NGC 300 OT2008-1 AS A SCALED-DOWN VERSION OF THE ETA CARINAE GREAT ERUPTION

AMIT KASHI, ADAM FRANKOWSKI, AND NOAM SOKER
Department of Physics, Technion-Israel Institute of Technology, Haifa 32000, Israel; kashia@physics.technion.ac.il, adamf@physics.technion.ac.il, soker@physics.technion.ac.il

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ABSTRACT

We propose that the intermediate luminosity optical transient NGC 300 OT2008-1 was powered by a mass transfer episode from an extreme asymptotic giant branch star to a main sequence (MS) companion. We find a remarkable similarity in the shapes of the light curves of the several months long NGC 300 OT2008-1 outburst, of the three-month long 2002 enigmatic outburst of the B star V838 Mon, and the twenty-year long Great Eruption of the massive binary system Eta Carinae that occurred in the 19th century. Their similar decline properties hint to a common energy source: a gravitational energy that is released by accretion onto an MS star. These events populate a specific strip in the total energy versus outburst duration diagram. The strip is located between novae and supernovae.

We add recent transient events to that diagram and find them to occupy the same strip. This suggests that some intermediate luminosity optical transients are powered by accretion onto a compact object (not necessarily an MS star). These transients are expected to produce bipolar ejecta as a result of the geometry of the accretion process.

Key words: stars: individual (NGC 300 OT) – stars: mass-loss – stars: variables: general – stars: winds, outflows – supernovae: general

Online-only material: color figures

1. INTRODUCTION

The Intermediate Luminosity Optical Transient (ILOT) NGC 300 OT2008-1 (hereafter NGC 300 OT) was discovered in 2008 April 24 (Monard 2008), a few weeks after its assumed outburst. The distance to the host galaxy NGC 300 is ∼1.88 Mpc (Gieren et al. 2005; Freedman et al. 2001). With abolometric luminosity of \( L_{\text{bol}} = 1.6 \times 10^{40} \text{erg s}^{-1} \) at discovery (Bond et al. 2009), it is located between supernovae (SNe) and novae, and cannot be easily grouped within any subtype of these two classes (Kulkarni & Kasliwal 2009). The pre-outburst progenitor system was discovered by Prieto (2008). It was enshrouded by dust (Bond et al. 2009; Berger et al. 2009), and had a luminosity of about \( 6 \times 10^5 \ L_\odot \) corresponding to an \( M = 10–15 \ M_\odot \) star, probably in the extreme asymptotic giant branch (AGB) stage (Thompson et al. 2009). A more massive red supergiant of mass \( M = 12–25 \ M_\odot \), as found by Gogarten et al. (2009) based on stellar evolution considerations, would also be consistent with the data.

Berger et al. (2009) could fit the UV–visual spectral energy distribution (SED) during outburst with a blackbody spectrum with a temperature of \( T_B = 4670 \pm 140 \ K \), and a radius of \( R_B = 14.7 \pm 1.4 \ \text{AU} \). But if inter- and circumstellar extinction is considered (Bond et al. 2009), based on the appearance of the absorption spectrum at maximum, a temperature of \( \sim 7500 \ K \) is more consistent with the SED. The source was neither detected in the X-ray band (\( F_x < 1.2 \times 10^{-14} \text{erg s}^{-1} \text{cm}^{-2} \)) nor in the radio band. Berger et al. (2009) attributed the \( \sim 10^3 \text{km s}^{-1} \) red wing of the Ca ii H&K absorption lines either to an infalling gas from a previous eruption or to a wind of a companion star. In either case, the star accreting this matter is likely to be a main sequence (MS) star. Together with the evidence for the supergiant nature of the progenitor, this implies that there are two different stars in the system. Bond et al. (2009) interpreted the hydrogen Balmer lines’ and the Ca ii IR triplet’s double features as indicating the presence of a bipolar outflow expanding at a velocity of \( \sim 75 \text{km s}^{-1} \). None of the observed lines exhibited P-Cygni profiles or velocities exceeding \( 10^3 \text{km s}^{-1} \) (Berger et al. 2009); the latter property is a clear departure from typical SN behavior.

According to Prieto et al. (2009) the ILOT event that most resembles NGC 300 OT is SN 2008S (Prieto et al. 2008; Wesson et al. 2009). Both ILOTs were the result of an energetic eruption in a dust-enshrouded \( 10–20 \ M_\odot \) star that survived the eruption (namely, SN 2008S was not an SN at all). Smith et al. (2009) suggested that the physical mechanism which produced SN 2008S is a super-Edington wind, similar to the super-outbursts of massive luminous blue variables (LBVs). Botticella et al. (2009) suggested that the progenitor was an extreme (“super”) AGB star. Bond et al. (2009) suggested that both SN 2008S and NGC 300 OT originated form evolved massive stars on a blue loop to warmer temperatures, and were subjected to increased instability due to prior mass loss.

An asymmetric dusty environment extending a few thousand AU surrounding NGC 300 OT (Patat et al. 2009) hints to a previous possible eruption. This asymmetry may further hint to the presence of a companion star, although we note that up to date there has been no definitive observation proving a companion existence. Thompson et al. (2009) suggested that ILOTs occur due to single star processes, e.g., electron-capture SN, an explosive birth of a massive WD, or an enormous outburst of a massive star. In their model for NGC 300 OT and SN 2008S the progenitors were luminous \( \sim (4–6) \times 10^4 \ L_\odot \) dust-enshrouded stars, at the end of their AGB stage.

Based on the model proposed by Soker (2004), we examine in this Letter (Section 2) whether an eruptive mass transfer onto a companion can account for the properties of NGC 300 OT. In that model, most of the energy of the outburst was gravitational energy released by \( \sim \text{few} \times 0.1 \ M_\odot \) accreted by an MS B-type companion. The binary system survives the event. In Section 3, we suggest a physical mechanism to account for most of the gravitationally powered outbursts.

2. ACCRETION BY A SURVIVING COMPANION

We examine a model where the source of the mass is an extreme-AGB star, while the main source of the energy is a
gravitational energy released by the mass accreted onto an MS companion.

Based on previous papers (Berger et al. 2009; Bond et al. 2009; Gogarten et al. 2009; Prieto et al. 2009) we scale the mass of the extreme-AGB star by $M_1 \simeq 15 M_\odot$. We also assume that the MS companion is not much lighter than the primary, and scale it with $M_2 \simeq 8 M_\odot$, corresponding to an MS radius of $R_2 \simeq 3.5 R_\odot$ (our model can work for $3 M_\odot \lesssim M_2 \lesssim 10 M_\odot$). We attribute the slow outflow of up to $\sim 600 \text{ km s}^{-1}$ fits better the escape velocity from the MS companion.

Our scenario starts with some kind of instability in the extreme-AGB star that causes a mass of several $\times 0.1 M_\odot$ to be lost from the star at a slow velocity. In our model, the instability is not the source of the extra energy. Therefore, we can assume that the instability does not increase much, or even reduces the primary luminosity. We do not specify the source of the instability, but it might be, for example, a strong magnetic eruption. AGB stars are known to have extensive convective region with strong convection (the convective cells have a relative high velocity and long mixing length). If the star has a non-negligible rotation due to its tidal interaction with the companion, then a strong magnetic activity might be expected (e.g., Garcia-Segura et al. 2001). The magnetic eruption causes the primary to overfill its Roche lobe, resulting in both mass loss from the system and mass transfer to the companion.

According to Bond et al. (2009), the transient at maximum light exhibited a spectrum of an F supergiant. The underlying radiation source during the event could be even hotter, if the observed spectrum was produced in an optically thick wind. However, this cannot be used to constrain the spectral type of the progenitor before the event. We take the most conservative approach and take the star to have the lowest temperature possible for its mass at this evolutionary stage (extreme AGB), $\sim 3500 \text{ K}$. For an extreme AGB effective temperature of $\sim 3500 \text{ K}$ the radius of the progenitor of NGC 300 OT was $R_1 \sim 3 \text{ AU}$. The dynamical timescale for a mass of $M_1 = 15 M_\odot$ is $\sim 5$ months. The outburst duration of 80 days can be understood as dynamical timescale. Namely, in our model a dynamical instability lead to high mass transfer episode. The super-Eddington luminosity of the accreting secondary might have helped in terminating the high mass transfer rate. For an efficient accretion the companion in our model of NGC 300 OT has to be very close to the primary, $\sim 2R_1$. We note that if the orbit is highly eccentric, say $e = 0.9$ as in $\eta$ Car, and periastron passage is at $a_p = 2R_1 \simeq 6 \text{ AU}$, then the orbital period is $\sim 100 \text{ yr}$. Furthermore, if the outburst was caused by the periastron passage, then some high mass loss episode could have occurred 100 years ago, but not necessarily as strong. Assuming a velocity of 75 km s$^{-1}$ (as observed for the present bipolar outflow) these ejecta are at a distance of $\sim 1500 \text{ AU}$. If the progenitor was indeed an F star, its higher temperature would imply a smaller radius, and hence a shorter dynamical timescale of about half a month for an effective temperature of 7500 K. This will considerably ease the constraints on our model, as the outburst in our model is limited from below by the dynamical timescale.

In our scenario most of the outburst energy comes from accretion onto the companion. Therefore, we can use the observed luminosity and total energy to constrain the accretion mass and timescale. The total radiated energy is $E_{\text{rad}} = 10^{47} \text{ erg}$ (Bond et al. 2009; Berger et al. 2009). Adding the kinetic energy of the ejected mass doubles (or even more) the total eruption energy, which we scale with $E_{\text{tot}} = 2 \times 10^{47} \text{ erg}$. The accreted mass onto the companion is constrained to be

$$\Delta M_{\text{acc}} = 0.05 \left( \frac{E_{\text{tot}}}{2 \times 10^{47} \text{ erg}} \right) \left( \frac{M_2}{8 M_\odot} \right)^{-1} \times \left( \frac{R_2}{3.5 R_\odot} \right) \left( \frac{\chi}{0.5} \right) M_\odot,$$

(1)

where $\chi$ is the efficiency of converting gravitational energy to eruption energy. If the accreting star does not rotate fast, then $\chi$ is very close to 1. Here we take a conservative approach, and scale with $\chi = 0.5$.

The timescale of the high state of the eruption was $\sim 60 \text{ days}$ (Bond et al. 2008). This would give an average mass accretion rate of $\gtrsim 0.3 M_\odot \text{ yr}^{-1}$, depending on $\chi$ and the other parameters.

There are some similarities between our suggested model of NGC 300 OT and the merger model of the outburst of V838 Mon (Tylenda & Soker 2006). In both ILOTs, the energy is obtained from a process of mass transfer. In V838 Mon, according to the model proposed by Tylenda & Soker (2006), it was a merger process, in which a $\sim 0.3 M_\odot$ star merged with a massive one, on a timescale of $\sim 80 \text{ days}$. This results in an accretion rate of $\sim 1.4 M_\odot \text{ yr}^{-1}$, close to that of NGC 300 OT. The ejection velocities in V838 Mon ($\sim 300 \text{ km s}^{-1}$) are also similar. The duration of the V838 Mon eruption is also quite similar to that of NGC 300 OT. Indeed, the total energy of the two ILOTs is few times $10^{47} \text{ erg}$.

In some sense the NGC 300 OT eruption is a scaled-down version of the Great Eruption (GE) of $\eta$ Car. The GE of $\eta$ Car in 1843 ejected more than $10 M_\odot$ (Smith et al. 2003) from the 100–150 $M_\odot$ progenitor LBV star. Soker (2004) suggested that a large fraction of this mass was accreted by the secondary star, of mass $\sim 25 M_\odot$. Part of the mass transferred to the companion was expelled in a bipolar outflow, that shaped the bipolar structure of $\eta$ Car, the Homunculus (e.g., recent review by Smith 2009). In $\eta$ Car more data are available from observations, e.g., we know the binary period and the ejecta energy, therefore the accretion-powered model could be worked out quantitatively in more detail (Soker 2004).

It is possible that the trigger for the impulsive mass loss episode in $\eta$ Car and NGC 300 OT was the same. Harpaz & Soker (2009) suggested that the mass loss from the primary in the GE of $\eta$ Car was triggered by magnetic eruption in the primary envelope. The magnetic eruption does not increase much the luminosity, but mainly causes an impulsive mass loss episode from the primary. The secondary accretes a large fraction of the outflowing mass.

We now turn to discuss the light curves (Figure 1). The early light curve of V838 Mon showed three peaks (Munari et al. 2002), and then had a rapid decay by 5 mag in about 20 days, shorter than the $\sim 80 \text{ days}$ duration of the high-brightness phase. It is unknown if such peaks existed in NGC 300 OT (Bond et al. 2009), but this may be due to a poor time coverage of the early light curve. However, in the decline phase, the light curve of NGC 300 OT resembles those of V838 Mon and $\eta$ Car GE (Figure 1). The similarity of NGC 300 OT to V838 Mon and few other ILOTs was already noticed by other authors (e.g., Berger et al. 2009; Smith et al. 2009).

In the case of NGC 300 OT, 120 days were required for a decay by 5 mag, a time longer than the high-brightness phase. For the GE of $\eta$ Car, it took no less than $\sim 18 \text{ yr}$ for the light curve to decay by 5 mag (Humphreys et al. 1999).

Remarkably, when we normalize the timescales of the three objects without changing the magnitude scale we find that the
Figure 1. Comparison of the V-band light curves of the η Car GE, V838 Mon and NGC 300 OT. The timescale was normalized so that 1 time unit equals 1 yr for η Car GE, 2.2 days for V838 Mon, and 5.6 days for NGC 300 OT. For NGC 300 OT the R-band is also plotted, for which there has been one observation before the maximum (Bond et al. 2009), marked with a red circle. Top: the three separated light curves; the apparent V-mag axis was not rescaled. Bottom: the same curves translated vertically to bring peak luminosities to overlap (see legend for the shift values). It can be easily seen that the slope of the decline phase and its rate of change are similar for the three eruptions. (A color version of this figure is available in the online journal.)

light curves look very similar (Figure 2). A similar procedure is known as “stretch correction” when applied to SN light curves. The normalized slope of the decline varies the same way for all three eruptions. We consider this a hint that all three eruptions are governed by the same physical mechanism. For example, the residual energy source is not as high (even when the bolometric light curve is considered) as in radioactive decay in SNe. Weaker contribution is possible, e.g., from mass accretion at a low rate (like in the scenario for V838 Mon; Tylenda 2005). Our leading candidate for the powering mechanism is dissipation of accretion energy. We consider the similar slopes as supporting a hint that NGC 300 OT is a scaled-down version of the GE of η Car. The rapid decay in luminosity is determined by the decrease in the supply of accreted mass. Later, the slower decay is dictated by the settling of the inner part of the inflated envelope on the accreting object. In this later phase the luminosity is below the Eddington luminosity. The timescale itself depends on the accreting object and on the structure of the inflated envelope.

On the other hand, when we compare NGC 300 OT to SNe (Figure 1) we find that the slope of the decline phase of NGC 300 OT is steeper than the slope of the decline phase of SNe. Even SN 2008S, which is considered to be the “twin” of NGC 300 OT (Prieto et al. 2008), shows this discrepancy—its decay was more gradual than that of NGC 300 OT in the V band. This is despite the fact that its progenitor had properties similar to those of NGC 300 OT, and the outburst duration was similar. If SN 2008S is indeed an SN, as argued by Botticella et al. (2009), its kinetic energy is expected to be ~10–100 larger than the radiated energy. In such a case, SN 2008S would be located in the region of exploding stars in Figure 3, consistent with its claimed SN nature.

Figure 2. Comparison of the light curve of NGC 300 OT to SN light curves. The timescale was normalized so that 1 time unit equals 5.6 days for NGC 300 OT, 4.5 days for SN 2008S, 1.3 days for SN 2008HA, 2.9 days for SN Ia, and 1.3 days for SN II. The magnitude was shifted to bring peak luminosities to overlap. It can be easily seen that the decline of NGC 300 OT is much steeper than the decline of SNe. The references for the data are: SN 2008S, Botticella et al. (2009); SN Ia (represented by SN 1991T), Patat et al. (2001); SN II (represented by SN 1993J), Patat et al. (2001). (A color version of this figure is available in the online journal.)

Figure 3. Total (radiated plus kinetic) energy of the transients discussed in Section 3 as a function of the duration of their outbursts. We did not include the energy which is deposited in lifting the envelope since it is not observed. See text and Table 1 for information about the different transients and the derivation of their total energy. The shaded area marks the group of transients we study in the paper. We propose that most of these transients are associated with mass-transfer processes. (A color version of this figure is available in the online journal.)
To summarize this section, we suggest that the eruption of NGC 300 OT can be understood as a scaled-down version of the GE of η Car, in terms of a similar dominating physical process—accretion.

3. THE TOTAL ENERGY BUDGET OF ACCRETION-POWERED ILOTs

The objects presented in Section 2 as examples of the accretion-powered transient scenario fall between the regions of novae and SNe in the peak visible brightness versus event timescale observational diagrams (e.g., Kulkarni & Kasliwal 2009; Rau et al. 2009). This region contains more objects that are termed ILOTs. With the accretion scenario at hand, it may be instructive to plot a diagram based on the total energy of the transient events instead of their luminosity.

Part of the energy liberated by accretion is not radiated, but rather channeled to other processes, such as lifting envelope material. Energy radiated outside the optical bands is usually not observed. Also, the kinetic energy of the ejecta is hard to estimate due to model-dependent mass loss values, and a somewhat wide range of measured velocities. Therefore, there is no unique way to define the total energy of the event. Nevertheless, we define the total “observed” energy as the bolometric energy (estimated from the optical measurements) emitted during the outburst, plus the ejecta kinetic energy. The duration of the outburst is formally defined as the time by which the event brightness (in the V band) drops by 2 mag. In Figure 3, this total energy is plotted as a function of the event timescale for several ILOTs and compared to the values for SNe and classical novae. Table 1 presents the data used to plot Figure 3 with references.

SNe Ib/c, and II are grouped as Exploding Massive Stars (this includes hypernovae). Note that for classical novae we plot both the observed range from Della Valle & Livio (1995, the two wavy green lines) and the model values from Yaron et al. (2005) (red dots). The nova model values include the kinetic energy of the ejecta, but this is usually much smaller or at most equal to the radiated energy (Epelstain et al. 2007). A few models from Yaron et al. (2005) with extreme, unobserved, values of average velocity (>2500 km s\(^{-1}\)) and mass loss (>3 × 10\(^{-4}\) M\(_{\odot}\)) were not included in the plot.

It is evident that the locus of ILOTs in Figure 3 is more separated from that of classical novae than in the luminosity versus timescale plane (e.g., Kulkarni & Kasliwal 2009; Rau et al. 2009). The difference from SNe is also clearer, even though less striking. The use of energy instead of luminosity apparently highlights the physical mechanisms underlying the various transient classes. The region of the diagram populated by the supposedly accretion-powered events is tentatively marked with a colored strip. We take the appearance of this sequence as further evidence for a common physical mechanism behind these transients (although not all ILOTs are necessarily powered by accretion). As for P Cygni, which is not yet proven to be a binary system, we predict that a binary companion exists in that system, or that a common envelope occurred in the recent past.

To summarize, we suggest that most (but probably not all) of the ILOTs are accretion-powered events. Based on the common energy source they should be grouped in one class together with stellar merger tidal, disruption flares, and large eruptions in LBV binary systems. The shape of the light curve (Figure 1), related to the accretion as the energy source, is an important distinguishing feature of many systems in this group.
We also predict that because of the geometry of the accretion process the ejecta in this class of transients should systematically exhibit bipolar structure, as suggested by Soker (2004). We note that in some single star models circumstellar material can also possess bipolar structure (e.g., Smith 2009).

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