The Very Massive and Hot LMC Star VFTS 682: Progenitor of a Future Dark Gamma-Ray Burst?

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ABSTRACT

VFTS 682, a very massive and very hot Wolf-Rayet (WR) star recently discovered in the Large Magellanic Cloud near the famous star cluster R136, might be providing us with a glimpse of a missing link in our understanding of Long Gamma-Ray Bursts (LGRBs), including dark GRBs. It is likely its properties result from chemically homogeneous evolution (CHE), believed to be a key process for a massive star to become a GRB. It is also heavily obscured by dust extinction, which could make it a dark GRB upon explosion. Using Spitzer data we investigate the properties of interstellar dust in the vicinity of R136, and argue that its high obscuration is not unusual for its environment and that it could indeed be a slow runaway (“walkaway”) from R136. Unfortunately, based on its current mass loss rate, VFTS 682 is unlikely to become a GRB, because it will lose too much angular momentum at its death. If it were to become a GRB, it probably would also not be dark, either escaping or destroying its surrounding dusty region. Nevertheless, it is a very interesting star, deserving further studies, and being one of only three presently identified WR stars (two others in the Small Magellanic Cloud) that seems to be undergoing CHE.

Key words: Stars: mass-loss – Stars: Wolf-Rayet – Gamma-ray burst: general – Magellanic Clouds

1. Introduction

Ideally, in order to fully understand the mapping between massive star progenitors and when and how they explode (or not, Kochanek \textit{et al.} 2008), we would have extensive multi-wavelength data obtained for many such explosions both BEFORE and AFTER the event. The AFTER part has certainly undergone an explosive growth in the last decade or so, due to many successful supernova (SN) searches such as the galaxy-targeted Lick Observatory Supernova Search (LOSS), the Catalina Real-time Transient Survey (CRTS), the Robotic Optical Transient
Search Experiment (ROTSE), the Palomar Transient Factory (PTF); and gamma-ray burst searches such as the High Energy Transient Explorer-2 (HETE-2) and Swift. The BEFORE part is naturally limited by the fact that massive stars, while relatively bright, are only observable in the local Universe \((d \lesssim 10 \, \text{Mpc})\). Here we have had to rely on proximity (SN 1987A, Kunkel et al. 1987), luck based on archival data (e.g., Smartt et al. 2009), or the first systematic campaign to monitor future SN progenitors (Szczygieł et al. 2011), where many nearby galaxies are observed to sufficient depth so eventually they will provide progenitor data for a significant number of future SNe. We have by now compiled a fair amount of information on SN progenitors, such as the blue supergiant progenitor for SN 1987A (White and Malin 1987) or dusty progenitors of SN 2008S and 2008 NGC 300 transient (Prieto et al. 2008, Prieto 2008).

However, for very rare explosive events, such as long-duration gamma-ray bursts (LGRBs), the systematic approach that works for the normal core-collapse SNe is not yet possible because the events are so rare. Therefore the prospect of future systematic observational efforts that could identify nearby LGRB progenitors is very dim. Here we have to rely on a more extended chain of reasoning, with data being supplemented with reasonable, theoretical guesses. Discovery of the connection between LGRBs and broad-lined Type Ic SNe (e.g., Stanek et al. 2003, Hjorth et al. 2003), thought to result from core-collapse of hydrogen-free massive stars, favors two possible progenitor models: single massive Wolf-Rayet (WR) stars with rapidly rotating cores (Filippenko and Sargent 1985), or lower mass helium stars stripped by a close binary companion (Podsiadlowski et al. 2004). The prompt emission of an initial LGRB, lasting seconds or minutes, is usually followed by a multi-wavelength afterglow which lasts days to even years. Although X-ray afterglows of LGRBs are nearly always detected by Swift and Fermi, detection of optical and infrared afterglows is less common. A dark GRB is defined by either an absent or faint optical afterglow relative to its X-ray emission. The rapid detection of X-ray afterglows with Swift revealed that the dark fraction of LGRBs is about 30% of GRBs (Akerlof and Swan 2007, Perley et al. 2009). In general, besides the intrinsically optically faint GRBs, the optical attenuation of dark GRBs can be caused by dust extinction in GRB host galaxies, foreground extinction, or Lyman-\(\alpha\) absorption by neutral hydrogen at high redshifts (Perley et al. 2009).

Study of massive stars in very nearby galaxies can supply the other missing links in our understanding of LGRBs. The recently uncovered very massive stars up to 300 M\(_\odot\) in the Large Magellanic Cloud (LMC) young cluster R136 extend our knowledge of massive star formation and evolution (Crowther et al. 2010). In particular, the newly discovered very massive WR star VFTS 682, located 30 pc away from R136, drew our attention, mainly because of its very high foreground dust extinction and possibility of being a GRB progenitor (Bestenlehner et al. 2011). Its unusually high effective temperature can be understood as the consequence of chemically homogeneous evolution (CHE), which was proposed as the crucial part...
of the process of producing LGRBs (Yoon and Langer 2005). If VFTS 682 will indeed make a GRB at the end of its evolution, the high foreground dust extinction could mean that it will become a dark GRB. However, its high mass and strong mass-loss seem to prevent it from being a GRB progenitor, and the potential afterglow might destroy the surrounding dust even if VFTS 682 eventually produces a GRB. Therefore, it is worthwhile to look into the details of VFTS 682’s evolution and the fate of its circumstellar environment. Section 2 describes the dust properties in the VFTS 682 vicinity region. Section 3 investigates the possibility of VFTS 682 producing a LGRB and Section 4 discusses the fate of dusty clouds around VFTS 682. Conclusions are presented in Section 5.

2. Investigating the Properties of Interstellar Dust in the Vicinity of VFTS 682

Among the many striking properties of VFTS 682 discussed in Bestenlehner et al. (2011), the high value they derived for the foreground extinction to that star, $A_V = 4.45 \pm 0.12$ mag, particularly drew our attention. Indeed, for a random line of sight to an object in the LMC, a typical value of the interstellar extinction would be much lower, $A_V \sim 0.3$ mag (e.g., Pejcha and Stanek 2009). At the same time, other very massive, nearby stars in R136 – the central cluster of the 30 Doradus region – have estimated interstellar extinctions near $A_V \sim 2.0$ mag (see Table 3 in Crowther et al. 2010), significantly lower than VFTS 682. This high value of extinction could provide an interesting clue to the origin of VFTS 682, because if such values were indeed very rare in the 30 Dor region, it would argue against VFTS 682 being a slow runaway (“walkaway”) from the R136 cluster.

To investigate the properties of interstellar dust extinction in the vicinity of VFTS 682, we analyzed the archival Spitzer Space Telescope IRAC data for the 30 Dor region, which were obtained in 2003 by the “Comparative Study of Galactic and Extragalactic HII Regions” program (PI: Houck; Program ID: 63). For the purpose of this investigation, we limited our analyzes to a region $20' \times 20'$ centered on R136.

In Fig. 1 we show 3.6, 4.5, 5.8 and 8.0 $\mu$m IRAC images of the region near VFTS 682 and 30 Dor. We see a progression of still seeing significant stellar light in the 3.6 $\mu$m band, so the cluster still features prominently in this band, to being completely dominated by warm dust emission and PAH emission in the 8.0 $\mu$m band, where the cluster virtually disappears. If we can use the 8.0 $\mu$m band emission as a proxy for dust column density, then the high value of $A_V$ towards VFTS 682 is not at all unusual in the 30 Dor region, and there should be lines of sight with 5 to 10 times higher values of interstellar extinction near the location of VFTS 682. Therefore, despite our initial expectation, the high value of $A_V$ does not bring any new information about the nature of VFTS 682, namely was it ejected from R136 or was it born in situ. However, the presence of such large amounts of spatially complex
Fig. 1. Spitzer-IRAC archival images of the 30 Doradus region in 3.6, 4.5, 5.8 and 8.0 $\mu$m (upper left to bottom right) IRAC photometric bands. The location of VFTS 682 is marked with the small circle, while the location of the R136 cluster is shown with the large circle. The $60''$ scale bar corresponds to roughly 14.5 pc for an assumed LMC distance of 50 kpc.

dust raises the interesting possibility of there being other stars like VFTS 682 in the vicinity of R136, that are hidden behind still more dust.

For a more quantitative analyzes of the IRAC data, we used DAOPHOT (Stetson 1992) to identify point sources and measure their fluxes in the 3.6, 4.5 and 5.8 $\mu$m images. In Fig. 2 we show the resulting mid-IR color–magnitude diagrams (CMDs). In the $[4.5],[3.6]−[4.5]$ CMD we more or less agree with SAGE that VFTS 682 has a small 4.5 $\mu$m flux excess, but we find a bluer $[4.5]−[5.8]$ color, most likely due to differing treatments of the extended dust emission near VFTS 682. In any case, the amount of resolved mid-IR emission at the position of VFTS 682 is very small compared to its total bolometric luminosity. It is clear from these CMDs that the mid-IR properties of VFTS 682 are not at all unusual compared to other stars in the 30 Dor region, and there are many other stars nearby that are either more obscured or have significantly more mid-IR emission around them.
3. Can VFTS 682 be a GRB Progenitor?

VFTS 682 has a high temperature $T_{\text{eff}} = 52.2 \pm 2.5$ kK and luminosity $\log(L/L_\odot) = 6.5 \pm 0.2$, placing it blueward of the zero-age main sequence in the Hertzsprung–Russell (HR) diagram, which can be explained by CHE. Since CHE is believed to be the key process to make a LGRB, Bestenlehner et al. (2011) suggest VFTS 682 as a possible LGRB progenitor. A key ingredient to maintaining a CHE is sufficiently fast stellar rotation to induce a complete chemical mixing (Schwarzschild
However, the problem is that CHE might cease when the strong mass-loss from VFTS 682 carries away too much angular momentum before its death.

Theoretically low metallicity is favorable for single stars to be GRB progenitors, mainly because low metallicity leads to low mass-loss rates, that sustain the fast rotation required by LGRB models (Yoon and Langer 2005, Woosley and Heger 2006). Recent simulations proposed a metallicity threshold of $Z \leq 0.004$ for GRB production (Yoon et al. 2006). Observations find that local LGRBs associated with supernovae (SNe) have metal-poor host galaxies with oxygen abundance of $12 + \log (\text{O}/\text{H}) < 8.6$, or $Z < (0.2 - 0.5) Z_\odot$ (Stanek et al. 2006, Modjaz et al. 2008), but not as metal-poor as required by models. Stanek et al. (2006) argued that LGRBs trace only low-metallicity star formation. Although one or two high-metallicity GRB hosts have been discovered (Levesque et al. 2010), all of these GRBs lack an SN signature, leaving it unclear whether those GRBs can be linked with star formation or not. The half-solar metallicity of VFTS 682 is just in the upper metal range given by LGRB-SN events, so it is unclear whether it can be a LGRB progenitor just based on the metallicity criterion. A more direct constraint on the fate of VFTS 682 can be derived from its other physical parameters as follows.

The observed present mass-loss rate of VFTS 682 is $\log (\dot{M}/M_\odot \text{ yr}^{-1}) = -4.4 \pm 0.2$, with an estimate present-day mass as $M \sim 150 M_\odot$ (Bestenlehner et al. 2011). The mass-loss timescale for VFTS 682 of $\tau_{\text{wind}} = M/M \sim 3.8$ Myr is comparable to the stellar nuclear timescale $\tau_{\text{nuc}} \sim 5 \times 10^9$ yr $(M/M_\odot)(L/L_\odot)^{-1} \sim 2.6$ Myr for the current hydrogen abundance $X_\text{H} = 0.55$. This means that VFTS 682 can easily be stripped given its current mass-loss rate. For simplicity, if we take a remaining lifetime for VFTS 682 on the main-sequence (MS) as $\sim 2$ Myr with a constant mass-loss rate as its present value, the total mass lost when it evolves off the MS will be $M_{\text{loss}} \sim 80 M_\odot$. Since the hydrogen abundance will continue to decrease from its current value, the luminosity $L$ changes a little with both deceasing $M$ and $X_\text{H}$ (Gräfener et al. 2011), the theoretically predicted mass-loss rate $\dot{M} \propto 10^{-0.45X_\text{H}} (L/L_\odot)^{0.42}$ increases in the future (Gräfener and Hamann 2008). If the hydrogen abundance smoothly drops from $X_\text{H} = 0.55$ to $X_\text{H} \simeq 0$, the total mass-loss increases from the rough estimate $\sim 80 M_\odot$ to as high as $\sim 100 M_\odot$. This would leave a remaining core $M_r \sim 70 - 50 M_\odot$ star as the star leaves the MS, and its subsequent evolution could eject even more mass. Unlike normal stars, which include core and envelope components, stars undergoing CHE can be approximated as a chemically mixed, rigidly rotating bodies (Meynet and Maeder 2000). Treating VFTS 682 as a rigid object with a current surface rotation velocity $v_0$ and radius-mass relation $R \propto M^\alpha$, the final rotation velocity $v_f$ at the end of MS is $v_f/v_0 = (M_r/M_0)^{(3-2\alpha)/2}$. Taking $\alpha \sim 1$ for very massive stars (Yungelson et al. 2008), we have $v_f/v_0 \sim 0.6 - 0.7$ and the star will have lost more than 85% of its current angular momentum before its death. For currently $v_0 \leq 700$ km/s, the stellar final rotation velocity $v_f \leq 500$ km/s is unlikely high enough to maintain
CHE in the LMC (see the criterion in Meynet and Maeder 2000, or Fig. 7 in Brott et al. 2011). VFTS 682 will have a hydrogenic envelope at death, thus cannot become a LGRB. On the other hand, if VFTS 682 has an incredibly rapid rotation velocity \( v_0 > 700 \text{ km/s} \), the possibility of maintaining CHE and producing a GRB associated with a hypernova (Nomoto et al. 2005) is not excluded.

Some other effects such as shorter lifetimes or wind anisotropies can decrease the angular momentum loss and help maintain the angular momentum (Meynet and Maeder 2007). But even for a large helium star with sufficient angular momentum, there is still an extra problem for producing a GRB. A relativistic jet generated in the stellar center cannot break out of the star if the duration of central engine is shorter than the jet crossing time inside the star (Mészáros and Rees 2001). Taking a radius of \( \sim 10^{12} \text{ cm} \) for a helium star with a mass \( \sim 100 \text{ M}_\odot \), the jet crossing time inside the star is estimated as \( t_{\text{cross}} \gtrsim 100(r_{\text{He}}/10^{12} \text{ cm}) \text{ s} \) (Mészáros and Rees 2001), which requires the duration of GRB central engine to be longer than 100 seconds. Such durations are observed, but rare, compared to those of durations < 100 s (Sakamoto et al. 2011).

4. Fate of Dusty Clouds and Possible Dark Gamma-Ray Burst?

What is the fate of the dusty clouds near VFTS 682 after its death? Will the clouds be destroyed by the explosion of VFTS 682? Because the properties of dusty clouds around VFTS 682 are not at all unusual in the 30 Dor region, we adopt the gas density of the 30 Dor core region \( n \sim 200 \text{ cm}^{-3} \) (Kawada et al. 2011) with a typical value of \( N_H/A_V \approx 0.7 \times 10^{22} \text{ cm}^{-2} \) in the LMC (Schady et al. 2007). This implies that the foreground extinction region has a size of \( \sim 50 \text{ pc} \) for \( A_V \approx 4.45 \text{ mag} \). This is consistent with the 8.0 \( \mu \text{m} \) image in Fig. 1, where the dusty region around VFTS 682 has a projected size of \( \sim 30-40 \text{ pc} \). In the “walkaway” scenario, VFTS 682 has both a tangential and RV velocity of \( \sim 30 \text{ km/s} \) away from R136. Is so, VFTS 682 will probably escape the dusty region in its remaining \( \sim 2 \text{ Myr} \) lifetime. On the other hand, if VFTS 682 formed in situ, or has a much shorter lifetime, it will be still in the very dusty clouds at its death.

Since the luminosity of the afterglow of a GRB cannot be well determined from just the progenitor mass and rotation, it is uncertain whether the potential GRB from VFTS 682 will be dark, or the dusty clouds will be destroyed by the optical flashes produced by VFTS 682. Typically we would assume a relativistic jet breaks out of the star and emits an isotropic gamma-ray luminosity \( L_{\gamma}^{\text{iso}} \sim 10^{51} \text{ erg/s} \) (Lee et al. 2000), followed by an early optical afterglow with a luminosity \( L_{\text{opt}}^{\text{iso}} \sim 0.1 L_{\gamma}^{\text{iso}} \). In this case any dust region smaller than \( R \sim 30(t_{\text{opt}}^{\text{iso}}/10^{50} \text{ erg/s})^{1/2} \text{ pc} \) cannot survive because of dust sublimation by the optical flash and fragmentation by the burst and afterglow (Waxman and Draine 2000, Reichart and Price 2002). In other words, the dusty region covering VFTS 682 and R136 would probably be destroyed due to an early optical afterglow \( L_{\text{opt}}^{\text{iso}} > 10^{50} \text{ erg/s} \). Otherwise, the less luminous
early X-ray/optical afterglows will heat and ionize the surrounding environment out to $\sim 100$ pc, decreasing the dust column density on a timescale of tens to hundreds of minutes in the observer’s frame (Perna and Loeb 1998).

However, it will be another story if VFTS 682 produces an intrinsically faint GRB. It is possible that the inefficient jet propagation inside the star only gives an underluminous burst, as well as a dim optical afterglow ($L_{\text{iso}}^{\text{opt}} < 10^{50}$ erg/s) linked with the weak burst. Then the dusty clouds will be heated and ionized, but not be totally destroyed.

5. Conclusions and Discussion

We give a first order estimate whether VFTS 682 can be a LGRB progenitor in the sense of CHE, which is still a question mark in previous work. VFTS 682 will most likely lose more than 85% of its current angular momentum and cease its CHE evolution before it leaves MS with a remaining mass $\sim 50$–$70$ M$_\odot$. In general VFTS 682 will fail to produce a GRB due to its strong mass-loss and the resulting angular momentum loss, unless it has a currently extreme rapid rotation ($v_0 > 700$ km/s) which helps it maintain CHE and eventually produce a GRB associated with a hypernova. Wind anisotropies and shorter lifetime could leave a more massive faster rotating star, but it is doubtful whether a relativistic jet could travel through such a thick stellar envelope and break out of the stellar surface, unless it is a rare long-lived ($\gtrsim 100$ s) LGRBs. Similarly, it is unlikely that VFTS 682 will be heavily obscured at death and produce a dark GRB. Its proper motion will probably cause it out of the dusty region, and a GRB of an early optical afterglow $L_{\text{opt}} > 10^{50}$ erg/s would destroy the dust clouds within 30 pc, otherwise the dusty clouds can be heated and ionized up to a region of $\sim 100$ pc by X-ray and optical radiation given by the death of VFTS 682.

CHE is believed to be the crucial process in the evolution path towards LGRBs. However, the observed sample of WRs likely undergoing CHE is quite small. The only observation of WR stars besides VFTS 682 which might be undergoing are two WNh stars in the SMC (i.e., SMC-WR1 and WR2 in Martins et al. 2009), which makes these three WR stars extremely important to understanding the evolution of WR stars undergoing CHE and the related problem of LGRB formation. The angular momentum losses of the two WR stars in the SMC will be much less significant than VFTS 682 in the LMC. Taking the stellar parameters in Martins et al. (2009), we estimate that the nuclear timescale of SMC-WR1 (WR2) $\tau_{\text{nuc}} \sim 4$ Myr (5 Myr) is shorter than the wind timescale $\tau_{\text{wind}} \sim 10$–$20$ Myr, and the final stellar rotation velocity should be 90% of the current velocity. Therefore, the two WR stars in the SMC are more likely GRB progenitors in the scenario of CHE, although the metallicity threshold is still an issue (Martins et al. 2009). In any case, finding CHE WR stars in the LMC and SMC promotes a future work on theory models.

VFTS 682 is a very interesting star. As mentioned in Section 2, because there is
no observation evidence to show that VFTS 682 is unusual compared to other stars in the 30 Dor region, the interesting possibility of existence of others massive stars like VFTS 682 in the vicinity of R136 is not excluded. Note that R136 is sufficient young and massive (\( \leq 5.5 \times 10^4 \, M_\odot \)) to generate runaway stars beyond 150 \( M_\odot \). Recently Banerjee et al. (2012) gives a theoretical model study on the dynamical ejection of runaway massive stars from R136. We suggest that there might be other massive stars that “walked away” from R136, but are currently hidden behind even more dust than VFTS 682. Since mid-IR date cannot be used to flag such stars, spectroscopic observations, which are beyond the scope of this paper, should be further investigated to show the possibility of their existence.

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