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GAIA IDENTIFIES VFTS682 AS THE MOST MASSIVE, DYNAMICALLY EJECTED RUNAWAY STAR KNOWN TO DATE

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ABSTRACT

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Subject headings: stars: kinematics, stars: runaways, stars: individual: VFTS682

1. INTRODUCTION

How do 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 they remain enshrouded in their parent cloud during the formation process. Major progress has been made on the theoretical side, (e.g. Kuiper et al. 2015; Rosen et al. 2016), but the simulations are computationally very expensive. They can typically not yet resolve the length scales that are of interest to understand the high level of multiplicity among massive stars (Sana et al. 2012, 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 as sources of feedback, but also for understanding the transients that mark their death and the compact remnants they leave behind. This is therefore a key question for the present and upcoming transient surveys e.g., LSST and LIGO/Virgo, which will reveal transients associated to massive stars evolution and death.

In has been conjectured that most, if not all, stars form in clusters Lada & Lada (2003), where massive stars are thought to form preferentially in the dense cores of clusters. In this picture, field stars are primarily the result of the dissolution of dense groups. However, a significant population of massive stars has been in relative isolation, far from dense clusters or OB associations. The origin of this population still remains debated (Lamb et al. 2016). 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 been ejected from their birth locations. Such ejections may result from (e,g, Poveda et al. 1967) or from the dsiruption of binary systems by the supernova of the companion star (Zwicky 1957; Blaauw 1961).

A very interesting contribution to the debate whether or not massive stars an form in relative isolation was presented in recent years by Bestenlehner et al. (2011a), who discuss 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) of massive stars (Evans et al. 2011a). It's spectral type WNh5, inferred present-day mass of $138^{+xx}_{-xx}\,M_{\odot}$

an inferred initial mass of $150^{+28.7}_{-17.4}\,M_{\odot}$ and a mass loss rate of $\sim 10^{-4.1\pm0.2}\,M_{\odot}\,\mathrm{yr}^{-1}$ (Bestenlehner et al. 2011a; Schneider et al. 2018) it belongs to the most extreme objects in the region. It is reminiscent of the very massive stars, a.k.a. "monster stars", identified by Crowther et al. (2010a) and Crowther et al. (2016).

Most remarkable is the location of VFTS682, at a projected distance of ~29 pc from the core of the central ionizing star cluster R136. Bestenlehner et al. (2011a) discuss two possibilities for the origin of VFTS 682. Quoting directly from their abstract: "either (i) the star either formed in situ, which would have profound implications for the formation mechanism of massive stars, or (ii) VFTS 682 is a slow runaway star that originated from the dense cluster R136, which would make it the most massive runaway known to date."

In this study we report on our analysis of Gaia data that was was part of the second data release (DR2) (Gaia Collabora-

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tion et al. 2016, 2018a). We combine the radial velocity measurements from the VFTS survey (Evans et al. 2011b) 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.

Our results indicate that VFTS 682 is a bona fide runaway star. The direction an magnitude of the velocity vector is fully consistent with dynamical ejection from R136. Its inferred age is consistent with the inferred travel time. This means that the hypothesis that VFTS 682 is formed in relative isolation is rejected. This makes VFTS 682, with an inferred present day mass well above a hundred solar masses, the most massive runaway star known to date.

2. OBSERVATIONS

In this section we summarize the remarkable properties derived for VFTS682 Sec. 2.1 in earlier studies and we discuss how we Gaia data in Sec. 2.2.

2.1. *Overview of the stellar parameters of VFTS682 derived in previous studies*

The star VFTS682 (Evans et al. 2011a), located at RA 05:38:55.510 Dec -69:04:26.72 ■ **[format properly]** ■ was originally classified as a young stellar object (Gruendl & Chu 2009) based on its mid-infrared excess. Evans et al. (2011a) classified the object a Wolf-Rayet star using spectroscopic observations taken a part of the VLT-FLAMES Tarantula survey. The spectra available covered λ4000–7000 and were taken at multiple epochs. (Bestenlehner et al. 2011b) studied this object in more detail used and looked for radial velocity variations. This allowed them to exclude the presence of a close companion with high confidence.

(Bestenlehner et al. 2011b) further analyzed the spectra using the non-LTE model atmosphere code CMFGEN (Hillier & Miller 1998) to derive the stellar parameters and surface abundances. They derive a find a peculiar extinction ($R_V \sim 4.7$), leading to a surprisingly high luminosity $\log_{10} L(\mathrm{L}_\odot) = 6.5 \pm 0.2$. Bayesian analysis with the Bonsai code (Schneider et al. 2017) against evolutionary models by Brott et al. (2011) and Köhler et al. (2015) leads to an estimated present-day mass of $138^{+28}_{-16}\,\mathrm{M}_\odot$, an age of $1.0^{+0.2}_{-0.2}$ Myr and an inferred initial masse of $150^{+29}_{-17}\,\mathrm{M}_\odot$. This places around the "canonical upper limit" of 150 $\mathrm{M}_\odot$ by Figer (2005).

The star is very similar to R136a3, located inside the star cluster R136, (Crowther et al. 2010a) for which Crowther et al. (2016) report a current mass estimate of $180^{30}_{-30\,\mathrm{M}_\odot}$. The R136 cluster hosts two further very massive WN5h stars R1361 and R136a2, whose estimated current masses are even higher. However, VFTS682 stands out by its location a projected offset of 32 pc from the center of the cluster.

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

■ **[Report mass loss rate. Report LOS velocity.]** ■

2.2. *Kinematic data from Gaia DR2*

The Gaia Data Release 2, which became available on 25 April 2018, provides the five-parameter astrometric solution (positions, parallaxes, and proper motions) for more than a bilion sources (Gaia Collaboration et al. 2018b). The median uncertainty in the proper motion components the corresponding uncertainties are 0.05 mas yr^{-1} for bright sources ($G < 14$ mag) and 0.2 mas yr^{-1} at $G = 17$ mag (Lindegren et al. 2018a). The uncertainties quoted above to xx km s^{-1} and yy km s^{-1} respectively. This unprecedented accuracy allows the identification of bright runaway stars at the distance to the LMC, 50 kpc.

TABLE 1
ASTROMETRIC PARAMETERS FOR VFTS682.

Parameter	Value	Source
RA [degree]	84.73 ± 0.03	Gaia DR2
DEC [degree]	-69.07 ± 0.05	
μ_{RA} [mas yr^{-1}]	1.84 ± 0.07	
μ_{DEC} [mas yr^{-1}]	0.78 ± 0.08	
δv_{rad} [km s^{-1}]	-45 ± 25	Bestenlehner et al. (2011a)

NOTE. — The peculiar radial velocity δv_{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}).

VFTS682 is identified with the gaia source with id 4657685637907503744 in the Gaia DR2 catalog[1]. Gaia reports a G-band magnitude is 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. 2018b), 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. (2011a), 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 (DEC) in the IGCS frame (Gaia Collaboration et al. 2018a), its proper motion components (μ_{RA}, and μ_{DEC}, 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. (2011a). Table 2 lists the values adopted throughout this work for each of these quantities.

We define a local standard frame of reference 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) 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. 2011b). 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} $\simeq$ 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

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

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

$$\langle\mu_i\rangle = \frac{\sum_{\rm stars} \frac{1}{\Delta\mu_i}\mu_i}{\sum_{\rm stars} \frac{1}{\Delta\mu_i}} \ , \ \ \Delta\langle\mu_i\rangle = \frac{\sqrt{N}}{\sum_{\rm stars} \frac{1}{\Delta\mu_i}} \ , \qquad (1)$$

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 (a subset is shown in blue in Fig. 1), we find averaged proper motion components of $\langle\mu_{\rm RA}\rangle$ = 1.683 ± 0.002 mas yr^{-1} and $\langle\mu_{\rm DEC}\rangle$ = 0.672 ± 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 2), we obtain the components of proper motion of the star relative to the surrounding region $\mu_{\rm RA}$ = 0.16 ± 0.07 mas yr^{-1} and $\mu_{\rm DEC}$ = 0.11 ± 0.08 mas yr^{-1}. We note that the error budget is dominated by the errors on the proper motion components of VFTS682.

These can be converted in the the components of the relative transverse velocity $\delta v_{\rm RA}$ = 38 ± 17 km s^{-1}, $\delta v_{\rm DEC}$ = 26 ± 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. (2011a) then gives the third component along the line of sight, allowing us to calculate the three-dimensional peculiar speed of the star:

$$v_{\rm pec} = \sqrt{(\delta v_{\rm RA})^2 + (\delta v_{\rm DEC})^2 + (\delta v_{\rm rad})^2} = 64\pm21 \ {\rm km\ s^{-1}} \ . \qquad (2)$$

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?*

The red arrow in Fig. 1 shows the proper motion of VFTS682 relative to the region, and the lighter red arrows show the possible range of directions within the uncertainties in the measured proper motion. It is clear that the most likely origin of the star is R136, as predicted by Fujii & Portegies Zwart (2011); Banerjee et al. (2012).

We can therefore consider the kinematic age for this star assuming that it originates from the cluster,

$$\tau_{\rm kin} = \frac{d_{\parallel}}{v_{\parallel}} = \frac{29\ {\rm pc}}{46\ {\rm km\ s^{-1}}} \simeq 0.63\,{\rm Myr} \ , \qquad (3)$$

where $d_{\parallel}$ = 29 pc is the projected distance from VFTS682 to the core of R136 (Bestenlehner et al. 2011a), $v_{\parallel} \equiv \sqrt{(\delta v_{\rm RA})^2 + (\delta v_{\rm DEC})^2}$ = 46 ± 17 km s^{-1} is the speed of the star relative to the cluster projected on the sky, obtained using the relative proper motion components calculated in Sec. 3.1, and we use the approximation 1 km s^{-1} ≃ 1pc Myr^{-1}.

The kinematic age $\tau_{\rm kin}$ is smaller than the apparent age of the star age 1.0 ± 0.2 Myr from Schneider et al. (2018), which corroborates the idea that the star is the result of a dynamical ejection.

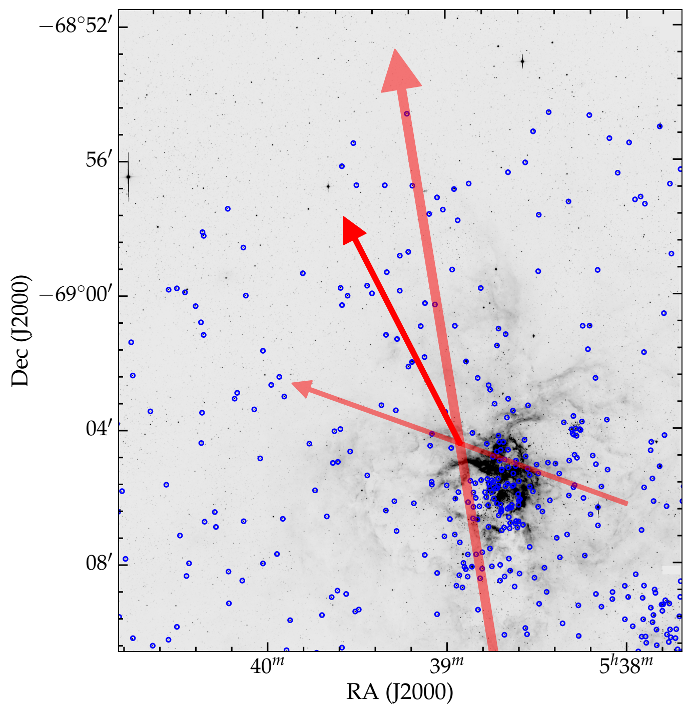

FIG. 1.— The red cross indicates the position of VFTS682. Blue stars are those we use to define the generic "surroundings", while the green dots indicate the stars we use to probe the core of R136, magnified in the inset. The red arrow shows the direction of the proper motion of VFTS682 relative to R136, and the gray shade indicates the uncertainty in the direction. ■ **[load color picture on background]** ■

4. DISCUSSION

Based on our results, we can claim that VFTS682 is the most massive runaway known to date, with a peculiar three-dimensional spatial velocity of ∼60 km s^{-1}. This means that isolated star formation is *not* required to explain this star. Its proper motion suggests that it was ejected from the cluster R136 ∼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 ■ **[ref]** ■. This means that, just based on the kinematic properties of VFTS682, we would expect several stars with initial masses larger than ∼150 $M_\odot$ in the cluster R136. This can be considered an independent confirmation of the detection of extremely massive stars by Crowther et al. (2010b) in the core of the cluster. The projected rotational equatorial velocity of VFTS682 reported by Schneider et al. (2018) is $v \sin(i) < 200$ km s^{-1}, which is in line with the average rotation rate of massive stars in the region (Ramírez-Agudelo et al. 2015). This suggests that VFTS682 has not experienced binary interactions, nor it will, since the multi-epoch data of the VFTS survey rule out the presence of a companion at present day. Moreover, the spectral type of VFTS682 (WNh5, Bestenlehner et al. 2011a) is the same as R136a1-a3, i.e. the three most massive stars detected in the core of the cluster by Crowther et al. (2010b). Therefore, VFTS682 might be an ideal target to constrain the stellar physics of stars with masses well above $\sim 100\,M_{\odot}$: its isolation makes it an easier target for observations compared to the similar stars present the crowded core of R136.

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 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).

The kinematic age of VFTS682 puts an upperlimit to the timescale to form such "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. (2010b); Sabbi et al. (2012) and the kinematic age of VFTS16.

■ **[check ? and rewrite next paragraph, they have stuff]** ■ Unfortunately, their simulations did not include stars more massive than $100\,M_{\odot}$, so it is difficult to predict, based on the existence of VFTS682, how many other stars should have been ejected from the cluster already and what is their mass distribution. A comprehensive study of the kinematic properties of the large sample of stars with extremely large inferred masses visible around R136 is encouraged.

? have carried out a similar study on VFTS16, another massive star ($\sim 90\,M_{\odot}$) in the 30 Doradus region, previously known to be a runaway from the value of its radial velocity. They also concluded that VFTS16 is the result of a dynamical ejection from the R136 cluster. The value of $\tau_{\rm kin} \simeq 0.63$ Myr we find for VFTS682 (see Sec. 3.2) is smaller than the corresponding value for VFTS16: **?** 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.

- 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?

■ **[Merge Selma's my_bib bibtex file with Mathieu's and prevent double refs.]** ■

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