A study of full space motions of outer Galactic disk A and F stars in two deep pencil-beams

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ABSTRACT

A and F stars can be used as probes of outer Galactic disk kinematics: here we extend the work of Harris et al. (2018) by crossmatching their A/F sample with Gaia DR2 to bring in proper motions. These are combined with the already measured radial velocities and spectro-photometric distances to obtain full space motions. We use this sample of 1173 stars, located in two pencil-beam sightlines (ℓ = 178° and ℓ = 118°), to sample the Galactocentric velocity field out to almost RG = 15 kpc. We find there are significant differences in all three (radial, azimuthal and vertical) kinematic components between the two directions. The rotation curve is roughly flat in the anticentre direction, confirming and extending the result of Kawata et al. (2018a) thanks to the greater reach of our spectro-photometric distance scale. However at ℓ = 118° the circular velocity rises outwards from RG = 10.5 kpc and there is a more pronounced gradient in radial motion than is seen at ℓ = 178°. Furthermore, the A star radial motion differs from the F stars by ∼ 10 km s⁻¹. We discuss our findings in the context of perturbers potentially responsible for the trends, such as the central bar, spiral arms, the warp and external satellites. Our results at ℓ = 178° are broadly consistent with previous work on K giants in the anticentre, but the kinematics at ℓ = 118° in the Perseus region do not yet reconcile easily with bar or spiral arm perturbation.

Key words: Galaxy: disc – Galaxy: kinematics and dynamics – stars: early-type – methods: observational

1 INTRODUCTION

Tracing the kinematics of the Galactic disk allows us to map out its structure and so gain insight into its formation and evolution. The disk is expected to be rich in substructure imprinted from dynamical processes such as resonant effects from the central bar (Monari et al. 2014), the spiral arms (Monari, Famaey & Siebert 2016) Grand et al. (2016), and infalling and external satellites (Gmez et al. 2013) Antoja et al. (2018). The mean structure contains important information about the Galactic potential and yet remains uncertain. To form a complete picture it is vital to study not only the accessible inner disk and Solar Neighbourhood, but also the outer disk. So far, the outer disk is less well known.

With the DR2 release from the Gaia mission (Gaia Collaboration et al. 2018a) (2016), there is now an abundance of kinematic data in the form of positions, parallaxes, proper motions and some radial velocities. However for the faint distant stars that populate the outer disk, Gaia DR2 provides valuable proper motion data, but not radial velocities and parallaxes good enough for use in kinematic studies. Previous studies have tended to use either masers in star-forming regions (Honma et al. 2012) (Reid et al. 2014) or clump giants (López-Corredoira 2014) (Huang et al. 2016) Tian et al. (2017), both boasting reasonably well-defined distances. But both of these tracers have down sides too - masers in star forming regions are sparse in the outer disk, making it difficult to sufficiently sample the kinematic structure, and clump giants are old and hence are subject to large kinematic scatter and asymmetric drift. More recently, Kawata et al. (2018a) used > 10⁶ stars from Gaia DR2 to study the azimuthal and vertical velocity field out to Galactocentric radius RG < 12 kpc in the anticentre direction, but the lack of radial velocity information and large parallax uncertainties for the fainter more distant stars prevented them from delving further into the outer disk (see also Gaia Collaboration et al. 2018b).

There is however another path to explore. Harris et al. (2018) (hereafter H18) showed that A and F stars can begin to be used as probes of outer Galactic disk kinematics on combining radial velocities and spectro-photometric dis-
tances. These stars offer the following advantages: i) they are intrinsically relatively luminous with absolute magnitudes in the $i$ band of $\sim$0 to 3, ii) as younger objects ($< 1$ Gyr), they have experienced significantly less scattering within the Galactic disk (Dehnen & Binney, 1998), iii) A stars especially are efficiently selected from photometric Hα surveys (H18). Here we extend the work of H18 by completing the kinematics of their A and F star sample by bringing in the since-released Gaia DR2 proper motions. We examine the resultant Galactocentric radial, azimuthal and vertical velocity fields in their two pencil-beam sightlines in the outer disk at longitudes $\ell = 118^\circ$ and $\ell = 178^\circ$. We re-use the H18 spectro-photometric distance scale, which reaches out to Galactocentric radii of 14-15 kpc.

The layout of the paper is as follows: in section 2 we describe the data, coordinate systems and how we compute full space motions. We also demonstrate the advantages of the H18 spectro-photometric distance scale relative to parallax-based alternatives. The results are presented in section 3 detailing the profile of radial, azimuthal and vertical velocity with Galactocentric radius along the two sightlines. We also compare the kinematics and velocity ellipsoids of the A and F star populations. In section 4 we discuss possible kinematic perturbers that may be at work and examine the results with these in mind. We end the paper with our conclusions; that there are departures from axisymmetry such that (to good precision) the disk circular speed rises with Galactocentric radius at $\ell = 118^\circ$, whilst remaining flat at $\ell = 178^\circ$. We also find a strong trend in Galactocentric radial velocity at $\ell = 118^\circ$ that is much weaker at $\ell = 178^\circ$.

2 SAMPLE AND METHOD

The sample we use is that from H18\footnote{The data from H18 can be found here: [http://vizier.u-strasbg.fr/viz-bin/VizieR?source=J/MNRAS/475/1680](http://vizier.u-strasbg.fr/viz-bin/VizieR?source=J/MNRAS/475/1680)\footnote{INT (Isaac Newton Telescope) Photometric Hα Survey of the Northern Galactic Plane, see [Drew et al. 2005](http://journals.iop.org/iopconf/975/1680)}} comprising spectra of 1173 A and F stars. The sample was selected using the IPHAS\footnote{INT (Isaac Newton Telescope) Photometric Hα Survey of the Northern Galactic Plane, see [Drew et al. 2005](http://journals.iop.org/iopconf/975/1680)} ($r - i$, $r - H\alpha$) colour-colour diagrams, and spectra were gathered using MMT's multi-object spectrograph, HectorSpec. The stars have apparent magnitudes $15 \lesssim G \lesssim 19$ (equivalently $14 \lesssim i \lesssim 18$), sampling heliocentric distances of $2 - 10$ kpc. They are located in two pencil-beams of $1^\circ$ diameter in the Galactic plane, at $(\ell, b) = (118^\circ, 2^\circ)$ and $(178^\circ, 1^\circ)$ (see figure 1). Radial velocities and stellar parameters were measured using a MCMC-assisted parameter fitting routine relative to synthetic spectra as templates, which were calculated using the approach of Gebran et al. (2016) and Palacios et al. (2010). Spectro-photometric distances were calculated taking into account measured extinctions and with the use of Padova isochrones (Bressan et al. 2012; Chen et al. 2015). For a detailed description of the determination of radial velocities, stellar parameters and distances, see H18.

There are 780 stars in the $\ell = 118^\circ$ sightline, and 393 in the $\ell = 178^\circ$ sightline. We crossmatch this sample with the Gaia DR2 database, finding matches for all objects. This provides proper motions with typical uncertainties of $< 0.2$ mas yr$^{-1}$, or typical percentage uncertainties of $< 15\%$. We then apply the following quality cuts:

- Following the suggestions of Lindegren et al. (2018), we apply a quality cut depending on the unit weight error, $u_L$, of the Gaia data, which is a goodness-of-fit statistic on the model used to determine the astrometric parameters. We remove objects from the sample that have $u_L > 1.2 \times \max(1, \exp(-0.2(G - 19.5)))$, where $G$ is the magnitude in the Gaia G band. This quality cut results in 23 objects being removed from the $\ell = 118^\circ$ sample, and 6 from the $\ell = 178^\circ$ sample.
- Again following Lindegren et al. (2018), we apply a cut based on the number of ‘visibility periods used’ of the Gaia data, indicating an astronomically well-observed source. We remove objects with $< 8$ visibility periods. This affects no objects at $\ell = 118^\circ$. A further 2 objects are removed from the $\ell = 178^\circ$ sample.
- Finally, we remove objects with unrealistically large spectro-photometric distances. We set this limit to a heliocentric distance of 10 kpc, since it is the maximum distance expected from the initial target selection. This cut removes a further 27 objects from the $\ell = 118^\circ$ sample, and 10 from the $\ell = 178^\circ$ sample. In our analysis we further reduce the heliocentric distance range considered to 6.5 kpc ($\ell = 178^\circ$) and 8.1 kpc ($\ell = 118^\circ$).

The final sample size is then 730 stars at $\ell = 118^\circ$ and 375 at $\ell = 178^\circ$. By combining the now-complete kinematic data of our sample with our spectro-photometric distances, we have a full 6D phase-space solution.
2.1 Distance scale

For the magnitude range of the target stars (15 < G < 19), the measurement uncertainty on Gaia DR2 parallaxes range from ~ 0.04 mas for the brightest objects to ~ 0.3 mas for the faintest. The majority have an uncertainty around 0.1 mas. Over the distance range targeted (2-10 kpc, or a parallax range of 0.1-0.5 mas), these uncertainties are significant, amounting to percentage uncertainties of ~ 20–100%. Additionally, the Gaia DR2 parallaxes carry systematic errors of order ±0.1 mas on global scales, with actual magnitude and distribution of the errors unknown (Lindegren et al. 2018). For these reasons, it is not obvious that Gaia DR2 parallax information would provide any improvement to our spectro-photometric distance scale. To check this, we have made comparisons with 2 alternative distance scales that make use of the Gaia DR2 parallaxes: i) Bailer-Jones et al. (2018) (hereafter BJ18) who infer a distance scale using a prior that varies according to a Galaxy model, and ii) the TOPCAT ‘distanceEstimateEdsd’ function (hereafter EDSD) which uses an exponentially decreasing space density prior for a chosen length scale (we use L=1500 pc) to estimate the distance (Luri et al. 2018).

Figure 2 compares the HectoSpec spectro-photometric distance scale with that from BJ18. The comparison with EDSD is not shown since it is very similar. We see that at ≥ 4 kpc the BJ18/EDSD distances become significantly smaller than our spectro-photometric distances. This is signalling that at distances of 3 – 4 kpc the parallax measurements are becoming sufficiently imprecise that the prior in the parallax inversion takes over. Hence it is not appropriate to rely on Gaia DR2 parallax-based distance scales to probe further out than a few kpc from the Solar neighbourhood (Hogg, Eilers & Rix 2018) support this view, instead making use of the APOGEEGaia2MASSWISE overlap to train a function that at distances of 3-4 kpc the parallax measure is accounting for the Solar motion, its uncertainty and distribution of the errors unknown (Lindegren et al. 2018). For these reasons, it is not obvious that Gaia DR2 parallax information would provide any improvement to our spectro-photometric distance scale.

In addition to this, the BJ18/EDSD distances suffer from large asymmetric uncertainties. The median percentage uncertainty for the BJ18 distances is 24% for the inside tail of the probability distribution, and 39% for the outside tail. Similarly for the EDSD distances, the median percentage uncertainty is 14% for the inside tail and 59% for the outside tail. The uncertainties on our spectro-photometric distances are symmetric and the percentage uncertainties range between ~ 5 – 25%, with a median of just 13%. Hence continued use of the spectro-photometric distance scale is warranted as it is free of the aforementioned systematic errors, benefits from relatively small, symmetric uncertainties, and most importantly can be trusted out to distances beyond those that can be inferred from Gaia DR2 parallaxes.

2.2 Coordinate systems and conversion to the Galactocentric frame

Throughout this paper we mainly use the Galactic coordinate system defined by longitude ℓ and latitude b, with heliocentric radial velocity v_r, defined as positive if the object is moving away from the Sun, and tangential velocities v_t, v_b, regarded as positive in the direction of increasing ℓ and b. The tangential velocities are derived from Gaia DR2 proper motions, which we convert from RA, DEC to ℓ, b following Poleski (2018), making use of the covariance matrix when propagating the errors.

We also use a cylindrically Galactocentric coordinate frame, defined by: Galactocentric azimuth φ measured from the centre-anticentre line with φ increasing in the direction of Galactic rotation; Galactocentric radius R_G, and the distance from the mid plane Z. In this frame, the velocities are (u, v, w), with u being the Galactocentric radial velocity, positive in the direction towards the Galactic centre, v being the azimuthal velocity, positive in the direction of rotation, and w being the vertical velocity, positive in the same sense as the Northern Galactic Pole. We calculate u, v, w using a combination of the measured proper motions (in the tangential velocities) and radial velocities,

\[ u = (v_r + k_1) \cos b \cos(\phi + \ell) - (v_b + k_2) \sin(\phi + \ell) \]

\[ v = (v_r + k_1) \cos b \sin(\phi + \ell) + (v_t + k_2) \cos(\phi + \ell) \]

\[ w = (v_r + k_1) \sin b + (v_b + k_3) \cos b \]

in which k_1, k_2 and k_3 account for the Solar motion,

\[ k_1 = U_⊙ \cos \ell \cos b + V_φ,⊙ \sin \ell \cos b + W_⊙ \sin b \]

\[ k_2 = - U_⊙ \sin \ell + V_φ,⊙ \cos \ell \]

\[ k_3 = - U_⊙ \cos \ell \sin b - V_φ,⊙ \sin \ell \sin b + W_⊙ \cos b \]

where (U_⊙, V_φ,⊙, W_⊙) describe the Solar peculiar motion and V_φ,⊙ is the azimuthal velocity of the Sun about the Galactic centre, given by V_φ,⊙=V_⊙+V_⊙ with V_⊙ the azimuthal velocity of the LSR. We adopt for these the values of McMillan (2017): U_⊙ = 8.6 ± 0.9 km s⁻¹, V_φ,⊙ = 13.9 ± 1 km s⁻¹, W_⊙ = 7.1 ± 1.0 km s⁻¹, Vg,⊙ = 247 ± 3 km s⁻¹, and distance of the Sun to the Galactic centre R_⊙ = 8.20 ± 0.09.
3 RESULTS

The data used here is available through CDS, including positions, distances, velocities etc of the final sample (see also the Appendix).

3.1 Radial motion

The trend of \( u \) with Galactocentric distance, \( u(R_G) \), is shown in figure 3 for \( \ell = 178^\circ \) (top) and \( \ell = 118^\circ \) (bottom). Both sightlines show an overall negative gradient in \( u \), determined from the weighted linear regression line (dashed line) fit to the data points, along with some wiggles in the weighted mean trend (green line, shaded to represent standard error of the mean). This negative gradient has been measured previously. For example, López-Corredoira & González-Fernández (2016) and Tian et al. (2017) have both used clump giants located near the anticentre direction to achieve this (note that their definition of \( u \) is opposite in sign to ours). The López-Corredoira & González-Fernández (2016) result is plotted in figure 3 as a dotted black line, and is very similar to our result in the anticentre direction. From the line fitted to our data at \( \ell = 178^\circ \), we find a gradient in Galactocentric radial velocity of \( du/dR_G = -1.67 \pm 0.14 \text{ km s}^{-1} \text{ kpc}^{-1} \), with a zero point at \( R_G(u = 0) = 7.46 \pm 1.13 \text{ kpc} \), to be compared with López-Corredoira & González-Fernández (2016) result of \( du/dR_G = -1.48 \pm 0.35 \text{ km s}^{-1} \text{ kpc}^{-1} \) and \( R_G(u = 0) = 8.84 \pm 2.74 \text{ kpc} \) (Tian et al. 2017) do not fit a linear trend but find the radial profile crosses \( u = 0 \) at \( R_G \sim 9 \text{ kpc} \) which is slightly further out than our measurement. Since the stated values depend on the adopted Solar motion which varies between studies, we have recomputed our results switching to the adopted Solar motions of these earlier works. Our results remain compatible with López-Corredoira & González-Fernández (2016), and still fall short of the \( R_G \sim 9 \text{ kpc} \) cross-point obtained by Tian et al. (2017).

The linear fit to the radial velocity profile at \( \ell = 118^\circ \) is notably different. The measured gradient is steeper than in the anticentre, and the \( u = 0 \) crosspoint is further out: we measure \( du/dR_G = -3.25 \pm 0.15 \text{ km s}^{-1} \text{ kpc}^{-1} \) and \( R_G(u = 0) = 11.23 \pm 0.71 \text{ kpc} \) for the range covered. However if we move away from the idea of a linear trend and examine the mean trend directly, we notice at \( \ell = 118^\circ \) the profile is almost step-like with a section of \( u \sim 10 \text{ km s}^{-1} \) for \( R_G < 11 \), a section of \( u \sim 0 \) from 11 < \( R_G \) (kpc) 13, and a section of \( u \sim -10 \text{ km s}^{-1} \) for \( R_G > 13 \text{ kpc} \).

The wiggles in the running means are likely to be due to the noise level of the data - hence why it is more noticeable in the less well-sampled \( \ell = 178^\circ \) sightline. However, kinematic perturbations in the radial direction, for example linked to spiral arms and/or the bar, could be present. We explore possible explanations for the observed behaviour in the discussion (section 4).

3.2 Azimuthal motion - the rotation curve

The rotation curve, \( v(R_G) \), measured at \( \ell = 178^\circ \) is shown in the top panel of figure 4 (green line). It is roughly flat. The absolute value at which it lies scales directly with the assumed solar motion, \( (U_0, V_{g0}, W_0) \). For our adopted solar azimuthal velocity \( V_{g0} = 247 \text{ km s}^{-1} \), we measure a mean rotation speed over \( R_G = 11 - 15 \text{ kpc} \) of \( 215 \text{ km s}^{-1} \). More generally, it is \( \sim 32 \text{ km s}^{-1} \) slower than the adopted rotation speed of the Sun \( (u - V_{g0} = 215 - 247 = -32 \text{ km s}^{-1}) \). This is consistent with the findings of Kawata et al. (2018a), who use Gaia DR2 proper motions for a very large sample (>10°) of stars located along the Galactic centre-anticentre line to determine the rotation speed. At \( R_G = 10 - 12 \text{ kpc} \), they measure the rotation speed to be \( \sim 31 \text{ km s}^{-1} \) slower than their assumed \( V_{g0} \). Our work confirms this result and almost doubles their range measured in the outer disk, extending to \( R_G = 15 \text{ kpc} \) thanks to the greater reach of our spectro-photometric distance scale.

The rotation curve measured at \( \ell = 118^\circ \), shown in the bottom panel of figure 4 is not the flat profile observed in the anticentre. Instead we observe a gradual increase from \( \sim 222 \text{ km s}^{-1} \) at 10.5 kpc to 242 km s\(^{-1}\) near 14 kpc - that is an increase of \( \sim 20 \text{ km s}^{-1} \) over \( R_G = 10.5 - 14 \text{ kpc} \).

A rising rotation law has been measured before, for example by Tian et al. (2017) in the anticentre direction. It was also measured in H18, who use the same sample as here but with only the heliocentric radial velocity data available. In this situation, it was necessary to make an assumption about the behaviour of \( u(R_G) \). H18 chose to treat \( u(R_G) \) as averaging to zero at all distances along the pencil beam. The H18 result, recalculated using the Solar motion adopted in this paper, is plotted on the \( \ell = 118^\circ \) panel in figure 4 for comparison (yellow line). We see that the new result from this paper, able to take into account proper motion measurements, is slightly flatter than the previous result in H18 - it does not dip as low at \( R_G \sim 10.5 \text{ kpc} \) or reach as high at \( R_G > 13 \text{ kpc} \). Clearly, the presence of a significant radial velocity term that does not average to zero has an impact on the rotation curve deduced from observed stellar motions.

Huang et al. (2016) also measured a sharply rising rotation curve between \( R_G = 11 - 15 \text{ kpc} \) that is very similar to that of H18 by using clump giants sampled over a broad fan of outer disk longitudes. However, unlike H18 they did not make the assumption of zero radial motion, and instead treated a longitude-averaged \( u(R_G) \) as a free parameter in their kinematic model of the Galaxy. The trend they find is much weaker than the \( u(R_G) \) trend we find here at \( \ell = 118^\circ \).

3.3 Vertical motion

Figure 5 shows the vertical velocities as a function of Galactocentric distance, \( v(R_G) \), at \( \ell = 178^\circ \) (top panel) and \( \ell = 118^\circ \) (bottom panel).

In the case of \( \ell = 118^\circ \), the trend is roughly flat. The weighted linear regression line (black dashed) has a slope of \( 0.06 \pm 0.09 \text{ km s}^{-1} \text{ kpc}^{-1} \) - consistent with zero gradient. On average the vertical velocity is slightly positive at \( \sim 2 \text{ km s}^{-1} \), although this scales with the assumed \( W_0 \).

At \( \ell = 178^\circ \) we observe something different. Firstly, the weighted linear regression (black dashed line) returns a slope of \( dw/dR_G = 1.03 \pm 0.13 \text{ km s}^{-1} \text{ kpc}^{-1} \). Secondly, the weighted mean (green line) indicates the trend is also

\(^3\) It also scales with the assumed \( R_0 \), but this is much less significant than the effect from assumed Solar motion.
oscillating. Whilst this wiggling may be in-part due to low number statistics, a similar effect has been noted in previous studies: most recently, Kawata et al. (2018a) use Gaia DR2 proper motions of stars along the Galactic centre-anticentre line out to $R_G = 12$ kpc to find a positive gradient of vertical velocity with Galactocentric radius and they also observe oscillations around this gradient. The results of Schönrich & Dehnen (2018), based on the Gaia-TGAS data set, exhibited this behaviour also. We discuss possible explanations of these perturbations in section 4.3.4.

### 3.4 A and F star comparison - radial motion, asymmetric drift and vertex deviation

In order to determine if there are any intrinsic differences in the kinematics of the A and F stars measured, we examine the $u - v$ plane. Figure 4 shows the $\ell = 178^\circ$ objects in the
**Figure 4.** The rotation curve for $\ell = 178^\circ$ (top) and $\ell = 118^\circ$ (bottom). The green line is the weighted mean of the grey data points, and the shaded region represents the standard error of the mean. The red points are the mean $v$ of 1 kpc bins, and the error bars are the standard error of the binned mean. The blue diamonds are the median $v$ of 1 kpc bins. The yellow line shows the result of H18 for comparison. Arrows indicate the approximate location of the Perseus and Outer Arms (Reid et al. 2014).

In the $u - v$ plane, split into two distance bins: an inner region $10 < R_G \leq 13$, and an outer region $13 < R_G \leq 16$. There are a total of 235 stars (113 A and 122 F) in the inner region, and 117 stars (93 A and 24 F) in the outer region. Similarly, figure 7 shows the $\ell = 118^\circ$ objects in the $u - v$ plane, in distance bins of $9 < R_G \leq 11$, and $11 < R_G \leq 14$. The $\ell = 118^\circ$ distance bins are better sampled than at $\ell = 178^\circ$, with 420 stars (225 A and 195 F) in the inner region and 257 stars (185 A and 72 F) in the outer region. We compare the kinematics of the two stellar types in each distance bin, keeping in mind that the inner bin of each sightline has the largest sample size and most comparable number of A and F stars, and the $\ell = 118^\circ$ sightline in general has the larger number of stars, providing the more robust statistics.

### 3.4.1 Radial motion

The median $u$ values (vertical dashed lines) are consistent within 1σ for the different stellar types in each distance bin.
at $\ell = 178^\circ$. However in the better sampled $\ell = 118^\circ$ distance bins, the $u$ value for A stars is positively offset from the F stars by $\sim 10$ km s$^{-1}$. It is not obvious (to us) why these population samples should exhibit this difference in both the distance regions. Nevertheless, both stellar groups exhibit a positive (inward) radial motion inside $R_G = 11$ kpc, while outwards motion is the norm beyond this radius.

3.4.2 Asymmetric drift

A slight lag in azimuthal velocity of F stars compared to A stars would not be a surprise, since they are slightly older and hence have been subject to larger kinematic scatter and have had more time to build up asymmetric drift. For our sample, the median $v$ values (horizontal dashed lines) are consistent to within $1\sigma$ in all panels in both sightlines, except for the $\ell = 178^\circ$ outer region where the F stars lag the A stars by $12$ km s$^{-1}$. This is the least populated distance bin.

Figure 5. The trend of $w$ with $R_G$ for $\ell = 178^\circ$ (top) and $\ell = 118^\circ$ (bottom). The green line is the weighted mean of the grey data points, and the shaded region represents the standard error of the mean. The red points are the mean $w$ of 1 kpc bins, and the error bars are the standard error of the binned mean. The blue diamonds are the median $w$ of 1 kpc bins. The black dashed line is a weighted linear regression line fit to the grey data points. Arrows indicate the approximate location of the Perseus and Outer Arms (Reid et al. 2014). Note the vertical scale is $2\times$ more sensitive than in the equivalent $u$ and $v$ plots.
with only 24 F stars, and hence the result is accompanied by significant error. Hence, our results indicate the difference in asymmetric drift between A and F stars is negligible.

Asymmetric drift, $v_\phi$, in young stars is small, but the exact magnitude expected for A and F stars is not well known. Dehnen & Binney (1998) use Hipparcos data to study the kinematics of main sequence stars as a function of $B-V$ colour. Figure 10.12 of Dehnen & Merrifield (1998) shows the $v_\phi$ values of their sample. For late A stars with $B-V \sim 0.2$, they find $v_\phi = 4 - 5$ km s$^{-1}$, and for early F stars with $B-V \sim 0.4$, they find $v_\phi = 5 - 6$ km s$^{-1}$. Robin et al. (2017) model the asymmetric drift as a function of $R_G$ and $Z$, and similarly find for stars younger than 1 Gyr the vertex drift is $\lesssim 3$ km s$^{-1}$ in the plane of the disk, increasing by just $\sim 1$ km s$^{-1}$ for stars aged 1 $\sim 2$ Gyr. Kawata et al. (2018) apply an axisymmetric disk model to 218 Galactic Cepheids - young objects like those in our sample - and find negligible asymmetric drift of $0.28 \pm 0.2$ km s$^{-1}$ at $R_0$. Clearly the consistent theme from previous work is that A/F star asymmetric drift is small and hence will not significantly affect our measured rotation curve.

### 3.4.3 Vertex deviation

For the distance ranges with comparable numbers of A and F stars, we calculate the vertex deviation for the two stellar types. The vertex deviation, $l_v$, is the Galactic longitude at which the principal (or major) axis of the velocity ellipsoid is aligned, given by

$$l_v = 0.5 \tan^{-1} \left( \frac{2\sigma_u^2}{\sigma_v^2 - \sigma_u^2} \right)$$

(3)

where $\sigma_u$ and $\sigma_v$ are the velocity dispersions in the $u$ and $v$ velocity components (see table 4), and $\sigma_{uv}^2 = (u - \bar{u})(v - \bar{v})$, with the superposed bar representing the average. Following Vorobyov & Theis (2006) and to account for possible large deviations, we correct $l_v$ with

$$l_v = \begin{cases} 
\bar{l}_v & \sigma_u^2 > \sigma_v^2 \\
\bar{l}_v + \text{sign}(\sigma_{uv}^2) \sqrt{2} & \sigma_u^2 < \sigma_v^2
\end{cases}$$

(4)

We determine the vertex deviation and its uncertainty for the A and F samples using Monte Carlo simulations, drawing each $u$ and $v$ value from a gaussian distribution with spread determined by their individual errors, and calculating $l_v$ with this drawn sample. We do this 1000 times, and take the mean and standard deviation of the resulting distribution as the measured vertex deviation and its corresponding uncertainty. The left panels of figures 6 and 7 show the velocity ellipsoid and principal axis drawn for A stars and F stars. The vertex deviations and velocity dispersions per-
Figure 6. The $\ell = 178^\circ$ objects in the u-v plane split into two distance ranges: an inner region $10 < R_G \text{ (kpc)} \leq 13$ (left), and an outer region $13 < R_G \text{ (kpc)} \leq 16$ (right). Blue circles represent A stars and red crosses represent F stars. The blue (red) dashed lines show the median $u$ and $v$ values for A (F) stars. The black dashed (dotted) lines show the velocity ellipsoid and its major axis, defining the vertex deviation, for the A (F) stars.

Figure 7. The $\ell = 118^\circ$ objects in the u-v plane, split into two distance ranges: an inner region $9 < R_G \text{ (kpc)} \leq 11$ (left), and an outer region $11 < R_G \text{ (kpc)} \leq 14$ (right). Blue circles represent A stars and red crosses represent F stars. The blue (red) dashed lines show the median $u$ and $v$ values for A (F) stars. The black dashed (dotted) lines show the velocity ellipsoid and its major axis, defining the vertex deviation, for the A (F) stars.
sharp step-like feature is predicted in the perturbation as
the sign of \( u \) switches from negative to positive with a
total amplitude of \( 10 - 15 \, \text{km} \, \text{s}^{-1} \) for younger populations.
With increasing \( R_G \) beyond the OLR, this perturbation dies away until, in MD03's model, it is negligible at \( \sim 1.4 R_0 \) (or \( R_G \sim 11.5 \, \text{kpc} \)). The magnitude of perturbation scales with
the strength of the bar potential. Perturbations from higher
order modes such as \( m = 4 \) are also expected, but their
magnitude of effect is considerably smaller – as recently con-
figured by [Hunt & Bovy] (2018) who explored a range of bar
models.

At \( \ell = 118^\circ \), \( \phi_R \) ranges from \( \sim 0 - 15^\circ \) (for a bar oriented
at \( \phi = 30^\circ \), see figure [1]), whereas \( \phi_R \sim 30^\circ \) at \( \ell = 178^\circ \). Since
bar perturbation is strongest at \( \phi_R = 45^\circ \), a weaker signal is
expected at \( \ell = 118^\circ \) than at \( \ell = 178^\circ \). However, comparing
our \( u(R_G) \) profiles, the overall amplitude of change in \( u \) at
\( \ell = 118^\circ \) is greater than at \( \ell = 178^\circ \). Additionally, there is
no clear evidence of the sign switch toward more positive \( u \)
signalling the OLR, and so the data do not inform us about
the location of the OLR. We have to conclude bar perturba-
tion is not the dominant factor shaping the observed radial
velocity profiles.

### 4.2 Spiral structure

Spiral arms also give rise to non-axisymmetric perturbation.
The scale of perturbation expected depends on the model
adopted for the creation of the spiral arms. For example,
[Monari, Famaey & Siebert] (2016) find Galactocentric ra-
dial velocity perturbations of order \( \pm 5 \, \text{km} \, \text{s}^{-1} \) within and
between the arms, by simulating the effect of a spiral po-
tential on the Milky Way thin stellar disk. Observationally,
[Grosbol & Carraro] (2018) support this by using B and A
type stars in the Galactic centre direction to measure radial
perturbations of \( 3 - 4 \, \text{km} \, \text{s}^{-1} \), and although they focus on
density wave theory their results can not exclude a transient
perturbation.

Examining our results at \( \ell = 178^\circ \), the wiggles in the
mean trend of \( u \) in figure [2] do not correlate with the location of
spiral arms (black arrows), and seem to have a wavelength
too short to link to spiral arm perturbations expected from
spiral density wave theory. These bumps could be noise due
to low-number statistics. At \( \ell = 118^\circ \) we see a small bump in the trend at \( 10 - 11 \, \text{kpc} \), slightly further out than the
Perseus Arm, and also possibly at \( 12 - 13 \, \text{kpc} \), close to the
Outer Arm, but it is difficult to determine if these are real
features or if again, they are noise. This was already evident
in the results of H18.

Studies favouring the transient winding arm view pre-
dict a change in the velocity field across spiral arms. The
general picture of a spiral arm in its mid-life phase is that,
on the trailing side of the arm, stars rotate more slowly and
move radially outwards, whereas stars on the leading side
rotate faster and move radially inwards ([Grand, Kawata &
Cropper] 2012; [Kawata et al. 2014]). [Grand et al.] (2016) con-
side the transient winding arm model and find the radial
perturbation of young stars (< 3 Gyr) to be considerably
stronger at up to \( \pm 20 \, \text{km} \, \text{s}^{-1} \) across the loci of the arm. They
find the azimuthal perturbation to be of order \( \sim 10 \, \text{km} \, \text{s}^{-1} \).
[Baba et al.] (2015) (hereafter B18) use Cepheids with Gaia
DR1 data to confirm a velocity field that changes on crossing
the Perseus Arm. However, they measure the trailing side to
be rotating faster and moving inward toward the Galactic
centre compared to the leading side - i.e of opposite sense
to a transient arm in its mid-life phase. They attribute this
pattern to the arm being in the disruption phase.

In order to test whether there is a difference in the velocity
field on either side of an arm, as predicted from transient
winding arm theory, we follow the concept of B18 and
compare median \( u \) and \( v \) values within \( 0.2 - 1.5 \, \text{kpc} \) of the locus
of the Outer Arm (as determined by [Reid et al.] 2014). We
restrict our analysis to the Outer Arm since we have com-
parable sample sizes for the two (leading & trailing) sides
in both sightlines. Our results are summarised in table [2].
In our sightlines the trailing side of the arm has a smaller \( R_G \)
than the leading.

The median \( u \) and \( v \) values are consistent within \( 1 \sigma \)
errors across the Outer Arm at \( \ell = 178^\circ \), going against ex-
pectations of transient winding arm theory. However, there
is a significant difference in median \( u \) values and \( v \) values
on either side of the Arm at \( \ell = 118^\circ \). The leading side is
rotating faster than the trailing side. At the same time, the
arm is migrating radially outwards on the whole, but the
leading side is moving faster and hence the Arm appears to
be expanding in this sightline. This points to a combination
of \( u \) and \( v \) perturbations that do not fit consistently with
the mid-life stage of the transient winding arm model.

### Table 1. Velocity dispersions and vertex deviations for the A and F stars at \( R_G = 10 - 13 \, \text{kpc} \) at \( \ell = 178^\circ \) and \( R_G = 9 - 11 \, \text{kpc} \) at
\( \ell = 118^\circ \). \( \sigma_u \) and \( \sigma_v \) are dispersions along the Galactocentric radial and azimuthal directions, and \( \sigma_1 \) and \( \sigma_2 \) are dispersions along the
principal axes of the velocity ellipsoid.

| Sightline & distance | A/F | \( \sigma_u \) (kms\(^{-1}\)) | \( \sigma_v \) (kms\(^{-1}\)) | \( \sigma_1 \) (kms\(^{-1}\)) | \( \sigma_2 \) (kms\(^{-1}\)) | \( \nu_1 \) (deg) |
|---------------------|-----|-----------------|-----------------|-----------------|-----------------|----------------|
| 178\(^\circ\)       | A   | 21.0 ± 1.4      | 0.74 ± 0.06     | 21.7 ± 1.8      | 0.63 ± 0.06     | −10 ± 3        |
| \( 10 < R_G \) (kpc)\( \leq 13 \) | F   | 29.3 ± 3.4      | 0.73 ± 0.10     | 26.8 ± 2.5      | 0.91 ± 0.11     | −49 ± 17       |
| 118\(^\circ\)       | A   | 16.1 ± 0.8      | 0.95 ± 0.06     | 17.8 ± 0.8      | 0.77 ± 0.04     | −19 ± 4        |
| \( 9 < R_G \) (kpc)\( \leq 11 \) | F   | 29.0 ± 2.2      | 0.60 ± 0.05     | 28.5 ± 1.7      | 0.60 ± 0.05     | −7 ± 4         |

### Table 2. Median \( u \) and \( v \) values (kms\(^{-1}\)) for the trailing side and leading side of the Outer Arm at \( \ell = 178^\circ \) (top rows) and \( \ell = 118^\circ \) (bottom rows). The number of objects in each subsample is also shown.

| \( \ell \) | Subside | \( u \) | \( v \) | N  |
|----------|---------|-------|-------|----|
| 178\(^\circ\) | Trailing | −9.3 ± 3.2 | 217 ± 3 | 94 |
|          | Leading  | −11.8 ± 4.7 | 213 ± 5 | 35 |
| 118\(^\circ\) | Trailing | −0.6 ± 2.3 | 227 ± 2 | 169|
|          | Leading  | −11.7 ± 3.5 | 243 ± 3 | 61 |

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4.3 Satellites and the warp

Perturbations of vertical velocities can arise due to the passage of a satellite galaxy through the Galactic disk. Gmez et al. (2013) simulate the vertical density waves induced by the Sagittarius dwarf galaxy, and find vertical velocity perturbations of up to 8 km s$^{-1}$ in the outer disk. Ankoja et al. (2018) explore the vertical phase-space of more than 6 million Gaia DR2 stars and reveal a spiral-like distribution which could be caused by the latest passage of the Sagittarius dwarf galaxy, between 300 and 900 Myr ago. Additionally, large-scale systematic vertical velocities are expected due to the warp in the anticentre region. Poggio et al. (2018) confirm this using Gaia DR2 kinematics of both upper main sequence stars and giants, measuring an increase in vertical velocity of 5–6 km s$^{-1}$ over $R_G = 8 – 14$ kpc (i.e. $dw/dR_G \sim 1$ km s$^{-1}$ kpc$^{-1}$).

As noted in section 3.3, we observe a statistically significant positive gradient of $dw/dR_G = 1.03 \pm 0.13$ km s$^{-1}$ kpc$^{-1}$ at $\ell = 178^\circ$. This is in good agreement with the gradient measured in Poggio et al. (2018) due to the warp. The kinematic response to the warp is expected to be strongest in the anticentre direction, and hence it is unsurprising that we measure a steeper gradient at $\ell = 178^\circ$ than at $\ell = 118^\circ$. The oscillations observed in vertical velocity at $\ell = 178^\circ$ may be a kinematic signature from a satellite crossing the plane of the Milky Way, such as the Sagittarius dwarf galaxy as discussed in Gmez et al. (2013). It is expected that perturbations of this type present as mainly radially-dependent perturbations throughout the disk (see figure 5 of Gmez et al. 2013). However, we do not observe obviously correlated perturbations in the $\ell = 118^\circ$ sightline, which somewhat complicates the picture.

5 CONCLUSIONS

We have reused the sample of A and F stars from H18 with their radial velocities and spectro-photometric distances, and crossmatched with Gaia DR2 to bring in proper motions in order to obtain full space motions. Our spectro-photometric distance scale reaches almost twice as far as those that can be inferred from Gaia DR2 parallaxes. For example, Kawata et al. (2018a) use Gaia DR2 parallaxes to sample out to $R_G = 12$ kpc - a distance of under 4 kpc from the Sun in the anticentre direction, whereas our spectro-photometric scale extends to $R_G \sim 15$ kpc - almost 7 kpc from the Sun in the anticentre direction. We have examined the profile of radial, azimuthal and vertical velocities with Galactocentric radius. Our main results are:

- We measure the rotation curve in the anticentre direction to be roughly flat (figure 4), at a value that is 32 km s$^{-1}$ slower than the speed of the Sun. This confirms the recent work of Kawata et al. (2018a), but with the use of our spectro-photometric distances we extend this result to just short of $R_G = 15$ kpc.
- The rotation curve at $\ell = 118^\circ$ is different from that at $\ell = 178^\circ$ - it rises outwards from $R_G = 10.5$ kpc. We measure an increase of circular speed of roughly $+20$ km s$^{-1}$ in the range $10.5 < R_G$ (kpc) $< 14$, from $222$ km s$^{-1}$ to $242$ km s$^{-1}$. Additionally, we note the significance of the $u$ behaviour in the determination of the rotation curve. In H18, our previous study, only radial velocity data were available and hence an assumption about the mean $u$ behaviour as a function of $R_G$ was required. This resulted in a rotation curve with a steeper incline than here. By making use of the full space motions, as we do here, a rising rotation curve is still apparent but moderated compared to that of H18.

- The gradient in the Galactocentric radial velocity profile $(du/dR_G)$ is surprisingly steep at $\ell = 118^\circ$ compared to the more gentle gradient found at $\ell = 178^\circ$ that has also been reported in previous studies (see figure 4). This rules out the central bar as a dominant perturber shaping the $u(R_G)$ profile. We also find no consistent interpretation of our Outer Arm velocities in terms of the transient winding arm model. Additionally, we find that radial expansion at large radii is observed in both sightlines. It is apparent that in order to fully explain our results, a model encompassing all perturbers simultaneously may be required.

- The vertical velocity profile in the anticentre direction has a positive gradient of $dw/dR_G = 1.03 \pm 0.13$ km s$^{-1}$ which could be a signature of the warp in the outer disc. This profile also shows some oscillation. Previous studies have also noted this. This is not replicated in the $\ell = 118^\circ$ direction.

- We have separated and compared the median in-plane velocities and vertex deviations of the A and F stars. At $\ell = 118^\circ$ the radial velocity of the A stars is larger than that of the F stars by $\sim 10$ km s$^{-1}$, however at $\ell = 178^\circ$ there is no perceptible difference between the two types of star. Why the A and F stars at $\ell = 118^\circ$ should exhibit so much a difference out to large $R_G$ is unclear. The azimuthal velocities are broadly consistent between the two populations. This implies that asymmetric drift is comparable for A and F stars.

For this work we are privileged to have full space motions of our sample and hence are able to reframe them as Galactocentric velocities with no prior assumptions. By examining only two sightlines in the outer disk, we have demonstrated the significant kinematic variations resulting from the real non-axisymmetric Galactic disk. The need grows to acknowledge departures from a simple uniform rotation law for the Galactic disk. A rotation law that deviates from the often-used flat law has strong consequences for kinematic distance determinations. For example, an object that is really at a distance of 8 kpc at $\ell = 118^\circ$ would deliver a radial velocity that would return a distance of $\sim 6$ kpc if the assumed rotation law was the same flat law as applies at $\ell = 178^\circ$. This is an error in the region of 30%.

There is a history of reported velocity anomalies in a longitude range that includes the $\ell = 118^\circ$ sightline. Brand & Blitz (1993), for instance, presented a map of observed H II region radial velocities projected onto the Galactic plane, revealing surprisingly little variation of radial velocity over the range $110^\circ < \ell < 140^\circ$. Russell (2003) reported a departure of $-21 \pm 10.3$ km s$^{-1}$ from mean circular speed related to the Perseus Arm over $90^\circ < \ell < 150^\circ$. CO and H I data, as presented in Reid et al. (2016), favour differing velocities in this longitude range, with H I preferring typically more negative radial velocities than the CO, to the tune of $\sim 10 – 20$ km s$^{-1}$. Further studies like the one here will begin to fill out the picture of how exactly such anomalies arise and set contraints on their origin.
The opportunities for the kind of work presented here will increase as the next generation of massively-multiplexed spectrographs come into use. As an example, the WHT (William Herschel Telescope) Enhanced Area Velocity Explorer (WEAVE, Dalton et al. 2016) will complete the kinematics of the northern hemisphere stars, capturing much of the outer Galactic disk. Here, and in H18, we have established a method that can turn results on younger earlier-type stars from such a facility into new and distinctive insights into disk structure.

6 ACKNOWLEDGEMENTS

We thank Walter Dehnen for helpful comments regarding perturbations from the central bar. We are also grateful to the anonymous referee for useful comments which helped to improve the paper. AH acknowledges support from the UK’s Science and Technology Facilities Council (STFC), grant no. ST/K502029/1. JED and MM acknowledge funding via STFC grants ST/J001333/1 and ST/M001008/1. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

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APPENDIX A: TABLE OF DATA

The data used in this paper is available through CDS. Table A details the presented columns.
| Column | Label       | Units         | Description                                           |
|--------|-------------|---------------|-------------------------------------------------------|
| 1      | ID          | —             | Target ID                                             |
| 2      | RAJ2000     | deg           | Right ascension (J2000.0)                             |
| 3      | DEJ2000     | deg           | Declination (J2000.0)                                |
| 4      | GLON        | deg           | Galactic longitude                                   |
| 5      | GLAT        | deg           | Galactic latitude                                    |
| 6      | HRV         | km s\(^{-1}\) | Heliocentric radial velocity                         |
| 7      | e\(_{HRV}\) | km s\(^{-1}\) | Radial velocity negative error                        |
| 8      | E\(_{HRV}\) | km s\(^{-1}\) | Radial velocity positive error                        |
| 9      | Dist        | kpc           | Heliocentric distance                                |
| 10     | e\(_{Dist}\) | kpc           | Heliocentric distance error                          |
| 11     | RG          | kpc           | Galactocentric distance                              |
| 12     | e\(_{RG}\)  | kpc           | Galactocentric distance error                         |
| 13     | SourceID    | —             | Gaia Source ID                                       |
| 14     | pmlcosb     | mas yr\(^{-1}\)| Proper motion in Galactic longitude direction (multiplied by cos(b) factor) |
| 15     | e\(_{pmlcosb}\) | mas yr\(^{-1}\)| Error of proper motion in Galactic longitude direction |
| 16     | pmb         | mas yr\(^{-1}\)| Proper motion in Galactic latitude direction         |
| 17     | e\(_{pmb}\)  | mas yr\(^{-1}\)| Error of proper motion in Galactic latitude direction |
| 18     | u           | km s\(^{-1}\) | Galactocentric radial velocity                       |
| 19     | e\(_{u}\)  | km s\(^{-1}\) | Galactocentric radial velocity error                 |
| 20     | v           | km s\(^{-1}\) | Galactocentric azimuthal velocity                    |
| 21     | e\(_{v}\)  | km s\(^{-1}\) | Galactocentric azimuthal velocity error              |
| 22     | w           | km s\(^{-1}\) | Galactocentric vertical velocity                     |
| 23     | e\(_{w}\)  | km s\(^{-1}\) | Galactocentric vertical velocity error               |

Table A1. The columns presented in the table of data, available through CDS.