

Article

More Luminous Red Novae That Require Jets

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Abstract: In this paper, I study two intermediate luminosity optical transients (ILOTs), classified as luminous red novae (LRNe), and argue that their modeling with a common envelope evolution (CEE) without jets encounters challenges. LRNe are ILOTs powered by violent binary interaction. Although in the literature it is popular to assume a CEE is the cause of LRNe, I here repeat an old claim that many LRNe are powered by grazing envelope evolution (GEE) events; the GEE might end in a CEE or a detached binary system. I find that the LRN AT 2021biy might have continued to experience mass ejection episodes after its eruption and, therefore, might not have suffered a full CEE during the outburst. This adds to an earlier finding that a jetless model does not account for some of its properties. I find that a suggested jetless CEE model for the LRN AT 2019zhd does not reproduce its photosphere radius evolution. These results that challenge jetless models of two LRNe strengthen a previous claim that jets play major roles in powering ILOTs and shaping their ejecta and that, in many LRNe, the more compact companion launches the jets during a GEE.

Keywords: stars: jets; stars: variables: general; binaries (including multiple): close

1. Introduction

I adopt the theoretical definition of intermediate luminosity optical transients (ILOTs) to be all gravitationally powered transient events in binary (or triple) stellar systems, having peak luminosities in the range of somewhat below classical novae to approximately typical supernova luminosities (for earlier usage of the term ILOT, see, e.g., Berger et al. [1], Kashi & Soker [2], and Muthukrishna et al. [3]; some studies do not use the term ILOT at all, e.g., Jencson et al. [4]). The term ‘gravitationally powered’ refers here to the accretion of mass by one of the stars in the system, a process that releases gravitational energy that powers the transient event. The source of the accreted mass is the other star in the binary system, either by mass transfer or by a full merger.

The above definition of ILOT refers to outbursts that occur in interacting binary (or triple) stellar systems with peak emission in the IR, visible, or UV, and that last for a time period from approximately the dynamical time of the system to tens of times the dynamical time. For main sequence stars, the outburst timescale might be hours to weeks, while for giant stars (blue and red) it can be days to years. Note that Gamma-ray and X-ray transients are not included under ILOTs. The peak luminosities of ILOTs are typically between those of classical novae (but can be even fainter) and the peak luminosity of supernovae. For that, observations have classified them as gap transients (the gap between classical novae and supernovae). There is no consensus yet on the terminology, but it seems there is a large overlap between gap transients and ILOTs. However, some gap transients might be faint supernovae, which are not ILOTs.

ILOTs (or gap transients) form a heterogeneous group with diverse time scales, luminosities, and shapes of lightcurves (a partial list of papers include, e.g., Banerjee et al. [5], Blagorodnova et al. [6], Boian, & Groh [7], Bond et al. [8], Cai et al. [9,10,11], Jencson et al. [4], Kamiński et al. [12], Karambelkar et al. [13], Kasliwal [14,15], Mason et al. [16], Mould et al. [17], Ofek et al. [18], Pastorello et al. [19–22], Rau et al. [23], Stritzinger et al. [24], Tytenda et al. [25–27], and Wadhwa et al. [28]).



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One subclass of ILOTs is luminous red novae (LRNe). There is an observational definition of LRNe, e.g., [9], as ILOTs with a slow and long luminosity rise before the outburst, followed by two luminosity peaks; the second peak might be a plateau. LRN early-time optical spectra are similar to those of type II_n supernovae with a blue continuum with superposed narrow hydrogen emission lines. A theoretical common definition of LRNe is of ILOTs, fainter than typical supernovae, that are powered by full merger, including common envelope evolution (CEE; e.g., Ivanova [29]), whether the companion survives but not the CEE. I note that there is no consensus on the exact definitions of these terms and the subclasses of ILOTs, e.g., [2] versus [20,30], and Cai et al. [11]. In this study, I claim that there might be no one-to-one correspondence between the observational classification of LRNe and events experiencing a full CEE merger. Instead, many LRNe might experience grazing envelope evolution (GEE) during their outburst. The GEE might end with a CEE or with a detached binary system. In the GEE, the companion launches the jets at the outskirts of the envelope. Therefore, the jets collide with the stellar wind and the circumstellar material in zones with small optical depths, where the photon diffusion time approximately equals the outflow timescale (Soker [31]). This allows efficient conversion of the thermal energy of the post-shock gas to radiation, rather than most of it being channeled to kinetic energy (adiabatic cooling) when the photon diffusion time is much longer than the outflow time.

One of the motivations for considering the jet-powering of ILOTs is the bipolar morphologies of spatially resolved ILOTs, some with point symmetry. Such is the bipolar ejecta of the nineteenth-century Great Eruption of Eta Carinae, called the Homunculus (e.g., Davidson, & Humphreys [32]). The Great Eruption was a luminous blue variable major eruption, a subclass of ILOTs (see Section 3). Observations show bipolar morphologies in the ILOTs V4332 Sgr [12], Nova 1670 (Kamiński et al. [33,34], Shara et al. [35]), and V838 Mon (Chesneau et al. [36], Kamiński et al. [37], Mobeen et al. [38,39]). The stellar merger candidate TYC 2597-735-1 has a bipolar structure [40,41], supporting power by jets. The point-symmetric morphological features of some ILOTs, e.g., the Homunculus of Eta Carinae [42] and Nova 1670 (CK Vulpeculae; e.g., Kamiński [43]), are key elements in claiming the jet powering of ILOTs; while equatorial mass ejection during binary interaction can, in principle, explain bipolar structure, this process by itself cannot explain point symmetry. Jets are most likely to shape point-symmetric structures.

Processes that release gravitational energy in binary interaction and can power ILOTs include mass transfer via an accretion disk where the mass-accreting (more compact) companion launches jets (e.g., Soker [31], Kashi [44], Kashi et al. [45], Soker [46], Soker, & Kashi [47]), and/or the system ejects mass in and near the equatorial plane (e.g., Hubová & Pejcha [48], Pejcha et al. [49]) or the merger of two stars. The latter includes the onset of a CEE, whether the companion survives or not. Extreme cases are the spiraling-in of a neutron star or a black hole inside the envelope of a red supergiant. These events are expected to be as bright as luminous core-collapse supernovae (CCSNe) and are termed common envelope jets supernovae (CEJSNe; e.g., Gilkis et al. [50], Grichener & Soker [51], Schreier et al. [52], Soker, & Gilkis [53], Yalinewich, & Matzner [54]). CCSNe, which are most likely also powered by jets (e.g., Soker [55] for a recent review), and CEJSNe are not grouped under ILOTs despite being gravitationally-powered through jets because most of the gravitational energy in these systems is carried by neutrinos rather than jets or the ejecta in general.

In ILOTs that experience CEE, the compact companion is a star, main sequence, or slightly evolved (e.g., Blagorodnova et al. [6], Tylanda et al. [26], Soker [31], Addison et al. [56], Blagorodnova et al. [57], Howitt et al. [58], Ivanova et al. [59], Kamiński et al. [60], MacLeod & Loeb [61], MacLeod et al. [62,63], Matsumoto & Metzger [64], Nandez, Ivanova, & Lombardi [65], Pejcha et al. [66,67], Qian et al. [68], Schröder et al. [69], Segev et al. [70], Zhu et al. [71]) or a sub-stellar (i.e., a brown dwarf or a planet) companion (e.g., De et al. [72], Gurevich, Bear, & Soker [73], Kashi et al. [74], Metzger, Giannios, & Spiegel [75], O'Connor et al. [76], Retter & Marom [77], Retter et al. [78], Soker [79], Yamazaki, Hayasaki, & Loeb [80]).

Other energy sources to power the radiation of an ILOT in a CEE are the hot ejected gas (e.g., Chen & Ivanova [81]), which the spiraling-in process heats, and recombination energy (e.g., Howitt et al. [58], Ivanova et al. [59], Matsumoto & Metzger [64]). In [82], I compared these two energy sources with jet powering and concluded that only jets could power the rapidly rising lightcurves of bright ILOTs. In general, the collision of wide jets with a slower expanding ejecta efficiently channels the kinetic energy of the jets to radiation [46]; this is more efficient than equatorial ejecta collision with a shell (e.g., Pejcha et al. [66,67]) and a shell collision with a slow equatorial outflow (e.g., Andrews, & Smith [83], Kurfürst & Krtićka [84], Metzger, & Pejcha [85]) proposed by these studies as an energy source of radiation. In Section 2, I examine the jetless model that [81] proposed that is based on the ejected hot gas and recombination energy. Namely, a model that includes no jets and attributes most of the emitted energy to the recombination energy of the ejected envelope. I find that it does not reproduce all the observed properties of LRN AT 2019zhd.

Earlier studies of jet-powering have focused on bumps of short-period increased luminosity, e.g., ref. [86] studied the ILOT SNhunt120 (observations by Stritzinger et al. [87]) and the LRN AT 2014ej (observations by Stritzinger et al. [87]). In Section 3, I consider bumps in the lightcurve of AT 2021biy of decreased luminosity while the radius increases. I argue that these bumps suggest a continuous binary interaction that might imply that no CEE took place during this outburst. I also find that the ejecta is likely to be bipolar. In Section 4, I examine the multi-polar (multi-axes) morphology of CK Vulpeculae (Nova 1670). I summarize this short study in Section 5.

2. Challenging a Jetless Model of AT 2019zhd

This section addresses the dispute between models of LRNe that attribute significant roles to jets (see Section 1) and those that do not, i.e., jetless models.

Ref. [81] construct a jetless CEE LRN model, where the emission results from recombination and cooling of hot gas ejected by the CEE. They fit their parameters to (almost) exactly fit the lightcurve of the LRN AT 2019zhd, as reported by [88].

Ref. [88] calculated the blackbody temperature, T_{bb} , and radius of the photosphere of AT 2019zhd; I present two panels from their paper in Figure 1. To determine T_{bb} , they constructed the spectral energy distribution at any epoch with available multi-band photometry, mainly the g, v, r, i, and z bands, and corrected for reddening. They then apply Monte Carlo simulation to determine T_{bb} and the flux. With a distance of AT 2019zhd, they can calculate the photospheric radius, R_{ph} . Ref. [81] do not present their model's blackbody temperature or radius. They do present the optical depth as a function of radius and time, which they calculate by integration over the density times the Rosseland mean opacity from the given radius, r , to their outer radius of $r_{out} = 4000R_{\odot}$, $\tau_R(r) = \int \rho \kappa_R dr$. I take their value of $\tau(r, t) = 1$ to approximately give the radius of the photosphere and added the line $R(\tau = 1, t)$ on the right panel of Figure 1 by a light-blue line marked CI2024.

From the two lines for AT 2019zhd on the right panel of Figure 1, I conclude that the model of [81] does not reproduce the photospheric radius that [88] calculated from their observations of AT 2019zhd, not even qualitatively. Ref. [81] writes also that the time evolution of the gas at $T_g = 5000$ K resembles the shape of the lightcurve. This statement implies implicitly that they consider the photosphere to have a temperature of $T_g \simeq 5000$ K. However, as the left panel of Figure 1 shows, the blackbody temperature that [88] calculate for AT 2019zhd varies from approximately 7000 K near maximum light to 2400 K at $t = 34$ d. This is another manifestation of the incorrect photospheric radius that the model calculated by [81] gives.

The jetless model of [81] and the calculations of [88] do not agree with each other. Either one of them is wrong, or both miss the real behavior because they assume spherically symmetric ejecta and do not acknowledge the primary role that jets might play. I tend to accept the calculations of [88] as being approximately correct, but expect non-spherical effects to play significant roles (see Section 1 for observational indications of bipolar ILOTs).

In any case, the jetless model that [81] constructed seems not to explain the behavior of the LRN AT 2019zhd. The jets are probably needed.

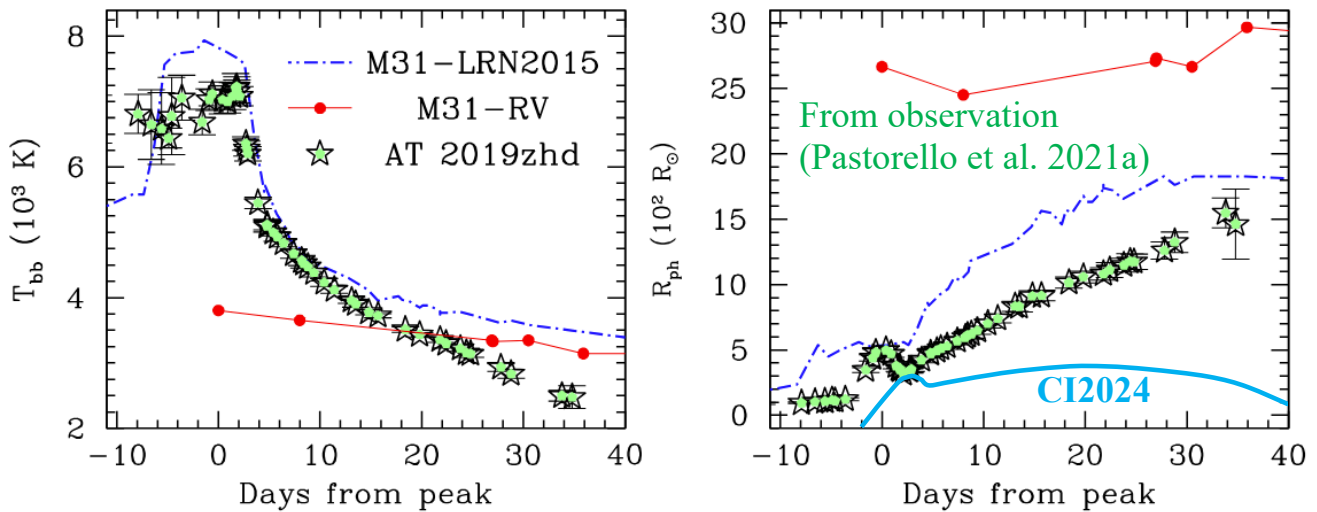


Figure 1. The evolution of the blackbody temperature (**left panel**) and photospheric radius (**right panel**) of three ILOTs that [88] calculated from their observations under the assumption of spherically symmetric ejecta. I added the light-blue line on the right panel, which is the radius of optical depth $\tau_R = 1$ from the jetless model that [81] built for LRN AT 2019zhd. Their model fails to reproduce the radius.

3. The Dips in the Lightcurve of AT 2021biy

Many studies attribute the bipolar morphology of many planetary nebulae to jets, whether there are direct signatures of jets, e.g., MyCn 18 (e.g., Bryce et al. [89], O'Connor et al. [90]), or indirect, e.g., NGC 6302 (e.g., Balick et al. [91]) and NGC 7027 (e.g., Moraga Baez et al. [92]). The same holds for many bipolar symbiotic nebulae, e.g., R Aquarii, which was shaped by precessing jets (e.g., Santamaría et al. [93]), and pre-planetary nebulae (e.g., Sahai [94]), e.g., M 1-92 (e.g., Alcolea et al. [95]). Direct signatures of jets include the observation of a bipolar outflow, whether the two opposite jets are narrow or wide. It can be made by direct imaging or by absorption in a binary system (e.g., Bollen et al. [96]). Indirect signatures are the formation of multipolar ejecta or 'S-shaped' ejecta (that result from processing jets). Based on bipolar planetary nebulae, some past studies attributed the bipolar structure of the ejecta of the nineteenth-century Great Eruption of Eta Carinae (approximately 1837–1856; Humphreys, Davidson, & Smith [97]), i.e., the Homunculus, to be powering by jets (e.g., Kashi & Soker [98], Soker [99]). The Great Eruption of Eta Carinae was a luminous blue variable major eruption (outburst) that belongs to a subclass of ILOTs. I argued before [82] that this claim of shaping by jets applies to the Great Eruption binary scenario models that involve no CEE (e.g., Soker [99,100]) and to the Great Eruption triple star scenarios where two of the three stars entered a CEE (e.g., Hirai et al. [101], Livio & Pringle [102], Portegies Zwart & van den Heuvel [103]). The difference is that, in the non-CEE scenario, the binary system interaction might repeat itself with several peaks in the same event or repeat in consecutive events. The non-repeating nature is one of the difficulties with the triple-star scenarios of the Great Eruption [101,103]. Specifically, the problems with the triple-star merger scenarios are as follows: (i) A second outburst in 1890–1895 (the Lesser Eruption; Humphreys, Davidson, & Smith [97]) required another merger according to the triple-star scenario. Namely, a system of four stars. (ii) The Homunculus and the present binary system share the same equatorial plane (e.g., Madura et al. [104]). This is difficult to explain in a non-coplanar triple-stellar system; merger scenarios require an unstable triple system likely not to be coplanar. (iii) The scenario proposed by [101] predicts the presence of a dense gas in the equatorial plane; this is not observed in the

Homunculus. For these, I consider it unnecessary and problematic to apply a triple-star or a quadruple-star model to the two nineteenth-century eruptions of Eta Carinae. In the binary model for the Great Eruption of Eta Carinae, the secondary star grazed the primary stellar envelope during periastron passages. The secondary star accreted mass via an accretion disk that launched the jets that powered the event and shaped the Homunculus (e.g., Kashi & Soker [98]). The interaction, namely the mass transfer onto the secondary star, started with an instability of the primary star that caused its envelope to expand, such that at periastron passages the secondary star grazed, or even somewhat entered, the envelope of the primary star. The binary model with jets (starting with Soker [99]) does not specify the cause of the instability but is based on observations that luminous blue variable stars experience such instabilities. The primary star of Eta Carinae is now smaller, and the mass accretion rate does not increase much at periastron passage to the degree that the secondary star launches jets. A strong observational support for this scenario is the two peaks in the lightcurve during the Great Eruption of Eta Carinae that coincide with periastron passages [98]. The point of this discussion is that Eta Carinae was an ILOT powered by a binary system that did not merge.

I elaborate here on the jet-powered ILOT scenario relevant to Eta Carinae, the LRNe studied here, and many other ILOTs (probably all bright ILOTs). The scenario assumes that one process or more triggers a strong binary interaction; these processes are mainly a rapid expansion of the mass-losing star and/or an instability that causes the orbital separation to decrease. The outcomes are an enhanced mass loss rate from the primary (mass-losing) star and an increase in mass transfer from the primary to the secondary star. The secondary star accretes mass through an accretion disk and launches two opposite jets. The bright event results from the conversion of some of the kinetic energy of the jets to thermal energy and the radiation of a fraction of the thermal energy. The jets must collide with a dense ambient material to convert some of their kinetic energy to thermal energy. This ambient material can be the outskirts of the inflated envelope of the mass-losing (primary) star or the dense wind of the primary star. The dense interaction region is optically thick, and it expands. It cools by radiation and by adiabatic cooling. Hence, only a fraction of the thermal energy ends in radiation. This photosphere is not part of either of the two stars because it is not in hydrostatic equilibrium. The gas in and near the photosphere expands supersonically; the location of the photosphere in radius and mass coordinates changes with time, and the gas in its vicinity escapes the system.

With the dispute between a one-time CEE event (e.g., Ivanova [29]) and repeating jet-launching episodes, likely in a GEE (e.g., Soker [105]), I examine the properties of the ILOT AT2021biy that [9] studied in detail. AT2021biy presents the longest plateau among LRNe, with a duration of 210 days. Ref. [9] find the progenitor to be a yellow supergiant of mass $\approx 20M_{\odot}$, a luminosity and radius at explosion of $L_{*} \simeq 10^5 L_{\odot}$, and $R_{*} \simeq 300R_{\odot}$. Ref. [9] tried to fit the lightcurve with the jetless recombination model of [64]. From the plateau duration of $t_{\text{pl}} = 210$ days and the expansion velocity of $\bar{v}_{\text{E}} = 430 \text{ km s}^{-1}$ that they deduced from the $H\alpha$ line, they estimated the ejected mass to be $M_{\text{ej}} \simeq 9.9M_{\odot}$. With these parameters, they found the jetless model of [64] to give a plateau luminosity of $\approx 3 \times 10^{39} \text{ erg s}^{-1}$, which is an order of magnitude below the observed plateau luminosity of $L_{\text{pl}} \simeq 5 \times 10^{40} \text{ erg s}^{-1}$. Therefore, [9] claimed an extra energy source powered the plateau. I attribute the extra energy to jets, or more accurately, most of the energy to jets.

Figure 2 from [9] presents the luminosity, blackbody temperature, and photosphere radius of four ILOTs. I refer to AT 2021biy. I examine three radius rises as marked on the lower panel. In the insets, I give the start and end times of the three time periods and the radii at these times. I take the times and radii from Table A.2 of [9]. From the start and end points, I calculate the average velocity of the increasing radius. The radii of these points are highly uncertain, and therefore so is the velocity I calculate. Assuming that this velocity is the velocity of a mass, I calculated the time the central stellar system ejected the mass. I mark these times with the green-double-lined arrow on the time axis.

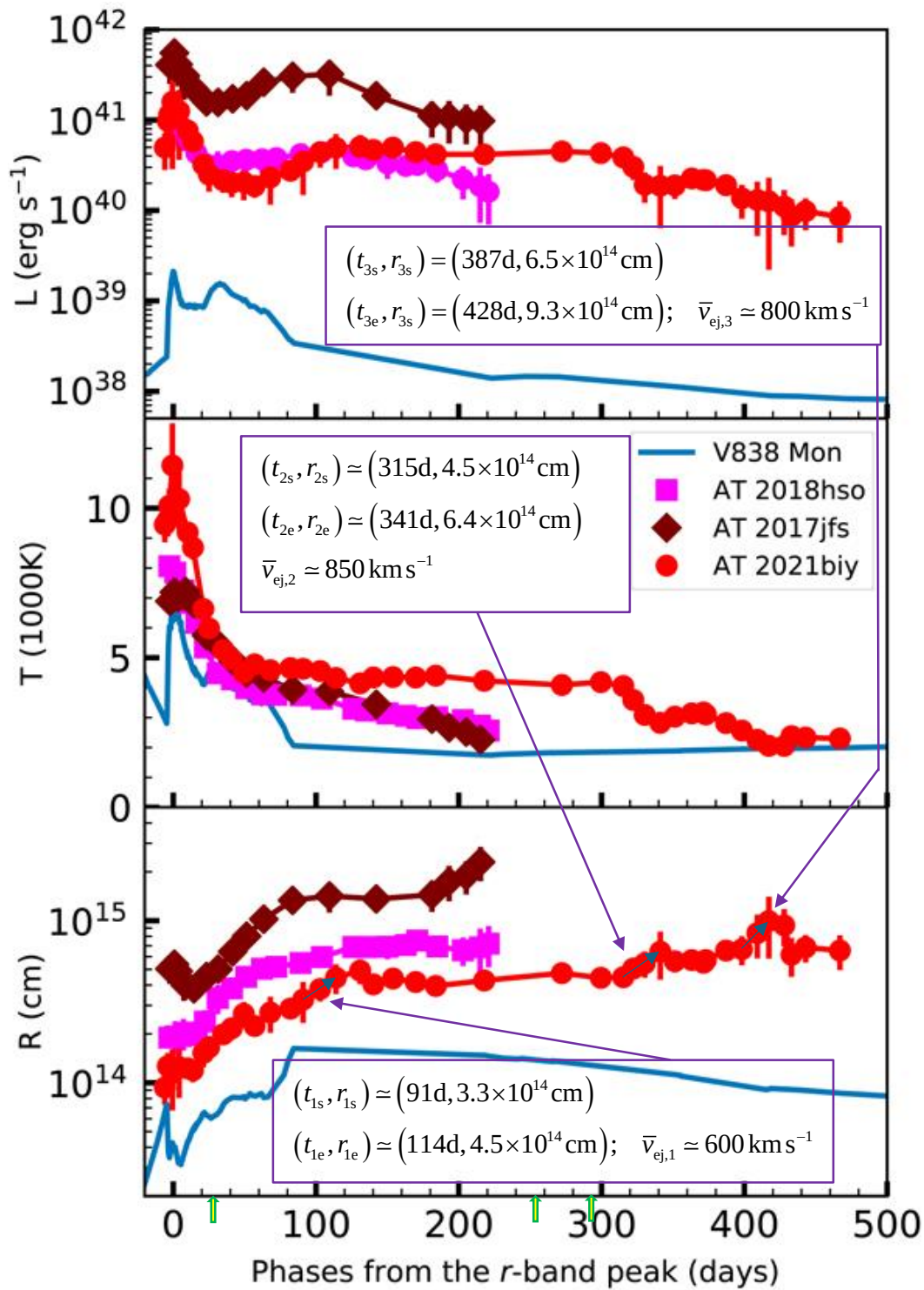


Figure 2. Figure adapted from [9] of the bolometric lightcurves, blackbody temperature evolution, and blackbody (photosphere) radius evolution of four ILOTs. I added the estimated starting and ending times and radii (three insets) of three rapid radius increase periods of AT2021biy, as indicated by the three arrows in the lower panel. The insets also indicate the expansion velocity of each rise, namely $v_{ej} = (r_e - r_s)/(t_e - t_s)$, for each of the three rapid rises. The green arrows indicate the estimated ejection time of the material calculated by $t_{ej} = t_s - r_s/v_{ej}$. I expect that there were other jet-launching episodes that did not obscure the equatorial photosphere.

A rapid rise in radius can result from a mass that the stellar system ejected late and which then catches up with the photosphere. Specifically, consider that the photosphere

of the ejecta is at a specific radius, $R_{p,1}(t)$, much larger than the pre-outburst radius of the star, and where the density is $\rho(R_{p,1})$. If a late ejected dense shell that catches up with this radius has a larger density, $\rho_{\text{shell}}(R_{p,1}) > \rho(R_{p,1})$, then as this dense shell continues to expand and the photosphere moves outward until optical depth to infinity decreases back to $\tau = 2/3$. What is different in the present case for the two late radius rises is that decreases in luminosity rather than increases accompany these increases in radius. A very moderate rise in luminosity accompanies the first radius rise. In the case of shell collision, the expectation is an increase in luminosity because kinetic energy is channeled to thermal energy that is partially radiated away. The two late radius rises end with a temperature where most of the gas is recombined. Therefore, it seems that the shell that catches up with the photosphere is already mainly neutral, and the collision with the rarefied photospheric gas does not heat it much.

It is possible that the flow structure will be non-spherical and possibly complicated. In one speculative flow structure, as an example, the main photosphere might be from an equatorial mass ejection before the rapid radius rise. The late ejecta might then be a wide bipolar outflow, say of a half opening angle of $\alpha_j \sim 45\text{--}60^\circ$. If we observe this LRN along the polar direction, the cold polar ejecta obscures the equatorial photosphere for several weeks; this explains a cool expanding photosphere. In that case, there might be more mass-ejection episodes of lower mass, those that do not obscure the equatorial gas. The possible parameter space of these late bipolar mass-ejection episodes is large. It deserves a study by itself.

The mass in the latest ejecta that caused the third rapid radius rise can be estimated as follows: The blackbody temperature of the gas in the last rise at maximum radius, $r_{3e} \simeq 10^{15}$ cm, at $t \simeq 410\text{--}430$ days, is $T_{\text{BB},3e} \simeq 2000$ K. At that low temperature, molecular opacity dominates, and the opacity is $\kappa \simeq 0.01 \text{ cm}^2 \text{ g}^{-1}$ (e.g., Ferguson et al. [106,107]), for a density of $\simeq 10^{-11} \text{ g cm}^{-3}$. For the required mass to have an optical depth of 1 at that radius is

$$M_3 \simeq 0.63 \left(\frac{r_{3e}}{10^{15} \text{ cm}} \right)^2 \left(\frac{\kappa}{0.01 \text{ cm}^2 \text{ g}^{-1}} \right)^{-1} \left(\frac{\Omega}{4\pi} \right) M_\odot. \quad (1)$$

There are large error bars on the radius of the third peak in the time period of 387–428 days, approximately the height of the radius peak. Therefore, the mass given by Equation (1) is uncertain by approximately a factor of two. The total mass is smaller if the mass is in a wide polar outflow rather than in a complete shell over a solid angle of $\Omega = 4\pi$. For a half opening angle of 60° (45° ; measured from the polar axis), the ejected mass is $M_3 \simeq 0.3M_\odot$ ($M_3 \simeq 0.2M_\odot$).

If the same approach is applied to the second rise, the required ejected mass is too high. The temperature at the largest radius in the second rise, $r_{2e} \simeq 6.4 \times 10^{14}$ cm, is $T_{\text{BB},2e} \simeq 3000$ K, where the opacity is only $\kappa \simeq 3 \times 10^{-4} \text{ cm}^2 \text{ g}^{-1}$ (e.g., Ferguson et al. [106,107]). This implies, for a spherical shell by Equation (1), an ejected shell mass of $M_2 \simeq 8.6M_\odot$. Ref. [9] find the progenitor to be a yellow supergiant of mass $\approx 20M_\odot$, which in principle can accommodate an ejected mass of $M_2 \simeq 8.6M_\odot$. However, considering that this ejecta is only the late shell and that the progenitor has already lost mass before the outburst and during the outburst before the late shell ejection, and there is the core mass that is not ejected, a mass of $M_2 \simeq 8.6M_\odot$ in a late shell seems to be too large for this system. A more likely explanation is that the ejecta is wide polar ejecta (to two pools). This reduces the required ejected mass from two effects. The first effect is that $\Omega < 4\pi$. The second is that the polar ejecta does not cover the entire photosphere of the equatorial ejecta. In that case, the inferred temperature of $T_{\text{BB},2e} \simeq 3000$ K may be a combination of two photospheres: one of the equatorial ejecta at ≈ 4000 K and one of the polar ejecta at ≈ 2000 K. At both these temperatures, the opacity is higher than at ≈ 3000 K, which implies a lower required mass. This implies that the ejected polar mass that obscures some of the equatorial photosphere is $M_2 \approx 0.1M_\odot$.

In the case of AT 2021biy, my suggestion is that the fast polar outflow recombines before it covers a large area, and, therefore, when it expands enough to start obscuring the

equatorial photosphere it is already cold at ≈ 2000 K. The polar and equatorial outflows collide on their overlapping solid angles, and the polar outflow further heats the equatorial outflow and prolongs the plateau. As said, I expect that there have been earlier jet-launching episodes that did not obscure the equatorial photosphere but heated it up.

Further detailed research is needed on the structure of two photospheres at different temperatures in a bipolar outflow: a denser and slower thick equatorial outflow and a faster eruptive bipolar outflow.

My conclusion from this short discussion is that the lightcurve of LRN AT2021biy, which, as noticed by [9], the jetless model of [64] cannot explain, was powered by late jet-launching episodes. This implies, in turn, that the interaction of the main outburst was more likely to have been a GEE than a CEE. Whether the binary system eventually entered a CEE or survived as a detached binary system is for future observations to determine. In the latter case, this system can experience another ILOT event, much like the Lesser Eruption of Eta Carinae at the end of the nineteenth century.

4. The Multi-Axes Bipolar Morphology of Nova 1670 (CK Vulpeculae)

One of the clearest outcomes of jets long after they cease is the bipolar structure they shaped. However, a jetless flow structure of a slow equatorial mass outflow can also confine a later spherical and faster ejecta to form a bipolar structure. The signatures that are almost unique to jets are an ‘S-shape’ resulting from precessing jets and a multi-axes morphology that indicates the launching of pairs of jets along different axes. An equatorial dense outflow cannot explain these morphological structures.

The ILOT (LRN) CK Vul (Nova 1670) plays a key role in this study’s arguments because it has a multi-axis bipolar structure, indicating shaping by jets. Several studies have revealed its general bipolar structure (e.g., Kamiński et al. [33], Shara et al. [35], Kamiński et al. [37], Hajduk, van Hoof, & Zijlstra [108], Hajduk et al. [109], Kamiński et al. [110,111], Shara & Moffat [112], Tylanda, Kamiński, & Mehner [113], Tylanda, Kamiński, & Smolec [114]). Ref. [114] suggest that CK Vul was powered by the merger of a red-giant branch star of a mass of $1 - 2M_{\odot}$ with a helium white dwarf (or, less likely, another giant). Most of the energy was accretion energy, while $\approx 12\%$ of the energy came from helium burning. In this study, I comment only on the role of jets. Of course, the jets are powered by the accretion process onto the more compact companion via an accretion disk that launches the jets.

Ref. [37] mark three axes on the image of CK Vul, as I present in panel (a) of Figure 3 taken from their paper (the three dashed lines). Two of the axes, the red and black dashed lines, of the inner bipolar structure are very close to each other. Instead of two axes of two independent jet-launching episodes, I raise here the possibility that these two symmetry axes that [37] mark in the inner structure result from a precessing pair of jets (the jets’ power might have been varying during that specific outburst). I mark this ‘S-shaped’ line of the proposed precessing pair of jets with an S-shaped double-headed red arrow on an image from [114]; panel (b) without my marks, and panel (c) with my marks.

Ref. [35] presents the lightcurve of CK Vul that contains three peaks. There might have been more peaks as the observations were not continuous. In the approach of the present study, there should have been three jet-launching episodes. If I group two of the axes that [34] identify to one jet-launching episode, I should examine the presence of a third axis. To account for one of the three peaks in the light curve, I suggest a different pair of bubbles (lobes). I mark this pair of bubbles with two closed, thick yellow lines, one on each side of the center. Namely, I suggest that two bubbles (lobes) were inflated by a pair of jets along the two lobes I marked with the yellow line. The segments of the bubbles’ rim at the front of the two bubbles and towards the center of the largest bubbles expanded freely and are below the detection limit.

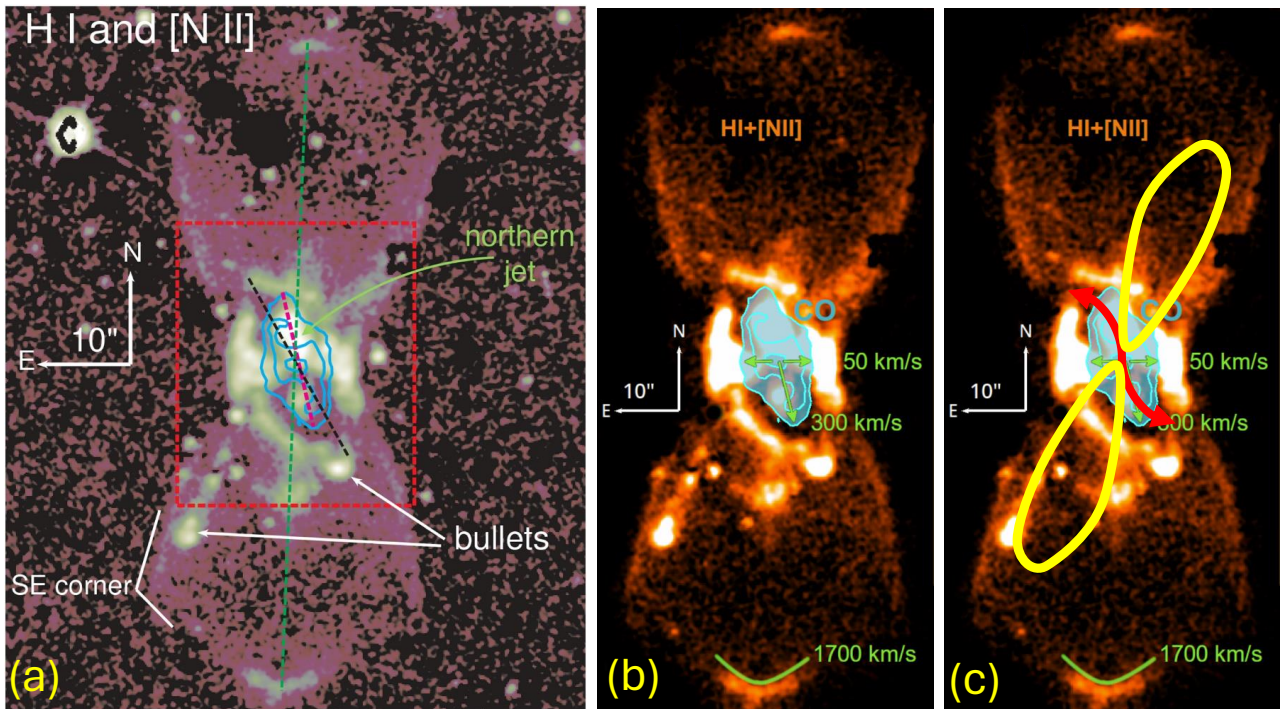


Figure 3. Figure of the LRN CK Vul (Nova 1670). (a) From [34]; (b) From [114]. The largest bipolar structure that fills the image is the nebular emission in lines of $H\alpha$ and $[N II]$. The cyan contours show molecular emission of CO 1–0. The three dashed lines on panel (a) mark the three symmetry axes that [34] identified. In panel (c), I present my suggestion that the two axes that [34] mark in the inner structure form a point symmetric structure of one pair of precessing jets, while there is another pair of jets in an inclined angle that inflated two lobes, those that I draw with thick yellow lines.

5. Summary

This study is motivated by two recent ILOTs classified as LRNe, AT 2019zhd and AT 2019zhd, which jetless models based on recombination energy have difficulty explaining. In Section 2, I found that the jetless model of [81] does not reproduce the radius evolution of LRN AT 2019zhd, as [88] calculated from their observations. As noticed by [9], the jetless model of [64] cannot reproduce both the luminosity and duration of LRN AT 2021biy. In Section 3, I further argued that the late lightcurve of AT 2021biy requires late mass-ejection episodes. As earlier studies suggested (see Section 1), a late activity that powers more energy to an ILOT and which also accounts for bumps in the lightcurve might be the launching of jets by the more compact companion in a binary system. I suggest this late binary activity for the LRN AT 2019zhd. This implies that the binary system did not enter a CEE at the main outburst.

For both these LRNe, I take the view that the binary interaction during the main outburst involved GEE rather than CEE. In [31], the last sentence of the Abstract reads: “Some future ILOTs of giant stars might be better explained by the GEE than by merger and CEE without jets”. The progenitor of AT 2021biy was a yellow giant ($R_* \simeq 300R_\odot$). I attribute the LRN AT 2021biy to a GEE event. It might have ended in a final CEE, or the two stars might have stayed detached. I repeat my earlier claim that a GEE event powers many ILOTs; it might end with a CEE or a detached binary system. There are no observational indications for the progenitor of AT 2019zhd, but I expect jets to have also powered this ILOT.

In Section 4, I examined the morphology of the ILOT (LRN) CK Vul (Nova 1670). I suggested that the inner structure was shaped by a processing pair of jets and identified an ‘S-shaped’ structure (Panel c of Figure 3). I suggested the presence of a third symmetry axis of a pair of jets that inflated two bubbles (lobes) that I mark with the thick-yellow

lines in panel (c) of Figure 3. I suggest that the three jet-launching episodes that inflated the structures of the three symmetry-axes account for the three peaks in the lightcurve of CK Vul.

I end by proposing a scenario for the pre-outburst, long-lasting slow brightening in LRNe. The first mass transfer occurs as the companion accretes mass from the wind of the mass-losing star. As the two stars slowly approach each other due to tidal interaction, this mass accretion rate slowly increases. This, in turn, implies increased accretion power, including possible jets. As the two stars approach each other, the mass-losing star overflows its Roche lobe, initiating a high mass transfer rate via Roche lobe overflow (RLOF). The accretion power increases even more. When the system enters the GEE, the mass transfer is a combination of RLOF and a Bondi–Hoyle–Lyttleton (BHL) type accretion from the envelope outskirts, which within a short time reaches very high power; this is the main outburst. The binary might then enter a CEE, where the high mass accretion rate continues via a BHL accretion, but the jets might be choked in the envelope as the companion deepens into the envelope. This scenario requires further exploration.

This study adds to the accumulating evidence, observationally and theoretically, that jets play major roles in powering most ILOTs, including all subclasses of LRNe and luminous blue variable major eruptions, whether the system enters a CEE during the outburst or experiences a GEE. Note that the binary interaction might be with a sub-stellar companion in some LRNe.

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