Astronomy & Astrophysics manuscript no. VFTS682 ©ESO 2018
May 10, 2018

VFTS682: a confirmed dynamical ejection?

M. Renzo[1] and ■ **[TBD]** ■.

Astronomical Institute Anton Pannekoek, University of Amsterdam, 1098 XH Amsterdam, The Netherlands

ABSTRACT

Key words. stars: kinematics, stars: runaways, stars: individual: VFTS682

1. Introduction

How do massive stars form is one longstanding question in astrophysics (e.g., Lada & Lada 2003; Zinnecker & Yorke 2007), because they are intrinsically rare (e.g., Salpeter 1955; Kroupa 2001; Schneider et al. 2018), evolve fast, and remain enshrouded in their parent cloud during the formation process. Moreover, observations of young massive stars reveal a complicated multiplicty structure which requires explanation (Sana et al. 2012, 2017). Understanding massive star formation, possibly as a function of metallicity, is a key question given the present and upcoming transient survey (e.g., LSST, BlackGem, LIGO/Virgo O3)■ **[ref]** ■ which will reveal transients associated to massive stars evolution and death.

Two competing classes of models for massive star formation exist. One class predicts that massive stars can form in relative isolation ■ **[ref]** ■, while the other predicts they always form in cluster and/or associations, and therefore isolated massive stars should necessarily peculiar velocities to reach an isolated position on the sky■ **[ref]** ■.

The second data release (DR2) from the Gaia satellite (Gaia Collaboration et al. 2016, 2018) allows us to test these hypothesis using one particular star, VFTS682. This star belongs to the 30 Doradus region in the Large Magellanic Cloud (LMC), and has an inferred initial mass of $M_{\mathrm{ZAMS}} = 150.0^{+28.7}_{-17.4}\,M_{\odot}$ (Bestenlehner et al. 2011; Schneider et al. 2018). Its spectral type is WNh5, and it is presently observed at a projected distance of ~29 pc from the nearest cluster of massive stars R136 (also known as NGC2070 Bestenlehner et al. 2011). The inferred mass loss rate is $\sim 10^{-XX}\,M_{\odot}\,\mathrm{yr}^{-1}$ ■ **[ref]** ■.

Based on the extremely high mass of this star and its present-day apparent isolation, Bestenlehner et al. (2011) proposed it could be a candidate for isolated star formation, or a "slow runaway" ejected from R136 in the past. Their study raised the interest in the origin of this star. Fujii & Portegies Zwart (2011); Banerjee et al. (2012) carried out N-body simulations of massive young stellar clusters and concluded that the ejection of such a massive object from R136 through dynamical interactions (e,g, Poveda et al. 1967) would be possible. The competing ejection mechanism, the disruption of a binary system by a core-collapse event (Zwicky 1957; Blaauw 1961), is thought to be ruled out, since the cluster has an estimated age of $\lesssim$ 2 Myr (Sabbi et al. 2012), which is shorter than the shortest stellar lifetime (~3 Myr, e.g., Zapartas et al. 2017).

In this study, we combine the radial velocity measurements from the VFTS survey (Evans et al. 2011) with the proper motion from Gaia DR2 to reconstruct the three-dimensional velocity of VFTS682, and test the hypothesis that this star was ejected from R136. We discuss in Sec. 2 the data for VFTS682, and the selection of stars used to define a local reference frame. Our results indicate that R136 is a bona fide runaway star (Sec. 3.1), therefore isolated star formation is *not* required to explain it. We also find that a dynamical ejection from R136 is compatible with the direction of its velocity vector. We conclude with a very brief discussion on the implications for theories of star formation, N-body interactions, and binary evolution in Sec. 4.

2. Gaia DR2 data selection

VFTS682 is labeled in the Gaia DR2 catalog[1] with the source id 4657685637907503744. The star has a `visibility_period` = 17, which counts how many observations have been used to reconstruct its astrometric solution (Lindegren et al. 2018). Its reported G-band magnitude is 15.65, cf. the V-band magnitude of 16.08 (Evans et al. 2011; Bestenlehner et al. 2011), and the reported `astrometric_excess_noise` = 0. These values suggest that the Gaia data for VFTS682 are trustworthy. However, the effective temperature reported in Gaia DR2 is one order of magnitude lower than what found by Bestenlehner et al. (2011), and the best fit parallax of this star is negative. We do not use the effective temperature of the star anywhere in this study, and we attribute the unphysical value of the parallax to the large distance to the LMC. Our main findings do not rely on the parallax nor the effective temperature values reported in the Gaia DR2 catalog.

We retrieve for VFTS682 the position in right ascension (RA) and declination (DE) in the IGCS frame (Gaia Collaboration et al. 2018), its proper motion components (μ_{RA}, and μ_{DE}, respectively). For the radial velocity of VFTS682 and of the 30 Doradus region as a whole, we instead use the VFTS data as quoted in Bestenlehner et al. (2011). Table 1 lists the values adopted throughout this work for each of these quantities.

We define a local standard frame to derive the peculiar velocity of VFTS682 by selecting from the Gaia DR2 catalog a sample of nearby stars, following closely the approach of **?**. We select all the stars in a target of 0.2 degrees around R136 (NGC2070)

Send offprint requests to: M. Renzo, m.renzo@uva.nl

[1] `https://vizier.u-strasbg.fr/viz-bin/VizieR-3?-source=I/345/gaia2`

Table 1. Astrometric parameters for VFTS682. The peculiar radial velocity $\delta\upsilon_{\rm rad}$ is obtained as the difference between the average radial velocity of the 30 Doradus region (270±10 km s^{-1}) minus the radial velocity measured from the HeII λ4686 line for VFTS682 (315 ± 15 km s^{-1}).

Parameter	Value	Source
RA [degree]	84.73 ± 0.03	Gaia DR2
DE [degree]	-69.07 ± 0.05	
$\mu_{\rm RA}$ [mas yr^{-1}]	1.84 ± 0.07	
$\mu_{\rm DE}$ [mas yr^{-1}]	0.78 ± 0.08	
$\delta\upsilon_{\rm rad}$ [km s^{-1}]	-45 ± 25	Bestenlehner et al. (2011)

fulfilling the following criteria. First, we require G-band magnitude brighter than 17, correspondingly roughly to the completeness level of the VFTS survey (here we implicitly assume G∼V, Evans et al. 2011). Then we require `visibility_period` ≥ 5, `astrometric_excess_noise` < 1, the errors on the proper motion components to be smaller than 0.1 mas yr^{-1}, and the proper motion components themselves to be smaller than 2 mas yr^{-1} in absolute value. At the distance to the LMC, 1mas yr^{-1} ≃ 250 km s^{-1} (e.g., ?), so the cut on the values of the proper motions removes stars that would have projected tangential velocities in excess of ∼500 km s^{-1}, which are most likely to be foreground stars. We checked that the additional requirement of having parallaxes smaller than 2 mas does not reduces further our sample.

We calculate the averaged proper motion components for the whole region using

$$\langle\mu_i\rangle = \frac{\sum_{\rm stars}\frac{1}{\Delta\mu_i}\mu_i}{\sum_{\rm stars}\frac{1}{\Delta\mu_i}} \quad , \quad \Delta\langle\mu_i\rangle = \frac{\sqrt{N}}{\sum_{\rm stars}\frac{1}{\Delta\mu_i}} \quad , \tag{1}$$

where i = RA, DEC, and $\Delta\mu_i$ is the error on the proper motion component reported by Gaia. The sums run over all the $N = 651$ stars in our selected sample. We evaluate each proper motion component separately. For simplicity, throughout this study, we assume the same distance of 50 kpc to the star (Lebouteiller et al. 2008), and to the 30 Doradus region as a whole. We do not consider the error bars on the distance determination when converting proper motions into physical velocities. The data retrieved, and the ipython notebook used for the analysis presented here will be made available at ■ **[probably git repo on bitbucket?]** ■.

3. The kinematics of VFTS682

3.1. Is it a runaway star?

We first address the question of whether VFTS682 is a typical star from the kinematic point of view, or whether it is a runaway star with a significantly large peculiar velocity compared to its surrounding population. The former is what should be expected if it formed where we observe it today, in relative isolation from other massive stars.

Using the 651 stars selected as described in Sec. 2 and shown in blue in Fig. 1, we find averaged proper motion components of $\langle\mu^{\rm sur}_{\rm RA}\rangle = 1.683 \pm 0.002$ mas yr^{-1} and $\langle\mu^{\rm sur}_{\rm DE}\rangle = 0.672 \pm 0.003$ mas yr^{-1}. We note that these values are in good agreement with what found by ?. Subtracting these values from the proper motions of VFTS682 (see Table 1), we obtain the components of proper motion of the star relative to the surrounding region $\mu^{\rm sur}_{\rm RA} = 0.16 \pm 0.07$ mas yr^{-1} and $\mu^{\rm sur}_{\rm DE} = 0.11 \pm 0.08$ mas yr^{-1}. These can be converted in the the components of the transverse velocity $\upsilon^{\rm sur}_{\rm RA} = 38 \pm 17$ km s^{-1}, $\upsilon^{\rm sur}_{\rm DE} = 26 \pm 19$ km s^{-1}, assuming a distance of 50 kpc (we do not account for the uncertainty in the distance estimate when propagating errors). The radial velocity from Bestenlehner et al. (2011) then gives the third component along the line of sight, allowing us to calculate the speed of the star:

$$\upsilon^{\rm sur} = \sqrt{\left(\upsilon^{\rm sur}_{\rm RA}\right)^2 + \left(\upsilon^{\rm sur}_{\rm DE}\right)^2 + (\delta\upsilon_{\rm rad})^2} = 64 \pm 21 \text{ km s}^{-1} . \tag{2}$$

This value for the three-dimensional speed of VFTS682 with respect the surrounding stars make it the most massive "bona fide" runaway star known to date.

3.2. Does it come from the R136 cluster?

3.3. Kinematic age

4. Discussion

■ **[compare to Lennon: time of ejection is the same? what does it say for cluster]** ■ ■ **[say implications for center of R136 (same stars are there), how many ejected given this one, was a binary ejected in the other direction?]** ■ ■ **[does this imply there is a binary in the core ?]** ■

- VFTS682 is a bona fide runaway with $\upsilon \sim 60$ km s^{-1} thrown out from R136. Both its speed and the age of the cluster are consitent with a dynamical ejection.
- VFTS682 comes from R136 as was expected by Bestenlehner et al. (2011); Fujii & Portegies Zwart (2011); Banerjee et al. (2012), so it does not require isolated SFH to be explained
- apparent age tension (connect to VFTS16 as well).
- is R136 a single young cluster or a merger
- estimate the influence of the gravitational potential of R136, what is its total mass and relaxation time?

5. Summary

1. Gaia data confirm a 150Msun runaway with v 60, thus the most massive known to date 2. directions suggest ejection from R136, confirming prediction of fuji+ banerjee+ 2b. This fits with the observation from crowther of M>300Msun in R136 (and mention vfts682 has the same spectral type): the most likely mechanism needs encounter with 2 more massive -> additional evidence for Crowther claim 3. comment on final fate (BH)

Random notes: $\upsilon\sin(i) < 200$ km s^{-1} form Schneider et al. (2018), age 1.0 ± 0.2 Myr from Schneider et al. (2018)

Many other very massive stars are present in the surroundings this cluster, and a more detailed analysis on the larger sample is desirable.

References

Banerjee, S., Kroupa, P., & Oh, S. 2012, ApJ, 746, 15
Bestenlehner, J. M., Vink, J. S., Gräfener, G., et al. 2011, A&A, 530, L14
Blaauw, A. 1961, Bull. Astron. Inst. Netherlands, 15, 265
Evans, C. J., Taylor, W. D., Hénault-Brunet, V., et al. 2011, A&A, 530, A108
Fujii, M. S. & Portegies Zwart, S. 2011, Science, 334, 1380
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, ArXiv e-prints
Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, A&A, 595, A1
Kroupa, P. 2001, MNRAS, 322, 231
Lada, C. J. & Lada, E. A. 2003, ARA&A, 41, 57
Lebouteiller, V., Bernard-Salas, J., Brandl, B., et al. 2008, ApJ, 680, 398

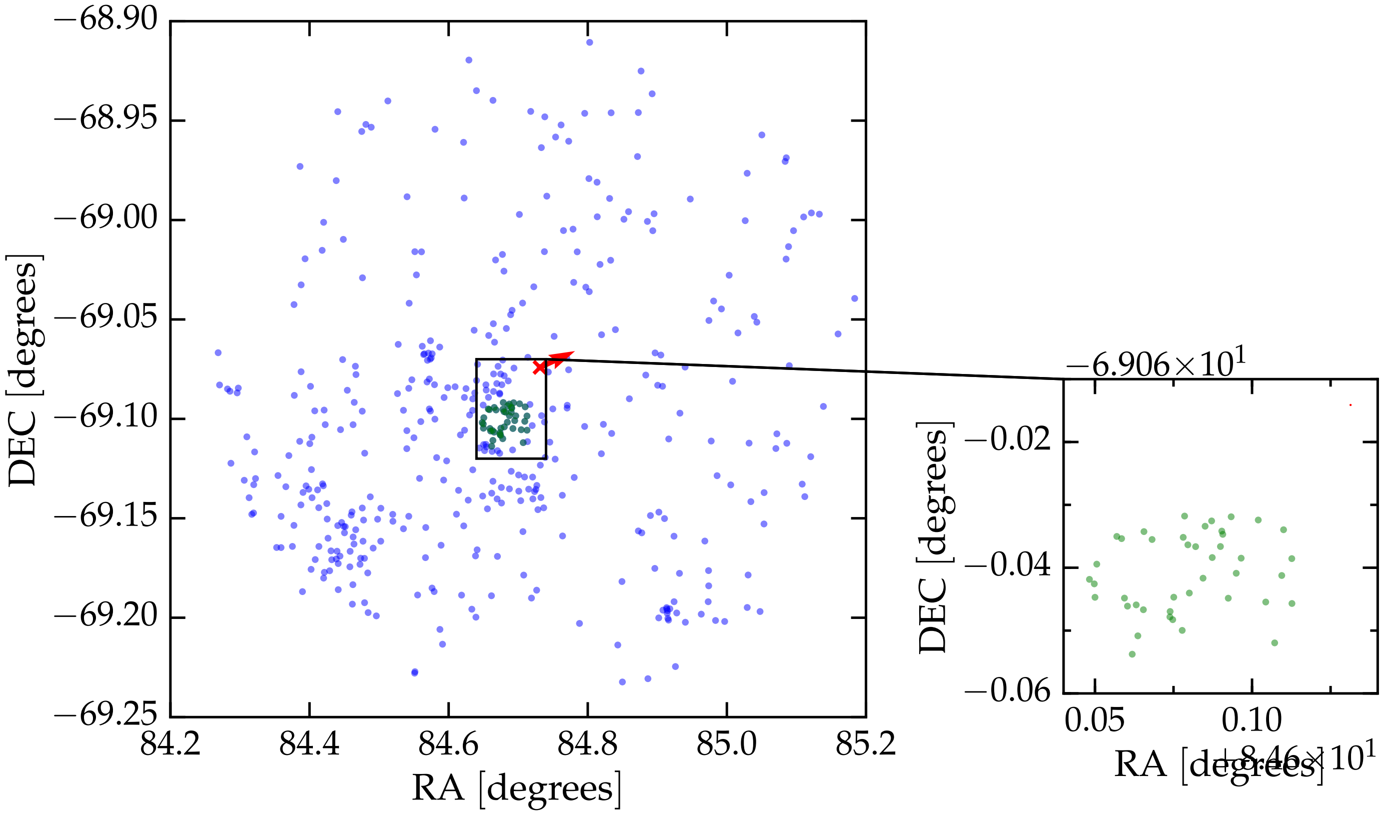

Fig. 1. The red cross indicates the position of VFTS682. Blue stars are those we use to define the generic "surroundings", while the green dots indicate the stars we use to probe the core of R136, magnified in the inset. The red arrow shows the direction of the proper motion of VFTS682 relative to R136, and the gray shade indicates the uncertainty in the direction. ■ **[orient properly, load picture on background, add cone of uncertainty, maybe show pm for all stars in inset?]** ■

Lindegren, L., Hernandez, J., Bombrun, A., et al. 2018, ArXiv e-prints
Poveda, A., Ruiz, J., & Allen, C. 1967, Boletin de los Observatorios Tonantzintla y Tacubaya, 4, 86
Robitaille, T. & Bressert, E. 2012, APLpy: Astronomical Plotting Library in Python, Astrophysics Source Code Library
Sabbi, E., Lennon, D. J., Gieles, M., et al. 2012, ApJ, 754, L37
Salpeter, E. E. 1955, ApJ, 121, 161
Sana, H., de Mink, S. E., de Koter, A., et al. 2012, Science, 337, 444
Sana, H., Ramírez-Tannus, M. C., de Koter, A., et al. 2017, A&A, 599, L9
Schneider, F. R. N., Sana, H., Evans, C. J., et al. 2018, Science, 359, 69
Zapartas, E., de Mink, S. E., Izzard, R. G., et al. 2017, A&A, 601, A29
Zinnecker, H. & Yorke, H. W. 2007, ARA&A, 45, 481
Zwicky, F. 1957, ZAp, 44, 64

Acknowledgements. The background image of Fig. 1 is based on observations made with ESO Telescopes at the La Silla Observatory under programme ID 076.C-0888, processed and released by the ESO VOS/ADP group. This research made use of APLpy, an open-source plotting package for Python Robitaille & Bressert (2012). We are grateful to S. Torres for extremely useful discussions on the Gaia DR2 dataset.