Peer Review File

Manuscript Title: Two waves of massive stars running away from the young cluster R136

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referee #1 (Remarks to the Author):

A. Summary of the key results

This paper presents evidence for two different channels of dynamically ejected runaways in the young cluster R136 in the Large Magellanic Cloud. The first channel ejects massive stars in all directions and is consistent with dynamical interactions during and shortly after the birth of R136. Those identified runaways who were ejected longest ago (with a kinematic age higher than 1.0 Myr) are found to be associated to this first ejection mechanism. The second channel ejects stars in a preferred direction (to the north of R136) and may be related to a cluster interaction. The identified runaways associated with this second mechanism are evolutionary older but with kinematic ages less than 1.0 Myr, in agreement with average evolutionary age of the nearby cluster located to the north-east. Therefore, runaways may be produced by an encounter of R136 with this nearby cluster. It is estimated that both mechanisms together eject 33% of the most luminous early-type massive stars. The results presented in this manuscript show that OB runaway stars have important consequences on the cosmological reionisation, the heating of the interstellar medium, and gas and metal escape from their host galaxies.

B. Originality and significance

This paper results in a significant contribution to the present day knowledge of massive runaway stars in this important region. It represents an advance in understanding the origin of massive runaway stars and the efficiency of possible ejection channels, which are important unsolved problems in astrophysics. Understanding these ejection mechanisms and their relative frequency is pivotal not only to understand the evolutionary pathways of massive stars but also to estimate their impact in the context of reionisation and the chemical enrichment of galaxies. Therefore it deserves publication in Nature.

C. Data & methodology: validity of approach, quality of data, quality of presentation

Data used in this paper comes from the latest Gaia Data Release 3 (DR3), which provides full astrometric solution for around 1.46 billion billions sources. The effect of distance (49.59 kpc) is offset by the low extinction present in the LMC, thus providing reliable astrometry in the region. Authors also applied several filters to prevent spurious astrometric solutions from contaminating the runaway sample.

The authors search for massive runaways originating from the centre of R136 by determining the dynamic trace-back age (kinematic age) of the candidates using Gaia DR3 proper motions. This procedure allow them to trace back runaways to the approximate surroundings of R136 where the ejected stars are expected to be found. Authors use the runaway candidates themselves to determine the proper motion of R136 since it is a highly crowded region and Gaia resolved no stars with reliable astrometry within several parsec of the cluster centre. They keep both proper motion components as free parameters and adopt an iterative approach, as previously done by team members in NGC 6618. They correctly filter possible field stars among the sample and determine transverse velocity and the kinematic age with Markov Chain Monte Carlo simulations. The software and code developed in the manuscript to produce the findings will be available in a Zenodo repository once the article is published.

Described methodology and reported data are detailed and transparent, with strong consistency. The code provided to referees enable reproducing results and all figures of this manuscript. Extended data and supplementary information is also adequate and supports main article text. It is also very useful for future reference.

D. Appropriate use of statistics and treatment of uncertainties

The authors include a specific section on statistical analysis as supplementary information. They make use of the ConTEST method as a consistency tests for comparing astrophysical models and observations. It is an appropriate statistical test to assess the consistency between observations and astrophysical models in a model-independent way. They perform analysis on the kinematic age distribution, the distribution of ejection angles and the distribution of transverse velocities. Results support reported findings and conclusions. They also explore the inherent structure of the dataset by employing K-means clustering. This is a common technique for partitioning data into distinct groups based on similarity. They found two clusters showing differences in the evolutionary age, kinematic age, and ejection angle distribution. Results provide the statistical basis for the presence of two physically different waves of runaways originate from R136.

The authors include error bars when appropriate (Fig. 2, 3, 4 and Extended data Fig 2, 6). However, these error bars are not defined in the corresponding figure legends or captions. Uncertainties on the probability function of Extended Data Fig. 5 are described in the corresponding text and figure caption.

E. Conclusions: robustness, validity, reliability

Conclusions on this work are reliable and of high importance, well supported by the analysis data.

F. Suggested improvements: experiments, data for possible revision

Few minor comments, concerns and suggestions follow:

- The authors select candidates considering the radial-velocity dispersion determined in R136 by

Hénault-Brunet et al. 2012 (σ_{1D}= 3.9 km s-1) and adopt a transverse velocity difference larger than $5\sigma_{2D} \simeq 27.6$ km s−1. This is similar to the runaway threshold velocity found in a previous spectroscopic study in 30 Dor (Sana et al. 2022), which requires a radial velocity deviating from the mean larger than three times the radial-velocity dispersion of all apparently single O stars observed by the VFTS survey in the 30 Doradus region ($\sim$ 5.8 km s−1). Although this assumption is well justified given the lack of spectroscopic information to derive radial velocities for all identified runaways, further comment on the possibility of false positives is desirable (and quantify them, if such a case).

- The authors correctly use 2MASS and Gaia color-color diagrams to constrain the OB nature of the selected candidates and discard field stars (Extended data Fig. 2 and 3). I recommend including reddening lines or tracks for early-type stars in Fig. 3 to show that the final runaway sample is consistent with the theoretical location of OB stars (as in Fig. 2).

G. References: appropriate credit to previous work?

Relevant references to previous related work are properly included.

H. Clarity and context: lucidity of abstract/summary, appropriateness of abstract, introduction and conclusions

The paper is well written with a proper abstract, introduction and conclusions sections. The data are adequately described and the methods applied in the analysis are clearly explained.

Referee #1 (Remarks on code availability):

The authors provided a ready-made code to produce all results. You just need to install the free Jupyter Notebook software as it is a web-based interactive computing platform. The package includes all necessary data, a readme file with clear instructions and the 2 main codes: a first one for obtaining runaway candidates from Gaia (I get 21,382 sources, as claimed in the manuscript). And a second one to obtain the dataset of 69 runaway candidates, that after determine transverse velocity, ejection angle, and kinematic age with MCMC simulations leads to the final sample of 55 runaways. Running this second MCMC code takes 7-8 hours, although authors have included a way to run a smaller dataset of three runaways as proof-of-concept (you are free to choose). This last option only takes 20 minutes.

Codes are user-friendly and include many comments about each step. Running the code is straightforward, even for a user with poor coding knowledge.

Referee #2 (Remarks to the Author):

I read with great interest the paper on "Two Waves of Massive Stars Running Away from R136." I believe this work is worthy of publication in Nature. The paper presents novel and compelling insights into the formation and early evolution of young massive clusters. The results have significant implications for our understanding of the reionization problem in the early universe. The paper is well-written and organized, and the evidence for a double episode of stellar ejection is strong.

While I strongly recommend publication in Nature, I have some reservations regarding the conclusions about the slope of the initial mass functon(IMF). The paper provides robust statistical analysis for the proper motions, but does not address the potential impact of incompleteness on the IMF.

Specifically:

- Before concluding that the mass function of the runaway stars is shallower than Salpeter, the paper should include a discuss the completeness of the Gaia data for stars in the 30 Doradus star-forming complex and demonstrate the absence of biases in completeness or proper motion errors as a function of magnitude, stellar color, spectral type, and kinematic age. If biases are identified, the paper should explain how these can be taken into account.
- Plots comparing magnitude, kinematic ages, and spectral types with the proper motion uncertainties would strengthen the argument regarding the IMF.
- Similarly, the Gaia catalog have been filtered to include only stars with high-quality positional measurements. It would be useful to demonstrate that these filters do not disproportionately affect a specific group of stars.

Minor comments:

I find Extended Fig. 2 to be redundant, as the final distinction between early- and late-type stars relies solely on the Gaia CMD (which is perfectly acceptable). The inclusion of this figure complicates the discussion of field star selection based on their location in the color-color diagram. While the text states that early-type stars should have colors (J-H) < 0 and (H-K) < 0, the constraints provided for field stars only consider (J-H) colors. Furthermore, the color-color diagram itself shows a fraction of early-type stars with (H-K) > 0.5. This inconsistency is further amplified by including stars with no JHK photometry in the analysis, selected solely based on their Gaia colors

Proper motion of R136 – 3rd paragraph: …; therefore, we therefore only used..” remove one of the “therefore”.

In the caption of Extended data Figs. 7, 8, 9, and 10 “the dashed blue line” should be corrected to be “the dashed black line”.

Referee #2 (Remarks on code availability):

The link to the code bring to a "DOI not found" error message page.
The text in the paper states that the code and software are available in that repository once the paper is published

Author Rebuttals to Initial Comments:

Dear anonymous referees,

We would like to thank the referees for their positive reception and constructive feedback regarding our paper. Below we discuss the comments and issues raised point-by-point. Changes are marked in the full paper in magenta/pink.

> *Referee 1:*
> *- The authors select candidates considering the radial-velocity dispersion determined in R136 by Hénault-Brunet et al. 2012 (σ1D= 3.9 km s-1) and adopt a transverse velocity difference larger than 5σ2D ≃ 27.6 km s−1. This is similar to the runaway threshold velocity found in a previous spectroscopic study in 30 Dor (Sana et al. 2022), which requires a radial velocity deviating from the mean larger than three times the radial-velocity dispersion of all apparently single O stars observed by the VFTS survey in the 30 Doradus region (∼ 5.8 km s−1). Although this assumption is well justified given the lack of spectroscopic information to derive radial velocities for all identified runaways, further comment on the possibility of false positives is desirable (and quantify them, if such a case).*

We have estimated the false positive rate assuming that all candidate runaways have a random velocity according to the 1D radial velocity dispersion measured in the VFTS survey in the 30 Doradus region (~5.8 km s-1; Sana et al. 2022). We have added a short subsection in the Supplementary Information describing this, which results in a probability equal to 2.8 x 10^-6 for one of the early-type candidate runaways (n = 9,368) to be a false positive runaway. The probability that one of the 55 observed runaways is a false positive is 1.6 x 10^-4. We deem it unlikely that our runaway sample is contaminated by false positive runaways.

This is explained in the subsection “False-positive rate” in the Supplementary Information.

> *- The authors correctly use 2MASS and Gaia color-color diagrams to constrain the OB nature of the selected candidates and discard field stars (Extended data Fig. 2 and 3). I recommend including reddening lines or tracks for early-type stars in Fig. 3 to show that the final runaway sample is consistent with the theoretical location of OB stars (as in Fig. 2).*

We have added reddening lines from the Parsec models in Extended Fig. 3 for a 100, 60, 30, 18, and 10 M_sun star assuming that the distance to the LMC = 49.59 kpc, a stellar age = 1.8 Myr and R_V = 3.1. This shows that the observed runaways are consistent with OB stars with A_V typically between 0.5 and 2.5 mag, with VFTS 682 the obvious exception.

> *Referee #2:*
> *While I strongly recommend publication in Nature, I have some reservations regarding the conclusions about the slope of the initial mass functon(IMF). The paper provides robust statistical analysis for the proper motions, but does not address the potential impact of incompleteness on the IMF.*
> *Specifically:*
> *• Before concluding that the mass function of the runaway stars is shallower than Salpeter, the paper should include a discuss the completeness of the Gaia data for stars in the 30 Doradus star-forming complex and demonstrate the absence of biases in completeness or proper motion errors as a function of magnitude, stellar color, spectral type, and kinematic age. If biases are identified, the paper should explain how these can be taken into account.*
> *• Plots comparing magnitude, kinematic ages, and spectral types with the proper motion uncertainties would strengthen the argument regarding the IMF.*
> *• Similarly, the Gaia catalog have been filtered to include only stars with high-quality positional measurements. It would be useful to demonstrate that these filters do not disproportionately affect a specific group of stars.*

We have investigated possible biases in the filters introduced and completeness limits and its impact on the initial mass function of the runaways.

One of the important filters introduced is the maximum uncertainty on the parallax (0.05 mas). As a result of this, we reach 95% completeness between G ~ 16.2 to 16.4 mag. This is equivalent to a ~ 16 M_sun star at the distance to the LMC assuming A_V = 1.2 mag. We reach 50% completeness around G ~ 16.8 mag, equivalent to a ~ 13 M_sun star with equal assumptions. We can therefore miss out on late-type O stars with relatively large A_V and a significant part of the early B-type runaways if present. Correcting for this bias would require us to know the intrinsic luminosity function and therefore the mass function of the runaways, which is exactly what we are trying to determine. While we could loosen the restriction on the parallax uncertainty, this would add additional biases as we would start to include a significant population of foreground stars due to their more uncertain distance. We therefore restrict the determination of the mass function of the runaways to stars with masses larger than 16 M_sun.

An additional filter that could create a bias is that the transverse velocity is required to be larger than 3 times the uncertainty on the transverse velocity (v_t / sigma_v_t > 3). Similar to the parallax uncertainty, this disproportionally affects fainter stars more than brighter stars. Out of the 9,368 runaway candidates with Bp – Rp < 1.0 mag, already 1,011 are excluded because their transverse velocity is not accurate (v_t / sigma_v_t > 3). These 1,011 stars are specifically fainter stars with a large proper motion error, with 95% of these stars having G between 15.7-17.0 mag. As a result, we can miss out on late-type O stars and early B-type stars as they are excluded. Notably, their transverse velocity is smaller than ~ 55 km s-1 with respect to R136. If the ratio of observed runaways to runaway candidates is similar, we can estimate the number of runaways missed out on. We observe 23 runaways with a transverse smaller than 55 km s-1 among the 3,097 candidate runaways. The 1,011 candidate runaways now excluded are estimated to contain ~ 8 true runaways.

We correct for this in the mass function of the runaways by randomly selecting 8 ‘runaways’ from these 1,011 excluded stars. We include these 8 runaways into the determination of the IMF. As a result, we find an initial mass function slope equal to -1.87 +- 0.07 for the runaways between 16 and 200 M_sun. These biases are important below a stellar mass of ~ 20 M_sun, and they do not change the result that the IMF of R136 is shallow, rather than the IMF of the surrounding 30 Dor, since we calculate this only for stars with an initial mass larger than 30 M_sun.

We find that correlations between other quantities such as spectral type, color, and kinematic age do not significantly affect our results.

The above findings are explained in detail in the subsection “Selection biases” in the Supplementary Information.

Minor comments:

I find Extended Fig. 2 to be redundant, as the final distinction between early- and late-type stars relies solely on the Gaia CMD (which is perfectly acceptable). The inclusion of this figure complicates the discussion of field star selection based on their location in the color-color diagram. While the text states that early-type stars should have colors (J-H) < 0 and (H-K) < 0, the constraints provided for field stars only consider (J-H) colors. Furthermore, the color-color diagram itself shows a fraction of early-type stars with (H-K) > 0.5. This inconsistency is further amplified by including stars with no JHK photometry in the analysis, selected solely based on their Gaia colors

We find Extended Fig. 2 not to be redundant. While most runaways have Bp – Rp < 1.0 mag, highly reddened runaways (in this case VFTS 682), could be missed out on if we did not regard the JHK photometry. Several stars indeed have (H – K) > 0.5, making it unclear what type of stars these are, although we do note that most are consistent within 2sigma uncertainties with the OB reddening line. The JHK photometry also lends support to the idea that the stars with Bp – Rp > 1.0 mag in Extended Data Fig. 3 are late-type stars such as red giants. Their position in the JHK color-color diagram shows that they are not heavily extincted OB stars and instead are consistent with the position of cool M-type stars.

> *Proper motion of R136 – 3rd paragraph: …; therefore, we therefore only used..” remove one of the “therefore”.*

We have removed one of the “therefore”.

> *In the caption of Extended data Figs. 7, 8, 9, and 10 “the dashed blue line” should be corrected to be “the dashed black line”.*

We have corrected this.

Reviewer Reports on the First Revision:

Referee #2 (Remarks to the Author):

I would like to thank the authors for taking into account my recommendations and address my request. I find the results very interesting and I am satisfied with the updated version of the manuscript. I recommend the paper for publication.