On the Response of Massive Main Sequence Stars to Mass Accretion and Outflow at High Rates postprint

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Abstract

With a one-dimensional stellar evolution model, we find that massive main sequence stars can accrete mass at very high mass accretion rates without expanding much if they lose a significant fraction of this mass from their outer layers simultaneously with mass accretion. We assume the accretion process is via an accretion disk that launches powerful jets from its inner zones. These jets remove the outer high-entropy layers of the mass-accreting star. This process operates in a negative feedback cycle, as the jets remove more envelope mass when the star expands. With the one-dimensional model, we mimic the mass removal by jets by alternating mass addition and mass removal phases. For the simulated models of 30M and 60M , the star does not expand much if we remove more than about half of the added mass in not-too-short episodes. This holds even if we deposit the energy the jets do not carry into the envelope. As the star does not expand much, its gravitational potential well stays deep, and the jets are energetic. These results are relevant to bright transient events of binary systems powered by accretion and the launching of jets, e.g., intermediate luminosity optical transients, including some luminous red novae, the grazing envelope evolution, and the 1837–1856 Great Eruption of Eta Carinae.

Full Text

Preamble

On the Response of Massive Main Sequence Stars to Mass Accretion and Outflow at High Rates

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Abstract

Using a one-dimensional stellar evolution model, we find that massive main sequence stars can accrete mass at very high rates without significant expansion if they simultaneously lose a substantial fraction of this mass from their outer layers. We assume the accretion occurs via an accretion disk that launches powerful jets from its inner zones, which remove the high-entropy outer layers of the mass-accreting star. This process operates in a negative feedback cycle, as the jets remove more envelope mass when the star expands. In our one-dimensional model, we mimic this mass removal by alternating phases of mass addition and mass removal. For simulated models of 30 M and 60 M , the star does not expand significantly if we remove more than about half of the added mass in not-too-short episodes, even when depositing the energy not carried by the jets into the envelope. Because the star does not expand much, its deep gravitational potential well is maintained and the jets remain energetic. These results are relevant to bright transient events in binary systems powered by accretion and jet launching, such as intermediate luminosity optical transients (including some luminous red novae), grazing envelope evolution, and the 1837–1856 Great Eruption of Carinae.

Key words: stars: jets -stars: massive -stars: mass-loss

1. Introduction

Intermediate luminosity optical transients (ILOTs; Berger et al. 2009; Kashi & Soker 2016a; Muthukrishna et al. 2019) constitute a heterogeneous group of transients with peak luminosities between those of classical novae and supernovae (e.g., Mould et al. 1990; Bond et al. 2003; Rau et al. 2007; Ofek et al. 2008; Mason et al. 2010; Kasliwal 2011; Kasliwal et al. 2012; Tylenda et al. 2013; Kamiński et al. 2018, 2020, 2021, 2023; Boian & Groh 2019; Cai et al. 2019, 2022a; Jencson et al. 2019; Kashi et al. 2019; Pastorello et al. 2019, 2021, 2023; Blagorodnova et al. 2020, 2021; Banerjee et al. 2020; Howitt et al. 2020; Jones 2020; Klencki et al. 2021; Stritzinger et al. 2020a, 2020b; Mobeen et al. 2021, 2024; Addison et al. 2022; Wadhwa et al. 2022; Karambelkar et al. 2023; Kaminski 2024).

No consensus exists on the naming of this heterogeneous transient group. We use the term ILOTs for all events powered by gravitational energy, whether triggered by merger processes or mass transfer. Other researchers employ alternative terms such as gap transients or intermediate luminosity red transients (e.g., Jencson et al. 2019; Cai et al. 2022b). Similarly, there is no consensus on sub-classifications (e.g., Kashi & Soker 2016a versus Pastorello et al. 2019 and Pastorello & Fraser 2019). We use the term luminous red novae (LRNe) for ILOTs powered by complete mergers that leave a single stellar remnant (Kashi

& Soker 2016a), as during the bright phase there is only one photosphere. We also include ILOTs from grazing envelope evolution of low-mass stars under LRNe, to distinguish them from eruptions of luminous blue variables.

Common envelope evolution (CEE) LRNe might be powered even by sub-stellar companions such as planets or brown dwarfs (e.g., Retter & Marom 2003; Metzger et al. 2012; Yamazaki et al. 2017; Kashi et al. 2019; Gurevich et al. 2022; De et al. 2023; O' Connor et al. 2023), although most events are thought to involve stellar companions (e.g., Tylenda et al. 2011, 2024; Ivanova et al. 2013; Nandez et al. 2014; Kamiński et al. 2015; Pejcha et al. 2016a, 2016b; Soker 2016; Blagorodnova et al. 2017; MacLeod et al. 2017, 2018; Segev et al. 2019; Howitt et al. 2020; MacLeod & Loeb 2020; Qian et al. 2020; Schrøder et al. 2020; Blagorodnova et al. 2021; Addison et al. 2022; Zhu et al. 2023).

In CEE LRNe, the primary energy sources might be the dynamical interaction of the companion inside the envelope of the engulfing star, the recombination of the ejected common envelope (e.g., Matsumoto & Metzger 2022), or accretion energy onto the more compact companion. The dynamical companion spirals in and ejects the envelope. Radiation can result from the collision of ejected envelope gas with itself in and near the equatorial plane (e.g., Pejcha et al. 2016a, 2016b, 2017; Metzger & Pejcha 2017; Hubová & Pejcha 2019), or from heating of the envelope by the spiraling-in companion. We adopt the view that the most efficient energy source to power a bright ILOT is the accretion energy of gas onto one of the two stars in a binary system, followed by jet launching (e.g., Soker 2020). The bipolar morphology of spatially resolved ILOTs (e.g., Kaminski 2024) suggests that most, or even all, bright ILOTs are powered by jets (e.g., Soker 2023, 2024). The companion accretes mass via an accretion disk and launches jets. When the companion is a neutron star or black hole, the event can mimic a core-collapse supernova (e.g., Soker & Gilkis 2018; Gilkis et al. 2019; Grichener & Soker 2019; Yalinewich & Matzner 2019; Schreier et al. 2021), and is termed a common envelope jet supernova rather than an LRN. In a CEE LRN (including an LRN in grazing envelope evolution; Soker 2016), the companion launches jets that collide with the common envelope or circumstellar material (CSM), transferring kinetic energy to thermal energy and radiation (e.g., Soker 2020; Soker & Kaplan 2021).

Luminous blue variables also constitute a group of ILOTs. The most famous example is the Great Eruption of Carinae, which ejected the bipolar Homunculus Nebula. The bipolar morphology of the Homunculus affirms that the Great Eruption was powered by jets (e.g., Soker 2001; Kashi & Soker 2010). The mass of the companion that accreted gas during the Great Eruption and launched jets is M_2 30–80 M (Kashi & Soker 2016b). Kashi & Soker (2010) estimated the average mass accretion rate onto the companion at 0.2 M yr^{-1}. We aim here to explain such high mass accretion rates without envelope expansion. Due to numerical difficulties, we will not simulate such high rates, but we will present the principles of the process. We examine the response of such a companion to mass accretion accompanied by mass removal that we attribute to jet launching.

The large momentum of some planetary nebulae and pre-planetary nebulae also suggests that the companion can accrete mass at high rates and launch powerful jets (e.g., Blackman & Lucchini 2014). Most companions to central stars of planetary nebulae are low-mass main sequence stars, for which Blackman & Lucchini (2014) found required accretion rates of 10^{-3} M yr^{-1} in these high-momentum planetary nebulae. The stars we simulate are two orders of magnitude more massive, so the accretion rate scales to 0.1 M yr^{-1}.

Another group of ILOTs includes pre-explosion outbursts, where a massive star experiences an outburst years to days before a core-collapse supernova explosion. The energy source of these outbursts can be accretion onto a companion (e.g., Mcley & Soker 2014; Danieli & Soker 2019; Tsuna et al. 2024; see Soker 2022 for a review). The compact companion accretes mass and launches jets that power the pre-explosion outburst when colliding with the CSM. We here consider cases where the compact object is a main sequence companion with mass M_2 1.5 M and therefore has a radiative envelope.

In this study, we examine one aspect of ILOTs powered by accretion onto massive main sequence stars with radiative envelopes, considering that the mass-accreting star launches jets. We do not simulate the entire accretion process via a disk that launches jets, but rather mimic this process using the one-dimensional stellar code Modules for Experiments in Stellar Astrophysics (MESA) (Section 2). We present our results in Section 3, and summarize our findings, compare them to Schürmann & Langer (2024), and discuss their implications for ILOTs and CEE with massive main sequence companions in Section 4.

2. Method

We used version 23.05.1 of the stellar evolution code MESA (Paxton et al. 2011, 2013, 2015, 2018, 2019; Jermyn et al. 2023) in its single-star mode. We evolved stellar models with initial zero-age main sequence (ZAMS) masses of M = 30 M and M = 60 M and metallicity Z = 0.019. We initiated mass accretion and energy deposition on the main sequence at ages of t_{MS} = 1.3 × 10^6 yr for M = 30 M models and t_{MS} = 0.9 × 10^6 yr for M = 60 M models. We based our simulations on the example of 20 M pre-main-sequence to core-collapse models; all other parameters remained at MESA' s default values.[1]

We mimicked the process by which jets remove envelope mass from the mass-accreting star using small alternating pulses of accretion and mass removal; each mass addition phase has duration Δt_p. MESA removes and adds mass with the same properties (e.g., entropy) as the outermost stellar shell. Each pulse has two parts. In the first part, we accrete mass and simultaneously deposit energy. In the second part of the pulse, we remove mass equal to a fraction _{MR} of the mass accreted in the first part. We deposit energy in the outer 10% of the stellar radius (by radius). We found (see Section 3) that if we remove only a small fraction of the accreted mass (_{MR}   0.33), the star inflates to a very large radius in many simulations, violating model assumptions such as hydrostatic equilibrium. In all simulations, we start the pulses on the early main sequence. The exact starting time has little influence on results because only the outer envelope participates in mass addition and removal, which changes little during the main sequence.

The amount of added energy is _{acc} = 0.25 of the accretion energy during the mass addition phase. In most simulations that achieve our goal of non-expansion (moderated in reality by feedback), the mass removed in a cycle is 2/3 of the added mass. The energy required to remove this mass equals the energy deposited during accretion. However, the removed mass reaches a positive terminal velocity, implying it carries more energy than it added while being accreted. Therefore, the energy remaining in the stellar envelope is _{acc} < 0.33 of the accreted energy. Since the ejected mass will have terminal speed close to the escape velocity, we expect this fraction to be _{acc} = 0.33. We take a conservative approach with _{acc} = 0.25; using an even lower value, as we expect, would result in more moderate envelope expansion, favoring our scenario.

Following mass addition, removal, and energy injection, the star either rapidly expands or reaches a more or less constant radius (or expands only very slowly). We stop the simulations once the stellar response is identified.

3. Results

We aim to present a process by which massive main sequence stars can accrete mass at high rates without significant expansion. We therefore focus on the evolution of the stellar radius following high mass accretion rates under different conditions. We emphasize that the process we mimic involves accretion from an accretion disk and mass loss by jets launched from the inner disk zone and its boundary with the stellar surface. The jets remove material from the stellar outskirts. The inflow-outflow occurs simultaneously, but we alternate mass accretion and mass removal due to limitations of the one-dimensional stellar model. We refer to each mass addition phase as a pulse of duration Δt_p. During the mass addition pulse, we also inject energy into the envelope. After this pulse, we remove mass.

In most cases, the duration of mass removal equals that of mass addition (the pulse duration). In two simulations, the mass removal time is longer. To avoid complicated graphs, the first three figures present only the mass addition and energy deposition parts of the pulses, not the mass removal parts. This causes discontinuities in the lines from one pulse to the next: after the mass removal phase, the star contracts and its mass decreases, so the next line segment starts below and to the left of the endpoint of the previous pulse.

Figure 1 [Figure 1: see original paper] shows the evolution of the stellar radius for a main sequence star with M_{ZAMS} = 60 M for different pulse durations as indicated. The total number of pulses differs between simulations (see caption), as we stop the simulations after identifying the stellar behavior (rapid expansion, approximately constant radius, or very slow expansion). The black line (24 pulses) shows Δt_p = 2 yr, the blue line (48 pulses) shows Δt_p = 1 yr, the cyan line (24 pulses) shows Δt_p = 0.5 yr, and the red line (72 pulses) shows Δt_p = 0.1 yr. For all pulses, the mass addition rate is 0.03 M yr^{-1}, the mass removal rate is 0.67 of the addition rate, the addition and removal times are equal, and the net mass accretion rate is 0.01 M yr^{-1}. We add energy to the outer 10% of the stellar radius at a power of 3.16 × 10^{39} erg s^{-1}, which is a fraction _{acc} = 0.25 of the gravitational energy released by the accreted mass (see Section 2). The net energy deposition power (since we add energy only during half the cycle) is E_{acc} = 3.16 × 10^{39} erg s^{-1}.

In three cases shown in Figure 1, the star does not expand much; in one case it rapidly expands. When _{MR} = 0.33 (i.e., we remove less mass after a mass addition pulse), the star rapidly expands in all cases, for all pulse durations. This demonstrates that to prevent rapid stellar expansion, the star must lose its outer high-entropy layers. According to our assumption, jets from the accretion disk carry high-entropy gas, removing both energy and high-entropy material from the envelope outskirts, which we mimic in our simulations.

Figure 1 shows that when the pulse duration is short (red line for Δt_p = 0.1 yr), the star rapidly expands. We present additional simulated cases in Figure 2 [Figure 2: see original paper] to investigate this phenomenon.

Figure 2 shows similar results for more cases. The thin red line (72 pulses) is identical to the thin red line in Figure 1 (Δt_p = 0.1 yr, _{MR} = 0.67, removal duration = 0.1 yr). The magenta line shows the same _{MR} = 0.67 but for Δt_p = 0.15 yr (72 pulses). The green line (24 pulses) shows a parameter variation where we let the star evolve on the red track: Δt_p = 0.1 yr with _{MR} = 0.67 for 55 pulses, then switch to Δt_p = 0.5 yr with _{MR} = 0.67 for 24 additional pulses when the stellar radius reaches 16 R . The blue line shows a simulation with Δt_p = 0.1 yr but higher mass removal rate _{MR} = 0.8; in this case the star does not expand (336 pulses). The black line (168 pulses) shows a simulation with Δt_p = 0.1 yr and mass addition rate of 0.03 M yr^{-1}, but mass removal rate of 0.004 M yr^{-1} lasting for 5Δt_p = 0.5 yr, giving an effective _{MR} = 0.67. Here the net average mass accretion rate is 0.001 M yr^{-1}, and the star does not expand. For all simulations in this figure, the power at which we add energy to the envelope during the mass addition phase is 3.16 × 10^{39} erg s^{-1}, equal to _{acc} = 0.25 of the accretion energy, deposited in the outer 10% of the star (by radius).

Figure 2 demonstrates several key points. Even for Δt_p = 0.15 yr with other parameters as in Figure 1, the star rapidly expands (thick magenta line). However, if we remove more mass during the removal phase, the star does not expand much, as shown by the blue line for _{MR} = 0.8 (mass removal rate = 0.8 × mass accretion rate), giving a new average mass accretion rate of 0.006 M yr^{-1}. The green line shows that once the star begins rapid expansion, it is difficult to halt: starting like the thin red line (Δt_p = 0.1 yr, _{MR} = 0.67), then switching to Δt_p = 0.5 yr at _{MR} = 0.67 when the radius reaches 16 R , the star continues expanding, albeit more slowly. Notably, starting with Δt_p = 0.5 yr from the beginning prevents expansion (cyan line in Figure 1).

Another simulation kept the ratio of total removed mass to total added mass at _{MR} = 0.67 but removed mass over a longer time: the accretion pulse duration and mass addition rate remain Δt_p = 0.1 yr and 0.03 M yr^{-1}, respectively, but mass removal occurs over 5Δt_p = 0.5 yr (168 pulses), giving an effective _{MR} = 0.67. The total cycle time is 0.1 + 0.5 = 0.6 yr, with net addition of 0.001 M per cycle. The net average mass accretion rate is 0.0017 M yr^{-1}, and the star does not expand.

These results show sensitivity to the durations of accretion and ejection phases. The connection to real systems lies in the operation of jets in a negative feedback cycle. As the star expands, the outer envelope layers engulf the inner parts of the accretion disk that launch jets inside the envelope. These jets remove the envelope' s outskirts. The system reaches equilibrium where jet power and accretion power balance to maintain a roughly constant stellar radius or oscillations around a slowly changing radius. The pulse durations in our numerical scheme are a numerical artifact.

We also examined a main sequence stellar model with M_{ZAMS} = 30 M , presented in Figure 3 [Figure 3: see original paper]. The mass addition rate during pulses is 0.015 M yr^{-1}, half that for the M_{ZAMS} = 60 M simulations. Figure 3 shows that when sufficient mass is removed in each cycle (_{MR} 2/3; we did not extensively scan parameter space as explained in Section 4), the star does not expand much (black and magenta lines). The red line shows expansion occurring later for Δt_p = 0.5 yr with low _{MR} = 1/3. The blue line shows earlier expansion for Δt_p = 1 yr with _{MR} = 1/3, as insufficient mass is removed.

Figure 4 [Figure 4: see original paper] presents entropy and density profiles at several evolutionary points as we add mass to the M_{ZAMS} = 60 M model. The insets give the pulse number for each profile. The first row shows entropy versus mass coordinate in the outer region where mass is added, the second row shows entropy versus radius, and the bottom row shows density versus radius. Figure 5 [Figure 5: see original paper] shows similar profiles for M_{ZAMS} = 30 M simulations.

The density profiles in the bottom rows of Figures 4 and 5 show envelope expansion as expected. In the case of large mass removal (left column), the star does not expand much. The entropy profiles in the upper row (versus mass coordinate) are crucial: as we add mass, a sharp entropy rise develops at the envelope edge in a very thin mass layer. Removing this high-entropy thin layer causes the star to contract, explaining why mass removal substantially reduces or prevents expansion. A star with a radiative envelope can grow in mass without significant expansion if high-entropy outer layers are removed alongside mass accretion. Since these outer layers have less mass than the added mass, the net average mass accretion remains positive.

4. Discussion and Summary

We mimic a process where a massive main sequence star accretes mass via an accretion disk that launches energetic jets from its inner zones attached to the star. The jets carry most of the gravitational energy released by the accreted mass and remove the outer layers of the mass-accreting star. This occurs because the star expands as it accretes mass at high rates to radii larger than the inner radius of the accretion disk. Jets launched from the disk's inner zone collide with the rarefied outer layers of the swollen star and remove mass from them. We alternately added and removed mass from stellar models to mimic this process using MESA (Section 2), which adds and removes mass from the outer layer. The accreted and removed mass has the same properties (e.g., entropy) as the outermost layer. After a mass accretion episode (pulse), the star expands and the outermost layer has higher entropy than before (Figures 4 and 5). In the subsequent removal phase, we remove this high-entropy outer layer, causing the star to shrink.

We simulated accretion onto non-rotating, spherically symmetric main sequence models of 30 M and 60 M . We found (Section 3) that for not-too-short alternating inflow-outflow cycles and for outflow carrying more than about half the accreted mass, mass loss substantially reduces the expansion rate of the mass-accreting star (Figures 1-3). We did not explore a large parameter space for two reasons. First, the simulations are computationally expensive, and our goal was to demonstrate that substantial mass removal—as might occur when an accretion disk launches energetic jets—permits high mass accretion rates without much expansion. Second, mass removal by jets operates in a negative feedback cycle: if the star expands, jets immediately remove more mass, causing contraction; if the star contracts, jets are less efficient at removing envelope mass, allowing accretion to cause expansion. This feedback mechanism prevents significant expansion (unless the mass accretion rate is far too high).

Schürmann & Langer (2024) used MESA to thoroughly study main sequence stars accreting at constant rates, covering a much larger parameter space than ours. However, they simulated pure accretion without mass loss, a crucial difference from our study. They also did not inject energy alongside accretion, as we did. We differ on these ingredients from Lau et al. (2024) as well, who simulated lower-mass models (M_{ZAMS} ≤ 20 M) than ours.

Comparing results for M = 30 M , Schürmann & Langer (2024) found that when the mass accretion timescale is shorter than the thermal timescale, the star expands. At an accretion rate of 10^{-3} M yr^{-1}, their star expands by 30% as its mass grows to 34 M . At higher accretion rates, their models expand unstably. In contrast, we find that when adding mass at 0.03 M yr^{-1} during the addition phase and removing 2/3 of this mass (net accretion rate of 0.01 M yr^{-1}), the model does not expand much (black lines in Figure 3), even with extra energy injection at _{acc} = 0.25. With pure accretion (no mass removal) and no energy addition, adding 1.6 M increases the radius by a factor of 10.

Schürmann & Langer (2024) did not simulate a 60 M star; their 50 M and 70 M models expand very slowly at accretion rates of 10^{-3} M yr^{-1} but unstably at higher rates. We find that under appropriate conditions (removing 2/3 of added mass in each pulse), our 60 M model does not expand much even at a net accretion rate as high as 0.01 M yr^{-1} (Figure 1). These comparisons emphasize that mass removal, even with energy injection that tends to expand the star, prevents large expansion.

Our results are most relevant to vigorous binary interactions where high-rate mass transfer leads the accreting star to launch jets, such as in grazing envelope evolution. This likely occurred during the 1837-1856 Great Eruption of Carinae (e.g., Soker 2001; Akashi & Kashi 2020). The companion mass in the jet-powered model of the Great Eruption is M$_2$(Car)   30–80 M , more likely in the upper range. Near periastron passages during the Great Eruption, the system experienced grazing envelope evolution. The secondary star accreted M_{acc}   4 M over 20 years (Kashi & Soker 2010). Our results show that such a secondary can accrete mass at high rates without much expansion if jets remove mass from the outer high-entropy layers, keeping the gravitational potential well deep and the jets powerful. Our results thus support the high mass accretion rates required by the jet-powered binary model of the Great Eruption.[2] If this also holds for lower-mass stars (under study), our results permit high-mass-accretion rates in other ILOTs; some recent studies argue that only jets can power luminous ILOTs (e.g., Soker 2024).

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[1] The default capabilities of MESA-single rely on the MESA EOS, a blend of OPAL (Rogers & Nayfonov 2002), SCVH (Saumon et al. 1995), FreeEOS (Irwin et al. 2004), HELM (Timmes & Swesty 2000), PC (Potekhin & Chabrier 2010), and Skye (Jermyn et al. 2021) EOSes. Radiative opacities are primarily from OPAL (Iglesias & Rogers 1993, 1996), with low-temperature data from Ferguson et al. (2005) and high-temperature Compton-scattering dominated regime from Poutanen (2017). Electron conduction opacities are from Cassisi et al. (2007) and Blouin et al. (2020). Nuclear reaction rates are from JINA REACLIB (Cyburt et al. 2010), NACRE (Angulo et al. 1999), and additional tabulated weak reaction rates (Fuller et al. 1985; Oda et al. 1994; Langanke & Martìnez-Pinedo 2000). Screening is included via the prescription of Chugunov et al. (2007). Thermal neutrino loss rates are from Itoh et al. (1996).

[2] The triple-star models of the Great Eruption (Portegies Zwart & van den Heuvel 2016; Hirai et al. 2021) suffer from difficulties and we consider them unlikely. (i) The Lesser Eruption in 1890–1895 required another merging star in triple-star scenarios, implying a quadruple-star system. (ii) The Homunculus and present binary system share an equatorial plane (e.g., Madura et al. 2012), requiring a coplanar triple system; merger scenarios need an unstable triple system that would likely not be coplanar. (iii) The Hirai et al. (2021) scenario predicts dense gas in the equatorial plane, which is not observed in the

Homunculus. Applying triple- or quadruple-star models to Carinae’ s two nineteenth-century eruptions is unnecessary and problematic.

Note: Figure translations are in progress. See original paper for figures.

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