Draft version June 6, 2018
Preprint typeset using LaTeX style emulateapj v. 01/23/15

GAIA DR2 ADDS CLUES FOR DYNAMICAL EJECTION OF A ∼150 $M_\odot$ STAR

M. Renzo[1], S. E. de Mink[1], D. J. Lennon[2], R. P. van der Marel[3,4], I. Platais[4], J. Bestenlehner[5], V. Hénault-Brunet[6], S. Justham[7,8], A. de Koter[1], N. Langer[9], H. Sana[10], F. R. Schneider[11], J. S. Vink[12]
[1]Astronomical Institute Anton Pannekoek, University of Amsterdam, 1098 XH Amsterdam, The Netherlands
[2] ESA, European Space Astronomy Centre, Apdo. de Correos 78, E-28691 Villanueva de la Cañada, Madrid, Spain
[3] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[4] Center for Astrophysical Sciences, Department of Physics & Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
[5]Department of Physics and Astronomy, Hicks Building, Hounsfield Road, University of Sheffield, Sheffield S3 7RH, UK
[6] National Research Council, Herzberg Astronomy & Astrophysics, 5071 West Saanich Road, Victoria, BC, V9E 2E7, Canada
[7] School of Astronomy & Space Science, University of the Chinese Academy of Sciences, Beijing 100012, China
[8] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
[9] Argelander-Institüt für Astronomie, Universität Bonn, Auf dem Hügel 71, 53121, Bonn, Germany
[10] Institute of Astronomy, KU Leuven, Celestijnenlaan 200 D, B-3001 Leuven, Belgium
[11] Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK
[12] Armagh Observatory, College Hill, Armagh BT61 9DG, UK

(Dated:)
Draft version June 6, 2018

ABSTRACT

The formation and fates of the most massive stars remain among the most elusive questions in stellar astrophysics. Previous spectroscopic studies identified VFTS682 as one of the most massive stars known. It resides in the field of the 30 Dor region in the Large Magellanic Cloud at a projected distance of 29 pc of the star cluster Radcliffe 136 (R136). The inconclusiveness of the radial velocity analysis for this emission line star led to speculations whether such extreme stars can form in relative isolation. We use the proper motions from the second *Gaia* data release (DR2) together with multiepoch *Hubble Space Telescope* proper motions to investigate the kinematics of this object. We show that the projected velocity of VFTS682 is consistent with it being a runaway star dynamically ejected from R136. Its projected two-dimensional speed relative to the cluster is $\sim 30 \pm 20\,\mathrm{km\,s^{-1}}$, implying a three-dimensional speed of about $\sim 40 \pm 20\,\mathrm{km\,s^{-1}}$ when accounting for the (uncertain) velocity component along the line of sight. The inferred kinematic age is also consistent with the dynamical ejection scenario from the cluster. If confirmed by future astrometric data, this would make VFTS682 the most massive runaway star known to date. It would prove that star clusters are capable of ejecting their most massive members. We discuss the implications for the existence of stars with masses well above $100\,\mathrm{M}_\odot$ inside the cluster, the internal dynamics in dense star clusters and the final fate of this object.

Subject headings: stars: kinematics, stars: runaways, stars: individual: VFTS 682

1. INTRODUCTION

How massive stars form is one of the major longstanding questions in astrophysics (e.g., Zinnecker & Yorke 2007). Obtaining clues from observations has been challenging, because massive stars are intrinsically rare, evolve fast, typically reside in dense groups and remain enshrouded in their parent cloud during the entirety of their formation process. Major progress has been made on the theoretical side, (e.g. Kuiper et al. 2015; Rosen et al. 2016), but simulations cannot yet resolve the length scales of interest to explain the high multiplicity of massive stars (e.g., Bate 2009; Sana et al. 2017). Understanding massive star formation, and its possible dependence on environment and metallicity, is crucial for understanding the role massive stars play within their host galaxies, but also for understanding the transients that mark their death and the compact remnants they leave behind.

In has been proposed that most, if not all, stars form in clusters (Lada & Lada 2003), where massive stars are thought to form preferentially in the dense cores. In this picture, field stars are primarily the result of the dissolution of dense groups. However, a significant population of massive stars exists in relative isolation, far from dense clusters or OB associations. The origin of this population still remains debated (Gvaramadze et al. 2012; Lamb et al. 2016; Ward & Kruijssen 2018). One hypothesis is that they formed in the field, but this poses a challenge for the theories of star formation. The alternative hypothesis is that these massive stars formed in clusters, and then were ejected from their birth locations. Such ejections may result from dynamical interactions (e.g., Poveda et al. 1967) or from the disruption of binary systems at the death of the companion star (e.g., Zwicky 1957; Blaauw 1961; Renzo et al. 2018).

A contribution to the debate on whether or not massive stars form in relative isolation was presented by Bestenlehner et al. (2011) and Bressert et al. (2012), who discussed the case of the very massive star VFTS682. This star is located in the field of the 30 Doradus region in the Large Magellanic Cloud (LMC) and was studied as part of the multi-epoch spectroscopic VLT-FLAMES Tarantula Survey (VFTS, Evans et al. 2011). Its spectral type is WNh5 and its present-day mass is $137.8^{+27.5}_{-15.9}\,M_\odot$, (Schneider et al. 2018). These correspond to an inferred initial mass of $150.0^{+28.7}_{-17.4}\,M_\odot$ and make VFTS682 one of the most extreme objects in the region. From the spectral point of view, it is reminiscent of the very massive stars identified by de Koter et al. (1997); Crowther et al. (2010, 2016) in the core of the R136 cluster. In particular, a remark-

Corresponding author: M. Renzo, m.renzo@uva.nl

able similarity exist between the spectrum of VFTS682 and R136a3, located in the core of the cluster (Crowther et al. 2010) for which Crowther et al. (2016) report a current mass estimate of $180^{+30}_{-30}\,M_{\odot}$. The R136 cluster hosts at least two more very massive WN5h stars, R136a1 and R136a2, whose estimated current masses are even higher. However, VFTS682 stands out by its isolation at a projected offset of 119.4 arcseconds, corresponding to ~29 pc from the core of the star cluster R136.

Bestenlehner et al. (2011) discuss two possibilities for the origin of VFTS682. From their abstract: "(i) the star either formed in situ, which would have profound implications for the formation mechanism of massive stars, or (ii) VFTS682 is a slow runaway star that originated from the dense cluster R136, which would make it the most massive runaway known to date". Based on their dynamical models, Fujii & Portegies Zwart (2011) and Banerjee et al. (2012) argued that ejection of VFTS682 from R136 would be natural. Testing the origin of VFTS682 is not only important for constraining isolated star formation; it should also help to improve understanding of early star-cluster dynamics.

Recently, Platais et al. (2015, 2018) used multi-epoch *Hubble Space Telescope* (HST) imaging to identify runaway stars in 30 Doradus based on their proper motions. Lennon et al. (2018) used data from the second *Gaia* data release (DR2, Gaia Collaboration et al. 2016, 2018) to further investigate the isolated O-type stars around R136. In this study, we report on our analysis of the *Gaia* DR2 data for VFTS682 which was not part of the sample of Lennon et al. (2018) because of its spectral type. 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 use the HST proper motions from Platais et al. (2018) to test our analysis of the *Gaia* DR2 data.

2. OBSERVATIONS

2.1. *Overview of VFTS682 from previous studies*

The star VFTS682, located at right ascension (RA) $05^{\mathrm{h}}38^{\mathrm{m}}55.510^{\mathrm{s}}$ and declination (DEC) -69°04'26.72" J2000 (Evans et al. 2011) was originally classified as a young stellar object (Gruendl & Chu 2009) based on its mid-infrared excess. Evans et al. (2011) reclassified the object as Wolf-Rayet star of spectral type WNh5 using multi-epoch spectra covering λ4000–7000 from the VFTS survey.

Using the same dataset, Bestenlehner et al. (2011) excluded the presence of a close companion with high confidence from the absence of radial velocity variations. Bestenlehner et al. (2011) also derived stellar parameters and surface abundances. They inferred an extinction of $A_V = 4.45 \pm 0.12$, leading to the high luminosity $\log_{10}(L/L_{\odot}) = 6.5 \pm 0.2$. Schneider et al. (2018) estimated a present-day mass for VFTS682 of $137.8^{+27.5}_{-15.9}\,M_{\odot}$, an apparent age of $1.0^{+0.2}_{-0.2}$ Myr and an inferred initial mass of $150.0^{+28.7}_{-17.4}\,M_{\odot}$, using the Bayesian analysis tool BONNSAI (Schneider et al. 2017), based on the evolutionary models from Brott et al. (2011) and Köhler et al. (2015).

Bestenlehner et al. (2011) reported for VFTS682 a wind mass loss rate of $\sim 10^{-4.1\pm0.2}\,M_{\odot}\,\mathrm{yr}^{-1}$, not accounting for clumping. The present-day surface helium mass fraction is $Y = 0.45\,(0.49)$ from the spectral analysis of Bestenlehner et al. (2011) (Rubio-Díez et al. 2017). This value can be used to constrain the age of the star and its past evolution.

Further worth noticing is the variability of the star. Bestenlehner et al. (2011) discuss the Optical Gravitational Lensing Experiment (OGLE-III) light curves (Udalski et al. 2008) and show a variability in the V-band at ~10% level on a timescale of years. They commented that this is unusual for Wolf-Rayet stars and more reminiscent of Luminous Blue Variable (LBV) stars.

We obtain the peculiar radial velocity δv_{rad} of VFTS682 as the difference between the average radial velocity of the 30 Doradus region ($270 \pm 10\,\mathrm{km\,s^{-1}}$) minus the radial velocity measured from the NV λ4944 line for VFTS682 ($300 \pm 10\,\mathrm{km\,s^{-1}}$, Bestenlehner et al. 2011). We implicitly assume that the use of a slightly different reference frame for δv_{rad} does not introduce significant errors. Bressert et al. (2012) also noted that VFTS682 shows a significant radial velocity offset compared to the nebular lines from the gas surrounding it, suggesting peculiar motion in the line of sight direction. However, the determination of radial velocities for emission-lines stars is difficult because of the presence of an optically thick, likely non-homogeneous, and variable wind obscuring the stellar surface. The radial velocity errors quoted above quantify only statistical uncertainties from the spectral analysis, and not the systematic errors arising from the modeling of emission line stars.

2.2. *HST astrometry for VFTS682*

Recently, Platais et al. (2018) presented HST astrometry and proper motions in the 30 Doradus region based on two epochs. While the most bright stars (V<14) were saturated in their data and missing from that catalog, due to its high extinction, VFTS682 is faint enough to be included in that catalog. Its proper motions are listed in Table 2.3. For large distances ($\gtrsim$ 50 kpc), HST astrometry can compete or even exceed *Gaia* DR2 data in quality.

The catalog from Platais et al. (2018) lists the proper motion components of VFTS682 relative to the field, providing a measure of the motion of this star completely independent from ours. They found proper motion components relative to the field $\delta\mu^{\mathrm{HST}}_{\mathrm{RA}} = 0.01 \pm 0.13\,\mathrm{mas\,yr^{-1}}$ and $\delta\mu^{\mathrm{HST}}_{\mathrm{DEC}} = 0.2 \pm 0.1\,\mathrm{mas\,yr^{-1}}$, which added in quadrature give a relative proper motion of $\delta\mu^{HST} = 0.20 \pm 0.15\,\mathrm{mas\,yr^{-1}}$.

These proper motion components can also be converted into projected velocities assuming a distance of 50 kpc, obtaining $\delta v^{HST}_{\mathrm{RA}} = 2 \pm 31\,\mathrm{km\,s^{-1}}$ and $\delta v^{HST}_{\mathrm{RA}} = 47 \pm 24\,\mathrm{km\,s^{-1}}$. Adding them in quadrature to the radial velocity measured by Bestenlehner et al. (2011) we obtain a three-dimensional velocity of $v^{HST}_{\mathrm{pec}} = 56 \pm 23\,\mathrm{km\,s^{-1}}$.

2.3. *New data from* Gaia *DR2*

The second *Gaia* Data Release (DR2)became available on 25 April 2018 and provides the five-parameter astrometric solution (positions, parallaxes, and proper motion components) for more than a billion sources (Gaia Collaboration et al. 2018). VFTS682 is identified with the source id 4657685637907503744 in the *Gaia* DR2 catalog[1]. *Gaia* reports a G-band magnitude of 15.65. The star has a `visibility_period` = 17, which counts how many observations have been used to reconstruct its astrometric solution (Lindegren et al. 2018), and the reported `astrometric_excess_noise` = 0. These values suggest that the *Gaia* data for VFTS682 are reliable. However, the effective temperature reported in *Gaia* DR2, based on the spectral

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

TABLE 1
ASTROMETRIC PARAMETERS FOR VFTS682.

Parameter	Value	Source
RA [degree]	84.73	Evans et al. (2011)
DEC [degree]	-69.07	
$\delta\mu_{\mathrm{RA}}^{Gaia}$ [mas yr^{-1}]	0.10±0.07	*Gaia* DR2
$\delta\mu_{\mathrm{DEC}}^{Gaia}$ [mas yr^{-1}]	0.08±0.09	
$\delta\mu_{\mathrm{RA}}^{HST}$ [mas yr^{-1}]	0.01±0.13	Platais et al. (2018)
$\delta\mu_{\mathrm{DEC}}^{HST}$ [mas yr^{-1}]	0.2±0.1	
δv_{rad} [km s^{-1}]	30±20	Bestenlehner et al. (2011)

The error on the RA and DEC positions, are of order $\sim10^{-2}$ mas yr^{-1} in *Gaia* DR2.

fitting around the CaII triplet, is one order of magnitude lower than what found by Bestenlehner et al. (2011), and the best fit parallax of this star is negative (see, e.g., Hogg 2018). 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.

While *Gaia* DR2 data can be correlated, this is not an issue for VFTS682, and we treat the proper motion components (μ_{RA}, and μ_{DEC}, respectively) of the star as uncorrelated for simplicity. 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 2.3 lists the values adopted throughout this work for each of these quantities.

We follow Lennon et al. (2018) to define a local frame of reference and derive the peculiar velocity of VFTS682 with respect to the cluster R136. Their selection (see their Sec. 2.1) of 153 bright ($G < 17$) stars around R136 with reliable astrometric data from *Gaia* DR2 yields $\langle\mu_{\mathrm{RA}}\rangle = 1.74 \pm 0.01$ mas yr^{-1} and $\langle\mu_{\mathrm{DEC}}\rangle = 0.70 \pm 0.02$ mas yr^{-1} for the components of the mean motion of the region projected on the sky.

For simplicity, throughout this study, we assume the same distance of 50 kpc to the star (Pietrzyński et al. 2013), and to the 30 Doradus region as a whole. We do not consider the error on the distance determination ($\lesssim 2\%$) when converting proper motions into physical velocities.

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 in the relative isolation that we observe today.

Subtracting the mean proper motion components given by Lennon et al. (2018) from the proper motion of VFTS682 (see Table 2.3), we obtain the components of proper motion of the star relative to the surrounding region $\delta\mu_{\mathrm{RA}}^{Gaia} = 0.10 \pm 0.07$ mas yr^{-1} and $\delta\mu_{\mathrm{DEC}}^{Gaia} = 0.08 \pm 0.09$ mas yr^{-1}. These components result in a two-dimensional relative proper motion of $\delta\mu^{Gaia} = 0.13 \pm 0.09$ mas yr^{-1}.

Figure Fig. 1 shows the distribution in relative proper motion of the stars used in Lennon et al. (2018) to define the frame of reference we also adopt here, cf. the right panel in their Fig. 2. The proper motions are decomposed in the radial and tangential direction from R136, to highlight the likelihood of it being the origin of fast moving stars. The plus sign

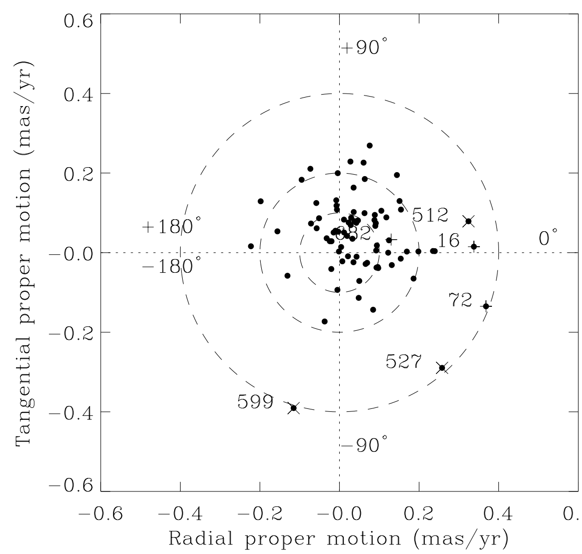

FIG. 1.— Polar plot of the relative proper motion components for the stars defining our reference frame. VFTS682 is indicated by the plus sign, and other notable outliers (see Lennon et al. (2018)) are also labeled. Concentric dashed-lines denote relative proper motions of 0.1, 0.2, and 0.4 mas yr^{-1}. Positive angle indicate a tangential component pointing in the counterclockwise direction, with 0 degrees corresponding to proper motion pointing radially outward from R136.

marks VFTS682, which sits at the edge of the proper motion distribution, but is not a clear outlier. Most relevant is the direction of the proper motion of VFTS682, which we discuss in Sec. 3.2.

The proper motion components can be converted into the components of the relative transverse velocity $\delta v_{\mathrm{RA}}^{Gaia} = 24 \pm 19$ km s^{-1}, $\delta v_{\mathrm{DEC}}^{Gaia} = 20 \pm 23$ km s^{-1}, assuming a distance of 50 kpc. These can be combined obtaining a projected two-dimensional velocity of 31 ± 21 km s^{-1}. The radial velocity from Bestenlehner et al. (2011) then gives the third component along the line of sight, which added in quadrature to the transverse components results in a three-dimensional velocity of 44 ± 21 km s^{-1}.

Therefore, two completely independent measures of the proper motion of VFTS682 relative to the surrounding field, one from HST and one from *Gaia* DR2, yield values of the peculiar three-dimensional velocity of VFTS682 which would make it the most massive runaway star known to date. However, the large errors on both the proper motion measures require confirmation with future astrometric data.

3.2. *Does it come from the R136 cluster?*

Assuming that the best estimate of the peculiar velocity of VFTS682 are reliable, we now address the question of its likely origin.

The red arrow in Fig. 2 shows the direction of relative proper motion of VFTS682 from *Gaia* DR2, and the yellow arrows illustrate the uncertainty. These arrows cross at the present-day location of VFTS682 and are prolonged in the direction opposite to the motion to illustrate the possible range of origins.

Although the large uncertainties on the relative proper motion components results in a wide range of possible direc-

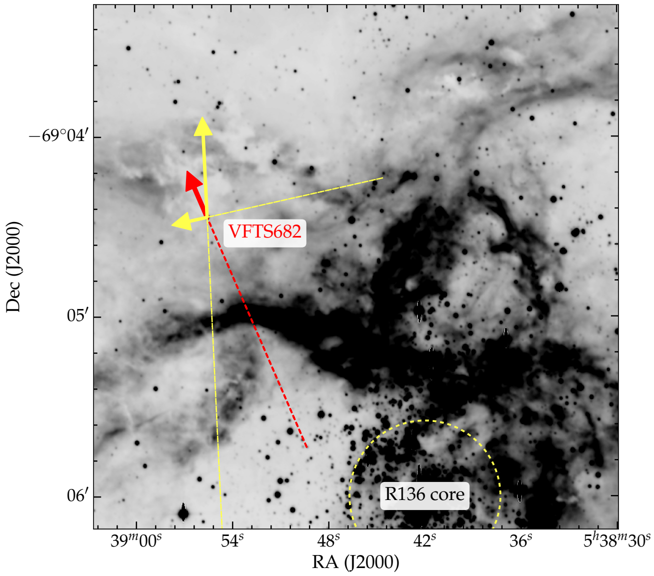

FIG. 2.— The red solid arrow indicates the proper motion of VFTS682 relative to the region from *Gaia* DR2, starting from the present day position of the star. The yellow arrows indicate the possible directions of projected motion within the *Gaia* DR2 errors, and are extended backwards (dashed) to illustrate the uncertainty on the origin of the star. The length of the prolongations is proportional to the relative proper motion times the kinetic age of VFTS682.

tions,we argue that the most likely origin of the star is R136, as suggested by the N-body simulations of Fujii & Portegies Zwart (2011) and Banerjee et al. (2012).

The kinematic age of this star, assuming it originates from the cluster, is

$$\tau_{\rm kin} = \frac{d_{||}}{\delta\mu^{\rm Gaia}} \simeq \frac{119.4\,\mathrm{arcsec}}{0.13\,\mathrm{mas\ yr^{-1}}} \simeq 0.9 \pm 0.6\,\mathrm{Myr} \ , \qquad (1)$$

where $d_{||} = 119.4$ arcsec is the angular distance from VFTS682 to the core of R136 (corresponding to $\sim$29 pc at LMC distance, Bestenlehner et al. 2011). As in the rest of this study, we neglect for simplicity the error on the distance estimates, because it is negligible compared to other uncertainties.

The kinematic age $\tau_{\rm kin}$ is compatible with a very early ejection from the cluster, given is apparent age of 1.0 ± 0.2 Myr (Schneider et al. 2018). Note that the present-day surface helium abundance ($Y \simeq 0.5$, Bestenlehner et al. 2011; Rubio-Díez et al. 2017) puts a lower limit on the age of the star of $\sim$0.9 Myr, corresponding to the time needed to synthesize this amount of helium in the models from Köhler et al. (2015).

4. DISCUSSION

Based on our results, we tentatively claim that VFTS682 is the most massive runaway known to date, with a peculiar three-dimensional speed of 44 ± 21 km s^{-1}. Due to the large error bars, this result will need to be revisited with future astrometric data. If confirmed, it means that isolated star formation is *not* required to explain the isolation of VFTS682. Its proper motion suggests that it was ejected from the cluster R136 0.9 ± 0.6 Myr ago. Because of the exceptionally large mass of this star, this raises the question of which stars must populate the core of the cluster.

Dynamical ejections due to N-body interactions typically (although, not necessarily) eject the least massive star among those interacting (e.g., Banerjee et al. 2012). This means that, just based on the kinematic properties of VFTS682, we would expect several stars with initial masses larger than $\sim$150 $M_\odot$ in the cluster R136. This is consistent with the detection of extremely massive stars in the core of the cluster.

The spectral type of VFTS682 (WNh5, Bestenlehner et al. 2011) is the same as R136a1-a3, i.e. the three most massive stars detected in the core of the cluster, with an astonishing similarity in particular with the spectrum of R136a3. Therefore, the isolation of VFTS682 makes it an ideal target to constrain the stellar physics of stars with masses well above $\sim$100 $M_\odot$ while avoiding crowding issues.

Banerjee et al. (2012) used N-body simulations of fully segregated clusters with all massive stars in binaries to suggest that VFTS682 was ejected from R136. They demonstrated that the cluster potential does not significantly change the velocity of the star after the ejection. In their model, they relied on (dynamically driven) stellar mergers to explain the high masses of VFTS682 and the massive members of R136.

To eject such a massive object, the cluster is expected to have produced a large number of massive runaways. Indeed, several isolated massive stars are observed in the region, some with known large radial velocities and/or proper motion. A comprehensive study of the kinematic properties of all the massive stars surrounding R136 might shed light on whether some can be unequivocally identified as merger products. It is also possible that the star or binary that caused the ejection of VFTS682 might have been ejected in the opposite direction, and is also isolated at present day. If the ejection was caused by an interaction with a binary, however, it is likely that the binary scattered in the opposite direction will experience further dynamical interactions on its way, modifying its trajectory and making it difficult to find.

The similarities between VFTS682 and the WNh5 stars in the core of R136 are also in agreement with the "bully binary" model of Fujii & Portegies Zwart (2011). Based on their numerical results, they suggested that early in the evolution of a cluster, dynamical interactions form an extremely massive binary, which then tightens its orbit by ejecting other stars passing by. Interpreting our results for VFTS682 through the lens of their simulations suggests the presence of a close binary with total mass $M_1 + M_2 \gtrsim 300\,M_\odot$ in the core of the cluster. Such bully binary could be R145 according to Fujii & Portegies Zwart (2011), and it might be an ideal observational candidate for a dynamically formed progenitor system of a binary black-hole, provided that stars this massive can avoid a pair-instability supernova (e.g., Rakavy & Shaviv 1967) at LMC metallicity (see also Langer et al. 2007). Similarly, the final fate of VFTS682 could be either a pair-instability supernova without compact remnant formation, or possibly direct collapse to a black hole above the 2$^{\rm nd}$ mass gap. The amount of mass loss of these stars will determine their final core mass and thus their final fate.

The kinematic age of VFTS682 puts an upper limit to the timescale to form the "bully binary" in R136. The cluster must have been at the very beginning of its evolution, given the age estimate of $\lesssim 2$ Myr (Crowther et al. 2010; Sabbi et al. 2012) and the kinematic age of VFTS682. If the cluster is indeed younger than the shortest stellar lifetime ($\sim$3 Myr, e.g., Brott et al. 2011; Zapartas et al. 2017), then the alternative explanation for ejection of VFTS682 from the disruption of a binary by a core-collapse event is excluded since the region is too young for stars to have experienced core-collapse already.

The variability of VFTS682, reminiscent of LBV stars, suggests that VFTS682 (and therefore its analogs in the core of R136) might experience enhanced mass loss episodes in LBV eruptions. Smith & Tombleson (2015) made the highly debated[2] claim that LBV stars are typically isolated form O-type stars. The fact that VFTS682 is a dynamically ejected runaway which might evolve into an LBV star suggests that N-body interactions also play a role in explaining the apparent isolation of at least some LBV stars.

Lennon et al. (2018) carried out a study similar to ours on the fast moving O-type stars in the region, and found two massive runaway stars ($\sim$90 $M_\odot$) in the 30 Doradus region. One of them (VFTS 16) was previously known as a runaway star from its line of sight velocity (Evans et al. 2010). Lennon et al. (2018) also concluded that VFTS16 is the result of a dynamical ejection from the R136 cluster, while the origin of the other star (VFTS 72) is less clear given its direction of motion. The value of $\tau_{\rm kin} \simeq 0.9$ Myr we find for VFTS682 (see Sec. 3.2) is smaller than the corresponding value for VFTS16: Lennon et al. (2018) inferred a kinematic age of $\sim$1.5 Myr, possibly in tension with the apparent age of that star. This means that the more massive VFTS682 was ejected later than VFTS16 from the same cluster.

The numerical simulations from Oh & Kroupa (2016) suggest that dynamical interaction eject the majority of the stars during or shortly after the cluster core-collapse. The large number of isolated massive stars around it suggest that R136 has already evolved past the time of maximum stellar density. This might have implications for the question of whether the cluster formed via a monolithic collapse, or as a (potentially ongoing) merger of several sub-structures (e.g., Sabbi et al. 2012).

Oh & Kroupa (2016) also showed that the mass and velocity distribution of the ejected star depends on the cluster initial conditions (whether it is segregated, its primordial binary fraction and initial period distribution of the binary population), therefore studies on the population of isolated massive stars in the surroundings of R136 might shed light on its initial stellar population and dynamical state.

VFTS682 is potentially the most massive runaway known to date, and its ejection from the cluster R136 likely implies that it is only the “tip of the iceberg” of possibly extremely massive runaways in the region. Studies of this population, enabled by recent HST and *Gaia* observations will put constraints on the evolution of these extreme stars, together with the formation and evolution of the central cluster itself.

REFERENCES

Banerjee S., Kroupa P., Oh S., 2012, ApJ, 746, 15 [2, 4]
Bate M. R., 2009, MNRAS, 392, 590 [1]
Bestenlehner J. M., et al., 2011, A&A, 530, L14 [1, 2, 3, 4]
Blaauw A., 1961, Bull. Astron. Inst. Netherlands, 15, 265 [1]
Bressert E., et al., 2012, A&A, 542, A49 [1, 2]
Brott I., et al., 2011, A&A, 530, A115 [2, 4]
Crowther P. A., Schnurr O., Hirschi R., Yusof N., Parker R. J., Goodwin S. P., Kassim H. A., 2010, MNRAS, 408, 731 [1, 2, 4]
Crowther P. A., et al., 2016, MNRAS, 458, 624 [1, 2]
Davidson K., Humphreys R. M., Weis K., 2016, arXiv:1608.02007, [5]
Evans C. J., et al., 2010, ApJ, 715, L74 [5]
Evans C. J., et al., 2011, A&A, 530, A108 [1, 2, 3]
Fujii M. S., Portegies Zwart S., 2011, Science, 334, 1380 [2, 4]
Gaia Collaboration et al., 2016, A&A, 595, A1 [2]
Gaia Collaboration Brown A. G. A., Vallenari A., Prusti T., de Bruijne J. H. J., Babusiaux C., Bailer-Jones C. A. L., 2018, ArXiv:1804.09365, [2]
Gruendl R. A., Chu Y.-H., 2009, ApJS, 184, 172 [2]
Gvaramadze V. V., Weidner C., Kroupa P., Pflamm-Altenburg J., 2012, MNRAS, 424, 3037 [1]
Hogg D. W., 2018, ArXiv:1804.07766, [3]
Humphreys R. M., Weis K., Davidson K., Gordon M. S., 2016, ApJ, 825, 64 [5]
Köhler K., et al., 2015, A&A, 573, A71 [2, 4]
Kuiper R., Yorke H. W., Turner N. J., 2015, ApJ, 800, 86 [1]
Lada C. J., Lada E. A., 2003, ARA&A, 41, 57 [1]
Lamb J. B., Oey M. S., Segura-Cox D. M., Graus A. S., Kiminki D. C., Golden-Marx J. B., Parker J. W., 2016, ApJ, 817, 113 [1]
Langer N., Norman C. A., de Koter A., Vink J. S., Cantiello M., Yoon S.-C., 2007, A&A, 475, L19 [4]
Lennon D. J., et al., 2018, ArXiv:1805.08277, [2, 3, 5]
Lindegren L., et al., 2018, ArXiv:1804.09366, [2]
Maeder A., Meynet G., 2000, A&A, 361, 159 []
Oh S., Kroupa P., 2016, A&A, 590, A107 [5]
Parker J. W., 1993, AJ, 106, 560 []
Pietrzyński G., et al., 2013, Nature, 495, 76 [3]
Platais I., van der Marel R. P., Lennon D. J., Anderson J., Bellini A., Sabbi E., Sana H., Bedin L. R., 2015, AJ, 150, 89 [2]
Platais I., et al., 2018, ArXiv:1804.08678, [2, 3]
Poveda A., Ruiz J., Allen C., 1967, Boletin de los Observatorios Tonantzintla y Tacubaya, 4, 86 [1]
Rakavy G., Shaviv G., 1967, ApJ, 148, 803 [4]
Ramírez-Agudelo O. H., et al., 2015, A&A, 580, A92 []
Renzo M., et al., 2018, ArXiv:1804.09164, [1]
Robitaille T., Bressert E., 2012, APLpy: Astronomical Plotting Library in Python, Astrophysics Source Code Library (ascl:1208.017) []
Rosen A. L., Krumholz M. R., McKee C. F., Klein R. I., 2016, MNRAS, 463, 2553 [1]
Rubio-Díez M. M., Najarro F., García M., Sundqvist J. O., 2017, in Eldridge J. J., Bray J. C., McClelland L. A. S., Xiao L., eds, IAU Symposium Vol. 329, The Lives and Death-Throes of Massive Stars. pp 131–135, doi:10.1017/S1743921317002447 [2, 4]
Sabbi E., et al., 2012, ApJ, 754, L37 [4, 5]
Sana H., Ramírez-Tannus M. C., de Koter A., Kaper L., Tramper F., Bik A., 2017, A&A, 599, L9 [1]
Schneider F. R. N., Castro N., Fossati L., Langer N., de Koter A., 2017, A&A, 598, A60 [2]
Schneider F. R. N., et al., 2018, Science, 359, 69 [1, 2, 4]
Smith N., 2016, MNRAS, 461, 3353 [5]
Smith N., Tombleson R., 2015, MNRAS, 447, 598 [5]
Udalski A., et al., 2008, Acta Astron., 58, 329 [2]
Ward J. L., Kruijssen J. M. D., 2018, MNRAS, 475, 5659 [1]
Zapartas E., et al., 2017, A&A, 601, A29 [4]
Zinnecker H., Yorke H. W., 2007, ARA&A, 45, 481 [1]
Zwicky F., 1957, ZAp, 44, 64 [1]
de Koter A., Heap S. R., Hubeny I., 1997, ApJ, 477, 792 [1]
de Mink S. E., Cantiello M., Langer N., Pols O. R., Brott I., Yoon S.-C., 2009, A&A, 497, 243 []

We are grateful to S. Torres, M. C. Ramirez-Tannus, and C. J. Evans for help and discussions. SdM has received funding under the European Unions Horizon 2020 research and innovation programme from the European Research Council (ERC) (Grant agreement No. 715063). VHB acknowledges support from the NRC-Canada Plaskett Fellowship. This work has made use of data from the ESA space mission *Gaia* (`http://www.cosmos.esa.int/gaia`), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, `http://www.cosmos.esa.int/web/gaia/dpac/consortium`). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

[2] See, e.g., Humphreys et al. (2016); Davidson et al. (2016); Smith (2016).