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GAIA'S CONSTRAINTS ON THE EXTREMELY MASSIVE ($\sim$150 $M_\odot$) RUNAWAY STAR CANDIDATE VFTS682

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ABSTRACT

How very massive stars form is still among the most intriguing open questions in stellar astrophysics. VFTS 682 is among the most extreme massive stars known, with an inferred initial mass of about 150 $M_\odot$. It is located in 30 Doradus at a projected distance of 29 pc from the central cluster R136. The absence of other massive stars in its immediate vicinity led to two intriguing hypotheses posed in earlier work: either (a) it formed in relative isolation through a new mode of star formation or (b) it was ejected dynamically from the central cluster.

Aiming to shine light on this debate, we investigate the kinematics of VFTS 682 as obtained by *Gaia* and multi-epoch *Hubble Space Telescope* photometry. We derive a projected velocity relative of to the cluster of $\sim 30 \pm 20$ km s^{-1}. The direction and magnitude of the proper is consistent with what is expected if VFTS 682 was ejected as a slow runaway from the central cluster, given its distance and the inferred age. However, the error bars are substantial and the proper motion measurements alone cannot rule out the counter hypothesis with high confidence.

If future data confirms the runaway nature, this would make the VFTS682 the most massive runaway star known to date. While we cannot prove this solidly from the current data alone, we do consider this hypothesis as the most plausible because of a variety of circumstantial clues. The central cluster is known to harbor several other stars more massive than 150 $M_\odot$ similar in spectral type. The very massive O star VFTS 16, which has recently been identified as a dynamically ejected runaway, provides direct evidence that R136 is indeed capable of ejecting some of its most massive members, consistent with the predictions by numerical simulations.

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). Improving our understanding of 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. 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. Important progress has been made on the theoretical side, (e.g. Bate 2009; Kuiper et al. 2015; Rosen et al. 2016), but the simulations of this multi-scale and multi-physics problem are computationally very expensive and therefore remain challenging.

In has been proposed that most, if not all, stars form in clusters (Lada & Lada 2003), where massive stars are thought to reside in the innermost 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 and their origin remains matter of debate (Gvaramadze et al. 2012; Lamb et al. 2016; Ward & Kruijssen 2018). One hypothesis to explain the population of relatively isolated massive stars is that they formed in the field. The alternative hypothesis is that these massive stars were ejected from the clusters in which they formed. 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).

One of the most extreme examples that has been considered in this debate is the very massive star VFTS682 (Bestenlehner et al. 2011; Bressert et al. 2012). 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). It is a hydrogen-rich Wolf-Rayet star of spectral type WNh5. Spectral analysis and comparison with evolutionary models lead to an inferred present-day mass of $\sim 140^{+30}_{-16}\,M_\odot$ corresponding to an initial mass of $\sim 150^{+30}_{-17}\,M_\odot$ (Schneider et al. 2018). This makes VFTS682 one of the most massive stars known and one of the most extreme objects in the region. From the spectral point of view, it is reminiscent of the very massive stars in the core of the R136 cluster (de Koter et al. 1997; Crowther et al. 2010, 2016). In particular, a remarkable similarity exist between the spectrum of VFTS682 and R136a3 (Rubio-Díez et al. 2017) for which Crowther et al. (2016) report a current mass estimate of $180^{+30}_{-30}\,\mathrm{M}_\odot$. R136 hosts at least two more very massive WN5h stars, R136a1 and R136a2, whose estimated current masses are even higher.

VFTS682 stands out by its relative isolation at a projected distance of 119.4 arcseconds, corresponding to $\sim$29 pc, from the star cluster R136. Bestenlehner et al. (2011) considered two possible explanation for the offset: either the star formed in situ as an isolated massive star, or it was ejected from R136. N-body simulations indicate that the ejection of very massive stars like VFTS682 is expected (e.g. Fujii & Portegies Zwart 2011; Banerjee et al. 2012). This is supported by the recent findings of other massive runaway stars in the region based on proper motion studies. Platais et al. (2015, 2018) analyze multi-epoch *Hubble Space Telescope* (HST) photometry

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TABLE 1
SELECTED STELLAR PARAMETERS FOR VFTS682.

Parameter	Units	Value	Ref.
Selected stellar parameters VFTS 682			
present day mass	[$M_\odot$]	$137.8^{+27.5}_{-15.9}$	
initial mass	[$M_\odot$]	$150.0^{+28.7}_{-17.4}$	
age	[Myr]	1.0 ± 0.2	
mass loss rate		*xxx*	
helium abundance		*xxx*	

NOTE. —

TABLE 2
KINEMATICS OF VFTS682.

Parameter	Units	Value	Ref.
Gaia's proper motion for VFTS 682 and average of the region			
$\mu_{\rm RA}$	[mas yr^{-1}]	1.843 ± 0.070	(1)
$\mu_{\rm DEC}$	[mas yr^{-1}]	0.786 ± 0.080	(1)
Correlation ($\mu_{\rm RA}, \mu_{\rm DEC}$)	[mas yr^{-1}]	0.023	(1)
$\langle\mu_{\rm RA}\rangle_{\rm R136}$	[mas yr^{-1}]	1.74 ± 0.01	(2)
$\langle\mu_{\rm DEC}\rangle_{\rm R136}$	[mas yr^{-1}]	0.70 ± 0.02	(2)
Gaia's relative proper motion for VFTS 682			
$\delta\mu_{\rm RA}$	[mas yr^{-1}]	0.103 ± 0.080	(1,4)
$\delta\mu_{\rm DEC}$	[mas yr^{-1}]	0.086 ± 0.100	(1,4)
$\delta\mu$	[mas yr^{-1}]	0.13 ± 0.09	(1,4)
$v_{\rm 2d}$	[km s^{-1}]	32 ± 21	(1,4)
θ^*	[degrees]	xxx±xxx	(1,4)
$v_{\rm 2d,\parallel}$	[km s^{-1}]	xxx±xxx	(1,4)
HST's independent determination of the relative proper motion for VFTS 682			
$\delta\mu_{\rm RA,HST}$	[mas yr^{-1}]	0.01 ± 0.13	(3)
$\delta\mu_{\rm DEC,HST}$	[mas yr^{-1}]	0.20 ± 0.10	(3)
$\delta\mu_{\rm HST}$	[mas yr^{-1}]	0.20 ± 0.10	(3)
$v_{\rm 2d,HST}$	[km s^{-1}]	47 ± 24	(3)
θ^*	[degrees]	xxx±xxx	(1,4)
$v_{\rm 2d,\parallel}$	[km s^{-1}]	xxx±xxx	(1,4)

NOTE. — Proper motions are based on Gaia data unless indicated otherwise in subscript. The angle θ is defined such that $\theta = 0$ corresponds to the direction pointing away from R136. [1]**?**, [2]Lennon et al. (2018), [3]Platais et al. (2018), [4]This work

and identify 10 stars, which appear to be ejected from R136. Lennon et al. (2018) investigate the kinematics of isolated O-type stars in the region using the second *Gaia* data release (DR2, Gaia Collaboration et al. 2016, 2018) and show that the proper motion, postion and direction of the $\sim 100\,{\rm M}_\odot$ star VFTS16 is consistent with a runaway origin from R136.

In this paper we present an analysis of the new kinematical constraints for VFTS682 provided by *Gaia* DR2 and constraints from HST proper data by Platais et al. (2018). We discuss the implications for the hypothesis that VFTS682 is a slow runaway star ejected from R136.

2. OBSERVATIONS

The star WNh5 star VFTS682, located at right ascension (RA) 05$^{\rm h}$38$^{\rm m}$55.510$^{\rm s}$ and declination (DEC) -69$^{\rm o}$04'26.72" J2000, was observed as part of the multi-epoch, spectroscopic VFTS campaign covering λ4000–7000 (Evans et al. 2011). Bestenlehner et al. (2011) analyzed the spectra to infer the stellar parameters and measure an extinction of $A_V = 4.45 \pm 0.12$, implying a luminosity of $\log_{10}(L/L_\odot) = 6.5 \pm 0.2$, making this one of the brightest stars in the region. The star is unlikely to have a close companion, because of the absence of clear radial velocity variations Bestenlehner et al. (2011). Bayesian fits of the stellar parameters against evolutionary tracks (Brott et al. 2011; Köhler et al. 2015) using the Bonsaii code (Schneider et al. 2017, 2018) provide estimates for the age, present mass and initial mass, indicating that this star among the most massive stars known, see Tab for an overview of the parameters.

Estimates of the radial velocity are complicated by the variable, optically thick winds that is typical for emission line stars. Bestenlehner et al. (2011) estimate a mass loss rate of $10^{-4.1\pm0.2}\,M_\odot$ yr^{-1}, not accounting for the possible effect of clumping. The V-band light curve of VFTS682 shows variations at a $\sim$10% level on a timescale of years, which is unusual for Wolf-Rayet stars and more typical for Luminous Blue Variable (LBV) stars (Udalski et al. 2008; Bestenlehner et al. 2011). It also shows mid-infrared excess (Gruendl & Chu 2009). We therefore caution for over-interpreting the estimates for the radial velocities, but we will summarize the estimates that have been published. Bestenlehner et al. (2011) estimate a radial velocity (RV) of 300 ± 10 km s^{-1} using the Nv λ4944 line, which is offset from the average radial velocity of the region, which is 270 ± 10 km s^{-1}. This is consistent with, but no proof of, a runaway nature. Bressert et al. (2012) note an offset compared between the RV of the star and the nebular lines from the gas filaments in its vicinity. This is consistent with, but also no proof of, the expectation if the star was not formed in situ. Newer measurements based on new Xshooter data give different estimates for the RV (Rubio-Díez et al. in prep). We will therefore refrain from using the RV measurements in this work.

The distance to 30 Doradus is 50 kpc (Pietrzyński et al. 2013). The error on the distance determination is small ($\lesssim 2\%$) and the possible difference between VFTS682 and the average of the region is probably even smaller (likely $\ll 1\%$). These uncertainties are negligible compared to the errors in the proper motion discussed below.

2.1. Gaia *astrometry for VFTS682*

VFTS682 is identified with the source id 4657685637907503744 in the *Gaia* DR2 catalog as a 15.65 mag star in the G band (Gaia Collaboration et al. 2016, 2018). The number of visibility periods, i.e. groups of observations separated from other groups by a gap of at least 4 days, used in the astrometric solution is 17 for this star. The reported astrometric excess noise is zero. (Lindegren et al. 2018). These values suggest that the *Gaia* DR2 data for VFTS682 are reliable. Generally the Gaia errors are correlated, but the correlation coefficient is small for this star, see Tab. 2. We can therefore treat the proper motion components as uncorrelated.

To determine the relative proper motion with respect to R136, we follow Lennon et al. (2018) to define the motion of the local frame of reference using the average proper motion of nearby stars with reliable astrometric data. They select bright ($G < 17$) stars within 0.05 degrees of R136 with and exclude sources with proper motion errors greater than 0.01 mas yr^{-1} in both co-ordinates (see their Sect. 2.1 for further discussion).

With these we compute the relative proper motion $\delta\mu_{\rm RA}$ and $\delta\mu_{\rm DEC}$. We also derive the angle θ between the direction of motion and the vector connecting the center of R136 with the current position of VFTS 682, i.e. such that $\theta = 0$ is the angle expected for a star ejected from R136. We further provide the 2D velocity projected onto the radial vector pointing away from R136 $v_{\rm 2d,\parallel}$ and the total projected 2d velocity $v_{\rm 2d}$. All

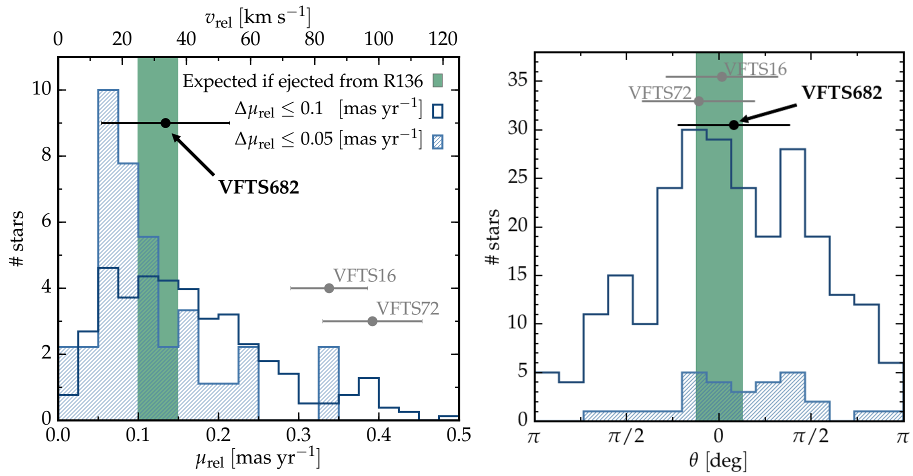

FIG. 1.— Left panel: distribution of OB-type and Wolf-Rayet stars in proper motion relative to R136. VFTS682 is not an outlier, but its relative proper motion matches the expected value if it were indeed ejected from R136 assuming an age of 1.0 ± 0.2 Myr. The top axis shows the conversion to physical units assuming a distance of 50 kpc. Right panel: distribution of angles between the relative proper motion direction and the radial direction to the star. The error bars for VFTS682 are large, but the best value is in agreement with the hypothesis of dynamical ejection. In both panels, the dark blue histograms contain 317 stars with error smaller than 0.1 mas yr^{-1} ≃ 25 km s^{-1} at 50 kpc, the lighter blue histograms contain 36 stars with errors smaller than 0.05 mas yr^{-1}. ■ **[Todo: [1] insert correct errorbars in right pabel, [2] make linewidth, shading and figure size of both panels consistent [3] fix normalization to be consistent in both pabels]** ■

kinematic quantities are provided in Tab. 2.

2.2. *HST astrometry for VFTS682*

The 30 doradus region was target of an a two-epoch photometric campaign with *HST* providing observations in the F775W filter in October 2011 and October 2014 (GO-12499; P.I.: D. J. Lennon, **?**). Visually, the star is clearly isolated and does not appear to have any close neighbor. This by itself gives further confidence in ability of *Gaia* to measure the proper motion reliably without being affected by crowding.

Platais et al. (2018) recently analyzed the HST data for candidate runaway stars. The brightest stars (V<14) are missing from the catalogue because of saturation effects, but the high extinction towards VFTS682 makes it faint enough to be included. Our star did not make the more conservative selection criteria for runaway stars adopted in that study. However, the measurements are useful here, since they provides a measurement of the proper motion of VFTS 682 that is completely independent from the *Gaia* measurement.

We list their data in Table 2. The errorbars are comparable with those we obtain from *Gaia*. However the direction and angle are different. Can we please get theta Gaia and theta HST in the table.

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), we obtain the components of proper motion of the star relative to the surrounding region $\delta\mu_{\rm RA}^{Gaia} = 0.10 \pm 0.07$ mas yr^{-1} and $\delta\mu_{\rm DEC}^{Gaia} = 0.08 \pm 0.09$ 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}.

The proper motion components can be converted into the components of the relative transverse velocity $\delta v_{\rm RA}^{Gaia} = 24 \pm 19$ km s^{-1}, $\delta v_{\rm DEC}^{Gaia} = 20 \pm 23$ 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?*

Figure 1 shows the distribution in proper motion relative to R136 of OB-type and Wolf-Rayet stars included both in the VFTS survey and *Gaia DR2* with reliable astrometric solutions. The bottom panel shows the distribution in angles θ between the relative proper motion direction and the direction from the core of R136 to the star. We emphasize that our subset of stars with reliable proper motion measurements is biased towards the fast moving objects, which results in a distribution of angles mildly peaked at small angles.

VFTS682 is not an outlier in relative proper motion. However, the star was expected to be a "slow runaway" by Bestenlehner et al. (2011) in the dynamical ejection scenario. The green shade in Fig. 1 shows the range of relative proper motions required to reach the present day location within the uncertainties on the apparent age of the star, assuming it was ejected from R136 very early in its life.

Because of the large error bars, the angle between the relative proper motion is not very constraining, but it is suggestive that the best value is close to zero. Therefore, the relative proper motion from *Gaia* DR2 are consistent with the hypothesis of dynamical ejection.

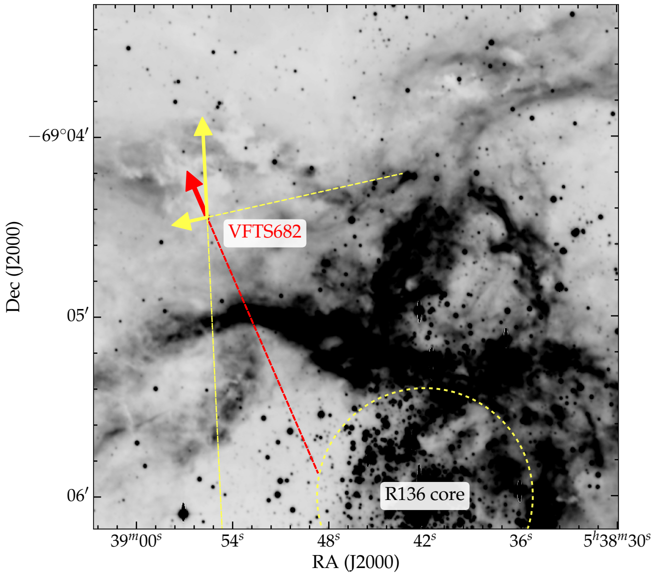

FIG. 2.— The red solid arrow indicates the proper motion of VFTS682 relative to the region from *Gaia* DR2, starting from the present day position of the star. The yellow arrows indicate the possible directions of projected motion within the *Gaia* DR2 errors, and are extended backwards (dashed) to illustrate the uncertainty on the origin of the star. The length of the prolongations is proportional to the relative proper motion times the age of VFTS682 (1.0 ± 0.2 Myr, Schneider et al. 2018).

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.

The kinematic age of this star, assuming it originates from R136, is

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

where $d_{\parallel} = 119.4$ arcsec is the angular distance from VFTS682 to the core of the cluster (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).

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[1] 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.

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

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