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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 $\sim 30 \pm 20\,\mathrm{km\,s^{-1}}$. 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: VFTS682

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) analyzed multi-epoch *Hubble Space Telescope* (HST) photometry and identified 10 stars likely ejected from R136. Lennon et al. (2018) investigate the

TABLE 1
SELECTED STELLAR PARAMETERS FOR VFTS682.

Parameter	Units	Value	Ref.
Selected stellar parameters VFTS 682			
present day mass	$[M_\odot]$	$137.8^{+27.5}_{-15.9}$	(1)
initial mass	$[M_\odot]$	$150.0^{+28.7}_{-17.4}$	(1)
age	[Myr]	1.0 ± 0.2	(1)
mass loss rate	$[M_\odot\ \mathrm{yr}^{-1}]$	$10^{-4.1\pm0.2}$	(2)

NOTE. — (1) Schneider et al. (2018) (2) Bestenlehner et al. (2011)

TABLE 2
KINEMATICS OF VFTS682.

Parameter	Units	Value	Ref.
Coordinates			
$\mathrm{RA}_{\mathrm{VFTS682}}$	[degrees]	84.7314	(1)
$\mathrm{DEC}_{\mathrm{VFTS682}}$	[degrees]	-69.0741	(1)
$\mathrm{RA}_{\mathrm{R136}}$	[degrees]	84.6767	SIMBAD
$\mathrm{DEC}_{\mathrm{R136}}$	[degrees]	-69.1009	SIMBAD
δRA	[degrees]	0.0547	(2, 5)
δDEC	[degrees]	0.0268	(2, 5)
Gaia proper motion for VFTS682 and average of the region			
μ_{RA}	[mas yr^{-1}]	1.843 ± 0.070	(1)
μ_{DEC}	[mas yr^{-1}]	0.786 ± 0.080	(1)
$\rho\,(\mu_{\mathrm{RA}}, \mu_{\mathrm{DEC}})$	[mas yr^{-1}]	0.026	(1)
$\langle\mu_{\mathrm{RA}}\rangle_{\mathrm{R136}}$	[mas yr^{-1}]	1.74 ± 0.01	(3)
$\langle\mu_{\mathrm{DEC}}\rangle_{\mathrm{R136}}$	[mas yr^{-1}]	0.70 ± 0.02	(3)
Gaia relative proper motion for VFTS682			
$\delta\mu_{\mathrm{RA}}$	[mas yr^{-1}]	0.103 ± 0.080	(1,5)
$\delta\mu_{\mathrm{DEC}}$	[mas yr^{-1}]	0.086 ± 0.100	(1,5)
$\delta\mu_{Gaia}$	[mas yr^{-1}]	0.13 ± 0.09	(1,5)
v_{2d}	[km s^{-1}]	32 ± 21	(1,5)
θ	[degrees]	14^{+44}_{-43}	(1,5)
HST relative proper motion for VFTS682			
$\delta\mu_{\mathrm{RA,HST}}$	[mas yr^{-1}]	0.01 ± 0.13	(4)
$\delta\mu_{\mathrm{DEC,HST}}$	[mas yr^{-1}]	0.20 ± 0.10	(4)
$\delta\mu_{\mathrm{HST}}$	[mas yr^{-1}]	0.20 ± 0.10	(4)
$v_{\mathrm{2d,HST}}$	[km s^{-1}]	47 ± 24	(4)
θ^*	[degrees]	-35^{+24}_{-51}	(1,5)

NOTE. — Proper motions are based on Gaia data unless indicated otherwise in subscript. The conversion factor assuming a distance of 50 kpc is such that 1 mas yr^{-1} corresponds to 237 km s^{-1}. The correlation coefficient is indicated as ρ. The angle θ is defined such that $\theta = 0$ for motions pointing away radially from R136. (1) Gaia Collaboration et al. (2018), (2) Bestenlehner et al. (2011), (3) Lennon et al. (2018), (4) Platais et al. (2018) and (5) this study.

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 $\mathrm{M}_\odot$ star VFTS16 is consistent with a runaway origin from R136. They also found a less clear case for VFTS72.

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 WNh5 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, 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 Table 2 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 $10^{-4.1\pm0.2}\ M_\odot\ \mathrm{yr}^{-1}$, 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 $300 \pm 10\,\mathrm{km\ s^{-1}}$ using the Nv λ4944 line, which is offset from the average radial velocity of the region, which is $270 \pm 10\,\mathrm{km\ s^{-1}}$. 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.

VFTS682 is relatively isolated in *Spitzer* images, except for the extended source S10 interpreted as star formation triggered by the wind of VFTS682 itself by Walborn et al. (2013). In X-rays ■ **[questions: does 682 show excess X-rays (wind collisions?)]** ■

For the distance we adopt the distance to the LMC of 50 kpc. The error on the distance determination is small ($\lesssim$ 2%, Pietrzyński et al. 2013) and any possible offset between R136 or VFTS682 and the distance we adopted for the LMC is probably much smaller (likely $\ll$ 1%, e.g. Luks & Rohlfs 1992). 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[1] 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 four days, used in the astrometric solution is seventeen for this star. The reported astrometric excess noise is zero. These values suggest that the *Gaia* DR2 data for VFTS682 are reliable. Gaia errors are correlated (Lindegren et al. 2018), but for this star the correlation coefficient is very small, $\rho\,(\mu_{\mathrm{RA}}, \mu_{\mathrm{DEC}}) = 0.026$, where zero is for completely un-correlated data and one is for fully correlated data. We

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

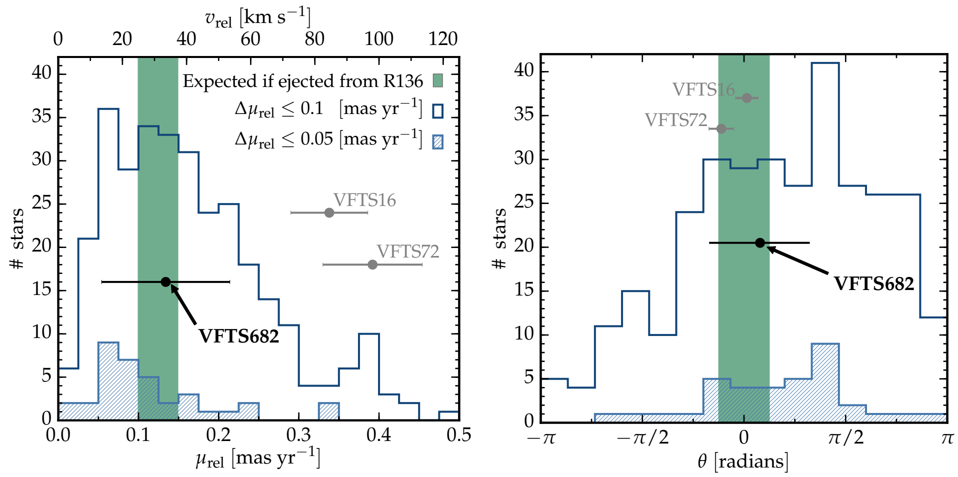

FIG. 1.— *Left panel*: distribution of OB-type and Wolf-Rayet stars in proper motion relative to R136. VFTS682 is not an outlier, but its relative proper motion matches the expected value if it were indeed ejected from R136 assuming an age of 1.0 ± 0.2 Myr. The top axis shows the conversion to physical units assuming a distance of 50 kpc. *Right panel*: distribution of angles between the relative proper motion direction and the radial direction from the center of the cluster to the star. The error bars from *Gaia* 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} $\simeq$ 25 km s^{-1} at 50 kpc, the lighter blue histograms contain 36 stars with errors smaller than 0.05 mas yr^{-1}.■ **[possibly: cartoon to illustrate angle definition, or add to fig.2 if not too messy, maybe also show HST measurements on this plot for 682? Redo right panel taking care of projection of the radial directions!It's misleading!]** ■

can thus safely 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 and exclude sources with proper motion errors greater than 0.01 mas yr^{-1} in both coordinates (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 corresponding to perfectly radial motion away from R136. We further provide the projected 2d velocity $v_{\rm 2d}$. All 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, Sabbi et al. 2013). 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 OB-type 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. This star was not included in their study because of its WNh5 spectral type and because it would not pass the more conservative selection criteria they adopted. However, the measurements are useful here, since they provides an estimate of the proper motion of VFTS 682 that is completely independent from the *Gaia* measurement.

We list their data in Table 2.

3. THE KINEMATICS OF VFTS682

Figure 1 illustrates the kinematic properties of VFTS OB-type and Wolf-Rayet stars in the 30 Doradus region with *Gaia* DR2 errors on the proper motion components of less than 0.1 mas yr^{-1} (dark blue lines, including VFTS682), and less than 0.05 mas yr^{-1} (light shaded blue). We highlight VFTS682 together with the two O-type runaways (re-)identified by Lennon et al. (2018) (VFTS16 and VFTS72, respectively). We emphasize that selecting stars with small error bars implicitly biases the sample toward fast moving objects.

The left panel shows the distribution in two-dimensional proper motion relative to R136, and shows that VFTS682 is not a peculiar star in terms of its motion relative to R136. Subtracting the mean motion of the field, we obtain $\delta\mu_{Gaia} = 0.13 \pm 0.09$ mas yr^{-1}(32 ± 21 km s^{-1}) and $\delta\mu_{HST} = 0.20 \pm 0.10$ mas yr^{-1}(47 ± 24 km s^{-1}). Both indicate a non-zero peculiar projected motion that would make it a slow runaway star as expected by Bestenlehner et al. (2011) if the star was ejected from the cluster, but in both cases the meaurements are also consistent with zero within 2σ. More importantly, both the proper motion measurement from *Gaia* and HST fall in the range expected to reach its present day location if the star was ejected very early in its evolution. This range is highlighted by the green vertical band, and its width is determined by the uncertainty in the present-day age of the star (cf. Table 2).

The right panel shows the distributions in flight direction for these stars: θ is the angle between the projected radial direction from the center of R136 to each star and its proper motion relative to R136 (see also Fig. 2). Dynamical ejections from the cluster should produce close to radial ejections, i.e. $\theta \simeq 0$. On this panel, the green band highlights the range of angles corresponding to an opening angle around the radial direction of 45 degrees. The direction of motion of VFTS682 is poorly constrained because of the large errors on the proper motion components both in HST and *Gaia* data, but it is consistent with dynamical ejection from R136. We note that VFTS72 has a small radial velocity, while VFTS16

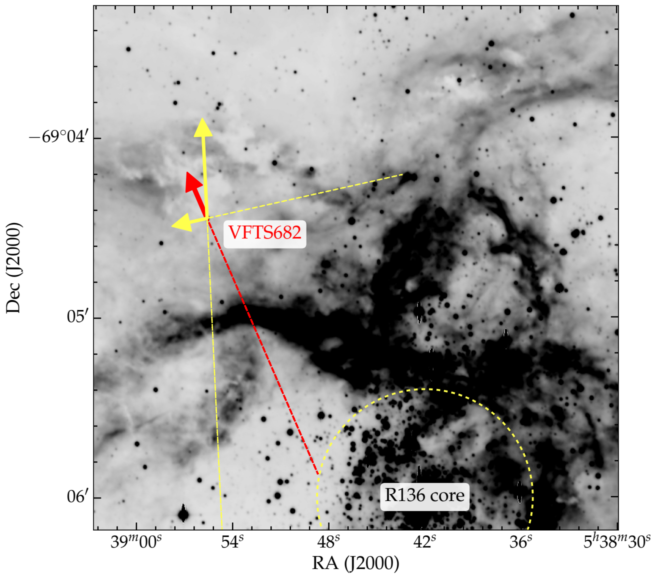

FIG. 2.— I don't see a reason why we would not show the HST data, except for wanting to hide it maybe. Let's sit together and find a good way to plot both. (Hope you still have the script to show the HST direction.) The red solid arrow indicates the proper motion of VFTS682 relative to the region from *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).

(and possibly VRTS682) has large peculiar radial velocity and therefore accurate distances are needed to contrain the flight direction in three dimensions.

Figure 2 shows the projected motion of VFTS682 relative to R136 on the sky. ■ **[fix colors]** ■ The dashed circle shows the location of the cluster, and the red (cyan) arrow shows the relative proper motion from *Gaia* DR2 (HST). The lighter arrows show the uncertainty on the direction of motion due to the large uncertainties. The length of each arrow is proportional to the speed of the star, and dashed prolungations show the possible region of origin assuming an age of 1.0 ± 0.2 Myr (Schneider et al. 2018). This figure illustrates that R136 is clearly the most likely origin of the star, although the large error bars prevent a robust identification.

Assuming VFTS682 indeed originates from R136, we can calculate its kinematic age simply as:

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

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

Therefore, although the motion of VFTS682 is not an outlier compared to other massive stars, it is possible to tentatively claim that it is a slow runaway with velocity compatible with dynamical ejection from R136 early in the evolution of both the star and the cluster.

4. DISCUSSION

Based on our results, we tentatively claim that VFTS682 is the most massive (slow) runaway known to date, with a peculiar two-dimensional projected velocity with respect to R136 of $\sim 38\,\rm km\,s^{-1}$ (averaging the *Gaia* DR2 and HST results) but compatible with zero within 2σ. 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 2nd 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 from 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 very massive runaway stars 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 (cf. Fig. 1). The value of $\tau_{\rm kin} \simeq 0.9$ Myr we find for VFTS682 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.

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

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