HST Astrometry in the 30 Doradus Region. II. Runaway Stars from New Proper Motions in the Large Magellanic Cloud

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Received 2018 April 24; revised 2018 June 28; accepted 2018 June 28; published 2018 August 17

Abstract

We present a catalog of relative proper motions for 368,787 stars in the 30 Doradus region of the Large Magellanic Cloud (LMC), based on a dedicated two-epoch survey with the Hubble Space Telescope and supplemented with proper motions from our pilot archival study. We demonstrate that a relatively short epoch difference of three years is sufficient to reach a level of precision of ~0.1 mas yr−1 or better. A number of stars with relative proper motions exceeding a 3σ error threshold represent a mixture of Milky Way denizens and 18 potential LMC runaway stars. Based upon 183 VFTS OB stars with the best proper motions, we conclude that none of them moves faster than ~0.3 mas yr−1 in each coordinate—equivalent to ~70 km s−1. Among the remaining 351 VFTS stars with less accurate proper motions, only one candidate OB runaway can be identified. We rule out any OB star in our sample moving at a tangential velocity exceeding ~120 km s−1. The most significant result of this study is finding 10 stars over a wide range of masses that appear to have been ejected from the massive star cluster R136 in the tangential plane to angular distances from 35″ out to 407″, equivalent to 8–98 pc. The tangential velocities of these runaways appear to be correlated with apparent magnitude, indicating a possible dependence on the stellar mass. Lastly, a comparison to proper motions from Gaia DR 2 shows that for several relatively bright stars the DR 2 has an unexpected scatter that cannot be accounted for by the formal errors.

Key words: astrometry – galaxies: Magellanic Clouds – galaxies: individual (30 Dor) – proper motions

Supporting material: machine-readable tables

1. Introduction

This study addresses new measurements of proper motions with the Hubble Space Telescope (HST) for individual stars in the 30 Doradus (hereafter 30 Dor) area of the Large Magellanic Cloud (LMC) in the context of a search for runaway OB stars and potential scenarios of how the massive OB stars are formed. In our first paper by Platais et al. (2015), hereafter Paper I, we present the motivation to study this region of the LMC and provide a detailed account of how to obtain high-accuracy positions and relative proper motions with various HST imaging instruments. We demonstrate that it is possible to measure reliably an individual relative proper motion down to ~0.1 mas yr−1, which corresponds to ~25 km s−1 at the distance of the LMC. As a result, we presented a pilot catalog of positions and relative proper motions, derived from a targeted single-epoch survey combined with numerous archival HST observations spanning up to 17 years. Although the precision of proper motions can be as good as ~20 μas yr−1, the accuracy of proper motions appears to be significantly lower due to residual systematic errors. In addition, as indicated by Figure 13 of Paper I, our pilot catalog has spatial discontinuities and covers only ~30% of the available contiguous area.

In Paper I, we also attempted to identify possible runaway OB stars using the calculated proper motions for 86,590 stars. That resulted in six candidate OB proper-motion runaway stars. Interestingly, three of them are part of the VLT-FLAMES Tarantula Survey (VFTS; Evans et al. 2011), and the other three are additional photometric OB stars. We noted that star VFTS 285 appears to have its proper motion and position consistent with the ejection scenario from the massive star cluster R136. Still, none of the astrometric candidate OB runaway stars could be considered as a conclusive case.

There are two studies of line-of-sight (LOS) velocities that also address potential OB runaway stars in the 30 Dor area and slightly eastward of it (Evans et al. 2015a, 2015b). These authors identify a total of 18 candidate runaway stars. Assuming that none of them is a large-amplitude binary, only five of them have an excess LOS velocity in the range 75 < vLOS < 108 km s−1, while the rest have lower velocities, with the lowest one at 40 km s−1. This range of excess LOS velocities implies that the expected total proper motion of true OB runaway stars may not exceed ~0.4 mas yr−1. This anticipated upper limit is still nontrivial to measure with HST over a time span of a few years. The concept of effective point-spread function (ePSF), accurate accounting for the geometric
distortions, and empirical correction for the effect of charge transfer efficiency (CTE) losses are the three crucial developments that now allow us to measure relative positions of stars to the level of \( \sim 0.5 \) mas (Anderson & King 2000, 2003; Anderson & Bedin 2010).

In addition, we designed the second-epoch observations such that they matched the first-epoch observations as closely as possible, thus minimizing the contribution from the main source of systematic errors related to a star’s location on the detector and possible changes in signal-to-noise ratio between the epochs. The combined set of first- and second-epoch observations is analyzed here. There is an overlap in terms of the applied techniques and methods of analysis with Paper I, hence the reader is frequently directed to this paper. This is also true for the Introduction—a more detailed scientific motivation is provided in Paper I.

2. HST Survey of 30 Dor and Data Reductions

One of the main intentions in our astrometric survey was to use the Wide Field Camera 3 (WFC3/UVIS) and the Advanced Camera for Surveys (ACS/WFC) in parallel, so as to cover as much of 30 Dor as possible and particularly to focus on the VFTS stars (Evans et al. 2011). The first-epoch observations (GO-12499: PI: D. Lennon) were mainly obtained in 2011 October 3–8, while nearly identical second-epoch observations (GO-13359) were repeated three years later in 2014 October 6–11. Details of the first-epoch observations are given in Paper I. For the second-epoch observations, the last subpointing D in each observational set (see Figure 3, Paper I) has a small \( \sim 3\% \) adjustment to its exposure time and some pointings have different guide stars. As opposed to the first-epoch observations, in 2014 we did not apply preflash to ACS short exposures. For all practical reasons, first- and second-epoch observations are nearly identical. Altogether, there are a total of 149 ACS/WFC and the same number of WFC3/UVIS frames, both sets obtained through filter F775W. Similar to Paper I, we used \_flc.fits files. The latter are corrected for the effect of CTE losses in images (Anderson & Bedin 2010). We note that these corrections reflect the status of adopted pipeline procedures in the year 2015. At the time of this writing, some of them have been updated, thus now resulting in a slightly different output of \_flc.fits files.

It should be mentioned that the Hubble Tarantula Treasury Project (HTTP, Sabbà et al. 2016) is a rich source of additional observations in the 30 Dor area. Although the instrumental setup is identical to our program and includes other filters such as F555W and F658N, there are differences in the visit pointings and orientation angles. This may introduce unwanted systematics if compared to our observations, which are optimized to exclude systematics in proper motions. Since these HTTP observations do not extend the available span of time coverage, we decided not to use them in our analysis.

The object detection, the calculation of their centroid, flux, quality parameter \texttt{qfit}, and correction for geometric distortion—all follow the guidelines provided in Paper I, Section 3.1.

2.1. Differential Charge Transfer Inefficiency

Complementary to the CTE losses is the charge transfer inefficiency (CTI) effect, which is just another way of interpreting small offsets in the positions introduced during the CCD readout process. Since all frames have already been corrected for the effect of CTE losses, we would expect that the residuals from a transformation of the second-epoch positions into the first-epoch positions do not contain any dependence on the magnitude of stars in the direction of CCD readout. If this is not true, then we call such a dependence the differential CTI, which in essence reflects the efficiency of CTE correction.

First, we examined pairs of identical WFC3/UVIS first- to second-epoch pointings taken with the same exposure time. It is expected that a linear transformation (offset, rotation, and scale) of distortion-uncorrected centroids from one epoch to another would enable us to characterize the stability of star pixel coordinates over time. Due to the large distance of the LMC, the expected proper motions over three years make a very limited contribution to the total budget of positional errors. This exercise brought to light two issues: a small offset (a few hundredths of a pixel) between the two CCD chips, and a slope in proper motions as a function of magnitude and the centroid’s \( Y \)-pixel location. The same pattern was discovered in the similar pairs of ACS/WFC frames. Small variations in the gap size between the chips are expected but they have no impact on proper motions because, in our final adjustment, each chip is transformed into the astrometric reference frame separately (Paper I, Section 3.2). The second issue is more serious. A slope in the centroid’s \( Y \)-pixel location as a function of magnitude appears to be a hallmark of some residual (differential) unaccounted-for CTE losses. It may appear odd to have this effect after the pipeline corrections for the CTE losses. However, Anderson & Bedin (2010) caution that the adopted empirical model for corrections may not be perfect. By comparing positions at, e.g., two epochs, we can actually test whether the adopted model might need a tweak for its time-dependent component.

In order to build a statistically significant sample, we selected three sets of frames—15 pairs taken with short exposure (35 s for WFC3/UVIS) of sub-pointing A (see Paper I, Figure 3), 15 pairs with long exposures (699 s for WFC3/UVIS) of the same sub-pointing, and 14 pairs of sub-pointing D with somewhat shorter exposure times (490–507 s for WF3/UVIS). Similarly, we selected the corresponding ACS/WFC pointings and their exposure times (see Paper I, Section 2). Then, for each pair we used least-squares minimization and a linear three-term polynomial to transform first-epoch positions into the system of second-epoch positions. In this transformation only positions of optimally exposed stars were used (instrumental magnitudes in the range \(-14 < m_{F775W} < -8 \) and obvious outliers were ignored. In the next step, residuals of all matching stars were collected and assigned to the applicable CCD chip, which include precise pixel location on that chip and measured instrumental magnitude.

To characterize differential CTI between the two epochs, the collection of individual residuals for each chip was redistributed into successive bins of instrumental magnitude. The total number of available residuals per chip varies between \( \sim 15,000 \) and \( \sim 150,000 \) depending on the imager (WFC3 or ACS) and the length of exposure time. Each bin is at least 0.333 mag wide and is shifted by 0.2 mag with respect to the adjoining bin. The minimum number of residuals per bin is adopted to be 105. If a bin contains fewer residuals, it is enlarged until the required number is reached. This procedure is essential for the bright end of magnitude bins, where the number of stars is always low. Then, in each bin a least-squares...
The Astronomical Journal, 156:98 (13pp), 2018 September

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Figure 1. Example of differential CTI slope distribution as a function of instrumental magnitude. It is for WFC3/UVIS Chip 1 and short exposures only, which produced a total of nearly 20,000 residuals.

Figure 2. Maximum effect of differential CTI for ACS/WFC as a function of magnitude, chip selection, and exposure length. Solid lines: CCD chip WFC1; dotted lines: WFC2. Black lines show the effect for short 32 s exposures, and red lines for long 640 s exposures.

Figure 3. Maximum effect of differential CTI for WFC3/UVIS as a function of magnitude, chip selection, and exposure length. Solid lines: Chip 1; dotted lines: Chip 2. Black lines show the effect for short 35 s exposures, and red lines for long 699 s exposures.

fit is applied to the residuals in Y-coordinate as a function of Y. We used a linear three-term polynomial, which provides a potential slope in these residuals characterizing differential CTI. We could not find statistically significant nonlinearity in the actual fits. An example provided in Figure 1 shows the general pattern of slopes as a function of magnitude, which reflects the presence of differential CTI. If this is ignored, then it will introduce a bias in the calculated proper motions.

In Figures 2 and 3 we show the maximum effect (at the far edge of a CCD chip) of differential CTI for both imaging instruments, for short and long exposures. Formally, the effect is dependent on the exposure time and is more pronounced for short exposures. The turnover at instrumental magnitude $m_{F775W} \sim -8$ appears to be an artifact of the pixel-based pipeline correction applied to our images. We hope that these findings will provide stimulus to the further improvements in minimization of the CTI effects on fluxes and positions. For this project, we applied differential CTI corrections to all second-epoch frames.

In order to apply these corrections to distortion-uncorrected coordinates, we generated a total of 12 empirical CTI curves. That is, each one for a short, a long, and an intermediate length (364–507 s) exposure, for each imaging instrument (ACS/WCS and WFC3/UVIS), and for each chip. We note that the shape and amplitude of the corresponding curves for long and intermediate exposures are quite similar, indicating that the differential CTI effect may not be linearly correlated with the length of exposure time. The raw distribution of slopes as a function of magnitude (Figure 1) is too noisy and coarse to work with. Therefore, we iteratively smoothed these distributions and then applied cubic splines to parameterize the resulting curves (see Figures 2 and 3). For instrumental magnitudes of $-15$ and brighter, a zero correction was adopted. Also, differential CTI correction of any magnitude is adopted to be zero at the near-edge of a CCD readout direction. Once positions of the second-epoch frames were corrected for differential CTI, the resulting coordinates were then corrected for geometric distortion using the same routines and parameters as in Paper I.

We also explored the possibility of some differential CTI effect in the serial direction because Anderson & Bedin (2010) reported the presence of the so-called x-hook in the direction away from the readout amplifier. None was detected, although we did not attempt to explore that for each separate CCD amplifier.

2.2. New Proper Motions

In Paper I we described all basic steps of how to calculate proper motions using mosaic-like observations with three different HST imaging instruments. A central role in these calculations served the astrometric reference catalog, which covers the entire field of view (FOV). At the time of constructing this reference frame, we noticed a need for nonlinear terms in the transformation of the ACS/WFC positional catalog into the WFC3/UVIS-based positions and some semi-periodic systematics after this transformation. Therefore, with the arrival of second-epoch HST observations in 2014, we decided to use the stand-alone version of the WFC3/UVIS positional catalog (Table 2, Paper I, the output of WFC3/UVIS “strip–strip” solution). Eliminating a small but detrimental contribution from the ACS/WFC reference catalog resulted in significantly better rms for the overlapping with...
ACS/WFC visits (pointings) 01–07 (see Figure 2, Paper I). This is confirmed by the distribution of corresponding rms in both axes (Figure 4). All WFC3/UVIS solutions yield small rms estimates and never exceed 0.025 pixel. We note that the second-epoch observations also include the contribution of proper motions over three years. Therefore, the second epochs clump together near the rms of ~0.02 pixel.

Similar solutions for the set of ACS/WFC frames show a noticeably different pattern. The rms of the first-epoch solutions, as expected, clump near 0.015 pixel but the second-epoch ACS/WFC frames obtained with a 32 s exposure cluster around the considerably higher ~0.04 UVIS pixel. Clearly, this is not due to the proper motions. First, we noticed that the image quality parameter $q_{fit}$ for nearly all ACS second-epoch frames is significantly elevated—up to twice that of the relatively bright first-epoch images. Despite using the same fiducial ePSFs as in Paper I, somehow the actual second-epoch stellar images may have slightly changed their shape, especially on frames with an exposure time of 32 s, which are least appropriate for constructing a new set of ePSFs. Second, the available correction for geometric distortion of ACS/WFC frames may not be optimal, as indicated by a necessity to apply a quadratic term in order to align with the WFC3/UVIS positions in constructing the astrometric reference catalog (Paper I). As a result, proper motions from ACS/WFC observations have somewhat lower precision and accuracy than those derived from the WFC3/UVIS observations. To alleviate the impact of potential residual geometric distortion, pixel positions on each chip for both WFC3/UVIS and ACS/WFC were separately translated into their respective reference frames.

New proper motions were calculated following the instructions given in Paper I, Section 3.3.2. As in Paper I, we used the same box, effectively a $4 \times 4$ pixel box, to find all common positions for a star on the system of the astrometric reference catalog. Since the epoch difference is three years, the chosen box size misses fast-moving stars exceeding ~25 mas yr$^{-1}$ in one coordinate. Likewise, we have proper motions from linear least-squares fits to the unweighted and weighted $XY$ positions. In the final catalogs of proper motions only the “weighted” version of the proper motions is provided. The principal improvement in our current version of the proper motions is a complete coverage of the entire available FOV, while the spatial coverage in Paper I is patchy and represents only ~30% of the total FOV.

For both coordinates, the mean error of proper motions from WFC3/UVIS observations and in the magnitude range $14 < m_{F775W} < 20$ is 0.088 mas yr$^{-1}$. This magnitude range contains all optimally exposed OB stars. Similarly, for ACS/WFC observations in the same magnitude range, the mean error is 0.12 mas yr$^{-1}$ in R.A. and 0.10 mas yr$^{-1}$ in decl. These larger errors as well as possible systematics in our astrometry lower the chances of detecting OB runaways using the ACS/WFC data.

2.3. Catalogs of Proper Motions

Measuring individual proper motions in the LMC is close to the limits of any ground- or space-based facility’s state-of-the-art status, including the Gaia mission. Therefore, here we provide four catalogs of proper motions that give an opportunity to examine their internal consistency and other properties (Table 1, in electronic format only). All our proper-motion measurements are relative and effectively local. The mean motion of stars from the astrometric reference catalog should be zero. These proper motions might be used to establish upper limits on the internal velocity dispersion for selected stellar populations. However, their main advantage is the ability to identify faster-moving stars.

In Paper I and here, we have used four $HST$ imagers: WFPC2 Planetary Camera (PC1), WFPC2 Wide Field, ACS/WFC, and WFC3/UVIS. In practice, it would be difficult to tease apart WFPC2’s PC1 data from its Wide Field contribution. Hence, the proper-motion catalog in Paper I represents a mixed contribution by these WFPC2 cameras but it is possible to separate the contribution by ACS/WFC from that by WFC3/UVIS, owing to their minimal spatial overlap.

In Table 1, proper motions and associated parameters from Paper I are marked by the suffix “c.” There are 86,606 such entries. A 16-star addition to the number of entries stated in Paper I is due to the later recoveries close to the boundary of frame FOV. The new proper motions and their parameters from ACS/WFC observations are marked by the suffix “a” (210,745 entries), and those from WFC3/UVIS observations with “u” (165,737 entries). Finally, a catalog of combined proper motions (suffix “m”) represents an attempt to calculate weighted mean proper motions and their errors using available combinations of individual proper motions. We did not address any case showing a clear discrepancy in proper motion between two separate measurements, unless it is a potential runaway. The rule of thumb in such cases is that a smaller total proper motion is more likely to be true and the new proper motions from WFC3/UVIS measurements are the most reliable. We note that a number of brighter stars with the proper-motion measurement in Paper I are missing in the new catalogs. This is because in Paper I we applied a universal image-cutoff threshold at the instrumental magnitude of $m_{F775W} = −14.33$, while in this study it was −14.0 for long exposures by ACS/WFC, and similarly −14.25 for WFC3/UVIS frames. These changes helped to eliminate poor measurements of proper motion.

Each proper-motion measurement comes with its standard error estimate, the number of data points (epochs), the normalized $\chi^2$, and the goodness-of-fit probability $Q$. Ancillary data include $VI$ photometric data from Sabbati et al. (2016), rectangular $XY$ coordinates aligned along the R.A. and decl. directions, and R.A. and decl. (J2000). The total number of entries in the consolidated proper motion catalog is 368,787.
Table 1

| Unit | Label | Explanations |
|------|-------|--------------|
| ...  | ID    | Sequential identifier |
| mag  | F775  | preliminary F775W magnitude |
| mag yr⁻¹ | px-m | weighted proper motion in X |
| mag yr⁻¹ | py-m | weighted proper motion in Y |
| mag yr⁻¹ | e_px-m | error of the weighted proper motion in X |
| mag yr⁻¹ | e_py-m | error of the weighted proper motion in Y |
| ...  | F     | proper motion flag[^a] |
| mag yr⁻¹ | px-a | proper motion in X, ACS/WFC |
| mag yr⁻¹ | py-a | proper motion in Y, ACS/WFC |
| ...  | n-a  | total number of data points (epochs) |
| mag yr⁻¹ | px-u | proper motion in X, WFC3/UVIS |
| mag yr⁻¹ | py-u | proper motion in Y, WFC3/UVIS |
| ...  | n-u  | total number of data points |
| mag yr⁻¹ | px-c | proper motion in X, Paper I |
| mag yr⁻¹ | py-c | proper motion in Y, Paper I |
| ...  | n-c  | total number of data points |
| mag yr⁻¹ | e_px-a | standard error of px-a |
| mag yr⁻¹ | e_py-a | standard error of py-a |
| ...  | cx-a  | normalized χ² for proper motion in X, ACS/WFC |
| ...  | cy-a  | normalized χ² for proper motion in Y, ACS/WFC |
| ...  | qx-a  | goodness-of-fit probability Q in X, ACS/WFC |
| ...  | qy-a  | goodness-of-fit probability Q in Y, ACS/WFC |
| mag yr⁻¹ | e_px-u | standard error of px-u |
| mag yr⁻¹ | e_py-u | standard error of py-u |
| ...  | cx-u  | normalized χ² for proper motion in X, WFC3/UVIS |
| ...  | cy-u  | normalized χ² for proper motion in Y, WFC3/UVIS |
| ...  | qx-u  | goodness-of-fit probability Q in X, WFC3/UVIS |
| ...  | qy-u  | goodness-of-fit probability Q in Y, WFC3/UVIS |
| mag yr⁻¹ | e_px-c | standard error of px-c |
| mag yr⁻¹ | e_py-c | standard error of py-c |
| ...  | cx-c  | normalized χ² for proper motion in X, Paper I |
| ...  | cy-c  | normalized χ² for proper motion in Y, Paper I |
| ...  | qx-c  | goodness-of-fit probability Q in X, Paper I |
| ...  | qy-c  | goodness-of-fit probability Q in Y, Paper I |
| mag | Vmag | V-mag from Sabbi et al. (2016), based on F555W filter |
| mag | e_Vmag | standard error of V-mag |
| mag | Imag | I-mag from Sabbi et al. (2016), based on ACS/WFC F775W filter |
| mag | e_Imag | standard error of I-mag |
| mag | V-I | V − I color index |
| pix | X | X-coordinate in WFC3/UVIS pixels aligned with R.A. |
| pix | Y | Y-coordinate in WFC3/UVIS pixels aligned with decl. |
| deg | RAdeg | R.A., decimal degrees (J2000) |
| deg | DEdeg | decl., decimal degrees (J2000) |
| ...  | VFTS | VFTS identifier, if different from zero |

Note:
[^a]: Flag showing the available proper motion or their combination: 1 = ACS/WFC, GO-12499 and 13359, suffix “a”; 2 = WFC3/UVIS, GO-12499 and 13359, suffix “u”; 3 = archival WFPC2 and GO-12499 observations with both cameras, ACS/WFC and WFC3/UVIS, suffix “c”; 4 = 1 + 2, only “a” and “u”; 5 = 1 + 3, only “a” and “c”; 6 = 2 + 3, only “u” and “c”; 7 = 1 + 2 + 3, all “a” and “u” and “c” available.

(These tables are available in their entirety in machine-readable form.)

2.4. Potential Impact of Gaia DR 1

The all-sky Gaia Data Release 1 (DR 1; Gaia Collaboration et al. 2016) is an obvious data set to compare with HST measurements. We retrieved a few thousand DR 1 sources near the cluster R136. There are issues with completeness of stars in the 30 Dor area and the apparent imbalance of positional errors. On average, the mean positional error in R.A. is ~4 times smaller than that in decl. It was decided to use only those stars with positional errors less than 2 mas in either coordinate, which limits the sample to ~2000 stars, all brighter than G = 19. First, we calculated J2000 equatorial coordinates for our astrometric reference catalog using the DR 1 stars as a reliable representation of the International Celestial Reference System (ICRS). We adopted a linear six-parameter polynomial model to transform the pixel coordinates into the tangential coordinates of DR 1 stars. As demonstrated by Figure 5, the calculated residuals contain significant systematics reaching up to ~50 mas. If we consider only the WFC3/UVIS positions, then the corresponding residuals reach only ~7 mas. This is direct evidence that the positions from observations with ACS/WFC are not free from residual geometric distortions. A similar conclusion has been reached from independent studies of an HST astrometric reference catalog based on ACS/WFC observations of the globular cluster 47 Tuc (Kozhurina-Platais et al. 2015). For the sake of proper motions in the 30 Dor area, the less than optimal accuracy of our ACS/WFC reference catalog is not as detrimental as it may look. The ACS/WFC CCD chip covers an area of 3/4 × 1/7 on the sky. Even the long side of a chip may be shorter than the characteristic length of correlated residuals, which is corroborated by the sub-milliarcsecond standard errors in local solutions (Table 2, Paper I). Since the placing of second-epoch frames relative to first-epoch frames is normally within 1–2 ACS/WFC pixels, we used essentially the same reference stars for both epochs. These mitigating factors significantly lower the impact of an imperfect reference catalog.
We also explored whether the DR 1 can be used as an additional epoch to improve the precision of proper motions. Note that the timing of our second epoch is ∼2014.8, while for DR 1 it is exactly 2015.0. This near simultaneity ensures easy comparison between two sets of positions. Only the WFC3/UVIS frames and the corresponding WFC3/UVIS astrometric reference catalog were used. It is more convenient to work in the system of our astrometric reference catalog. Therefore, we calculated the gnomonic projection’s tangential coordinates with their zero-point at R.A. = 84.51667 and decl. = −69.14361, both in decimal degrees. To emulate a WFC3/UVIS frame, we applied the absolute scale for the F775W filter from Bellini et al. (2011). Small offsets and the global rotation of these transformed Gaia coordinates with respect to our astrometric reference catalog were eliminated by a local linear least-squares adjustment to each DR 1 star using the 10 nearest positional data. First, there are a handful of outliers up to ∼15 mas, possibly indicating some structure/multiplicity in the star’s image. Second, the dispersion of Gaia positions in decl. at ∼1.6 mas is twice as large as that in R.A., just reflecting the range of listed Gaia errors for these stars. Third, the HST WFC3/UVIS positional uncertainty for optimally exposed stars is nearing ∼0.5 mas, while the corresponding positions from DR 1 may have up to four times worse positional accuracy. Given the large disparity of positional errors in the DR 1 along each of the axes, there was little to gain from incorporating them into our data set.

3. Discussion and Applications

The primary objective of this project is to provide proper motions and the related tangential velocities for a large sample of OB stars with measured multi-epoch LOS velocities in the framework of the VFTS survey. The existing measurements in the 30 Dor area indicate that a number of single VFTS stars have a large offset LOS velocity relative to the mean systemic motion of OB stars. Such offset velocities ranging from 30 to ∼100 km s⁻¹ (Evans et al. 2015a, 2015b; Vink et al. 2017), or equivalent to ∼0.1–0.4 mas yr⁻¹ in the tangential plane, may indicate potential runaway stars. However, a one-dimensional velocity cannot pinpoint the origin of these stars. Now we are in a position to test them with proper motions and to search for additional runaway stars.

The following analyses of our proper motions are subdivided by the associated HST imaging instrument. Furthermore, each analysis covers a specific range of proper motions along with corresponding random and likely systematic errors. We limit the search for astrometric runaways to stars brighter than V = 22 mag and generally ignore the older red giant branch (RGB) stars.

First, we checked for proper motions exceeding ∼0.4 mas yr⁻¹ among all potential OB stars with emphasis on the VFTS sample. The same exercise was done for the brighter RGB stars with V − I > 0.9 in order to find relatively fast-moving Milky Way stars. Second, we similarly parsed the range ∼0.1–0.4 mas yr⁻¹ but now employing the calculated and the estimated mean errors. There is a distinction between these two types of error estimates because a small number of data points (n ≤ 4) in the least-squares adjustment favors underestimated formal proper-motion errors. Unfortunately, many VFTS stars have this issue for our new proper motions. We note that a fit of only three data points was retained for stars with m_P775 < 20.0 in order to have a proper-motion estimate near the perimeter of the 30 Dor field.

Given the fact that the accuracy of our proper motions depends on the HST imaging instrument, we decided to divide all 481 measured VFTS stars into three groups: proper motions from ACS/WFC (152 stars), proper motions from WFC3/UVIS observations (183 stars), and those from Paper I that do not have counterparts in our new proper motion catalog (146 stars).

3.1. VFTS Stars and Paper I

In Paper I (Table 3) we made the first attempt to identify candidate OB runaway stars. This effort resulted in six such stars. Among these stars, the largest motion along either axis is 0.40 mas yr⁻¹. We note that all of them but ID 6 have their second epochs based on ACS/WFC observations. Only two OB runaway candidates (ID 1 and ID 6 = VFTS 285) have new proper motions. Star 1 (#264049) has its new proper motion incompatible with that from Paper I. We conclude that it is probably not an OB runaway. Star VFTS 285 has a consistent proper motion from both sources, although it appears to have a smaller newly measured motion (see Table 2). Therefore, it remains a good candidate OB runaway. The four remaining stars are too bright for us to derive credible new proper motions. However, two of them (ID 3 and ID 4) have only one reliable position at each epoch, which allows us to estimate the upper limit of a proper motion. Star 3 (#278880) has inconsistent positional data and in addition has a slightly asymmetric image, indicating a likely visual binary. Given the stated issues with our ACS/WFC data (Section 2.2), it is safer to downgrade our initial OB runaway candidates IDs 1–5 to young and massive stars from the ordinary stellar background.

Among the VFTS stars presented in Paper I, there are a dozen seemingly fast-moving stars outside the ±0.4 mas yr⁻¹ box centered on zero proper motion. An examination of individual fits for the proper motion indicates that all but one are likely spurious. Star VFTS 712, spectral type B1 V (Dunstall et al. 2015; Evans et al. 2015a) is a visual binary of nearly equal brightness (#290441 and #290538) separated by 228 mas, and oriented almost exactly along decl. For both components, the proper motion in decl. appears to be fairly large but that is not confirmed by additional checks. The case of VFTS 167 is instructive: it appears to have at least a 5σ proper motion and formally would qualify for a genuine OB runaway. However, VFTS 167 has only two good-quality data points at recent 2011–2014 epochs, which is not sufficient to obtain any error estimates. Just a direct difference of available epoch coordinates indicates a small proper motion of ∼0.2 mas yr⁻¹ in both axes, although with the opposite sign in the R.A. direction to that listed in Paper I. Clearly, its proper motion in Paper I is not reliable. Such cases are present in Paper I for two reasons: (1) the cutoff magnitude adopted earlier included some slightly overexposed stellar images, and (2) archival HST frames are placed randomly in the field of 30 Dor whereas our design is intended to optimize the astrometric output.
3.2. VFTS Stars and ACS/WFC Measurements

The vector-point diagram of ACS/WFC proper motions of 152 VFTS stars (Figure 6) shows a fairly large scatter and a visibly non-Gaussian distribution of the smaller motions. As stated in Section 2.2, for brighter stars, new proper motions from ACS/WFC measurements are a factor \( \sim 1.5 \) less precise than those obtained from the WFC3/UVIS observations. We suspect that some lingering systematics in the pixel positions after correcting them for geometric distortion might be responsible for this unusual feature. Consequently, the distribution of proper motions within 0.4 mas yr\(^{-1}\) around zero is too broad to allow a meaningful identification of potential relatively slow OB runaways. At higher proper motions, a total of five numbered stars survive a limited scrutiny. Among them, only VFTS 838 could be a potential OB runaway (see Table 2). The remaining four stars are of late spectral type (G0–K7) and marginally consistent with LMC membership from measured LOS velocities.

3.3. VFTS Stars and WFC3/UVIS Measurements

The sample of proper motions based upon WFC3/UVIS observations is the most accurate and reliable source of tangential velocities available from this project. As such, this sample is a cornerstone in our discussion of OB runaways and other fast-moving stars. There are 183 VFTS stars in the sample. First, we exclude VFTS 680, which is apparently a G-type Milky Way star with large proper motion: \( \mu_X = +11.15 \pm 0.22 \) mas yr\(^{-1} \), \( \mu_Y = -1.17 \pm 0.04 \) mas yr\(^{-1} \). There is no overlap with proper motions from ACS/WFC observations; however, there are 104 proper-motion measurements in common with Paper I. In the majority of cases, the formal proper-motion errors are similar between Paper I and the WFC3/UVIS sample of VFTS stars. Therefore, we can choose the smallest proper motion as a lower limit of the expected tangential motion if there is a significant variation between these two sources. Normally, the preference is given to the WFC3/UVIS sample because it was constructed to minimize systematic errors, which might be present in the proper motions of Paper I.

The vector-point diagram of 110 well-measured proper motions with errors \( \sigma_{\mu} \leq 0.13 \) mas yr\(^{-1} \) is shown in Figure 7. There are two labeled VFTS stars placed apart from the general distribution of relative proper motions around the zero motion. Star VFTS 8 of spectral type B0.5:V(n) (Evans et al. 2015a) appears to be a candidate runaway. VFTS 245 is a star of spectral type K (Evans et al. 2011) and therefore is not considered. The sum of unity Gaussians represents the empirical 1D proper-motion distributions in each axis, and a Gaussian fit to these distributions is provided in Figure 7 (compare that to Figure 15, Paper I). There are small offsets, \( \Delta \mu_X = -0.035 \) mas yr\(^{-1} \) and \( \Delta \mu_Y = +0.012 \) mas yr\(^{-1} \), which along with the distribution’s Gaussian width of 0.12 mas yr\(^{-1} \) for each axis indicate that our estimates of proper-motion errors are robust.

In order to isolate potential OB runaways, an obvious choice seems to be to compare each measured proper motion with its error and then to select cases of \( 3 \sigma \) and higher significance. Unfortunately, the majority of least-squares proper-motion fits have a very small number of positional data points (Figure 8), which leads to underestimated proper-motion errors. To mitigate this deficiency, we extracted the median error from each of the three catalogs as a function of magnitude, in four intervals of available data points: \( 3 \leq n \leq 5 \), \( 5 < n < 7 \), \( 7 \leq n \leq 12 \), and \( n > 12 \). For example, the average median error for the VFTS stars considered here is 0.07 mas yr\(^{-1} \). We designed a sequence of criteria and checks that were used to identify candidate runaway stars. It is safe to reject the cases where the actual error of proper motion is more than three times larger than its estimated median error and to use the latter as a

| Table 2 | Candidate OB Runaway Stars Based on Proper Motion |
|---------|-----------------------------------------------|
| VFTS   | Ident | \( V \) | \( V - I \) | Sp. Type | \( v_{LOS} \) | \( v \sin i \) | \( \mu_X \) | \( \mu_Y \) | \( \sigma_{\mu_X} \) | \( \sigma_{\mu_Y} \) | \( \chi^2_1 \) | \( \chi^2_1 \) | \( Q_X \) | \( Q_Y \) | \( N_{frame} \) |
|---------|-------|--------|----------|---------|------------|-------------|----------|----------|----------------|----------------|-------------|-------------|----------|----------|-------------|
| 8       | 188822 | 17.014 | 0.156    | B0.5 V(n) | 271        | 241 \pm 15  | -0.34    | 0.24     | 0.10          | 0.10          | 0.27        | 0.28        | 0.899    | 0.899    | 6           |
| 65      | 259107 | 16.036 | 0.142    | O8 V(n)   | 268        | 162 \pm 20  | -0.27    | -0.07    | 0.06          | 0.09          | 0.06        | 0.14        | 0.814    | 0.706    | 3           |
| 219     | 349614 | 17.043 | 0.088    | B3-5 III-V| 282        | 220 \pm 19  | -0.32    | 0.07     | 0.04          | 0.15          | 0.04        | 0.62        | 0.996    | 0.646    | 6           |
| 285     | 294979 | 15.616 | 0.052    | O7.5 Vnnn | 228        | 600 \pm ??  | -0.20    | 0.03     | 0.07          | 0.12          | 0.13        | 0.37        | 0.877    | 0.687    | 4           |
| 290     | 292849 | 15.708 | 0.113    | O9.5 IV   | 269        | <40        | -0.20    | -0.04    | 0.06          | 0.06          | 0.06        | 0.09        | 0.914    | 0.915    | 4           |
| 406     | 332741 | 14.340 | 0.166    | O6 Vm    | 304        | 356 \pm 30  | 0.19     | 0.12     | 0.05          | 0.06          | 0.06        | 0.06        | 0.946    | 0.944    | 4           |
| 838     | 143204 | 15.852 | 0.382    | B1: I(n)  | 263        | 239 \pm 23  | 0.24     | 0.41     | 0.20          | 0.11          | 1.03        | 0.29        | 0.355    | 0.750    | 4           |

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

![Figure 6](https://example.com/figure6.png)

Figure 6. Vector-point diagram of ACS/WFC-based proper motions for VFTS stars. The status of labeled stars is discussed in Section 3.2. Inconsistent or apparently flawed proper motions are crossed out. This diagram yields only a single candidate OB runaway (VFTS 838).
Section 3.3. The likely OB runaway star VFTS 285 is marked in red. The status of two labeled stars is of 0.12 mas yr\(^{-1}\) motions; red points show a Gaussian fit to these distributions yielding a width of 0.12 mas yr\(^{-1}\) and indicating small offsets.

**Figure 7.** Proper motions of 110 VFTS stars from the WFC3/UVIS measurements. Only proper motions with errors \(\sigma_\mu \leq 0.13 \text{ mas yr}^{-1}\) are selected. Upper panel: a vector-point diagram. The status of two labeled stars is discussed in Section 3.3. The likely OB runaway star VFTS 285 is marked in red. Bottom panels: black points represent empirical 1D distributions of proper motions; red points show a Gaussian fit to these distributions yielding a width of 0.12 mas yr\(^{-1}\) and indicating small offsets.

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**Figure 8.** Histogram of the number of positional data points for VFTS stars used in the WFC3/UVIS proper-motion measurements.

benchmarks to select potential runaway stars. In addition, we rejected the cases when the calculated proper motion errors in each axis differ by more than a factor of three and the number of available data points is only three or four. This eliminates the majority of unstable solutions for proper motion. The next step is to check the consistency of proper motion between our catalog in Paper I and that from WFC3/UVIS measurements. The smallest total proper motion is thought to be more likely. An additional criterion of reliability is the sign of the proper motion, which should be the same in both catalogs. The last step is a visual inspection of the actual least-squares fit and its residuals. Finally, each runaway candidate is visually inspected on a combined image (see Section 4.2 in Paper I). We examined all VFTS stars that have measured proper motion in either axis exceeding 0.17 mas yr\(^{-1}\) (equivalent to 40 km s\(^{-1}\) at the distance of LMC). The new candidate OB runaway stars matching all our criteria, when available, are given in Table 2. This table lists VFTS number (Evans et al. 2011), identifier from our electronic Table 1, \(VI\) photometry from Sabbi et al. (2016), spectral type, \(v\) \(\text{LOS}\) in km s\(^{-1}\), and \(v\) \(\sin i\) and its error in km s\(^{-1}\). Additional columns in Table 2 have the same meaning as in Table 3 of Paper I. We note that among these seven candidate OB runaways only two stars, VFTS 285 and 406, were previously flagged as potential runaways from their LOS velocity (Sana et al. 2013; Walborn et al. 2014). The remaining candidates have an LOS velocity close to that of the mean of all OB stars in the region (\(\sim 270 \text{ km s}^{-1}\)). Both VFTS 285 and 406 are also noteworthy due to their high rotational velocity (Ramírez-Agudelo et al. 2013; Sabin-Sanjulián et al. 2017), which would be consistent with a potential origin in the binary supernova ejection (BSE) scenario for runaways; that is, when one component of a binary explodes as a core-collapse supernova and the other component attains a large kick velocity. However, as we discuss in the following Section 3.4, the direction of motion of VFTS 406 is inconsistent with an R136 origin. In fact, only four stars in Table 2 have directions of motion consistent with an R136 origin: VFTS 65, 219, 285, and 290, which are discussed further below along with the non-VFTS candidate runaways. The remaining early B-type stars VFTS 8 and 838 have high rotational velocities that might indicate a BSE scenario but not from R136. Another feature common to all stars listed in Table 2 is the lack of significant variations in the measured multi-epoch LOS velocities (Sana et al. 2013; Evans et al. 2015a). All of them are classed as single stars.

### 3.3.1. Candidate Non-VFTS Young Runaways from WFC3/UVIS Measurements

The VFTS survey (Evans et al. 2011) contains a total of 917 stars down to \(V = 17\). The completeness of OB stars over the surveyed area is not well established, especially around the location of R136. Therefore, first we used \(VI\) photometry (Cignoni et al. 2015; Sabbi et al. 2016) and the location of the upper main sequence in the color–magnitude diagram (CMD) down to \(\sim 5M_{\odot}\), equivalent to \(V \sim 19\), and later extended that limit to \(V \sim 22\) mag. The color cut was initially adopted at \(V - I < +0.75\) mag. This selection of targets covers the majority of young main-sequence stars of spectral types O, B, A, F. Among the likely non-VFTS OB stars, only a couple of potential runaways can be tagged but none of them convincingly. At fainter magnitudes, \(18.0 < V < 22.0\), there are a few dozen somewhat redder stars with kinematics incompatible with LMC membership. To enhance the chances of finding young main-sequence stars in the area of 30 Dor, we adopted a tighter limit on the color cut at \(V - I < +0.43\). A list of 11 potential young lower-mass runaway stars is given in Table 3. This is the first ever such list in a galaxy other than the Milky Way. However, membership of these stars to LMC should be confirmed by other means such as spectroscopy.
### 3.4. Candidate Runaway Stars and the Star Cluster R136

A principal advantage of knowing proper motions of potential runaway stars is the ability to trace them backward to their place of origin, if we assume that massive star clusters are the likely nurseries of such stars. In our case, such a place is the young and massive star cluster R136, which is located at the edge of the field covered by our WFC3/UVIS observations. We explored how the direction of proper-motion vectors is oriented with respect to R136. This can be characterized by the positional angle of proper motion, measured relative to the direction outward from R136. If this angle is close to zero, then there is a high probability that a star has originated from this cluster. Figure 9 shows all stars from Tables 2 and 3. Indeed, there is a distinct concentration of proper-motion positional angles around zero. We used this to identify 10 plausible escapees from R136 (Table 4). These stars have their total proper motion in the range from 0.20 to 0.54 mas yr\(^{-1}\), equivalent to 50–130 km s\(^{-1}\). A caveat on the actual escape velocities is that our proper motions are relative. Due to the formal proper motion of R136 is equivalent to 50 km s\(^{-1}\), the mean proper motion of R136 is biased toward zero. The formal proper motion of R136 is \(\mu_X = -0.011\) mas yr\(^{-1}\), \(\mu_Y = +0.003\) mas yr\(^{-1}\) as calculated using the brighter and bluer stars \((V < 22, V - I < 0.5)\) within one arcminute around the center of R136. The distribution of rms for specific WFC3/UVIS frame transformations containing the cluster (see Figure 4) indicates that the uncertainty in the proper motion of R136 might be less than \(\pm 0.05\) mas yr\(^{-1}\).

The angular distance of an escapee and its proper motion provide the time when the star left R136. Thus, the slowest likely escapes—VFTS 285 and 290—have moved to their current positions in 0.67 Myr. Star VFTS 65 has traveled for 1.37 Myr and has covered 92 pc in the tangential plane away from R136. If we adopt the greatest age from the age probability density distribution for R136 (Crowther et al. 2016) at 3 Myr, then a potential early escapee with a mass of \(\sim 20 M_\odot\) or higher may have traveled as far as \(\sim 200\) pc away from R136, equivalent to \(\sim 14^\prime\) in the tangential plane. We note that the LOS velocities of VFTS stars imply an upper limit for runaways at \(\sim 100\) km s\(^{-1}\) (Vink et al. 2017). That would result in a distance of \(\sim 300\) pc \((\sim 20^\prime)\) over 3 Myr. \textit{Gaia} proper motions will eventually enable searches for ejected runaways from R136 at these larger distances from the cluster.

#### Table 3

| Ident | V  | V − I | R.A. (deg) | Decl. (deg) | \(\mu_X\) | \(\mu_Y\) | \(\sigma_X\) | \(\sigma_Y\) | \(\chi_X^2\) | \(\chi_Y^2\) | \(Q_X\) | \(Q_Y\) | \(N_{\text{frame}}\) |
|-------|----|-------|------------|-------------|----------|----------|----------|----------|----------|----------|------|------|-------------|
| 204988| 19.509 | 0.212 | 84.5362650 | −69.1332743 | −0.49 | 0.04 | 0.09 | 0.12 | 0.25 | 0.50 | 0.958 | 0.810 | 8 |
| 223800 | 17.790 | 0.292 | 84.5887628 | −69.1256231 | 0.59 | 0.14 | 0.04 | 0.08 | 0.03 | 0.12 | 0.971 | 0.888 | 4 |
| 271782 | 20.508 | 0.292 | 84.5679256 | −69.1085476 | 0.26 | 0.66 | 0.10 | 0.07 | 0.32 | 0.721 | 0.978 | 13 |
| 299597 | 19.188 | 0.281 | 84.6849573 | −69.0926151 | 0.10 | 0.46 | 0.09 | 0.11 | 0.43 | 0.64 | 0.901 | 0.747 | 10 |
| 306820 | 20.717 | 0.329 | 84.6791949 | −69.0887983 | −0.26 | −0.54 | 0.12 | 0.06 | 0.69 | 0.14 | 0.739 | 0.999 | 12 |
| 325244 | 18.757 | 0.147 | 84.4301820 | −69.0775362 | −0.34 | 0.02 | 0.11 | 0.06 | 1.22 | 0.41 | 0.248 | 0.978 | 17 |
| 346142 | 18.324 | 0.325 | 84.3832657 | −69.0627707 | −0.33 | 0.02 | 0.08 | 0.06 | 0.47 | 0.34 | 0.936 | 0.981 | 12 |
| 358588 | 20.637 | 0.285 | 84.4541695 | −69.0516393 | −0.35 | 0.41 | 0.11 | 0.11 | 0.77 | 0.75 | 0.778 | 0.704 | 14 |
| 359942 | 20.735 | 0.429 | 84.7535838 | −69.0506241 | −0.29 | 0.47 | 0.17 | 0.10 | 1.31 | 0.43 | 0.234 | 0.904 | 14 |
| 371614 | 18.147 | −0.029 | 84.7191400 | −69.0389415 | −0.33 | −0.30 | 0.07 | 0.10 | 0.27 | 0.53 | 0.977 | 0.833 | 10 |
| 373715 | 19.546 | 0.167 | 84.6501694 | −69.0366983 | −0.19 | 0.36 | 0.11 | 0.14 | 0.90 | 1.35 | 0.545 | 0.183 | 14 |

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

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For those VFTS stars with position angles consistent with ejection from R136 (stars VFTS 65, 219, 285, and 290), we can compare their evolutionary ages (Schneider et al. 2018) with the age of the central cluster, estimated to be 1.5 Myr (Crowther et al. 2016). The O-type stars VFTS 65 and 285 have ages estimated at 2.4 and 1.9 Myr, respectively, with uncertainties of approximately 1 and 2 Myr, hence they have ages consistent with that of R136. The remaining confirmed
O-type star, VFTS 290, has an age of 4.7 Myr with an uncertainty of approximately 0.5 Myr. Furthermore, from the analysis of Sabin-Sanjulián et al. (2017) it appears that to match the age of R136 this object would have to be a \( \sim 3\sigma \) outlier. Since this star has an age that is more consistent with the surrounding cluster NGC 2070 it may well be that this runaway is the product of the binary supernova mechanism (Blaaauw 1961) and originated in that region. The case of VFTS 219 is even more problematic because this mid-B star has an estimated age of 77 Myr, and while the uncertainty is \( \sim 10 \) Myr this star is inconsistent with previous membership of R136. We suggest that VFTS 219 (and potentially even VFTS 290) might be an interloper in the sense that it is a field runaway star that by chance has a position angle consistent with ejection from R136. Indeed, referring to the histogram in Figure 9, one can see that we expect approximately one star per 33° bin of position angle, irrespective of the bin’s orientation with respect to R136. In the central three bins we therefore expect about three stars that might be interlopers in our sample.

Among the more massive likely escapees, we single out a pair of main-sequence O-stars (VFTS 285 and 290) that are separated by only 4727. Their total proper motion is identical but not their LOS velocities and projected rotation velocities (Table 2). According to Evans et al. (2015a), the mean LOS velocity of NGC 2070, which also contains R136, is 271 km s\(^{-1}\). From the perspective of LOS velocities, only VFTS 285 appears to be a runaway star, albeit of a slow variety. However, our proper-motion measurement of these stars appears to be fairly robust, hence confirming their runaway status. It is unlikely that this pair is a wide physical binary due to the very large current projected separation in the tangential plane at \( \sim 213,000 \) au.

Another potential runaway pair, #371614 and VFTS 662, is even less understood. In Table 3, star #371614 is listed as a candidate runaway. Its orientation angle with respect to R136 is \( \sim 144^\circ \). Formally, that large angle rules out any connection to this star cluster. However, the derived proper motion appears to be biased by the nearby and more luminous VFTS 662 (separated by \( \sim 0.3^\circ \), which is missing in our catalogs. According to Evans et al. (2015a), VFTS 662 has an LOS velocity of 251 km s\(^{-1}\). It is expected that Gaia may eventually help to clarify the status of this pair.

### Table 4

| Ident  | X (arcmin) | Y (arcmin) | Angle (deg) | Total Proper Motion (mas yr\(^{-1}\)) |
|--------|------------|------------|-------------|-------------------------------------|
| 204988 | –3.0804    | –1.8681    | 35.9        | 0.49                                |
| 259107 | –6.3002    | –0.5612    | –9.4        | 0.28                                |
| 292849 | –2.2820    | 0.3702     | –20.5       | 0.20                                |
| 294979 | –2.3160    | 0.4293     | –2.0        | 0.20                                |
| 299597 | 0.0976     | 0.5751     | 2.6         | 0.47                                |
| 325244 | –5.3612    | 1.4689     | –12.0       | 0.34                                |
| 346142 | –6.3708    | 2.3503     | –16.8       | 0.33                                |
| 349614 | –3.8849    | 2.5365     | –20.8       | 0.33                                |
| 358858 | –4.8530    | 3.0247     | 17.6        | 0.54                                |
| 373715 | –0.6489    | 3.9299     | –18.4       | 0.41                                |

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

An additional argument that our candidate escapees from R136 are real comes from the distribution of redder main-sequence (0.43 < \( V-I \) < 0.75) runaway stars down to \( V = 22 \) mag. There are 34 such stars shown in Figure 10. The histogram of positional angles implies a lack of concentration at the zero orientation angle. In addition, the amplitude of the total proper motion in this sample is much larger—from 0.4 to more than 4 mas yr\(^{-1}\), indicating very different kinematics. We note that for would-be faster-moving stars with their origin in R136, this concentration would be much sharper due to the diminished impact of proper-motion errors. Nevertheless, there is no indication of such stars.

These two sets of kinematically selected stars also have a very different placement on the \( V-I \) versus V CMD (Figure 11) where the interchangeable axes are labeled F555W versus F555W in accordance with Cignoni et al. (2015). The 10 escapees are well separated from the fast-moving field stars. The likely escaped stars from R136 are located along the main sequence of this young cluster down to its pre-main sequence. As expected, the remaining eight candidate O-B-A-F runaways not originating from R136 are fairly close to the location of R136 escapees. The fast-moving field stars form a vertical sequence, similar to that toward the north Galactic pole (Reid & Majewski 1993). Apparently, these are Milky Way halo stars at various distances from the Sun. To illustrate this point, we overplotted an appropriate isochrone,
Figure 11. Color–magnitude diagram of the stars plotted in Figures 9 and 10. Red points: all stars from Table 4; open circles: candidate O-B-A-F runaways not kinematically associated with R136; green points: fast-moving field stars. The solid curve is a 3 Myr isochrone for the cluster R136, adopting $E(B - V) = 0.3$. The dotted curve shows an isochrone with the following parameters: 12 Gyr old, metal-poor [Fe/H] = −1.5 dex, $E(B - V) = 0.05$, and placed at 20 kpc from the Sun.

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Figure 12. Total motion of runaway stars consistent with escaping from R136. There is a correlation of total motion with the stellar magnitude, which acts as a proxy for stellar mass. The latter in solar units is indicated by a down-pointing arrow at four locations on the magnitude axis. The slope of this distribution is $0.061 ± 0.008$ mas yr$^{-1}$ per unit magnitude.

A potential issue with the interpretation of this correlation with mass might be neglecting the contribution of excess LOS velocity relative to the mean motion of R136. In fact, for three massive stars out of four, that contribution is negligible (see Table 2). For star VFTS 285, the total escape velocity would be equivalent to $0.27$ mas yr$^{-1}$. That alone cannot change significantly the slope shown in Figure 12. VFTS 285 has an extremely high $v \sin i$ estimate, which makes the measurement of LOS velocity nontrivial. However, Sana et al. (2013) provide seven independent and mutually consistent estimates of the LOS velocity for VFTS 285 that mitigate this concern.

The same trend as a function of V-magnitude can be detected among the eight candidate young O-B-A-F runaways not related to R136. However, with the exception of VFTS 406, their total proper motion is significantly higher (by $0.1–0.15$ mas yr$^{-1}$, or $25–40$ km s$^{-1}$) than that shown in Figure 12. This is puzzling, considering that the proper-motion errors in the two samples are similar. It is tempting to identify this sample of runaways and, as discussed above, even some stars in the R136 runaway sample as the products of the BSE scenario. These would be relatively fast runaways, with tangential velocities in the range of $50–100$ km s$^{-1}$. It is not straightforward to estimate the fraction of OB stars that might be BSE runaways given the incompleteness of detections in the ACS/WFC data and our bright-magnitude limit that excludes many O-stars. However, four of our eight BSE candidates are OB-type stars, and we measured a sample of 481 VFTS stars, heavily dominated by OB-type ones. This implies an upper limit of around 1% as the fraction of fast OB runaways. Given the various caveats referred to above, this is not inconsistent with model predictions of runaway fractions of at most a few per cent (Eldridge et al. 2011; Renzo et al. 2018) although the authors’ definition of a runaway adopts a peculiar velocity greater than $30$ km s$^{-1}$.

We refrain here from the deeper analysis and interpretation for two reasons: (1) our best proper motions cover a limited area of $\sim 15^2 \times 7'$, only partially probing the surroundings of R136; (2) our observations cannot provide reliable proper motions for stars brighter than $V \sim 15$, while luminous O-type supergiants in the 30 Dor area can be as bright as magnitude $V \sim 11$ (Selman et al. 1999).

which fits well the most distant stars, which are also kinematically slowest in our sample as indicated by their total proper motion. There is an ambiguity, though, as to which population we should assign three isolated stars at $V \sim 21.7$ and $V - I \sim 0.43$. Therefore, their status remains undefined.

There is an intriguing relationship for the likely escaped stars from R136—their total proper motion (see Table 4) is correlated with the apparent $V$-magnitude (Figure 12). Since these stars are located at approximately the same distance from the Sun, their apparent magnitudes become akin to absolute magnitudes and can be used as a proxy for mass for the main-sequence stars. Clearly, less massive stars are moving faster, which is contrary to what is expected in most dynamical ejection scenarios (e.g., Oh et al. 2015; Oh & Kroupa 2016), where the more massive runaways tend to have higher velocities. Perusing various simulations performed by Oh & Kroupa (2016), it appears that certain models do predict a trend of increasing velocity with decreasing mass. For example, in those scenarios that assume a random pairing of binary masses among the initial conditions, that trend is further strengthened when the initial conditions assume that the cluster is not mass-segregated (models MS3RP and NMS3RP of Oh & Kroupa 2016). However, we also note that the absence of faint runaways with smaller proper motions in Figure 12 is somewhat baffling. For stars fainter than $V = 19$, the limit for detection of runaways from total proper motions is $\sim 0.3$ mas yr$^{-1}$ It is possible that a lower proper-motion range at $0.2\text{–}0.3$ mas yr$^{-1}$ may contain additional runaways. This was not carefully explored owing to the large number of impostors and our inability to identify bona fide cases. Therefore, it is appropriate to state that we did not find any fast-moving massive escapee that could match the higher escape velocities of less massive stars, but the latter may still contain significantly slower escapees.
That is an proper-motion errors are smaller than 0.09 mas yr$^{-1}$ well-measured stars with consistent motion in both catalogs. The inset plot precision proper motions in DR 2 while the diagonal distribution shows considered. The vertical distribution of points indicates numerous low-proper motion HST the formal exceeding a 3σ motion (DR 2 and our OB runaway candidates (Table 2). Two cross-outs have larger proper-motion errors in the HST catalog (Table 1). The blue box shows an outlier in DR 2 with inferior proper motion (implied by the smaller motion from the HST measurement) but formally exceeding a 3σ level.

3.4.1. Addendum: WFC3/UVIS Measurements and Gaia DR 2

This paper was submitted shortly before the release of Gaia DR 2 (Gaia Collaboration et al. 2018), so we are obligated to sketch out what to expect from this monumental effort in the context of our study. Does it validate our proper motions? First, it is necessary to convert DR 2’s absolute proper motions into the relative motions using a small sample of 153 stars located around R136 (Lennon et al. 2018). Then, the mean absolute proper motion of this sample is subtracted from all DR 2 proper motions for the common stars of interest. This is not a perfect procedure because the angular size of the effective HST footprint using WFC3/UVIS is only $\sim 2/7 \times 1/4$. That is an area over which the measured relative proper motions are defined. Any displacement larger than this area may result in a slightly different relative proper motion, although at the distance of LMC such variations should be small—of the order of $\sim 0.05$ mas yr$^{-1}$ across the area of 30 Dor. It turns out that half of the stars with WFC3/UVIS measurements from Table 2 have discrepant proper motions in DR 2 at the level of 3σ–4σ. In particular, star VFTS 290 looks different from the perspective of DR 2: the proper motion in R.A. differs by 0.31 mas yr$^{-1}$. This is odd because its very close neighbor VFTS 285 (see Section 3.4) has a nearly identical relative proper motion in the two catalogs.

Figure 13. Comparison of relative proper motions along X-axis between Gaia DR 2 and HST WFC3/UVIS data. Only stars brighter than G-mag = 18 are considered. The vertical distribution of points indicates numerous low-precision proper motions in DR 2 while the diagonal distribution shows well-measured stars with consistent motion in both catalogs. The inset plot (marked by a red square) provides 39 common proper motions, if the DR 2 proper-motion errors are smaller than 0.09 mas yr$^{-1}$. The red-circled stars are our OB runaway candidates (Table 2). VFTS 290 has an inconsistent proper motion (see Section 3.4.1). Two cross-outs have larger proper-motion errors in the HST catalog (Table 1). The blue box shows an outlier in DR 2 with inferior proper motion (implied by the smaller motion from the HST measurement) but formally exceeding a 3σ level.

Figure 14. Comparison of relative proper motions along Y-axis between Gaia DR 2 and HST WFC3/UVIS data. All conventions are the same as in Figure 13. The green-circled star is VFTS 290—a star of G/K spectral type—well measured in both catalogs. Note a significant number of outliers in DR 2.

This prompted us to examine 871 common stars brighter than G-mag = 18. The DR 2 proper-motion errors of this sample range from 0.05 to 1.3 mas yr$^{-1}$ (856 stars or 98%) with a few as high as 2.3 mas yr$^{-1}$. Figures 13 and 14 show that a sizeable portion of DR 2 proper motions for our sample are essentially meaningless, especially in decl. (Y-direction). As pointed out in Section 2.4, positional errors in decl. of DR 1 are significantly larger than those in R.A. This disparity has apparently some imprint on the proper motion and its error in DR 2 as well. Even the high-accuracy DR 2 proper motions may contain some fictitious outliers mimicking a runaway star. Understanding this pattern is beyond the scope of our paper but it does serve as a cautionary tale while exploring the reality of proper motions at a level below 1 mas yr$^{-1}$. Some additional clues about the nature of such proper motions are provided by Lennon et al. (2018). In summary, our proper motions in terms of precision are clearly on par with DR 2 even for brighter stars and certainly offer an unsurpassed precision well beyond $V \sim 20$ mag.

4. Conclusions

We derived new proper-motion catalogs based on dedicated WFC3/UVIS and parallel ACS/WFC observations. Combined with the data from our pilot archival study, we provide proper motions for 368,787 stars in the region of 30 Dor. A number of fast-moving stars are identified among the stars brighter than $V \sim 22$ mag. A total of 10 runaway stars have a proper-motion direction consistent with an origin in the young and massive star cluster R136, although roughly one third of these may be chance alignments. Our WFC3/UVIS observations provide the
necessary accuracy to detect reliable proper motions in the range \(\sim 0.15-0.5 \text{ mas yr}^{-1}\) where the O-B-A-F runaways were identified. This is a unique sample of runaway stars, allowing us to better understand the processes of ejection of stars in very young clusters, and to put realistic limits on the rate of such ejections.

In summary, the main achievements of this study are as follows.

1. We detail an empirical approach to account for differential CTI, which is similar for both \(HST\) imaging instruments—ACS/WFC and WFC3/UVIS.

2. We calculated relative proper motions for a total of 368,787 stars down to \(V \sim 25\). This high-precision catalog of proper motions in the region of 30 Dor is instrumental for exploring young fast-moving stars.

3. We did not find any fast-moving OB star (with total proper motion \(\mu > 0.4\) mas yr\(^{-1}\), equivalent to \(\sim 100 \text{ km s}^{-1}\)) among a total of 481 measured VFTS stars. That may rule out some suggested pathway(s) for creating runaway stars in clusters. We predict that all the more massive runaways (mass greater than \(\sim 20M_{\odot}\)), originating from the young and massive star cluster R136, will be found within 200–300 pc from R136.

4. All candidate OB proper-motion runaway stars are single and most of them have high projected rotation velocities, including a record-high VFTS 285 at \(v \sin i = 600 \text{ km s}^{-1}\).

5. There is convincing evidence that a number of stars of spectral type O down to F have escaped from R136. It appears that these escapees have tangential velocities correlated with apparent magnitude, which points to the stellar mass as a driver for the distribution of escape velocity.

The authors gratefully acknowledge grant support for programs GO-12499, GO-12915, and GO-13359, provided by NASA through grants from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. We thank co-investigators Nate Bastian and Eli Bressert for their support in the development of this proposal. I.P. thanks Jay Anderson, Terrence Girard, and Rosemary Wyse for insights on astrometry and clarification on the properties of various stellar populations. D.J.L. would like to acknowledge the critical and enthusiastic contribution made by our departed and greatly missed colleague, Nolan Walborn. This work has made use of data from the European Space Agency (ESA) mission \textit{Gaia} (https://www.cosmos.esa.int/gaia), processed by the \textit{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 \textit{Gaia} Multilateral Agreement.

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