Gaia DR3 and nearby galaxies: where do foregrounds matter?

P. Barmby

Department of Physics & Astronomy and Institute for Earth and Space Exploration, Western University, London, Canada N6A 3K7

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ABSTRACT

Nearby galaxies provide populations of stellar and non-stellar sources at a common distance and in quantifiable environments. All are observed through the Milky Way foreground, with varying degrees of contamination that depend on observed Galactic latitude and the distance and size of the target galaxy. This work uses Gaia Data Release 3 (DR3) to identify foreground sources via astrometric measurements and thus quantify foreground contamination for a large sample of nearby galaxies. There are approximately half a million Gaia sources in the directions of 1401 galaxies listed in the Local Volume Galaxy catalogue (D < 11 Mpc), excluding the largest Local Group galaxies. About two thirds of the Gaia sources have astrometric properties consistent with foreground sources; these sources are brighter, redder, and less centrally-concentrated than non-foreground sources. Averaged over galaxies, foreground sources make up 50 per cent of Gaia sources at projected radius $r_{50} = 1.06a_{26}$, where $a_{26}$ is the angular diameter at the $B = 26.5$ isophote. Foreground sources make up 50 per cent of Gaia sources at apparent magnitude $m_{G,50} = 20.50$. This limit corresponds to the tip of the red giant branch absolute magnitude at $D = 450$ kpc, and to the globular cluster luminosity function peak absolute magnitude at 5 Mpc. Gaia data provide a powerful tool for removing foreground contamination in stellar population studies of nearby galaxies, although Gaia foreground removal will be incomplete beyond distances of 5 Mpc.

Key words: galaxies: stellar content – Galaxy: stellar content – parallaxes – proper motions – astronomical data bases: miscellaneous

1 INTRODUCTION

Observations of nearby external galaxies form the basis for understanding the diversity of present-day galaxy properties and their variation with internal and external environment. They complement studies of the Milky Way, where detailed studies of individual constituent objects are possible but measurement of distances to these objects and of integrated galaxy properties are difficult. Unlike the situation for distant galaxies, with nearby galaxies one cannot simply choose to study only sources at high Galactic latitudes and expect to get a complete picture of the population. Nearby galaxies are viewed through the Milky Way and their study is complicated by extinction from the Galactic interstellar medium and contamination from foreground Galactic stellar populations.

The Gaia mission (Gaia Collaboration 2016; Gaia Collaboration et al. 2022c) provides a new way to characterise the Galactic foreground stellar populations in front of nearby galaxies, and in some cases the contents of the galaxies themselves. The power of the Gaia data is found in their uniformity across the sky and well-characterised uncertainties. All-sky maps of Gaia source density demonstrate that the Gaia data contain many extragalactic sources: see, for example, figure 3 of Boubert & Everall (2020), in which the Magellanic Clouds and M31 as well as several Galactic star clusters are clearly visible off the plane of the Milky Way. The faintest sources with reliable parallax measurements have distances less than a few kiloparsecs, so a parallax measurement for such a source is an unambiguous indication that an object cannot be a member of even the nearest external galaxies. Reliable measurement of stellar proper motions extends to more distant stars and can be used to associate a star with either the Milky Way or a nearby galaxy (e.g. McConnachie et al. 2021; Battaglia et al. 2021). Non-detection of parallax or proper motion is a necessary but not sufficient indicator that an object is located beyond the Milky Way. For example, in searching for globular cluster candidates around NGC 1399 and NGC 3115, Buzzo et al. (2022) excluded sources whose Gaia proper motions were inconsistent with zero.

As well as using Gaia data to identify foreground contaminants, several recent works have made use of Gaia data to study the stellar contents of nearby galaxies themselves. Some examples include Grady et al. (2021), who mapped structures in the Magellanic Clouds using photometric estimates of individual stellar metallicities, McConnachie et al. (2021) who used Gaia proper motions to investigate the orbits of isolated Local Group dwarf galaxies, Huang & Kopysov (2021) who searched for globular clusters associated with Milky Way dwarf satellites and Qi et al. (2022) who studied stellar proper motions in the outskirts of Milky Way dwarf satellites. Gaia observations have been used to measure average proper motions of Local Group galaxies such as M31 and M33 (van der Marel et al. 2019) and to identify individual supergiant stars in M31 and M33 (Massey et al. 2021; Maravelias et al. 2022), the LMC (Yang et al. 2021a) and NGC 6822 (Yang et al. 2021b). As one of the nearest large galaxies outside the Local Group, NGC 5128 is an attractive target for Gaia studies. Voggel et al. (2020) and Hughes et al. (2021) used Gaia observations to identify new candidate ultra-compact dwarf galaxies (UCDs) and
luminous globular clusters in this galaxy’s halo. Voggel et al. (2020) estimated that Gaia studies can identify UCDs out to distances of approximately 25 Mpc. Several pre-launch predictions on Gaia detection of much more distant, unresolved galaxies (de Souza et al. 2014; de Bruijne et al. 2015) have not yet been followed-up with Gaia studies.

The purpose of this work is to inventory the contents of Gaia Data Release 3 (DR3) in the directions of nearby galaxies. With a a well-defined method for determining which sources have parallaxes and/or proper motions inconsistent with a target galaxy, the number, spatial distribution, and apparent magnitude distributions can be compared between foreground and non-foreground sources on a per-galaxy basis. The apparent magnitude distributions can also be compared to relevant luminosities of sources within the target galaxies. The overall research question is “where do foregrounds matter?” as determined by projected galactocentric radius within a galaxy field, position within the colour-magnitude diagram, and overall galaxy properties.

2 DATA AND METHODS

The characteristics of Gaia DR3 are described in detail by Gaia Collaboration et al. (2022c). Briefly, Gaia DR3 contains 1.8 × 10⁹ objects detected down to limiting magnitudes of G ~ 21, with five- or six-parameter astrometry (position, proper motion, parallax) for approximately two thirds of these. The Gaia data are still being collected and processed, and as such the precision and accuracy vary across the sky depending on how many times a particular area has been scanned (Lindegren et al. 2021). As a rough indication, typical Gaia uncertainties are 0.5 mas yr⁻¹ in proper motion and 0.5 mas in parallax at G ≈ 20, with uncertainties roughly a factor of 20 smaller for G < 15. Most stars in even the nearest Milky Way satellites are too faint for accurate Gaia parallax measurements, but individual proper motions are measurable for the brightest stars in galaxies throughout the Local Group (e.g. McConnachie & Venn 2020; Battaglia et al. 2021).

As a sample of nearby galaxies, I chose the Local Volume Galaxy sample of Karachentsev et al. (2013, hereafter LVG)¹. The catalogue contains 1421 objects that are located within 11 Mpc of the Milky Way or that have measured radial velocities < 600 km s⁻¹ with respect to the Local Group centroid. It does not include the Virgo cluster but does include over a dozen groups similar in size and population to the Local Group (Karachentsev et al. 2013). The majority of galaxies within the volume are classified as spheroidal dwarfs, with L/Lₘₜ < 10⁻⁴, typical radius ~ 2 kpc, and typical mass within the Holmberg radius ~ 10⁵ M☉. Because the nearest large galaxies have already been the subject of individual investigations with Gaia, I removed M31, M33, Sagittarius dSph, the Large and Small Magellanic Clouds, and the Milky Way itself, from the present study. Also removed were M32, because it is seen in projection against the M31 disk and will thus be heavily contaminated, and the large-angular-diameter dwarfs Antlia 2, Crater 2, and Böötes III (Torrealba et al. 2019, 2016; Grillmair 2009), which are expected to be completely dominated by foreground sources. Ten galaxies listed in the LVG without visible-light size measurements were also removed; these are poorly-studied objects detected only by their 21 cm atomic hydrogen emission. The final source list contains 1401 galaxies.

There is no one way to define the size of a galaxy; for the purposes of this study a consistent measure is needed. As a size indicator to define a Gaia search radius, I used the LVG-reported values of a₂₆ (the angular diameter at the B = 26.5 isophote) as the radius of a search cone. Extending the search cone to double the isophotal radius was done with the intention of reaching foreground-dominated galactocentric distances.

Foreground sources are identified based on their DR3 parallaxes (π) and proper motions (µ) ⋇ the corresponding uncertainties in those quantities and the covariances between them (σπ, σµ, Cov(µ)). Sources are identified as foreground at a level of significance nor if they satisfy either of two criteria similar to those used by Gaia Collaboration et al. (2022a), either significant non-zero parallax:

\[ \frac{\sigma + 0.017}{\sigma_{\pi}} > n \]  \hspace{1cm} (1)

where 0.017 mas is the median parallax zeropoint determined by Lindegren et al. (2021), or significant non-zero proper motion:

\[ \left| \begin{array}{c} \mu_x' \\ \mu_y' \end{array} \right| \text{Cov(µ)}^{-1} \left| \begin{array}{c} \mu_x \\ \mu_y \end{array} \right| > n^2. \]  \hspace{1cm} (2)

Equation 2 is implemented following Gaia Collaboration et al. (2022a) as

\[ (\text{power(pmra/pmra_error,2)} \>	ext{power(pmdec/pmdec_error,2)} \) + 2*pmra_pmdec_corr * pmra/pmra_error *pmdec/pmdec_error )/(1-power(pmra_pmdec_corr,2)) > power(n,2) \]

The analysis here differs from that of Gaia Collaboration et al. (2022a), who were concerned with identifying distant sources to define the celestial reference frame. As discussed in section 1, some galaxies with the Local Group are near enough for their stars to have proper motions measurable with Gaia. For these galaxies I add an additional classification criterion; for a source to be classified as foreground, it must have proper motions incompatible with the parent galaxy’s systemic proper motion as listed by Battaglia et al. (2021):

\[ (\mu_x' ± n\sigma_{\mu_x'}) \notin (\mu_x/\delta + n\sigma_{\mu_x/\delta}) \]  \hspace{1cm} (3)

and/or

\[ (\mu_x ± n\sigma_{\mu_x}) \notin (\mu_x/\delta + n\sigma_{\mu_x/\delta}) \]  \hspace{1cm} (4)

Sources without astrometric measurements are classified as non-foreground. In the analysis that follows, n = 2, 3, 5, 10 are considered.

Unlike other Gaia analyses where the goal is to select a high-quality sample with a high membership probability for a specific galaxy, here the goal is to achieve a broad characterization of the DR3 contents around nearby galaxies. As such, I did not apply quality flags when selecting Gaia sources, or attempt to use them to separate background galaxies from members of the target nearby galaxies. Previous studies of nearby galaxies provide additional information that could be used to determine whether a source is in the foreground, in the target galaxy, or in the background: for example, radial velocity measurements, high-resolution imaging, and multi-wavelength detection. Such information is valuable but also wildly heterogeneous across galaxies; in the interests of consistency, it was not used here. As described by Gaia Collaboration et al. (2021), Gaia measurements in regions of high projected stellar densities are potentially affected by crowding. This effect is a potential shortcoming of the present analysis; correcting for it is beyond the scope of this study.

¹ This catalogue has been updated since the above publication; the edition dated 2022 June was used, downloaded from http://www.sao.ru/lv/ lvgdb/.
work. Some of the very brightest Galactic stars are not (yet) included in the Gaia processing or DR3 database (Gaia Collaboration et al. 2021), but as these are rare their omission should not significantly affect the results.

After identifying foreground and non-foreground Gaia sources in the direction of each galaxy field, distributions of foreground and total source densities in both projected galactocentric distance and magnitude are compared. To ensure meaningful measurements that are not dominated by small number statistics, these distributions are computed only for galaxies with 50 or more Gaia sources. Kernel density estimates of the two distributions are performed separately, then used to compute the ratio of foreground to total sources which is then fit to a polynomial that is used to compute the radius or apparent magnitude at which 50 per cent of the sources are foreground, denoted as $r_{50}$ and $m_{50}$, respectively.

2.1 Case study: NGC 2403

Example outputs of the procedure for an individual galaxy field, NGC 2403, are shown in Figures 1–3. NGC 2403 is a spiral in the outskirts of the M81 group, at a Galactic latitude of $b = 29.2^\circ$ and with foreground extinction $E(B - V) = 0.11$. For comparison, I also show the results from applying the same algorithm to a control field of the same area and at the same Galactic latitude about a degree away. For both fields, foreground sources were identified using Equation 1 for non-zero parallax or Equation 2 for significant non-zero proper motion; Eqns 3 and 4 were not used since no proper motion for NGC 2403 is available. Results show that the proper motion criterion (Eqn. 2) dominates the foreground identification at all galactocentric distances: nearly all sources with significant parallaxes also have significant proper motions, but many sources have significant proper motions without significant parallax.

The galaxy field contained 33 per cent more Gaia sources over the same area, compared to the control field, indicating that at least some Gaia sources likely belong to the galaxy. There are 6389 Gaia sources within a projected radius of $a_{26} = 28.2$ from NGC 2403, of which 4424, 4115, 3775, and 3202 are identified as foreground at $n = 2$, 3, 5, and 10σ, significance, respectively. The control field contains 4808 sources, of which 3964, 3805, 3539, and 3019 are identified as foreground at the same significance. To demonstrate the effect of $n$ in foreground versus background classification, the sources are separated into three groups: the most likely foreground sources (classified as foreground at $n = 10$), the most likely non-foreground sources (classified as non-foreground at $n = 2$), and ambiguous sources which do not fall into either of the above two groups. The ambiguous sources make up similar fractions (19 and 20 per cent, respectively) of the total for galaxy and control field, respectively; however, the galaxy field has a greater proportion of non-foreground sources (31 per cent) than the control field (18 per cent).

Figure 1 shows that the density of Gaia sources, and particularly the highest-confidence non-foreground sources, is highest near the centre of the galaxy field and declines toward its outskirts. No similar central concentration is observed for the control field. These distributions are again consistent with the expectation that at least some Gaia sources belong to the target galaxy.

Figure 2 shows the spatial distribution of Gaia sources in NGC 2403 and the control field, marginalised to the radial distribution. This representation more clearly shows the decline in total source density, and the increase in the proportion of sources identified as foreground, with radius. Sources categorised as ambiguous show a density profile intermediate between the foreground and non-foreground sources, indicating that this category is a mixture of the other two. The increased density of foreground and ambiguous sources in the innermost bin is unphysical and is likely due to the limitations of the procedure and/or the Gaia data in crowded regions. (When binned by galactocentric distance, sources with $R_{GC} < 0.1a_{26}$ have mean uncertainties in both proper motion and parallax measurements about 50 per cent higher than those in the galaxy outskirts.) As expected, the projected density of control field sources shows no concentration toward the centre of the field.

Finally, Figure 3 shows the distribution of the different source categories in colour-magnitude space. Most of the brightest sources are foreground. The fraction of non-foreground sources increases at fainter magnitudes and toward bluer colours, and the ambiguous sources are again located between the foreground and non-foreground sources. The foreground sources with $R_{GC} < 0.1a_{26}$ are intermediate in colour and magnitude between foreground sources beyond this projected radius and non-foreground sources. The control field colour-magnitude distribution is similar to the galaxy field distribu-
Figure 2. Left axis: projected number densities (left axis) versus projected galactocentric radius for Gaia sources within a 28.1 arcmin radius of NGC 2403 and a control field. Black points: non-foreground sources, dark grey points: ambiguous sources, light grey points: foreground sources. Right axis and dashed grey line: ratio of foreground/non-foreground source densities.

Figure 3. Colour-magnitude diagram of foreground (light grey), ambiguous (dark grey) and non-foreground (black) Gaia sources within a 28.1 arcmin radius of NGC 2403 (upper panel) and a control field (lower panel). Measurements are not corrected for extinction.

3 RESULTS

3.1 Gaia source numbers and densities per galaxy field

451422 Gaia DR3 sources are detected within a radial distance \( r < a_{26} \) specified individually for each of the 1401 galaxies in the sample. Of these sources, a small fraction (0.6 per cent) are duplicates that lie within the search cones of multiple galaxies. These duplicates are spread over 39 pairs of parent galaxies and as such are not expected to strongly affect the results. They were retained in the sample. Figure 4 shows that the distribution of \( N_{\text{Gaia}} \) approximately follows a power law: most galaxy fields have only a few Gaia DR3 sources, while a handful have thousands. A total of 309 galaxy field positions have no Gaia sources at all, either foreground or non-foreground. A similar number (298) of galaxy fields have 50 or more Gaia sources, the minimum set for comparing the distribution of foreground and total Gaia sources with galactocentric distance or magnitude within an individual galaxy field.

All galaxy fields except six\(^2\) have \( N_{\text{Gaia}} < 12000 \), and the remainder have \( N_{\text{Gaia}} > 20000 \). Listed in descending order by number of Gaia sources, these six galaxies are NGC 4945, NGC 5128, the Fornax dSph, ESO 274-001, Circinus, and NGC 6822. Fornax is a very nearby (\( d = 140 \) kpc) Milky Way satellite, NGC 6822 is a Local Group dwarf irregular (\( d = 520 \) kpc), and the other four objects are much more distant galaxies (3–4 Mpc) seen at low Galactic latitude.

NGC 5128 is a giant elliptical while NGC 4945, Circinus, and ESO 274-001 are edge-on disk galaxies. Although five of the six (excluding Circinus) have large angular diameters (\( a_{26} \geq 15 \) arcmin), they are by no means the only large galaxies in the LVG sample: 37 galaxies fulfil this size criterion.\(^3\)

As expected, galaxies that sublend a larger area on the sky often have more Gaia sources detected: both foreground and non-foreground sources should increase with area. This can be accounted for by computing the average projected source density as \( \Sigma = N_{\text{Gaia}}/\pi a_{26}^2 \). As Figure 5 shows, the projected source density varies by about three orders of magnitude between galaxies, so galaxy size is not the only driver of Gaia source numbers. There is a break in

\(^2\) The reader is reminded that 10 of the largest galaxies are not included here.

\(^3\) The size of M31 dwarf companion And XIX as listed in the LVG is anomalously large at 28'4. That this is likely one of the galaxies discussed by Karachentsev et al. (2013) as a “dwarf extremely low surface brightness [where] the diameter \( a_{26} \) instead corresponds to the exponential scale \( h \) of [the] brightness profile.”
the projected density distribution at $\Sigma \sim 25$ arcmin$^{-2}$: galaxies above this break with $N_{\text{Gaia}} > 50$ are Fornax (for total sources but not foreground sources), Circinus, and ESO 274-001, discussed above, and ten faint irregular galaxies at $|b| < 10^\circ$ that are foreground-dominated or that may have poor size measurements (ESO 273-014, ESO 223-009, ESO 137-018, RKK1610, EZOA J2120+45, [KK2000] 59, HIPASS J1441-62, HIZOA J1616-55, Bedin 1).

Some but not all of the projected density variation between galaxy fields is due to Galactic foreground. Figure 6 shows that while there is a general trend that the minimum source density per galaxy field increases at lower Galactic latitude, many low-latitude galaxies have few Gaia sources, and some high-latitude nearby galaxies have many. At high Galactic latitudes ($|b| > 25^\circ$) the relationship between $b$ and projected source density is weak, with a scatter of about 1 dex. Non-foreground source density might be expected to be independent of galactic latitude or even to decrease towards low $|b|$; however, Figure 6 does not confirm these expectations. This implies that some sources identified here as non-foreground, even with a low threshold for significant proper motions, likely belong to the foreground. This incompleteness is quantified using spatial distributions in the following subsection.

The classification of Gaia sources provided by Delchambre et al. (2022) provides a check on the quality of this work’s classification based on astrometric criteria. Briefly, Delchambre et al. (2022) classified Gaia sources as stars, galaxies, quasars, white dwarfs or physical binary stars, using a combination of astrometric, photometric, and position information. Extragalactic stars or other components of nearby galaxies are not a focus of that investigation, and indeed those authors remark that sources projected near the Magellanic Clouds suffer significant misclassification. A detailed study of these classifications is the subject of future work (Hales & Barmby, in prep.); as a first comparison to the astrometric classification, I use the DR3 entry `classprob_dsc_combmod` entry and assign each source the classification with the highest combined probability above 50 per cent, and consider the foreground/non-foreground separation at 3$\sigma$ significance. Stars vastly outnumber all other categories in the Delchambre et al. (2022) classification: overall, 92 per cent of Gaia DR3 sources in the vicinity of nearby galaxies (97 per cent of foreground sources and 84 per cent of non-foreground sources) are classified as stars. As Delchambre et al. (2022) point out, such a large class imbalance complicates accuracy computations, since classifying every source as a star would result in a reasonably high accuracy. Considering the extragalactic sources in the vicinity of nearby galaxies as classified by Delchambre et al. (2022), 91 per cent of the 9760 quasars and 80 per cent of the 7028 galaxies were classified as non-foreground by the astrometric criteria in Eqns. 1–4. This comparison shows that the astrometric criteria are producing results consistent with the more complex classification possible from using more Gaia measurements.

3.2 Foreground and non-foreground Gaia sources: spatial distributions

Over the nearly half a million Gaia sources detected in the vicinity of nearby galaxies, 65.5 per cent are identified as foreground stars by applying the algorithm above to DR3 parallax or proper motion mea-
Figure 7. Surface density as a function of scaled galactocentric radius ($r = r_{GC}/(2a_{26})$) for foreground and non-foreground Gaia sources in the vicinity of nearby galaxies. Dashed line shows the ratio of foreground to non-foreground density.

...result of amalgamating data from many galaxies, the exact value of $n$ is not physically meaningful; however the fact that it lies between the $n = 1$ profile of disc galaxies and the $n = 4$ profile for bulge dominated systems gives confidence that these sources are indeed associated with the galaxies. In this fit the constant density term (representing foreground and background sources not identified as such) is 1.2 per cent of the central density, and 26 per cent of the asymptotic projected density reached by the identified foreground sources. At large radii the density of sources belonging to the parent galaxy should tend to zero, so the constant density term comprises background sources and foreground sources not identified as such. Thus we can estimate that the Gaia sources identified as foreground represent about three quarters of the true number of contaminating sources, to the Gaia magnitude limit.

For the 298 galaxies with more than 50 Gaia sources, $r_{50}$ was computed individually. There is considerable variation in this quantity, with no obvious trends with galaxy distance, angular size, morphological type or luminosity. Although $r_{50}$ has considerable scatter, it does increase with distance from the Galactic plane. The data are reasonably well fit by a linear trend $r_{50} = 0.226 + 0.006|b|$, consistent with the notion that the surface densities of foreground stars decreases as $|b|$ increases. The median value of $r_{50}$ is 0.56 with a standard deviation of 0.33, and a range from 0.06 for NGC 5206 ($a_{26}=3.72$, 643 foreground sources of 759 total) to 1.91 for the dwarf irregular Phoenix ($a_{26}=5.5$, 69 foreground sources of 434 total). Phoenix is a Milky Way satellite at high Galactic latitude, whose value of $a_{26} = 5.5$ as listed in the LVG may be an underestimate (e.g. the NASA Extragalactic Database gives $7.7$); if its true size is 50 per cent larger, the $r_{50}$ value would be correspondingly reduced.

3.3 Foreground and non-foreground Gaia sources: colour and magnitude distributions

Figure 8 shows where in the colour-magnitude diagram (CMD) foreground sources are important. Foreground sources completely dominate the brightest Gaia sources, outnumbering non-foreground sources by a factor of $\geq 100$ at $G < 15$. Here the limitations of the Gaia astrometric data are apparent: there are essentially no identified foreground sources with $G > 21$. The two populations reach equal numbers at $G \approx 20.6$, and non-foreground sources outnumber foreground sources by a factor of about 50 at the faintest magnitudes. However, even when restricting the non-foreground source sample to the magnitude limit at which foreground identification stops ($G = 21.1$), the distributions of the two populations are still significantly different as indicated by a KS test: the foreground sources are redder and brighter than the non-foreground sources (mean $B_p - R_p = 1.43$ and 1.11; mean $G = 18.67$ and 20.46, respectively). This is compatible with the inference that the foreground sources are primarily nearby dwarfs while the non-foreground sources are more intrinsically luminous giants, supergiants, or star clusters. The colour distributions of the two populations are much more similar than their magnitude distributions. There are about twice as many foreground as non-foreground sources in the central colour peak at $B_p - R_p \approx 1.25$, with non-foreground sources outnumbering foreground sources only on the blue side of this peak.

For the 298 galaxies with more than 50 Gaia sources, the crossover magnitude, at which foreground and non-foreground source numbers are equal, was computed individually. Figure 9 shows these values in both apparent magnitude and absolute magnitude at an individual galaxy’s distance using the distances given in the LVG. A few of the nearest galaxies have apparent $m_{50} < 19$ but the remainder all scatter around the median value of $m_{50} = 20.30$ (standard deviation...
Figure 8. Joint colour-apparent magnitude distribution for foreground and non-foreground Gaia sources in the vicinity of nearby galaxies. Histograms show all objects while the CMD plots only every tenth point. Measurements are not corrected for extinction.

0.82), with no obvious trends with galaxy distance, angular size, morphological type or luminosity. There are also no clear trends with Galactic latitude or foreground extinction. Because of the steep increase in the faint end of the magnitude distribution (see Figure 8), the kernel density estimates of $m_{50}$ can be strongly driven by a few outliers for galaxies with a small number of sources. For example, IC 2233 and Segue I each have < 200 sources, with ~ 80 per cent being foreground and only a few non-foreground sources brighter than $G = 20$, yet IC 2233 had the brightest apparent $m_{50}$ (10.20) and Segue I the faintest (20.86). With a much larger number of sources (1434 foreground sources of 33433 total), Fornax has the second-brightest $m_{50} = 16.75$. The absolute magnitude $M_{50}$ values are strongly dependent on distance, indicating that the foreground-to-non-foreground magnitude crossover points are primarily driven by the limits of the Gaia data.

For an individual galaxy field, it is also important to compare the apparent magnitudes of foreground sources to those of relevant features in the galaxy’s stellar population such as the tip of the red giant branch (TRGB: $M_G = -2.3$, Soltis et al. 2021) or the peak of the globular cluster luminosity function (GCLF: $M_G = -7.5$, Rejkuba 2012). Figure 9 shows that the current Gaia limit for identifying foreground sources ($G = 21$) corresponds to the absolute magnitudes of the TRGB ($G = -2.3$) at a distance of 450 kpc, the faint end of the GCLF (2 mag fainter than the peak) at $D = 2$ Mpc, and the GCLF peak ($G = -7.5$) at 5 Mpc. Detecting foreground contamination of these features will be incomplete for galaxies beyond these distances.

4 DISCUSSION

Figure 3 and Figure 8 both show sharp cutoffs in the colour of foreground stars at $B_p - R_p \approx 0.75$. Although this feature is visible in other similar figures made with Gaia photometry (e.g. Fouesneau et al. 2022; van der Marel et al. 2019), I was unable to find it discussed in the literature. By comparison with fig. 1 of Dal Tio et al. (2021) and fig. 1 of Gaia Collaboration et al. (2022b), it can be inferred that this colour corresponds to both the upper main sequence turn off in the solar neighbourhood and the approximate blue limit of galaxy colours. Varying distances and luminosities cause objects of this colour to spread in apparent magnitude.

Limitations of this work include the fact that many Gaia sources are too faint for reliable proper motion and/or parallax determinations in the current data release; future data releases can be expected to include more likely foreground sources. Improvements in Gaia data processing may lead to improved measurements in crowded regions such as near the centres of galaxies, although fundamental limits of spatial resolution will remain. Future development of a probabilistic classification method that makes use of uncertainties in the astrometric quantities is one way to better quantify these limits. Foreground sources whose space motion is primarily along, rather than tangential to, the line of sight will not be easily distinguishable via proper motions. Radial velocities and other Gaia measurements beyond parallax and proper motion may potentially be useful in future work. In this work no attempt was made to distinguish between Gaia sources within a target nearby galaxy and true background sources. For target galaxies at greater distances, the increase in number counts of background galaxies with magnitude means that contamination from background sources is expected to be more severe. The distances to the target galaxies are not always well-determined; however galaxy distances only come into play when considering colour-absolute magnitude diagrams.

5 CONCLUSIONS

Studies of resolved stellar populations in nearby galaxies are contaminated by both foreground sources (Milky Way stars) and background sources (galaxies and active galactic nuclei). Averaged over a sample of 1401 nearby galaxies, about two thirds of Gaia DR3 sources near these galaxies can be identified as foreground from their proper motion and/or parallax measurements. The fraction of foreground sources...
sources is anticipated to increase in future Gaia data releases, as astrometric solutions are measured for fainter sources. The foreground sources are redder and brighter than non-foreground sources.

As might be expected, foreground sources dominate near the outskirts of galaxies and at brighter magnitudes. On average, foreground sources outnumber non-foreground sources at galactocentric radii \( r > 1.06 \mu h_2 \) and at apparent magnitudes \( m_G < 20.50 \). Considered on an individual galaxy field basis, the radius where foreground sources outnumber non-foreground sources shows substantial variation, with no clear dependence on galaxy properties. The apparent magnitude at which foreground sources outnumber non-foreground sources is much less variable across galaxy fields, and is primarily due to the Gaia signal-to-noise limits. This means that the depth reached by Gaia studies of stellar populations in galaxies will be limited by galaxy distances: galaxies within 450 kpc have secure foreground identification at the magnitude of the tip of the red giant branch, while galaxies within 2 Mpc have foreground identification two magnitudes beyond the globular cluster luminosity function peak. For galaxies at distances beyond 5 Mpc, Gaia foreground removal for these features will be incomplete.

Gaia DR3 data provide a useful avenue for removing foreground contamination in photometric studies of stellar populations of nearby galaxies. The depth and uniformity of Gaia data will no doubt facilitate many investigations of stars and star clusters in the nearby Universe.

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DATA AVAILABILITY

The data underlying this article are available in Zenodo, at https://doi.org/10.5281/zenodo.7244987. The datasets were derived from sources in the public domain: Gaia Data Release 3 https://www.cosmos.esa.int/web/gaia/data-release-3, and the Local Volume Galaxy catalogue http://www.sao.ru/lv/lvgdb/.

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