alpha/\text{Fe}] = 0.4 \) for spectra with \( [\text{Fe}/\text{H}] < 1 \), and then \( [\alpha/\text{Fe}] \) decreases linearly as metallicity increases from \( -1 \leq [\text{Fe}/\text{H}] < 0 \), with \( [\alpha/\text{Fe}] = 0 \) for \( [\text{Fe}/\text{H}] \geq 0 \). The synthetic library spectra are calculated over the range 3000–10,000 Å at resolution 0.01 Å/pixel, which we degrade to 0.05 Å per pixel—twice as fine as our Hectochelle spectra.

Our spectral model, \( M(\lambda) \), is specified fully by a vector of 13 free parameters. In order to fit the model and obtain estimates for each parameter, we follow W15’s Bayesian approach and adopt the same priors specified in their Table 1. We use the software package MultiNest (Feroz & Hobson 2008; Feroz et al. 2009) to sample the posterior probability distribution functions (PDFs). As described in W15, the sampling of the PDFs allows one to evaluate the “Gaussianity” of the posterior PDFs by calculating the first four moments (mean, variance, skew, kurtosis) of the 1D marginalized PDFs of each parameter. W15 note that in the high S/N regime, the posterior PDFs become increasingly Gaussian and therefore allow one to define a measure of quality control. That is, the Gaussianity measure provides confidence that the calculated variance on the velocity is a good measure of the 1σ standard deviation (68% confidence interval). In practice, we keep only those spectra for which the model fits yield Gaussian shaped posterior PDFs as defined in W15 (see their Section 4.1 and Figure 4).

While our fits to the Hectochelle spectra return simultaneous estimates of stellar-atmospheric parameters \( T_{\text{eff}} \), \( \log g \), and \([\text{Fe}/\text{H}]\), we find that these quantities exhibit systematic as well as random errors that are larger than those found, using the same technique on spectra from the same instrument, by W15. The reason for this difference is that our current spectra were acquired in relatively bright conditions and our sky-subtracted spectra suffer significantly more residual contamination by scattered sunlight. Therefore, in this work we shall use only the velocities obtained from our Hectochelle spectra; for stellar-atmospheric parameters we will rely on the SDSS/SEGUE catalog.

We examined the data quality and measurement reliability using both repeat observations and the pipeline data quality measures described above. To ensure a reliable dataset, we adopted cuts on the radial velocity error (\( \sigma_{V_\text{rot}} < 2.1 \text{ km s}^{-1} \), or 3 times the median velocity error of 0.7 km s\(^{-1}\)) and removed spectra with large residual contamination from scattered sunlight. After applying these cuts, 411 stars remained in the Hectochelle sample. These data are presented in Table 2 and include the DECam magnitudes (corrected for Galactic extinction). The spatial positions of stars fainter than \( g = 18.5 \) are shown with respect to the smoothed spatial map of Hydra I in Figure 3 (left panel). The radial velocity error of the Hectochelle data as a function of magnitude is shown in Figure 4. We obtain velocity errors less than \( \sim 2 \text{ km s}^{-1} \) to a limiting magnitude of \( g \sim 20.5 \), approximately two magnitudes below the main sequence turnoff (MSTO) of Hydra I.

### 2.3. SDSS/SEGUE Spectroscopy

We complemented our Hectochelle data with archival spectroscopy from SDSS, adopting the spectroscopic parameters derived from the SSPP (Lee et al. 2008a, 2011). Unlike the MMT/Hectochelle target selection, the original SDSS/SEGUE survey spectroscopic selections were designed to meet a number of scientific goals. For example, because the SEGUE-1 survey was designed to broadly study all the major structural components of the MW (i.e., the disk, halo, and halo substructure), approximately 50% of the spectroscopic targeting excluded stars in the color range of the MSTO of Hydra I (Yanny et al. 2009). We analyze the same SEGUE pointing as Schlaufman et al. (2009, 2011; B-8/PCI-9/PCI-21), but because the SDSS data are more heterogeneously selected, we applied the same isochrone cut in color and magnitude used to select the Hectochelle targets—i.e., selecting only stars that might reasonably be Hydra I members. These data are presented in Table 3 and include the DECam magnitudes (corrected for Galactic extinction). Although SEGUE spectroscopic stars are a biased sampling of stars within this color–magnitude selection, they should still yield a unbiased measurement of its kinematic properties and a lower limit on its spread in \([\text{Fe}/\text{H}]\) and \([\alpha/\text{Fe}]\). The right panel of Figure 3
The DECam photometry reveals a prominent MSTO feature in the Hess diagram (Figure 2) at $g \approx 18.75$, $g - r \approx 0.18$ mag which is not apparent in the SDSS CMD. Because the DECam imaging covers a relatively large area (compared to the spatial extent of Hydra I), we consider only a small region of 2.3 deg$^2$ (radius of 0.86") centered on Hydra I in this study. This central region is shown on the smoothed spatial map of Hydra I in Figure 3. Figure 5 shows the DECam CMDs of the central 2.3 sq. deg region and an equal-area region adjacent to Hydra I for comparison. The comparison region was selected from the non-

Hydra I DECam imaging area located to the west of Hydra I. Only hints of the Hydra I MSTO and MS features which are present in the central pointing can be seen in the adjacent pointing, demonstrating that Hydra I is spatially concentrated. However, because the adjacent comparison region is located relatively close to Hydra I, this region may not be truly sampling the background. We can therefore not rule out the possibility that the MSTO stars in the comparison region are simply EBS/Hydra I member stars located slightly outside the primary spatial overdensities.

3. PHOTOMETRIC AND SPECTROSCOPIC SELECTION OF HYDRA I STARS

The DECam photometry reveals a prominent MSTO feature in the Hess diagram (Figure 2) at $g \approx 18.75$, $g - r \approx 0.18$ mag which is not apparent in the SDSS CMD. Because the DECam imaging covers a relatively large area (compared to the spatial extent of Hydra I), we consider only a small region of 2.3 deg$^2$ (radius of 0.86") centered on Hydra I in this study. This central region is shown on the smoothed spatial map of Hydra I in Figure 3. Figure 5 shows the DECam CMDs of the central 2.3 sq. deg region and an equal-area region adjacent to Hydra I for comparison. The comparison region was selected from the non-

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3.1. Minimizing Contamination in the Spectroscopic Samples

The Hectochelle targeting employed a relatively wide, SDSS-based CMD filter, and given that we have clearly detected the MSTO of Hydra I, we can remove likely contaminants using their location on the higher precision DECam CMD. Stars with Hectochelle/MMT observations are shown in Figure 6 and are colored by their measured radial velocities. The SDSS/SEGUE CMD is shown on the same CMD in Figure 7, where stars are colored by their velocities.

The radial velocities of stars along the MS are quite similar ($\sim 90$ km s$^{-1}$; see Figures 6(a) and 7(a)), whereas thick disk stars at brighter magnitudes show a larger velocity spread and have higher iron abundances ($-0.5 < \text{[Fe/H]} < 0$). At fainter magnitudes ($g > 18.5$), the SDSS sample shows that both the iron abundance and velocity of MSTO stars are well correlated. In contrast, stars at slightly redder colors ($g - r \gtrsim 0.24$) show a wider spread in velocity and may be on average more metal-poor than MSTO stars.

We define a “faint sample” of Hectochelle stars using a narrower CMD filter shown by the blue dashed lines in Figure 6(b). This filter has a red edge which is 0.06 mag bluer than our SDSS selection filter, minimizing contamination from redder stars ($g - r \gtrsim 0.24$). The filter also removes thick disk stars at brighter magnitudes ($g < 18.5$), slightly brighter than the MSTO. For our faint sample, we only include stars within the central 2.3 sq. degrees centered on Hydra I, resulting in a
Table 4
Properties of Hydra I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.A.</td>
<td>133°9</td>
</tr>
<tr>
<td>Decl.</td>
<td>3°6</td>
</tr>
<tr>
<td>Galactic Longitude</td>
<td>224°7</td>
</tr>
<tr>
<td>Galactic Latitude</td>
<td>29°1</td>
</tr>
<tr>
<td>Distance</td>
<td>12.7 ± 0.3 kpc</td>
</tr>
<tr>
<td>$L$</td>
<td>$\sim$1000 ± 200 $L_\odot$</td>
</tr>
<tr>
<td>$M_V$</td>
<td>$\sim$-2.5 ± 0.3 mag</td>
</tr>
<tr>
<td>Age$^a$</td>
<td>$\sim$5–6 Gyr</td>
</tr>
<tr>
<td>$V_{helio}$$^b$</td>
<td>89.4 ± 1.4 km s$^{-1}$</td>
</tr>
<tr>
<td>$V_{GSR}$</td>
<td>-55.5 ± 1.4 km s$^{-1}$</td>
</tr>
<tr>
<td>$\sigma_V$</td>
<td>8.4 ± 1.5 km s$^{-1}$</td>
</tr>
<tr>
<td>Rotation Amplitude$^b$</td>
<td>$\leq$6 km s$^{-1}$</td>
</tr>
<tr>
<td>$\langle[Fe/H]\rangle$</td>
<td>-0.91 ± 0.03 dex</td>
</tr>
<tr>
<td>$\langle[\alpha/Fe]\rangle$$^a$</td>
<td>0.13 ± 0.02 dex</td>
</tr>
<tr>
<td>$\langle[\alpha/Fe]\rangle$$^a$</td>
<td>0.14 ± 0.02 dex</td>
</tr>
<tr>
<td>$\langle[Fe/H]\rangle$</td>
<td>0.09 ± 0.03 dex</td>
</tr>
</tbody>
</table>

Notes.

$^a$ Youngest stellar populations only (see Section 4.3).
$^b$ Derived from the faint Hectochelle sample.
$^c$ Derived from the SDSS sample.

The SDSS faint sample is selected without the use of a narrower, bluer CMD filter due to the larger color measurement uncertainties. Although this may slightly increase contamination, we use the SSPP [Fe/H] measurements as an additional parameter in our membership probability calculations (see Section 3.2). We keep only stars fainter than $g = 18.5$ and within the 2.3 sq. degree region shown in Figure 3 for a total of 42 stars. Like the Hectochelle sample, the velocity histogram of the SDSS faint sample (Figure 7(e)) shows an strongly peaked overdensity of stars in velocity space, confirming the original discovery of this halo overdensity by Schlaufman et al. (2009).

3.2. Spectroscopic Membership Probabilities

We determine membership probabilities using the Expectation Maximization (EM) method described in Walker et al. (2009a). The EM method uses all available data to describe both the member and contamination distributions. We assume a Gaussian velocity distribution, allowing the algorithm to return membership probabilities for each star along with the mean and variance of the member distribution. The spatial probability distribution is described as a monotonically decreasing function of the stars’ distance from an assumed center between the two primary lobes (R.A. = 133°9, decl. = 3°6; see Figure 3; Grillmair 2011). The EM algorithm (and the derived membership probabilities) implicitly assumes that there are no gradients in velocity, metallicity, velocity dispersion, or metallicity dispersion. We use a Besancon model (Robin et al. 2003) to describe the Galactic contamination in our EM algorithm. For the faint Hectochelle sample, we use only the spatial and velocity information to determine membership probabilities. For the SDSS faint sample we also use the iron abundance as an additional parameter in determining memberships.

The result of the EM algorithm applied to the Hectochelle faint and SDSS samples are shown in Figures 8 and 9, respectively. Each point is colored by its membership probability ($P_M$). The EM algorithm infers a systemic heliocentric velocity of $V = 89.4 ± 1.9$ km s$^{-1}$ and dispersion $\sigma = 8.4 ± 1.5$ km s$^{-1}$ for the Hectochelle faint sample, and $V_{SDSS} = 89.6 ± 5.3$ km s$^{-1}$ and $\sigma_{SDSS} = 9.1 ± 3.1$ km s$^{-1}$ for the SDSS faint sample. Errors on the mean and dispersion were determined via bootstrapping. Schlaufman et al. (2009) found a similar mean velocity of 85 km s$^{-1}$ from their analysis of the SEGUE pointing coincident with Hydra I and a higher velocity dispersion of 14.9 km s$^{-1}$.
The spatial positions of the Hectochelle and SDSS samples, colored by membership probabilities, are shown on the smoothed surface density map of Hydra I in Figure 10. The high probability members are well correlated with the photometric overdensities, although contamination from likely non-members is clearly present. As also noted by Grillmair (2011), the SDSS data show a clump of high $P_M$ stars to the southeast of Hydra I. Examining the larger EBS region in Figure 1 shows that these stars fall along the southeast extent of the EBS stream.

4. RESULTS

4.1. Limits on Rotation and Proper Motion

The presence or lack of rotation in the Hydra I system is an important clue to its nature and possible ongoing destruction. To measure its rotation, we use a method similar to the one described by Lane et al. (2009, 2010a, 2010b) and Bellazzini et al. (2012) for stars in the Hectochelle faint sample and SDSS samples with membership probabilities $P_M > 0.5$. In this method, the sample is divided in two by a line that passes through the center of Hydra I, and a difference in the mean velocity of each subsample is taken. This velocity difference is calculated for dividing lines with position angles (PA) ranging from $0 < \text{PA} < 360^\circ$. The analysis of both samples show no evidence for rotation at a statistically significant level. We find rotation amplitudes of $\sim 3-4 \text{ km s}^{-1}$ with bootstrap-derived uncertainties of $\sim 2 \text{ km s}^{-1}$. We can therefore set a $3\sigma$ upper limit on the rotation of $\sim 6 \text{ km s}^{-1}$.

We use SDSS DR8 proper motions (USNO B; Munn et al. 2004, 2008) to measure the ensemble proper motion of Hydra I stars in the Hectochelle sample. The typical, per-star, random measurement uncertainty of this catalog is $\sim 4 \text{ mas yr}^{-1}$ (Munn et al. 2004). We find average proper motions of $\mu_\alpha \cos \delta = -0.04 \pm 0.57 \text{ mas yr}^{-1}$ ($2.4 \pm 34 \text{ km s}^{-1}$) and $\mu_\delta = -0.04 \pm 0.45 \text{ mas yr}^{-1}$ ($2.4 \pm 27 \text{ km s}^{-1}$) from Gaussian fits weighted by the EM membership probabilities. Using the uncertainties in proper motions, we set a $3\sigma$ upper limit to the proper motion of $\mu \sim 2.2 \text{ mas yr}^{-1}$ ($132 \text{ km s}^{-1}$). Although the measured proper motions are consistent with zero, they are very different than the proper motion of Hydra I predicted by Grillmair (2011): $\mu_\alpha \cos \delta = -0.15 \pm 0.57 \text{ mas yr}^{-1}$, $\mu_\delta = -2.67 \pm 0.45 \text{ mas yr}^{-1}$ for a prograde orbit. The differences between the measured and predicted proper motion are likely due to differences in methodology and sample selection: Grillmair (2011) use positions and radial velocities only to predict the proper motion of Hydra I, and we adopt only a subset of the SDSS stars (those within $r = 0.86$ centered on Hydra I) used by Grillmair (2011). A combination of increased numbers of stars and higher precision astrometry—perhaps from the Gaia mission—would be necessary for a refined proper motion measurement.
The mean iron- and alpha-abundances, and possible spreads, are important diagnostics for distinguishing between a globular cluster or dwarf galaxy progenitor for the EBS (Willman & Strader 2012; Kirby et al. 2013). As noted in Section 2.2, we use the SDSS sample to measure the iron and alpha-element abundances of Hydra I stars, adopting the [Fe/H] and [α/Fe] values from SSPP and membership probabilities determined using the EM algorithm. In the SSPP, the stellar iron abundances are determined from a calibration of Ca II H+K and Ca II triplet observations, while the value of [α/Fe] is determined primarily from the abundances of Mg I, Ti I, and Ti II. Detailed descriptions of the pipeline iron- and alpha-abundance determinations are given in Lee et al. (2008a, 2011), respectively.

Figure 11 shows the [Fe/H] histograms for the SDSS sample. As expected from the [Fe/H]-velocity distribution (Figure 9(b)), stars with PM > 50% show a strong peak in iron abundance space, while lower probability stars show a wider spread in [Fe/H]. The alpha-element [α/Fe] abundance measurements from SSPP (Lee et al. 2011) provide an additional diagnostic on the star-by-star membership, and possible origin, of Hydra I. Figure 12 shows [α/Fe] versus [Fe/H] for the SDSS sample. The [α/Fe] distribution of high probability member stars peaks near ~0.1 dex, whereas the low membership probability stars show a broad, non-peaked distribution of [α/Fe] values.

4.2. [Fe/H] and [α/Fe]

The mean iron- and alpha-abundances, and possible spreads, are important diagnostics for distinguishing between a globular cluster or dwarf galaxy progenitor for the EBS (Willman & Strader 2012; Kirby et al. 2013). As noted in Section 2.2, we use the SDSS sample to measure the iron and alpha-element abundances of Hydra I stars, adopting the [Fe/H] and [α/Fe] values from SSPP and membership probabilities determined using the EM algorithm. In the SSPP, the stellar iron abundances are determined from a calibration of Ca II H+K and Ca II triplet observations, while the value of [α/Fe] is determined primarily from the abundances of Mg I, Ti I, and Ti II. Detailed descriptions of the pipeline iron- and alpha-abundance determinations are given in Lee et al. (2008a, 2011), respectively.

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Figure 8. Velocity vs. radius for stars in the Hectochelle faint sample. Membership probabilities ($P_M$) were determined using velocity and spatial information with the EM method (Section 3.2). The mean velocity and velocity dispersion are listed.

We determine the mean and dispersions of the iron and alpha-element abundances using the full sample of SDSS stars, adopting the EM membership probabilities as weights. We find statistically significant dispersions in both abundance metrics ($\sigma_{[Fe/H]} = 0.09 \pm 0.02$ dex and $\sigma_{[\alpha/Fe]} = 0.09 \pm 0.02$ dex, respectively). We discuss the implications of these measurements in Sections 5.1 and 5.3.

How sensitive are the measured spreads in the abundances to the individual measurement uncertainties? To assess this, we recalculated the abundance spreads using larger measurement uncertainties of 0.1 dex when the reported random errors on individual measurements are <0.1 dex. Systematic comparisons to high resolution spectra and repeat SEGUE measurements have shown that the systematic errors on individual measurements are closer to ~0.1 dex, whereas the random errors on high S/N spectra are typically ~0.05 (Allende Prieto et al. 2008). With these conservative measurement uncertainties, we find $\sigma_{[Fe/H]} = 0.09 \pm 0.03$ dex and $\sigma_{[\alpha/Fe]} = 0.08 \pm 0.02$ dex. The use of larger uncertainties still yield statistically significant dispersions, and the values themselves remain relatively unchanged at a spread of ~0.1 dex in the iron and alpha-elements. We note that adopting errors larger than ~0.12 dex effectively erases evidence of an abundance spread.

Lastly, we note that the likely contaminants in our sample—those stars with $P_M < 50\%$—show distributions in $[\alpha/Fe]$ and $[Fe/H]$ consistent with the expected stellar populations. Given the spatial proximity to or association with the EBS stream, we expect that the $P_M < 50\%$ abundance distributions will be broad—containing stars from the EBS, the Galactic halo, and Hydra I itself. The small peak in the iron-abundance distribution at $[Fe/H] \sim -1.7$ dex (Figure 11) is consistent with Galactic halo contamination. These stars also show slightly higher values for the alpha-element abundances ($[\alpha/Fe] \sim 0.25$ dex), consistent with the expectation for halo stars (e.g., Pritzl et al. 2005; Hawkins et al. 2014).

4.3. Stellar Populations and Age Estimates

Given the measurement of a mean iron abundance of $[Fe/H] = -0.9$ dex from the SDSS sample, we explore the age range of Hydra I’s stellar populations using the observed CMD of spectroscopic members and theoretical isochrones. Although we used a color–magnitude cut to select spectroscopic targets (see Figures 2 and 6), we are sensitive to MSTO stellar populations in Hydra I as young as 4 Gyr (for $[Fe/H] = -0.9$ dex).

Figure 13 shows the CMD of the Hectochelle and SDSS samples compared to isochrones with ages 5–6 Gyr, $[Fe/H] = -0.9$ dex, and $[\alpha/Fe] = +0.2$ dex (Dotter et al. 2008). We infer a distance of $d = 12.7 \pm 0.3$ kpc based on the prominent location of the MSTO in the CMD. We find that fitting the blue MSTO population of Hydra I stars ($g - r \lesssim 0.2$ mag) requires a stellar population with an age of 5–6 Gyr, assuming a mean iron abundance of $[Fe/H] = -0.9$ dex. Changes of ±0.1–0.2 dex in the iron and alpha abundances result in older/younger ages by ~0.5 Gyr, which is below the age uncertainty of ~1 Gyr implied by the photometric uncertainties in the DECam $g - r$ colors at the MSTO. The age of the ~5–6 Gyr stellar populations correspond to a formation at redshift $z \approx 1–1.2$ for the standard ΛCDM cosmological model (Planck Collaboration et al. 2014). We discuss the implications of intermediate age stellar populations in Hydra I in Sections 5.1 and 5.3.

The bluest stars in Hydra I show good agreement with the ~5–6 Gyr isochrones and are clearly inconsistent with a single old stellar population (age $\gtrsim 7$ Gyr). The Hectochelle sample shows a number of high probability stars at colors redder than the blue MSTO ($g - r \gtrsim 0.2$), consistent with the expected colors of old, metal-poor MSTO stars. However, a number of factors limit our ability to draw conclusions about the presence of older stellar populations, including small numbers of candidate stars in both the Hectochelle and SDSS sample, as well as the limited/incomplete spectroscopic targeting of the reddest stars. We explored the possibility of a old metal-poor MSTO using a background subtracted Hess diagram of the region but found no statistically significant evidence for such a feature. Larger spectroscopic samples targeting the expected colors of older stars are necessary to further investigate the presence of complex stellar populations in Hydra I. We discuss the implications of the stellar populations analysis in Section 5.1.

4.4. Estimated Hydra I Luminosity

We estimate a total of ~400 stars brighter than $g = 22$ in Hydra I from a comparison of star counts in the overdensity to the adjacent field (Figure 5). As noted in Section 2.1, we expect no issues with completeness at this magnitude limit. We use the number count estimate, in combination with a luminosity function (LF) from Dotter et al. (2008), to place limits on the total luminosity of Hydra I. The LF of Hydra I was created with a Salpeter IMF, an age of 5.5 Gyr, $[Fe/H] = -0.9$ dex, and $[\alpha/Fe] = 0.2$ dex. We calculated the total luminosity of Hydra I by normalizing the LF with our value of 400 stars brighter than $g = 22$. The normalized LF was then integrated to find the total luminosity of Hydra I. We determine that the object has a total luminosity of ~1000 ± 200 $L_\odot$, or $M_L \approx -2.4 \pm 0.3$ and $M_M \approx -2.6 \pm 0.3$. Our uncertainties are determined assuming Poisson statistics describe the number
of star counts. Using the SDSS-Johnson filter transformations of Jordi et al. (2006), we find \( M_V \approx -2.5 \pm 0.3 \) mag. Because our background estimate is taken from an adjacent region not too far from Hydra I, it is possible that we have overestimated the background star counts by not sampling the “true” background. In this case, our measurement would be an underestimate of the true luminosity of Hydra I.

4.5. Constraints on Dynamical Mass and Tidal Radius

The measured velocity dispersion of Hydra I (\( \sigma = 8.4 \pm 1.5 \) km s\(^{-1}\)), in combination with a half-light or other characteristic radius, can yield an estimate of the dynamical mass of the system (Walker et al. 2009b; Wolf et al. 2010). The spatial morphology of Hydra I indicates that the object is likely undergoing significant tidal disturbance, so any measure of the dynamical mass is limited by the extent to which the present day stellar motions trace Hydra I’s underlying gravitational potential. We discuss this assumption further in Section 5.1.

Within the inner \( r = 0.786 \) (190 pc) region of interest, we find a velocity dispersion \( \sigma = 8.4 \) km s\(^{-1}\). If we assume this radius correspond to the half light radius of Hydra I, we can use Equation (2) from Wolf et al. (2010) to estimate the dynamical mass within the half light radius, \( M_{1/2} \). We derive a dynamical mass estimate of \( M_{1/2} = 9 \times 10^6 M_\odot \). If this mass estimate is within two orders of magnitude of the true dynamical mass, then Hydra I must have a significant dark matter component given the luminosity of \( \sim 1000 L_\odot \) derived in 4.4.

Given our stellar and dynamical mass estimates: Is the observation that Hydra I appears to be experiencing stellar mass loss consistent with the expected tidal radius of the object at its distance from the Galactic center? The tidal radius \( r_{\text{tidal}} \) of an object can be approximated using Equation (2) from Bellazzini (2004):

\[
r_{\text{tidal}} = \frac{2}{3} \left[ \frac{m_{\text{Hydra}}}{2M_\text{MW}(d_{\text{Hydra}})} \right]^{1/3} d_{\text{Hydra}},
\]

where \( m_{\text{Hydra}} \) is the mass of Hydra I, \( 2M_\text{MW} \) is the mass of the Milky Way, \( d_{\text{Hydra}} \) is the distance to Hydra I, and \( d_\odot \) is the distance to the Sun.

Figure 9. Velocity vs. radius (left panel) and [Fe/H] vs. radius (right panel) for stars in the SDSS/SEGUE sample. Membership probabilities (\( P_M \)) were determined using velocity, [Fe/H], and spatial information with the EM method (Section 3.2). The mean velocity and velocity dispersions are listed. The mean and dispersion in the iron abundance are discussed in Section 4.2.

Figure 10. Spatial distribution of the spectroscopic samples (identical to Figure 3) with stars colored by their EM membership probabilities (\( P_M \)). Membership probabilities were determined as described in Section 3.2 using velocity and spatial information; the SDSS sample uses [Fe/H] as an additional criteria for membership. The SDSS data show a clump of high \( P_M \) stars to the southeast of Hydra I overdensity. These stars fall along the extent of the EBS stream (see Figure 1; also Grillmair 2011).
where $m_{\text{Hydra}}$ is the mass of Hydra I, $d_{\text{Hydra}}$ is the galactocentric distance of Hydra I ($\sim 19$ kpc), and $M_{\text{MW}}(d_{\text{Hydra}})$ is the MW mass within the distance to Hydra I. We calculate the MW mass $M_{\text{MW}}(d_{\text{Hydra}})$ assuming an isothermal sphere with circular velocity of $V_{\text{circ}} = 220 \pm 40$ km s$^{-1}$ (Bellazzini 2004).

We calculate the tidal radius ($r_{\text{tidal}}$) using both dynamical and stellar mass estimates. For a dynamical mass of $9 \times 10^8 M_\odot$, we find tidal radius of $1.7 \, (\sim 370$ pc). However, assuming a stellar mass to light ratio $M_*/L = 1$ and $L = 1000 \, L_\odot$, we find a tidal radius of $r_{\text{tidal}} \sim 0.1 \, (\sim 22$ pc).

The instantaneous tidal radii of both the "only stars" and the high dynamical mass scenarios appear to be consistent with our observations of Hydra I. The small tidal radius, expected if Hydra I only contains stellar mass, is easily in good agreement with the spatial extent ($\sim 1^\circ$ radius) and asymmetric morphology of Hydra I. The larger tidal radius of $\sim 1^\circ$–$2^\circ$, expected from the estimated dynamical mass, is consistent with mass

Figure 11. Iron abundance histograms of the SDSS data for the probable member stars ($P_M > 0.5$; black histogram) and probable non-member stars $P_M < 0.5$; red histogram). Using all stars, and weighting by membership probabilities, we find a mean $[\text{Fe/H}] = -0.91 \pm 0.03$ dex and $\sigma_{[\text{Fe/H}]} = 0.13 \pm 0.02$ dex when adopting the formal SSPP $[\text{Fe/H}]$ uncertainties. Assuming more conservative errors on $[\text{Fe/H}]$ measurements (see Section 4.2) we find $\sigma_{[\text{Fe/H}]} = 0.09 \pm 0.03$ dex.

Figure 12. $[\alpha/\text{Fe}]$ vs. $[\text{Fe/H}]$ for the SDSS sample. Black points indicate likely members of Hydra I ($P_M > 0.5$) and red points indicate likely non-members ($P_M < 0.5$). The error bars show the reported internal uncertainties in the measurements as reported in the SSPP catalog. Using all stars, and weighting by membership probabilities, we find a mean $[\alpha/\text{Fe}] = 0.14 \pm 0.02$ and $\sigma_{[\alpha/\text{Fe}]} = 0.09 \pm 0.02$ when adopting the formal SSPP $[\alpha/\text{Fe}]$ uncertainties. Assuming more conservative errors on the $[\alpha/\text{Fe}]$ measurements (see Section 4.2), we find $\sigma_{[\alpha/\text{Fe}]} = 0.08 \pm 0.02$.

Figure 13. Comparison of the Hydra I CMD to theoretical isochrones. The top panel reproduces the CMD of the central region shown in Figure 5. The middle and bottom panels show the Hectochelle faint and SDSS samples, respectively, colored by the derived membership probabilities $P_M$. For the SDSS sample, membership probabilities are derived using the $[\text{Fe/H}]$ measurements as a second parameter (see Section 3.2). The median uncertainty in the color is shown as a function of magnitude. Each panel shows four isochrones for ages 5, 5.5, 6, and 7 Gyr for fixed values of $[\text{Fe/H}] = -0.9$, $[\alpha/\text{Fe}] = +0.2$, at a distance of $d = 12.7$ kpc (Dotter et al. 2008). Hydra I contains a significant population of bluer stars consistent with ages of $\sim 5$–6 Gyr (see Section 4.3).
loss at Hydra’s edges (possibly resulting in the EBS stream). If, however, the system is unbound, we can estimate the dissolution time for the system based on the crossing time—the timescale for an unbound star to reach the observed extent of the object. For simplicity, we assume a characteristic size of $1^\circ$ and that stars are moving at their measured velocity dispersion ($\sim 8 \, \text{km} \, \text{s}^{-1}$). We find that the system would have a dissolution time of only $\sim 30 \times 10^8$ years. Given such a short dissolution timescale, it would be surprising to observe this stellar overdensity at the present day if Hydra I were truly unbound. Although this provides general support for Hydra I as a bound object, additional kinematic data and numerical modeling would be necessary to draw more detailed conclusions.

5. DISCUSSION

We summarize the observed and derived properties from our study of Hydra I in Table 4. In the following discussion, we consider the consistency of these properties with different scenarios for the possible progenitor of the EBS stream.

5.1. Is Hydra I a Disrupting Dwarf Galaxy?

The hypothesis that Hydra I is a disrupting dwarf galaxy has been considered previously by Schlaufman et al. (2011) in the discussion of their cold halo objects (ECHOs) sample. They argued that the relatively high velocity dispersions of the ECHOs sample ($\langle \sigma_{\text{vel}} \rangle \sim 20 \, \text{km} \, \text{s}^{-1}$) are difficult to explain with globular cluster progenitors, which (on average) show velocity dispersions of $\sim 7 \, \text{km} \, \text{s}^{-1}$ (Kimmig et al. 2015). However, see the discussion below (Section 5.2) for a counterpoint to this broad dynamical argument.

If Hydra I is a dwarf galaxy, then the mass–metallicity and luminosity–metallicity relations for Local Group dwarf galaxies provide a means to estimate the stellar mass and luminosity of the stream progenitor (Kirby et al. 2013). For a mean iron abundance of $\langle \text{Fe/H} \rangle \sim -1$ dex, a dwarf galaxy stream progenitor would have been relatively massive—approximately $M_\text{k} \sim 10^9 M_\odot$—similar to a present-day Fornax dSph. Comparing the SSPP [Fe/H] to the Kirby et al. iron abundances could introduce small ($\sim 0.1–0.2$ dex) systematic differences due to the use of different lines and methodologies. The Kirby et al. abundances are directly measured from the iron lines, whereas the SSPP [Fe/H] values are determined via calibration of calcium lines. The mass–metallicity relation therefore only provides a first-order estimate of Hydra I’s progenitor stellar mass.

Given our stellar estimate of $M_\text{k} \sim 1000 M_\odot$ for Hydra I (see Sections 4.4), this implies that a dwarf galaxy stream progenitor would have lost $\approx 99.99\%$ of its stellar mass. If Hydra I has undergone such substantial stellar mass loss, it is unlikely that our analysis in Section 4.5 yields the true, gravitationally bound mass of the remnant. Smith et al. (2013) find that the velocity dispersion of a dwarf galaxy remnant is only a reasonable measure of the bound mass when the object has retained $\geq 10\%$ of the initial mass. When significant mass loss ($\geq 98\%$) has taken place and only a small bound object remains—the remnant mass can be overestimated by as many as three orders of magnitude. We therefore do not consider the large dynamical “mass” of Hydra I to provide support for a dwarf galaxy hypothesis.

The iron abundance spread $\sigma_{\text{Fe/H}}$ is a potentially strong discriminator between dwarf galaxies and GCs (Willman & Strader 2012). Comparing a sample of MW dwarfs and GCs, Willman & Strader (2012) find $\sigma_{\text{Fe/H}} \sim 0.3–0.7$ dex for dwarfs, while GCs less luminous than $M_V = -10$ have almost no measurable spread above the measurement uncertainties. Our estimate of $\sigma_{\text{Fe/H}} = 0.13 \pm 0.02$ dex is statistically significant and consistent with a dwarf galaxy progenitor hypothesis. Although the brightest (i.e., classical; $M_V < -8$) dwarfs generally have larger iron abundance spreads ($\sim 0.2–0.3$ dex) compared to Hydra I, a relatively small value $\sigma_{\text{Fe/H}}$ is consistent with the apparent decrease in $\sigma_{\text{Fe/H}}$ with increasing galaxy luminosity noted by Willman & Strader (2012).

All MW dwarfs with comprehensive studies of their stellar populations have shown evidence for an old, metal-poor stellar population (e.g., Kirby et al. 2013; Brown et al. 2014; Weisz et al. 2014). The addition of this population to the observed metallicity distribution would significantly increase its dispersion in [Fe/H], making the value more consistent with other luminous dwarf galaxies. If Hydra I is indeed a dwarf galaxy, our non-detection of this population could be partially due to our selection function (see Section 4.3). Another possibility is that Hydra I might have once possessed such a population, but due to its larger spatial extent (e.g., Battaglia et al. 2006; Bate et al. 2015), it has preferentially been tidally stripped compared to the more metal-rich subpopulation. We emphasize that our analysis does not rule out the possibility that Hydra I contains an old, metal-poor population. Additional spectroscopic targeting of candidate stars in the expected region of color–magnitude space and/or additional wide-field imaging would be necessary to find evidence for an older population.

The presence of intermediate age stellar population in Hydra I (ages $\sim 5–6$ Gyr; Section 4.3) is consistent with a dwarf galaxy progenitor hypothesis. Although MW dwarf spheriodals, on average, formed the majority of their stars prior to $\sim 2$ (10 Gyr ago), there is significant variation from galaxy to galaxy. Moreover, more massive dwarfs form a larger fraction of their stellar mass at later times (Weisz et al. 2014). For example, $\sim 50\%$ of the stellar mass in Fornax formed in the last $\sim 8$ Gyr and $\sim 40\%$ was formed in the last $\sim 6$ Gyr (Weisz et al. 2014). If Hydra I is a disrupting dwarf galaxy and was relatively massive at infall (as implied by the measured [Fe/H]), then the presence of an intermediate age stellar population is consistent with our expectations from the SFHs of Local Group dwarfs.

5.2. Is Hydra I a Disrupting Star Cluster?

The presence of tidal streams associated with MW GCs (e.g., Pal 5; Odenkirchen et al. 2001) raises the possibility that Hydra I could be a GC in the final throes of destruction. Grillmair (2011) discussed this scenario and concluded that the relatively high velocity dispersion of $\sim 15 \, \text{km} \, \text{s}^{-1}$ (determined by Schlaufman et al. 2009) did not rule out the possibility of Hydra I being a GC. They note that, because EBS/Hydra I may be on a highly eccentric orbit that brings it into the inner Galactic potential, a large velocity dispersion could be evidence of dynamical heating from frequent encounters with massive structures (such as giant molecular clouds) or dark matter.
subhalos. In this study, however, we find a significantly smaller velocity dispersion of $\sigma \approx 8$–$9$ km s$^{-1}$ (see Section 3.2), more consistent with GCs than dwarf galaxies.

To further explore the GC progenitor hypothesis, we consider the location of Hydra I in the age–metallicity relation (AMR) for MW globular and open clusters in Figure 14. The AMR of GCs has been well studied both in the MW (Forbes & Bridges 2010; Dotter et al. 2011) and M31 (Caldwell et al. 2011), as well as the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) (Pagel & Tautvaisiene 1998). For the MW, GCs within 8 kpc of the Galactic center show a narrow range of ages ($\sim$13 Gyr) but span a wide metallicity range. Outside a galactocentric distance of 8 kpc, however, GCs exhibit an AMR more like that of the LMC and SMC, with a trend showing younger ages at higher metallicities.

If Hydra I is a disrupting GC, then we expect it to contain (to first order) a single stellar population with the age of $\sim$5–6 Gyr as inferred from our stellar populations analysis (Section 4.3). The MW has few known, well studied GCs in the intermediate age ($\sim$6–8 Gyr) range. These include Pal 1 (Rosenberg et al. 1998a, 1998b), Pal 12, Terzan 7 (Dotter et al. 2010), Whiting 1 (Valcheva et al. 2015), and 47 Tuc (Hansen et al. 2013). With the exception of Whiting 1, all of these GCs have galactocentric distances $\leq$ 18 kpc (Harris 1996), similar to that of Hydra I ($d_{\text{MW}} = 19$ kpc). The youngest GCs of this subset (Pal 1 and Whiting 1), however, have higher iron abundances than Hydra I.

Outside of the MW, some evidence exists for massive star clusters with intermediate ages and metallicities. However, there are significant measurement uncertainties associated with these observations. For example, M31 contains a large population of massive $[\text{Fe/H}] \sim -1$ GCs, but age determinations from integrated light measurements (e.g., Lick indices) at this metallicity are highly sensitive to the presence of blue horizontal branch stars, resulting in artificially young and thus highly uncertain ages (see discussion in Caldwell et al. 2011). The LMC has a well known “age-gap” in its star cluster population (e.g., Harris & Zaritsky 2009); there are no massive clusters with ages from $\sim$5 to 12 Gyr, and only one relatively low mass, intermediate metallicity cluster ($M \sim 10^4 M_\odot$; $[\text{Fe/H}] \sim -1$) with an age $\sim$8–9 Gyr (Mackey et al. 2006).

In contrast, the SMC may contain a few $M \sim 10^4$–$10^5 M_\odot$ clusters consistent with the age and metallicity of Hydra I (see Dias et al. 2010 for a recent review), although the wide range of age estimates for individual clusters highlights the large uncertainty in their observed ages.

Given Hydra I’s outlying age and metallicity, relative to other known MW clusters, and the lack of strong evidence for analog clusters in M31 and the Magellanic Clouds, we conclude that the star cluster hypothesis is less likely than the dwarf galaxy hypothesis. If Hydra I is indeed a GC, the observed age and metallicity imply that it would have likely formed in dwarf galaxy (perhaps smaller than the LMC or SMC) which was subsequently accreted by the MW. However, the lack of known GCs with ages and metallicities consistent with Hydra I places limits on the plausibility of such a scenario.

5.3. Possible Association of Hydra I With a Larger Galactic Structure

Lastly, we consider the possibility that Hydra I and EBS may be part of a larger Galactic structure—in particular the Monoceros Ring stellar overdensity. The distance and metallicity of Hydra I are consistent with photometric and spectroscopic studies of the larger Monoceros Ring region (Conn et al. 2012; Meisner et al. 2012). Slater et al. (2014) recently presented a Pan-STARRS1 stellar density map for the Monoceros Ring, constructed using MSTO stars from a $\sim$9 Gyr population with $[\text{Fe/H}] = -1$ (colors in the range $0.2 < (g - r)_0 < 0.3$). They argue that the EBS and Anticenter streams are extended stellar arcs that are physically associated with the Monoceros Ring. Conversely, Grillmair (2011) argued that the EBS stream is kinematically distinct from the Monoceros Ring, given the high eccentricity orbital solution needed to explain EBS’s observed spatial curvature. The Monoceros Ring is believed to be on a nearly circular orbit (Crane et al. 2003; Martin et al. 2006). Although our study cannot shed additional light on whether either Hydra I or EBS might be associated with the Monoceros Ring, a more refined orbital solution for the EBS stream—using GAIA proper motions and a large sample of radial velocity measurements—is a promising avenue for investigating this hypothesis.

Given the proximity of Hydra I to the Monoceros Ring, it is possible we have isolated a younger population of stars recently speculated to be part of this structure. Carballo-Bello et al. (2015) noted that along the line of sight to the Monoceros Ring (at $l \sim 180^\circ$, $b \sim 25^\circ$), there exists a population of stars bluer than the $\sim$9 Gyr MSTO of Monoceros Ring stars. They suggested that this could be a $\sim$4 Gyr population (with an iron abundance of $[\text{Fe/H}] \sim -0.9$ dex) associated with the Monoceros Ring. Carballo-Bello et al. (2015) were unable to clearly detect a MSTO feature in the SDSS data but estimated a distance of $\sim$10 kpc for the population. The systemic velocities of the blue population—as well as Hydra I—are consistent with model predictions from Peñarrubbia et al. (2005) for the origin of the Monoceros Ring as an accreted dwarf galaxy.

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**Figure 14.** Age vs. $[\text{Fe/H}]$ for Galactic GCs (red circles, black triangles; Dotter et al. 2010, 2011) and open clusters (green squares; Dias et al. 2014). Ages and $[\text{Fe/H}]$ values for younger globular clusters 47 Tuc, Whiting 1, and Pal 1 from Hansen et al. (2013), Valcheva et al. (2015), and Rosenberg et al. (1998a, 1998b), respectively, are also included and labeled. As in Dotter et al. (2011), individual GCs are identified by their galactocentric distance $R_{GC} > 8$ kpc or $R_{GC} \leq 8$ kpc. The age range and mean metallicity of the stellar populations of Hydra I are shown as the gray boxed region. Very few known MW GCs or open clusters have ages and iron abundances similar to Hydra I.
Although suggestive, additional precision photometry over a much larger field will be necessary to further explore any spatial connections between the Carballo-Bello et al. (2015) detections and the EBS/Hydra I.

Another consideration is whether the iron- and alpha-element abundances of Hydra I are consistent with the MW’s halo or thick disk populations. Although this comparison may provide a general picture of the origin of Hydra I, the conclusions should be taken with caution. First, the distribution in [Fe/H] of the Galactic halo population is quite extended and shows a large spread in alpha-element abundances at a given [Fe/H] (Moll et al. 2014). Second, the metal-rich tail of halo stars and metal-poor thick disk stars overlap in both [Fe/H] and [$\alpha$/Fe] (Venn et al. 2004; Pritzl et al. 2005), blurring the distinction between these two Galactic populations in this metallicity regime. Lastly, comparisons of the SSPs abundances to those from heterogeneous compilations may introduce small systematic differences of order $\sim$0.1 dex or less (Venn et al. 2004).

A comparison of iron- and alpha-element abundances was done by Schlaufman et al. (2011) in their analysis of the SDSS/SEGUE observations of a set of cold halo substructures (ECHOs), one of which was Hydra I. In Figure 14 of Schlaufman et al. (2011), they compare the mean iron and alpha abundances of ECHOs to samples of thin disk, thick disk, and halo stars compiled by Venn et al. (2004). The mean [Fe/H] and [$\alpha$/Fe] of the ECHO associated with Hydra I is more iron-rich and less alpha-enhanced than both (1) the smooth halo along that line of sight ([Fe/H]$_{\text{halo}}$ $\sim$-1.4; [Fe/H]$_{\text{halo}}$ = -0.25) and (2) the mean values of the halo as compiled by Venn et al. (2004). Compared to the thick disk stars compiled by Venn et al. (2004), Hydra I is less alpha-enhanced (by $\sim$0.15 dex) than the metal-poor thick disk at [Fe/H] $\sim$ -1. As additional evidence pointing to Hydra I’s extragalactic origin, Schlaufman et al. (2011) note that the [Fe/H] and [$\alpha$/Fe] distributions of the ECHOs are in good agreement with the MW dwarf galaxy satellites Leo I and Sculptor (see their Figure 15). Taken together, the mean values of the iron- and alpha-elements suggest an extragalactic origin for Hydra I rather than a Galactic overdensity of halo or thick disk stars.

6. CONCLUSIONS

In this paper we present a wide-field DECam imaging and MMT/Hectochelle + archival SDSS spectroscopic study of Hydra I—the double-lobed, $\sim$2 deg$^2$ halo overdensity previously suggested to be the progenitor of the EBS stream—and quantify its present day chemo-dynamical properties. The results inferred using both Hectochelle and SDSS/SEGUE data are consistent. Hydra I contains an intermediate age stellar population of $\sim$5–6 Gyr with a mean iron abundance of [Fe/H] = -0.91 $\pm$ 0.03 dex and alpha abundance of [$\alpha$/Fe] = 0.14 $\pm$ 0.02 dex. We find spreads in both the iron and alpha abundances of $\sigma_{\text{Fe/H}}$ = 0.13 $\pm$ 0.02 dex and $\sigma_{\text{[Fe/H]}}$ = 0.09 $\pm$ 0.03 dex, respectively. We confirm previous observations that Hydra I is a kinematically cold structure, with a velocity dispersion of $8.4 \pm 1.5$ km s$^{-1}$ at a systemic heliocentric velocity of $V = 89.4 \pm 1.4$ km s$^{-1}$ ($V_{\text{GSR}} = -55.5 \pm 1.4$ km s$^{-1}$).

Hydra I’s stellar population appears initially inconsistent with earlier studies reporting that an old- and metal-poor stellar population yielded the strongest overdensity in matched-filtering maps of the Hydra I region (Grillmair 2006, 2011). Old and metal-poor populations can have MSTO populations as blue as those of intermediate age and [Fe/H] rich populations. Moreover, many approaches to searching for and mapping streams in the MW’s halo assume that streams will be composed of old and metal-poor populations. Assuming a metal-poor population can thus lead to erroneous conclusions about a substructure’s age and distance. Complimentary spectroscopy to measure the metal content of substructures provides a critical constraint on both their ages and distances, and ultimately provides a more accurate picture of the accretion events that formed the Galactic halo.

Hydra I’s intermediate age ($\sim$5–6 Gyr) and [Fe/H] ($\sim$–1 dex) make it an outlier among known MW globular cluster and open clusters. Conversely, Hydra I’s stellar populations, along with its spread in [Fe/H], is consistent with those of a Fornax-like dwarf galaxy progenitor. If Hydra I’s progenitor was a Fornax-like dwarf galaxy, then it must have lost >99.99% of its stars to bear the low luminosity it displays today. Hydra I may thus be the first example of a system truly in its final throes of disruption, making it an excellent benchmark of tidal disruption models.

Although evidence strongly points toward a dwarf galaxy interpretation of Hydra I, we cannot rule out the hypothesis that Hydra I originated as a star cluster or that it is physically associated with the Monoceros Ring. Higher S/N spectroscopic follow up of high probability member stars is a promising avenue for a more certain test of the dwarf galaxy hypothesis. With high resolution spectra, the apparent [Fe/H] spread presented in this work could be measured with higher fidelity. Combined with Gaia proper motions and deeper wide-field imaging, Hydra I modeling will further test whether it could be kinematically associated with the Monoceros Ring and will constrain the impact of secular and environmental factors on its observable properties.

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