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Cresting the wave: Proper motions of the Eastern Banded Structure

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ABSTRACT

We study the kinematic properties of the Eastern Banded Structure (EBS) and Hydra I overdensity using exquisite proper motions derived from the Sloan Digital Sky Survey (SDSS) and Gaia source catalog. Main sequence turn-off stars in the vicinity of the EBS are identified from SDSS photometry; we use the proper motions and, where applicable, spectroscopic measurements of these stars to probe the kinematics of this apparent stream. We find that the EBS and Hydra I share common kinematic and chemical properties with the nearby Monoceros Ring. In particular, the proper motions of the EBS, like Monoceros, are indicative of prograde rotation ($V_φ$ $\sim$ 180 − 220 km s$^{-1}$), which is similar to the Galactic thick disc. The kinematic structure of stars in the vicinity of the EBS suggest that it is not a distinct stellar stream, but rather marks the “edge” of the Monoceros Ring. The EBS and Hydra I are the latest substructures to be linked with Monoceros, leaving the Galactic anti-centre a mess of interlinked overdensities which likely share a unified, Galactic disc origin.

Key words: Galaxy: halo – Galaxy: kinematics and dynamics – Galaxy: structure

1 INTRODUCTION

Galaxies like the Milky Way consume and destroy several lower-mass dwarf galaxies over their lifetime. Evidence of these fatal accretion events can be seen in the form of streams, clouds, shells, and incoherent blobs that litter the stellar halo (e.g. Belokurov et al. 2006). The interaction between accreted dwarf galaxies and the Galactic disc can not only rip apart the dwarf, but can perturb, warp, and even “kick out” stars from the stellar disc (e.g. Velazquez & White 1999; Benson et al. 2004; Purcell et al. 2010).

A stunning example of a substructure at the disc-halo interface, is the so-called Monoceros Ring. This local ($D \sim 10$ kpc) overdensity located close to the Galactic anti-centre was first uncovered by Newberg et al. (2002) using imaging data from the Sloan Digital Sky Survey (SDSS; York et al. 2000), and the ring-like structure was later confirmed by Ibata et al. (2003). There are two main formation scenarios that have been put forward to explain this vast anti-centre structure: (1) Tidal debris from a disrupted dwarf galaxy, and (2) a perturbation of the Galactic disc. Subsequent scrutiny of the anti-centre region has uncovered yet more substructure which could be related to Monoceros: the Canis Major overdensity, which has been touted as a potential progenitor of Monoceros (Martin et al. 2004), the Eastern Banded Structure (EBS), the anti-centre stream (Grillmair 2006), and a Southern counterpart to Monoceros at larger distances ($D > 15$ kpc) called TriAnd (Majewski et al. 2004; Rocha-Pinto et al. 2004). More recently it has been suggested that the disc in this region has complex substructure, which is caused by an accreted dwarf galaxy. Thus, these apparently spatially separated substructures could have a unified origin (see e.g. Slater et al. 2014; Xu et al. 2015).

In this letter, we focus on the EBS, a faint, short structure first discovered by Grillmair (2006). Despite its proximity to Monoceros, a re-analysis by Grillmair (2011) found that the EBS was unlikely related to the Ring, and is instead a distinct stellar stream. Indeed, Grillmair (2011) suggested that a relatively high surface density, double-lobed feature found along the stream - called Hydra I - could be the dwarf galaxy or globular cluster progenitor of the stream. However, while the shallow SDSS imaging assumed an old, metal-poor stellar population, deeper imaging and spectroscopy of Hydra I by Hargis et al. (2016) revealed that the EBS was not a distinct stellar stream, and is instead a distinct structure. Indeed, Grillmair (2011) suggested that a relatively high surface density, double-lobed feature found along the stream - called Hydra I - could be the dwarf galaxy or globular cluster progenitor of the stream. However, while the shallow SDSS imaging assumed an old, metal-poor stellar population, deeper imaging and spectroscopy of Hydra I by Hargis et al. (2016) revealed that the EBS was not related to the Ring, and is instead a distinct structure. Therefore, the high metallicity is reminiscent of the Monoceros Ring ($[Fe/H] \approx -0.9$). This relatively high metallicity is reminiscent of the Monoceros Ring ($[Fe/H] \approx -1.0$, e.g. Ivezić et al. 2008; Meisner...
et al. 2012), which is only slightly more metal-poor than the thick disc ([Fe/H] ∼ −0.7, e.g. Gilmore & Wyse 1985).

It is clear that a kinematic exploration of the anti-centre region is desperately needed to dissect these complex structures. To this end, de Boer et al. (2017) recently exploited a proper motion catalog constructed from the SDSS and first data release of Gaia to infer the tangential motions of the Monoceros Ring. In this letter, we use the same SDSS-Gaia catalog to examine the kinematics of the EBS and Hydra I, and relate them to the Ring.

2 SDSS-GAIA PROPER MOTIONS

In order to examine the proper motions of the EBS we use a newly calibrated SDSS-Gaia catalog (Koposov et al. in prep). The details of the creation of the recalibrated SDSS astrometric catalogue, the measurement of SDSS-Gaia proper motions, and the statistical and systematic uncertainties of the derived proper motions, are described in more detail in Koposov et al. (in prep), Deason et al. (2017) and de Boer et al. (2017). Here, we give a very brief description.

A comparison between the positions of stars in the SDSS Data Release 10 (Ahn et al. 2014) and the Gaia source catalog (Gaia Collaboration et al. 2016) with a baseline of ∼ 5–10 years can potentially yield proper motions across a large area of sky. However, there are several systematics present in this naive cross-match, particularly due to the astrometric solution of the SDSS survey. To this end, Koposov et al. (in prep) recalibrate the SDSS astrometry based on the excellent astrometry of the Gaia source catalog. These recalibrated positions are then cross-matched with the Gaia catalog resulting in proper motion measurements for the majority of sources down to r ∼ 20 mag. The precision of the new SDSS-Gaia proper motions are examined in Deason et al. (2017) and de Boer et al. (2017) using spectroscopically confirmed QSOs. The systematics of the catalog are very low (∼ 0.1 mas/yr) and the statistical uncertainties are typically 1.5 mas/yr.

In this work, we adopt the proper motion uncertainties as a function of magnitude derived by de Boer et al. (2017) for the anti-centre region: σ₂µ = 36.04 − 3.867g + 0.107g², σµb = 26.50 − 2.894g + 0.082g².

3 SAMPLE SELECTION

In this Section, we outline our selection of stars associated with the EBS. In Fig. 1 we show how EBS stars are identified according to their position on the sky, color and magnitude. The top left panel shows a density map of SDSS stars in the vicinity of the EBS. Here, only stars with main sequence colors (0.2 < g − r < 0.6) in the magnitude range 17 < r < 22 are shown. The red box indicates the EBS, and the red line shows the range along the stream where there is obvious EBS signal (|X| < 5 deg).

Figure 1. Top left panel: Density map of SDSS stars in Equatorial coordinates. Only stars with main sequence colors (0.2 < g − r < 0.6) in the magnitude range 17 < r < 22 are shown. The red box indicates the EBS, and the dashed boxes show the regions used to calculate the background. Top middle and right panels: Hess diagrams in g − r (middle) and g − i (right) color-magnitude space. Here, we show the difference between stars in the EBS region and the background. The red box indicates the turn-off feature associated with the EBS, and the red line shows a 5.6 Gyr, [Fe/H] = −0.9 isochrone at D = 12.7 kpc. Bottom left and middle panels: The density of turn-off stars selected in the color and magnitude ranges: 0.11 < g − r < 0.24, 17.2 < r < 19.6, 0.17 < g − i < 0.31, 17.2 < i < 19.7. The red line in the bottom middle panel shows a great circle through the EBS. Bottom right panel: Density of turn-off stars in a coordinate system with equator aligned with the EBS stream. Hydra I lies at X, Y = [0, 0] deg. The solid red line indicates the approximate boundary of the EBS stream, |Y| < 1.0 deg, and the dotted line shows the range along the stream where there is obvious EBS signal (|X| < 5 deg).
4 PROPER MOTION OF HYDRA I

Before we turn our attention to the full extent of the EBS, we focus on the potential progenitor of this stream, Hydra I. Here, we use the spectroscopic sample of stars associated with Hydra I compiled by H16, and cross-match these stars with our SDSS-Gaia proper motion catalog. The top left panel of Fig. 2 shows the distribution of heliocentric velocities of the $N = 675$ candidate Hydra I stars. The filled red histogram shows the $N = 84$ turn-off stars that lie within the color and magnitude selection boundaries given in Eqn. 1.

H16 find a (probability weighted) systemic velocity of $V_{\text{hel}} = 89.4 \text{ km s}^{-1}$ for Hydra I, with dispersion $\sigma_V = 8.4 \text{ km s}^{-1}$. Our turn-off star criteria produces a well defined peak centered on this systemic velocity, and thus is clearly effective at isolating stars associated with Hydra I. The dotted lines in this panel indicate the $2\sigma$ boundaries of the Hydra I heliocentric velocity distribution.

The middle and right panels of Fig. 2 show the Galactic proper motion components of the candidate Hydra I stars. Stars that fall into our turn-off selection are highlighted in red, and the dotted red lines indicate the $2\sigma$ boundaries of the systemic velocity of Hydra I. Using the $N = 65$ turn-off selected stars that have heliocentric velocities within $2\sigma_V$ of Hydra I, we find median proper motions of: $\mu_l = 0.18 \pm 0.21 \text{ mas/yr}$ and $\mu_b = -0.67 \pm 0.21 \text{ mas/yr}$. The median values, and uncertainties in the medians, are calculated using a bootstrap method that takes into account the proper motion uncertainties of the SDSS-Gaia sample.

We can convert our derived proper motions and the line-of-sight velocity of Hydra I into a 3D velocity. Heliocentric quantities are converted to Galactocentric ones using a solar motion of $v_{\odot} = 238 \text{ km s}^{-1}$ and $(U, V, W) = (11.1, 12.24, 7.25) \text{ km s}^{-1}$ from Reid & Brunthaler (2004) and Schönrich et al. (2010). Adopting a distance to Hydra I of 12.7 kpc, we find: $(v_r, v_{\theta}, v_{\phi}) = (-22 \pm 5, -24 \pm 12, 179 \pm 12) \text{ km s}^{-1}$. Thus, the kinematics of Hydra I indicate a prograde orbit, with similar amplitude to the Galactic thick disc.
5 KINEMATICS OF THE EASTERN BANDED STRUCTURE

5.1 Proper motion properties

We now examine the proper motions of stars in the vicinity of the EBS. Here, we only use turn-off stars (see Fig. 1 and Eqn. 1) and use a rotated coordinate system aligned with a great circle through the EBS. In the bottom panels of Fig. 3 we show the median Galactic longitude (left panels) and latitude (right panels) proper motions of stars close to the EBS in bins of X and Y. Here, Hydra I is located at the origin (|X| < 1 deg, |Y| < 1 deg), and the star symbol indicates its estimated proper motion found in the previous section. For comparison, we show the proper motions of stars in the Galaxia model (Sharma et al. 2011) in the bottom panels. These stars are selected according to the same criteria as the EBS stars, and the model is dominated by halo stars in this region of the sky.

The proper motion structure in the vicinity of the EBS shows a sharp transition at Y ~ 0 deg that is not apparent in the Galaxia model. The Y coordinate runs perpendicular to the stream, and the Monoceros Ring dominates at Y < 0 deg. Thus, the EBS seems to mark the “edge” of the Monoceros feature, and indeed the EBS proper motions (at |Y| < 1 deg and 1 < |X|/deg < 5) are very similar to Monoceros. In Fig. 1 the density of the anti-centre features vary considerably with Galactic latitude (i.e. the EBS stands out as an obvious overdensity). Thus, if the EBS was a distinct structure, we would also expect to see a variation, or discontinuity, in the proper motions. Instead, we find that the proper motions in the vicinity of the EBS follow on continuously from the Monoceros Ring, as would be expected if the Monoceros star counts continue to dominate out to the EBS.

The transition between Monoceros and the halo can be seen more clearly in Fig. 4, where we collapse the X dimension (along the stream) and only use stars with 1 < |X|/deg < 5 deg. Note that we restrict to |X| > 1 deg to exclude Hydra I stars. Here, we show how the Galactic proper motion components vary perpendicular to the stream. The filled points show the median values (with associated errors) and the solid lines indicate the 1σ dispersion. The orange star symbol indicates Hydra I, and the dot-dashed blue line shows the prediction from the Galaxia model. The solid red region shows a simple disc model with rotation $V_\phi = 220$ km s$^{-1}$ at $D = 12.7$ kpc, where we assume the distance to EBS is

\[ V_\phi = 180 \text{ km s}^{-1} \text{ at } D = 12.7 \text{ kpc.} \]
6 SUMMARY AND DISCUSSION

In this letter, we have examined the kinematic properties of the EBS and Hydra I using exquisite proper motions derived from the SDSS and Gaia source catalog. We find that the EBS and Hydra I share common kinematic and chemical properties with the Monoceros Ring; the proper motions, line-of-sight velocity, distance and metallicity of the EBS all closely resemble Monoceros and do not appear like a halo population. In particular, the proper motions of the EBS, like Monoceros, are indicative of prograde rotation, which only slightly lags behind the Galactic thin disc. At higher Galactic latitudes than the EBS, the stellar field transitions to a halo dominated population. Thus, we conclude that the EBS is not a distinct stellar stream, but rather marks the “edge” of the Monoceros Ring.

A detailed kinematic analysis of the Galactic anti-centre was recently performed by de Boer et al. (2017). These authors used the same SDSS-Gaia proper motion catalog described in this work, and find that the Monoceros Ring has a prograde rotation signal with $V_\phi \sim 220 - 240$ km s$^{-1}$. de Boer et al. (2017) also map the proper motion structure of the anti-centre stream (ACS), and although they find that it is distinct from Monoceros, the ACS has similar kinematic properties and likely shares a common origin with the Ring. There are two leading formation mechanisms for the Monoceros structure: (1) a disrupted dwarf galaxy and (2) a perturbation of the Galactic disc. de Boer et al. (2017) suggest that their results indicate a mix of these two scenarios, where both are likely needed to explain the complex structures in the anti-centre.

Our results point to yet another Galactic sub-structure associated with the Monoceros Ring. Indeed, the kinematic structure of the EBS could be likened to the “crest” of the Monoceros wave. We also find that Hydra I, the presumed progenitor of the EBS, is both kinematically and chemically related to both the EBS and Monoceros. The fact that these substructures, in addition to the ACS, are not substantially different from Monoceros puts the disrupted dwarf scenario into serious doubt. Indeed, the main remaining evidence for the debris of an accreted satellite are the reported detections of thin substructures in the anti-centre region (like EBS). Thus, our finding that the EBS is in fact not a distinct stream, and is instead an overdensity related to Monoceros, indicates that the similarity of the various stellar components in the anti-centre favors a unified, disc origin.

The Galactic anti-centre is proving to be a region of...
the Galaxy littered with multiple, interlinked sub-structures. This unique probe of the disc/halo interface not only allows us to study the disruption of dwarf galaxies, but also the synergy between accretion events and the response of the Galactic disc. With the advent of more detailed kinematics from Gaia and upcoming spectroscopic surveys (such as DESI and WEAVE; DESI Collaboration et al. 2016; Dalton et al. 2012), we can hope to piece together the complex formation scenario of Monoceros and its denizens.

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