Intermediate Luminosity Optical Transients (ILOTs) from Merging Giants

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Abstract

We suggest and study the formation of intermediate luminosity optical transients (ILOTs) from the merger of two cool giant stars. For the two stars to merge when both are in their giant phases, they must have close masses at their zero-age main sequence, and the orbital separation must be in the right range. After the two giants merge, the two cores spiral in toward each other within a common envelope. We study the energy sources of radiation in this process, which includes the ejection of mass that powers radiation by both recombination and by collision with previously ejected mass. This process includes no jets, unlike many other types of ILOTs, hence the event will not form a bipolar nebula. Using the stellar evolution numerical code MESA for two binary systems with stellar masses of (15M\textsubscript{\odot}, 15.75M\textsubscript{\odot}) and (31M\textsubscript{\odot}, 31.5M\textsubscript{\odot}), we find that the merger of the two cores releases gravitational energy that marginally ejects the entire common envelope. This implies that in many cases the two cores merge, i.e., a fatal common envelope evolution, leading to a somewhat more luminous ILOT. A typical ILOT from the merger of two cool giant stars lasts for several months to several years, and has a typical average luminosity of \(L_{\text{ILOT}} \approx 10^6(M_{\text{CE}}/10M_\odot)L_\odot\), where \(M_{\text{CE}}\) is the ejected common envelope mass. The merger-driven massive outflow forms dust, hence leading to a very red ILOT, possibly even infrared luminous and undetectable in the visible.

\textit{Unified Astronomy Thesaurus concepts: Red supergiant stars (1375); Transient sources (1851); Stellar jets (1607); Close binary stars (254); Variable stars (1761)}

1. Introduction

Observations over the years have filled-up the domain of eruptive stars with peak luminosities above typical nova luminosities, but below typical supernova luminosities (e.g., Mould et al. 1990; Rau et al. 2007; Ofek et al. 2008; Botticella et al. 2009; Kulkarni & Kasliwal 2009; Prieto et al. 2009; Smith et al. 2009; Mason et al. 2010; Pastorello et al. 2010, 2018; Kasliwal 2011, 2013; Tylenda et al. 2013; Blagorodnova et al. 2017; Kaminski et al. 2018; Boian & Groh 2019). Thermonuclear outbursts and explosions power some of these, while gravitational energy powers others.

We will refer to transient events that are not supernovae (SNe) and that are powered by gravitational energy as intermediate luminosity optical transients (ILOTs; Berger et al. 2009; Kashi & Soker 2016; Muthukrishna et al. 2019). The heterogeneous class of ILOTs contains several subclasses. Kashi & Soker (2016) list the following classes.\textsuperscript{3} (i) Intermediate-luminous red transients (RTs). These are ILOTs of evolved stars, such as asymptotic giant branch (AGB) or extreme AGB (ExAGB) stars, such as SN 2008S (Arbour & Boles 2008) and NGC 300 OT2008-1 (Monard 2008; Bond et al. 2009). (ii) Giant eruptions of luminous blue variables (LBV), such as the Great Eruption of \(\eta\) Carinae in the years 1837–1856, and SN Impostors, such as the pre-explosion outbursts of SN 2009ip. (iii) Luminous red novae (LRN) or RTs or merger-bursts, such as V838 Mon and V1309 Sco. A full merger of two stars powers these events. Merger events of stars with substellar objects also belong to this class.

We note that there are alternative names to ILOTs in use. Jencson et al. (2019), as an example, do not use the name ILOT, but rather use intermediate luminosity RTs for explosions of ExAGB stars, and LRN for merging stars. Pastorello et al. (2019) do use the term ILOTs, but their division of ILOTs to different classes is different than that of Kashi & Soker (2016), which we use here.

We take the view that binary interaction powers ILOTs (e.g., Kashi et al. 2010; Kashi & Soker 2010; Soker & Kashi 2013; Mcley & Soker 2014; Pejcha et al. 2016, 2019; MacLeod et al. 2018; Michaelis et al. 2018; Pastorello et al. 2019; see Soker 2016 for a review). The merger of two stars to form an ILOT can result in the destruction of one of them or the formation of a common envelope. Soker & Tylenda (2003) and Tylenda & Soker (2006) suggested that the ILOT V838 Mon resulted from the merger of two stars where the low-mass star had been destroyed onto the more massive star. On the other hand, Retter & Marom (2003) and Retter et al. (2006) suggested an alternative model that is based on a common envelope evolution (CEE) where planets entered the envelope of the stellar progenitor of V838 Mon. Other researchers followed and suggested the CEE scenario, but with stellar companions, to explain other ILOTs, e.g., OGLE-2002-BLG-360 (Tylenda et al. 2013), V1309 Sco (Tylenda et al. 2011; Ivanova et al. 2013a; Nandez et al. 2014; Kamiński et al. 2015), and M31LRN 2015 (MacLeod et al. 2017).

In the scenarios listed above, the basic energy source is the high accretion rate of mass, either by a mass transfer process or by the destruction of one star. In many cases, the mass transfer involves the launching of jets. This powering source is termed the high-accretion-powered ILOTs (HAPI) model (Kashi & Soker 2016). In the present paper, we study a specific type of CEE ILOT, where two giant stars merge to form a CEE. In some cases, the two cores of the giant stars merge as well.

There are works that mention the process of the merger of a companion with the core of a giant, but these concentrate on a companion that is a substellar object (e.g., Harpaz & Soker 1994; Siess & Livio 1999); a main-sequence star, e.g., as in the progenitor of SN 1987A (e.g., Chevalier & Soker 1989; Podsiadlowski et al. 1990; Menon & Heger 2017; Menon et al. 2019; Urushibata et al. 2018) or unusual nucleosynthesis.

\textsuperscript{3} See http://physics.technion.ac.il/~ILOT/ for an updated list.
(Ivanova & Podsiadlowski 2002); a white dwarf (as in the progenitor of SNe Ia in the core degenerate scenario; e.g., Ilkov & Soker 2012); or a neutron star (as in common envelope jet supernovae; Soker & Gilkis 2018; Soker et al. 2019). Soker (2019) summarizes these different cases and their properties.

In this paper we study the a rare type of ILOTs where the two merging stars are giants and the two cores merge. There are other studies of the merger of two giant stars that examine other aspects. Vigna-Gómez et al. (2018), for example, examine the formation of double neutron star systems. They do not consider the merger of the two cores and the formation of an ILOT. Vigna-Gómez et al. (2019) consider the merger of two massive stars (>30M_☉) after they have both developed a hydrogen-exhausted core, as a route to form progenitors of pair instability supernovae. They did not study the ILOT that might result from the merger itself. Therefore, our present study contains novel aspects of merging giants.

In Section 2 we present the motivation to study the merger of two cores. In Section 3 we estimate the luminosity and the duration of bright ILOTs that might result from the merger of two massive giants, and in Section 4 we examine the properties of two red supergiants binary systems that might merge. We summarize our results in Section 5.

2. The Case for Merging Giant Stars

From stellar evolution calculations (e.g., Ekström et al. 2012; Choi et al. 2016), we find the following relation for the life span of a star of mass M_i on the main sequence:

\[
\log \left( \frac{\tau_{\text{MS}}}{10^{10} \text{ yr}} \right) \simeq 0.75(\log M_i)^2 - 3.3 \log M_i,
\]

where mass is in solar units. From that relation, we find

\[
\frac{d \log \tau_{\text{MS}}}{d \log M_i} \simeq 1.5 \log M_i - 3.3.
\]

The total duration of the giant phases is \( \tau_i \simeq 0.1 \tau_{\text{MS}} \). The condition for the two stellar giant phases to overlap reads

\[
\frac{\Delta M}{M} \lesssim 0.1 \left( \frac{d \log \tau_{\text{MS}}}{d \log M_i} \right)^{-1},
\]

where \( \Delta M = M_{1i} - M_{2i} \) is the difference between the initial masses of the two stars. For a solar mass star, this reads (\( \Delta M/M_i \)) \lesssim 0.03, while for two stars with \( M_i \approx 30M_\odot \), this reads (\( \Delta M/M_\odot \)) \lesssim 0.09. Considering that the fraction of binary massive stars is larger than that of low-mass stars (e.g., Moe & Di Stefano 2017), the merger rate of two massive giant stars relative to the total number of massive stars is significantly greater than that of two low-mass stars. In both cases, though, the merger rate of two giants is nonnegligible compared with the total merger rate at the specific mass range.

The chance of any two stars merging depends mainly on the orbital separation of the binary system being smaller than a critical value (≈few – 30 au, depending on masses and eccentricity), and on eccentricity (higher eccentricity increases the merger probability as periastron distance is shorter, hence tidal interaction is stronger). For the specific case we study here, time is critical also, as we want the giant phases of the two stars to overlap, and to make them merge during that overlapping time period.

The chance to merge as two giants is much greater before core helium exhaustion, as the giants spend a longer time during that phase (i.e., a larger overlapping giant phases time period). In particular for low-mass stars, the red giant branch lasts much longer than the AGB. We also note that rotation changes somewhat the evolution time. If the two stars have different rotation velocities, this can somewhat increase or decrease the allowed mass difference.

One big difference between the present case and that of a compact companion that enters the giant envelope, is that a giant companion cannot launch jets. Jets might help in removing the envelope (Shiber & Soker 2018). We consider, therefore, the case that the two cores spiral toward each other and reach a close distance, and even merge.

3. The CEE Luminosity

3.1. Photon-diffusion-dominated ILOT

We consider here the spiralling-in process before the two cores might merge inside the common envelope. At this phase, the system is basically composed of three components. The first is the extended-tenuous common envelope, which is the merger of the two envelopes; the second and third components are the cores of the two giants. The entire system rotates around the center of mass, but not as a solid body. Due to gravitational interaction of the two cores with the envelope, they spiral in toward each other, and their orbital period decreases.

The outer part of the envelope, outside the orbit of the two cores, cannot keep pace with the cores, and its angular velocity is lower. The two cores therefore transfer orbital angular momentum to the outer envelope and continue to spiral in toward each other. The key issue when two cores that burn hydrogen and/or helium on their outskirts is that they cannot accrete mass from the common envelope at a high rate. Their accretion rate is limited to the very slow rate of nuclear burning (the same as the core of a giant star accretes from its own envelope in single-star evolution). As the cores do not accrete mass, they do not launch jets which in some other cases of CEE might facilitate envelope removal (e.g., Shiber et al. 2019). This implies that there is no extra energy source of mass accretion onto the compact object.

Therefore, the energy that is available to remove the common envelope is only the orbital gravitational energy that the two spiralling-in cores release. Most of this orbital gravitational energy is channeled to remove the envelope and accelerate it to its terminal velocity. The recombination energy of the hydrogen and helium in the expanding envelope does not contribute much to envelope removal, as this energy is mainly radiated away and mostly adds to the luminosity of the system as we discuss below.

We emphasize that we expect no jets during the main CEE: namely, before the two cores merge. Therefore, the outflow from the ILOT will not be as asymmetrical as ILOTs that have jets. In the latter, the jets shape bipolar nebulae, such as some bipolar planetary nebulae that ILOTs might form, and the nebula of Eta Carinae (the Homunculus). Hence, we consider the following spherically symmetric treatment to be adequate for our purposes.

We first consider the case where a large fraction, but not all, of the common envelope is removed on a timescale shorter than the photon-diffusion time that we derive below. In Section 3.2 we discuss the opposite inequality.
Let a substantial fraction of the gas of the two merged envelopes (the common envelope), a mass of $M_{\text{CE}}$, leave the system during the first phase of the CEE with a terminal velocity of $v_t$. (The rest of the envelope is lost on a longer timescale, hence with a much lower luminosity.) This gas becomes transparent for radiation diffusion on a timescale of (e.g., see the discussion of the diffusion time for supernovae by Kasen & Woosley (2009))

$$t_{\text{diff}} \simeq \frac{\kappa M_{\text{CE}}}{4c R_{\text{diff}}},$$

where $\kappa$ is the opacity and $R_{\text{diff}} = t_{\text{diff}} v_t$. Substituting scaled values, we find

$$t_{\text{diff}} \simeq 4 \left( \frac{\kappa}{1 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/2} \times \left( \frac{M_{\text{CE}}}{10 M_\odot} \right)^{1/2} \left( \frac{v_t}{100 \text{ km s}^{-1}} \right)^{-1/2} \text{yr.}$$

If all the luminosity comes from recombination energy of solar composition, $E_{\text{rec}} = 3 \times 10^{46} (M_{\text{CE}}/M_\odot) \text{ erg}$, we find the average recombination luminosity to be

$$L_{\text{rec,diff}} \approx \frac{E_{\text{rec}}}{t_{\text{diff}}} \simeq 6 \times 10^{46} \left( \frac{\kappa}{1 \text{ cm}^2 \text{ g}^{-1}} \right)^{-1/2} \times \left( \frac{M_{\text{CE}}}{10 M_\odot} \right)^{1/2} \left( \frac{v_t}{100 \text{ km s}^{-1}} \right)^{1/2} L_\odot.$$

For the same values the kinetic energy is

$$E_{\text{kin}} = 10^{48} \left( \frac{M_{\text{CE}}}{10 M_\odot} \right) \left( \frac{v_t}{100 \text{ km s}^{-1}} \right)^2 \text{ erg} \approx 3.4 E_{\text{rec}}.$$

This recombination luminosity might be observed as a brightness that lasts for about 5 months to several years. We expect, though, that the ejected mass will collide with previously ejected mass, or that the late CEE phases that is ejected at higher velocities collides with earlier ejected mass. The collision transfers kinetic energy to luminosity. Overall, we expect to have a transient event, an ILOT, that lasts for several months to several years, with a luminosity of $L_{\text{ILOT}} \approx \text{few} \times 10^3 L_\odot \sim \text{few} \times 10^6 L_\odot \approx 10^{39} - 10^{40} \text{ erg s}^{-1}$.

At an age of a few months to a few years, the outer radius of the gas is at $\approx 10^{14} - 10^{15} \text{ cm}$, and for the above luminosity values the blackbody temperature is $T_{\text{bb,diff}} \approx 3000 \text{ K}$. This is a RT, as are most ILOTs, and it might even become a bright infrared ILOT. In a recent study, Jencson et al. (2019) report the observations of infrared bright ILOTs (although they do not term them ILOTs). We raise the possibility that some infrared bright ILOTs might be the merger processes of two giant stars.

### 3.2. Slow ILOT

In the initial spiralling-in phase of a CEE, the so called plunge-in phase, the companion spirals deep into the envelope within about the dynamical scale of the common envelope (Ivanova et al. 2013b for a review). During that phase, the two spiralling-in cores in our case might remove a large portion of the common envelope. For the two cores of the two giants, the plunge-in time is $t_{\text{pl}} \approx \text{several } \times \text{ yr}$. This timescale is of the order of the diffusion timescale $t_{\text{diff}}$ as given by Equation (5). This implies that we might have two basic situations: namely, of $t_{\text{pl}} \approx t_{\text{diff}}$ and $t_{\text{pl}} \gtrsim t_{\text{diff}}$. For cases where the merging process is shorter than the diffusion time, $t_{\text{pl}} \lesssim t_{\text{diff}}$ the analysis of Section 3.1 holds.

When the merging processes is longer than the diffusion time, i.e., $t_{\text{pl}} \gtrsim t_{\text{diff}}$, the ILOT duration is dictated by the merging processes rather than by the photon-diffusion time. This might change the observed event by allowing dust formation and by converting more kinetic energy to radiation.

Consider a volume of gas that left the star at time $t'$. At time $t > t' + t_{\text{diff}}$, this volume of gas had time to cool by radiation (and it further cools with adiabatic expansion). Dust forms now in this outflowing gas. Consider then a small ejected mass from the common envelope, say $M_{\text{out}} \approx 0.1-1 M_\odot$, that flows out at a velocity of $v_t \approx 100 \text{ km s}^{-1}$. It cools within a year (Equation (5)). Therefore, within a few years we might have a shell of mass of $\approx 1 M_\odot$ of few $\times M_\odot$ at a distance of $r_d \approx 10^{15} \text{ cm}$. During these several years, the average luminosity of the recombining envelope in this case of a slow spiralling-in process is (for parameters we took) $L_{\text{rec,slow}} < L_{\text{rec,diff}}$, where $L_{\text{rec,diff}} \approx \text{few } \times 10^3 - 10^5 L_\odot$ by Equation (6). However, a new process might contribute to the luminosity.

When the spiralling-in process continues, it might eject mass at higher velocities. As the newly ejected mass collides with previously ejected mass, it might convert some of the kinetic energy to radiation. As the kinetic energy is only few times that of recombination (Equation (7)), this process will at most double the luminosity from recombination. We term this factor of increasing radiated energy by the collision of the expanding gas with itself, $\eta$. Overall, if we take the available energy to be twice the recombination energy, i.e., $\eta = 2$, the luminosity in the case where $t_{\text{pl}} > t_{\text{diff}}$ is

$$L_{\text{slow}} \approx 5 \times 10^4 \left( \frac{\eta}{2} \right) \left( \frac{M_{\text{CE}}}{10 M_\odot} \right) \left( \frac{t_{\text{pl}}}{10 \text{ yr}} \right)^{-1} L_\odot.$$

We now need to consider the dusty expanding shell that once was the common envelope. Over a time period of $t_{\text{pl}} \approx 5-50 \text{ yr}$, the expanding envelope reaches a distance of $r_d \approx 3 \times 10^3 (v_t/100 \text{ km s}^{-1}) (t_{\text{pl}}/10 \text{ yr}) \text{ cm}$. The optical depth of this dusty shell is

$$T_{\text{d}} \approx 500 \left( \frac{\kappa_{\text{d}}}{3 \text{ cm}^2 \text{ g}^{-1}} \right) \left( \frac{M_{\text{CE}}}{10 M_\odot} \right) \left( \frac{v_t}{100 \text{ km s}^{-1}} \right)^{-2} \left( \frac{t_{\text{pl}}}{10 \text{ yr}} \right)^{-2} L_\odot.$$

The dust opacity is as in dense winds from giants, $\kappa_{\text{d}} = 1-10 \text{ cm}^2 \text{ g}^{-1}$ (e.g., Höfner et al. 2003).

The dusty shell will obscure the ILOT and the remnant of the merger for tens to hundreds of years, with the photosphere at $\approx r_d$. For the average luminosity as given by Equation (8) the blackbody temperature of the photosphere of the dusty shell for the parameters as we use here, and for the relevant time period of $\approx 5-50 \text{ yr}$ is $T_{\text{bb,slow}} \approx 700 (t_{\text{pl}}/10 \text{ yr})^{-3/2} \text{K}$. This slow ILOT lasts for a longer time than the photon-diffusion-dominated ILOT that we studied in Section 3.1; it is fainter, its radius is larger, hence it is much redder. During the relevant time, depending on the duration of the plunge-in phase $t_{\text{pl}}$, in this case the ILOT is a bright source in the IR band of about 2–10 $\mu\text{m}$, rather than in the red or in the very near-IR as the photon-diffusion-dominated ILOT.
3.3. Merger of the Two Cores

After most of the envelope, but not all, leaves the binary cores the two cores might spiral in further due to several effects: (1) some mass that is left around the binary system (e.g., Kashi & Soker 2011; Chen & Podsiadlowski 2017), (2) tidal interaction between the two cores, and (3) further evolution that causes the cores to expand.

If the two cores merge, they liberate a gravitational energy of

\[ E_{\text{merg}} \simeq 0.5 \frac{GM_{\text{core,1}}M_{\text{core,2}}}{R_{\text{core,1}} + R_{\text{core,2}}} = 4.7 \times 10^{49} \times \left( \frac{M_{\text{core,1}}M_{\text{core,2}}}{(5M_\odot)^2} \right) \left( \frac{R_{\text{core,1}} + R_{\text{core,2}}}{100 \text{ km s}^{-1}} \right)^{-1} \text{erg.} \tag{10} \]

A large fraction of the merger energy goes to eject the rest of the common envelope and to bring it to its terminal velocity as it escapes the system. If some of the envelope stays bound, it absorbs energy and inflates. After one core is destroyed onto the other core, a large fraction of the merger energy goes to uplift the destructed core mass to form an envelope around the more massive core. Only a small fraction of the total merger energy adds up to the radiated energy. However, the merger process is rapid (timescales of hours to days), and might power the ejected mass in a timescale of weeks to many years after CEE as the merger products reaches thermal equilibrium. Furthermore, fast ejected mass can catch up with previously ejected mass and increase the luminosity as kinetic energy is channeled to radiation.

4. Examining Two Close-mass Binaries

4.1. Numerical Setup

We use the MESA code (Modules for Experiments in Stellar Astrophysics, version 10398; Paxton et al. 2011, 2013, 2015, 2018) to study the parameter range leading to the spiraling-in process. We examine some properties of two binary systems. One binary system with zero-age main sequence (ZAMS) masses of \( M_{\text{ZAMS,1}} = 15.75 M_\odot \) and \( M_{\text{ZAMS,2}} = 15 M_\odot \), and a second binary system with \( M_{\text{ZAMS,1}} = 31.5 M_\odot \) and \( M_{\text{ZAMS,2}} = 30 M_\odot \). Both systems are with a ZAMS metallicity of \( Z = 0.019 \) and an equatorial velocity of \( v_{\text{rot,1}} = 100 \text{ km s}^{-1} \). Stellar winds are taken as Vink et al. (2001) for \( T_{\text{eff}} = 7 \times 10^{4} \text{ K} \) and de Jager et al. (1988) for \( T_{\text{eff}} = 10,000 \text{ K} \).

4.2. Stellar Structures

We present the evolution of the radii and core masses of these two binary systems at late evolutionary phases in Figures 1 and 2, respectively. In the first binary, the primary explains its rapid expansion 13 ± 10^7 yr before the secondary star does, and in the second binary system the time difference is 2.2 ± 10^7 yr. We assume that the orbital separation between the two stars is such that the two giants merge when the secondary experiences its large expansion. We discuss later the case of mass transfer from the primary to the secondary star before the secondary expands.

In Figures 3 and 4, we present the stellar models of the stars in the two binary systems we study here when the lower-mass companion experiences its large and rapid expansion. We assume that merger occurs during this phase.

\[ \frac{E_{\text{merg}}}{E_{\text{bind, envs}}} \approx 1.5 \left( \frac{R_{\text{core,1}} + R_{\text{core,2}}}{0.7 R_\odot} \right) \left[ \frac{M_{\text{core,1}}M_{\text{core,2}}}{(4M_\odot)^2} \right] \left( \frac{E_{\text{bind,1}} + E_{\text{bind,2}}}{3 \times 10^{49} \text{ erg}} \right)^{-1}. \tag{11} \]

This is the typical ratio for the \( M_{\text{ZAMS,1}} = 15.75 M_\odot \) and \( M_{\text{ZAMS,2}} = 15 M_\odot \) binary system (using the data from Table 2).
For the $M_{\text{ZAMS,1}} = 31.5M_\odot$ and $M_{\text{ZAMS,2}} = 30M_\odot$ binary system this ratio is 0.8 (using the data from Table 2). As the efficiency of channeling the gravitational energy of the merging cores to envelope removal is $\alpha_{\text{CE}} < 1$, when the cores merge there is still bound envelope, but a large fraction of the envelope is leaving the system, and a fraction might form an extended envelope.

4.3. The ILOT Properties

Using these results and Equation (10), we can crudely estimate the total radiated energy in the ILOT. Very crudely, in many ILOTs the typical ratio of radiated to kinetic energy is $E_{\text{rad}} \approx 0.1E_{\text{kin}}$ (e.g., Kashi & Soker 2010). We take about half of the envelope to be ejected at the escape speed.
Properties of the Giant Primary Star and the Pre-giant Secondary Star When the More Massive (primary) Star Finishes Its Rapid Expansion

| M_{ZAMS} (M_{\odot}) | \text{L} (10^{3} L_{\odot}) | T_{eff} (10^{3} K) | M_{s} (M_{\odot}) | M_{core} (M_{\odot}) | R_{s} (R_{\odot}) | R_{core} (R_{\odot}) | E_{\text{bind}} (10^{49} \text{erg}) |
|---------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 15                  | 3.89            | 24.82           | 14.8            | ...             | 11              | ...             | ...             |
| 15.75               | 6.10            | 3.32            | 15.2            | 3.9             | 745             | 0.35            | 1.3             |
| 30                  | 20.31           | 31.13           | 28.3            | ...             | 15              | ...             | ...             |
| 31                  | 33.43           | 5.95            | 28.0            | 11.1            | 546             | 0.61            | 12.7            |

Note. At this phase, the core of the secondary star is not relevant for our study, and we do not present its properties.

Properties of the Giant Stars When the Lower-mass Star in the Binary System Finishes Its Rapid Expansion

| M_{ZAMS} (M_{\odot}) | \text{L} (10^{3} L_{\odot}) | T_{eff} (10^{3} K) | M_{s} (M_{\odot}) | M_{core} (M_{\odot}) | R_{s} (R_{\odot}) | R_{core} (R_{\odot}) | E_{\text{bind}} (10^{49} \text{erg}) |
|---------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 15                  | 6.83            | 3.26            | 14.5            | 3.73            | 821             | 0.33            | 1.1             |
| 15.75               | 4.77            | 3.46            | 14.1            | 4.69            | 610             | 0.38            | 1.67            |
| 30                  | 31.11           | 8.21            | 27.0            | 10.37           | 276             | 0.59            | 12.73           |
| 31                  | 32.91           | 5.89            | 24.1            | 11.58           | 552             | 0.64            | 10.28           |

Note. We assume that in many cases merger takes place during this time (see Figures 1 and 2 for the models).

V_{\text{eject}} \approx 100 \text{ km s}^{-1}, and the radiation to carry a fraction of \chi \approx 0.1 of that energy. For an ejected mass of M_{\text{eject}} = 10 M_{\odot}, we find E_{\text{rad}} \approx 10^{47} \text{ erg}. This is the general median value of the radiated energy of ILOTs (e.g., Kashii 2018).

The photon-diffusion time from an ejected mass of M_{\text{eject}} = 10 M_{\odot}, expanding at V_{\text{eject}} \approx 100 \text{ km s}^{-1}, and with an average opacity of \kappa \approx 1 \text{ cm}^{2} \text{ g}^{-1}, is about few years. This can be of the order of the merger process from an orbital separation of several astronomical units. Overall, the merger of the two cores can have the properties of an ILOT lasting a few years and radiating with a luminosity of \text{L} \approx \text{few} \times 10^{5} L_{\odot} \approx 10^{6} L_{\odot}. This is about equal to the luminosity from the recombination as given in Equation (6). Adding together recombination and core merger, the ILOT of this fatal CEE lasts for about months to several years (or even up to a few tens of years; see Section 3.2) with a luminosity of \text{L}_{\text{rad,tot}} \approx 10^{6} L_{\odot}.

These properties make a brighter and longer ILOT than OGLE-2002-BLG-360, whose progenitor was a lower-mass star at earlier evolutionary stages (Tylenda et al. 2013). Hence, this was not a merger of two giants. The common property of that merger and the scenario we study here is that they are both binary systems experiencing a long CEE that ended with a merger of the core with a compact companion, i.e., a fatal CEE. This was already suggested by Tylenda et al. (2013). They also find that this system contains a massive dusty outflow.

The ILOT properties we estimate here are more like those of the LBV star R71 in the Large Magellanic Cloud (Mehner et al. 2013), but the progenitor of R71 had a radius of only \approx 100 R_{\odot}. (Mehner et al. 2017). The merger of two giants we consider here will be redder, and might even be detected only in the infrared.

We could not find an ILOT that fits our expectation from two merging giants. This is not in contradiction with our expectation, as these events are very rare (Soker 2019).

4.4. Mass Transfer

The initial orbital separation can be smaller than the maximum radius that the initial more massive (primary) achieves. In that case, the more massive star transfers mass to the companion as it expands. Vigna-Gómez et al. (2019) showed that even in this case the two stars can merge after they both have an hydrogen-exhausted core. Because the two stars are of about equal masses, the secondary star brings the envelope of the expanding primary giant to synchronization, i.e., between the spin and orbital period. This makes the tidal forces very small, and the secondary star does not spiral in into the envelope of the giant star. Instead, the primary star transfers mass to the secondary star, and after the secondary becomes the more massive star, further mass transfer increases somewhat the orbital separation. The system will merge only after the secondary star becomes a giant.

The mass transfer from the primary to the secondary does not change much our conclusion for the present paper, because by the time the primary star suffers its rapid expansion its core is already 85\% or more of its final mass (Figures 1 and 2). When the secondary expands and the primary core spirals inside its envelope, we have a CEE with core masses about the same as in cases without a mass transfer, and it does not matter much where the common envelope comes from. The energy that the two merging stars and spiralling-in cores release and the timescale of the process are about the same as without mass transfer. Despite our expectation that the implication of mass transfer for the ILOT will be small, there is a need for a more detailed simulation of evolution that includes mass transfer.

4.5. Rate of Events

Vigna-Gómez et al. (2019) study the merger of two post-main-sequence very massive stars, i.e., with ZAMS mass of \gtrsim 45 M_{\odot}, as they are looking for a merger product that might lead to pair instability supernovae. They estimate that between 13\% and 47\% of this type of close-mass binaries are in the right orbital separation for them to merge, while having each a helium core. They further estimate that the merger rate of such two very massive stars that might lead to pair instability supernovae is in the range of about \text{10}^{-3} - 0.003 times the rate of core collapse supernovae (CCSNe). Because we deal here with lower-mass stars, the rate of ILOTs of two merging giants is greater. Soker (2019) crudely estimates that the rate of merger of two giants that lead to a CCSN is \approx 0.01 the rate of all CCSNe.

To crudely estimate the number of ILOTs coming from merging giants, we take the following stellar binary properties from (Zapartas et al. 2017), who also discuss some uncertainties. The initial mass function \text{dn} \propto M^{-2.3} dM_{*}, an orbital separation that is flat in log scale in the period range of 0.15 < \log(P/\text{day}) < 3.5, a mass ratio in binary stars that is flat in the range 0.1 < \text{M}_{1}/\text{M}_{2} < 1, i.e., 0 < \Delta M/\text{M}_{*} < \Delta_{m} = 0.9, and a binary fraction in the above period range of about \text{f}_{\text{b}} \approx 50\%. We crudely approximate Equation (3) for the condition of overlapping giant phases as \text{\Delta M/\text{M}_{*}} \lesssim 0.03 + 0.002M_{*} \equiv \Delta_{OG}, where mass is in solar units. The fraction of systems that are binary systems where both stellar components have overlapping giant phases is then \text{f}_{\text{OG,al}} \approx \left( \int \text{d}N \right)^{-1} \int \left( \Delta_{OG}/\Delta_{m} \right) \text{d}N \approx 0.02, where the integration is from \text{M}_{1} = 1 M_{\odot} to large masses, and we substituted the above values for the different quantities in the integration. \text{f}_{\text{OG,al}} is the approximate fraction of all binary systems that have
overlapping giants phases, whether they explode as CCSNe or form planetary nebulae, and whether or not they merge.

The large uncertainty regarding the merging probability is in the orbital separation that might lead the two stars to merge while both are giants. We very crudely take this range to be a factor of 2 in orbital separation, e.g., the initial orbital separation should be $a_{\text{min}} = 2 \, \text{au} \lesssim a \lesssim 4 \, \text{au} = a_{\text{max}}$. This gives a range of a factor of $2^{3/2}$ in orbital period, i.e., $\log(P_{\text{max}}/P_{\text{min}}) = \log 2^{3/2} = 0.45$, and so the fraction of binary systems in the right orbital range is $f_0 \approx [0.45/(3.5 - 0.15)] = 0.13$.

Therefore, the fraction of binary systems that form ILOTs by the merger of two giants is very crudely $f_{0, \text{ILOT}} \approx f_0 \log_{\text{all}} \approx 0.003$. This is the fraction from all systems (including single stars) with $M > 1M_{\odot}$. As the number of CCSNe is $f_{\text{CCSNe}} \approx 0.1$, of these systems, we find the ratio of ILOTs from the merger of two giants to the number of CCSNe to be $f_{0, \text{ILOT}}/f_{\text{CCSNe}} \approx 0.03$.

The contribution from binaries that start with a primary stellar mass of $>8M_{\odot}$ out of all giant binary mergers is $\approx 12\%$ of the $f_{0, \text{ILOT}}$. However, the merger of two stars of masses $>4M_{\odot}$ might lead to a massive core that explodes also as a CCSNe. The contribution from binary systems that start with a primary stellar mass of $>4M_{\odot}$ out of all giant binary mergers is $\approx 25\%$, or a fraction of $\approx 0.0075$ of the number of CCSNe. This is close to the value of $\approx 0.01$ that Soker (2019) estimated for the fraction of ILOTs from the merger of giants that will explode as CCSNe out of all CCSNe (keeping in mind the large uncertainties).

Overall, we crudely estimate the event rate of ILOTs coming from two merging giants to be $\approx 0.03$ times the event rate of CCSNe, but the uncertainties are large and the number can be in the range of $0.01-0.05$. The uncertainties come from uncertainties in the mass transfer physics and tidal interaction of two evolved stars, as well as from the initial parameters of binary systems.

5. Summary

We examined the possible observational signature of the merger of two giant stars in a binary system, which we suggest leads to a new type of a luminous transient (ILOT). The main properties and evolutionary phases of this novel type of ILOTs are as follows.

The orbital separation between the two stars is such that they enter a CEE where the two cores spiral in toward each other, and eject a large fraction of the common envelope, or even all of it. In cases where the two cores eject the entire envelope before they merge, they might survive. For the two stars to simultaneously be in their giant phases, the two stars must have close masses on their ZAMS (Section 2; Equation (3)). If the two cores do not merge they might end up as two white dwarfs, or two neutron stars. In both cases, a later merger is possible. We did not study these later evolutionary phases here.

In cases where the two cores do not merge, there are two energy sources to power the radiation of the ILOT. The first is the recombination energy of the ejected envelope. Either the photon-diffusion time determines the duration of the ILOT (Equation (5); Section 3.1) leading to a luminosity of $\approx 10^8L_{\odot}$ depending on the envelope mass (Equation (6)), or the rapid spiralling-in phase determines the duration of the ILOT (Section 3.2). The other energy source is the gravitational energy of the spiralling-in cores that accelerates the outflowing envelope (Equation (7)), even to a full merger of the cores (Section 3.3). If fast outflowing gas collides with earlier ejected slower envelope gas, the collision transfers kinetic energy to thermal energy and radiation (Section 3.2).

Using the stellar evolution numerical code MESA, we evolved stars of two binary systems as shown in Figures 1–4. In this study, we evolved each of the stars as a single star. The next step will be to conduct a thorough study that includes the evolution of the two stars as a binary system, including tidal forces and mass transfer, e.g., by using the MESA binary code. This type of calculations has several free parameters and deserves its own study. Although we have evolved only massive stars that end as CCSNe, the merger of two giants can take place in stars as low as $\approx 1M_{\odot}$.

From the properties of the stars, we found that the merger of the two cores releases gravitational energy that marginally ejects the entire envelope (Equation (11)). This implies that in many cases the two cores merge, i.e., a fatal CEE, leading to a more massive core, which, in cases of massive stars, later explodes as a CCSN (Soker 2019). The merger of the two cores releases an amount of gravitational energy much greater than that of the recombination energy. However, most of this energy goes to unbind the envelope and accelerate it, as well as to inflate some of the mass of the destroyed core. The energy of the merging cores does not add much to the radiation energy.

The merger of two giant stars is different than that of a giant with a main-sequence star in one important aspect. While a compact companion, such as a main-sequence or a neutron star, can accrete mass from the giant envelope inside or outside the envelope (e.g., Shiber et al. 2019) and launch jets, the merger of two giants involves no jets, at least until the two cores merge. The merger of the two cores can launch jets. The energy that such jets carry is part of the energy of the cores merger (Equation (10)). Thejets can facilitate mass removal and power a brighter ILOT (e.g., Soker & Kashi 2016). The descendant nebula that the outflowing envelope forms is bipolar as the jets inflate two (or more if the jets precess) opposite bubbles. The merging two giants of the present study are not expected to form a bipolar nebula. They most likely form an elliptical nebula because the merger process ejects more mass in the equatorial plane.

The lack of jets, which implies that the outflow from the merger process of two giants does not deviate by a large degree from being spherically symmetric, justifies our usage of spherically symmetric photon-diffusion treatment (Section 3).

Broadly speaking, the outcome of the merger of two giant stars is a transient event, an ILOT, that lasts for several months to several years, with a luminosity of $L_{\text{ILOT}} \approx \text{few} \times 10^5L_{\odot}$–few $\times 10^6L_{\odot} \approx 10^{39}–10^{40}$ erg s$^{-1}$, for a common envelope mass of $\approx 10M_{\odot}$. The radiated energy scales more or less linearly with the common envelope mass. Due to high mass-loss rate and massive outflow, we expect dust formation. The ILOT might be very red, or even infrared bright and undetectable in the visible. Jencson et al. (2019) reported recently the observations of such infrared luminous transients, although most of these transients are likely to be infrared bright and visibly hidden CCSNe.

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