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On the nature of the planet-powered transient event ZTF SLRN-2020

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ABSTRACT

The Red Nova ZTF SLRN-2020 is the third transient event with properties that are compatible with the merger of a planet with a main sequence (or close to) star on a dynamical timescale. While the two first transient events occurred in young systems, ZTF SLRN-2020 occurred in an old system. Nonetheless, I show that the three star-planet intermediate luminosity optical transients (ILOTs, also termed Red Novae) occupy the same area in the energy-time diagram of ILOTs. Based on models for ILOTs that are power by stellar binary interaction I suggest that the planet in ZTF SLRN-2020 launched jets at about its escape speed before it was engulfed by the star. Interestingly, the escape speed from the planet is similar to the orbital speed of the planet. This leads to an outflow with a very low terminal velocity, much below the escape velocity from the star, and in concentration around $\approx 45^\circ$ to the equatorial plane. As well, the planet might have lost back some of the accreted mass just before engulfment, forming an accretion disk around the star. This disk might have launched jets during the main outburst of the event. The jets form a bipolar expanding nebula.

Keywords: stars: jets; planet–star interactions; planetary systems; stars: variables: general; Astrophysics - Earth and Planetary Astrophysics; Astrophysics - Solar and Stellar Astrophysics

1. INTRODUCTION

The recently analyzed (De et al. 2023) interesting transient event ZTF SLRN-2020 is the fourth intermediate luminosity optical transient (ILOT; or Red Nova) that was claimed to be powered by star-planet interaction.[1]

The first claim by Retter & Marom (2003) and Retter et al. (2006) that V838Mon was powered by star-planet interaction was refuted on the ground of energy considerations (e.g., Soker & Tylenda 2003).

The second claim for an ILOT powered by a star-planet interaction is that the unusual outburst of the young stellar object ASASSN-15qi was powered by the accretion of a tidally-disrupted Jupiter-like planet (Kashi & Soker 2017). The accretion via an accretion disk powered the event, probably by launching jets. Kashi et al. (2019) made the third claim and argued that the $\approx$ 800 days-long eruption of the young stellar object ASASSN-13db was powered by engulfment of the remains of a planet that was tidally-shredded by the young star. These last two claims are not refuted (yet), and so the new claim by De et al. (2023) is the third claim for a star-planet-powered Red Nova that still holds.

From their analyses of the observations De et al. (2023) deduce that a star of a mass $M_1 \simeq 0.8-1.5 M_\odot$ on the main sequence or early sub-giant phase (Hertzsprung gap) and with a radius of $R_1 \simeq 1-4 R_\odot$ engulfed a planet to power this event that radiated in the first 150 days an energy of $E_{\rm rad} \simeq 6.5 \times 10^{41} (d/4 \ {\rm kpc})^2$ erg, where d is the distance to this ILOT. De et al. (2023) argue for a planet mass of $M_{\rm p} \simeq 0.01 M_\odot$. They further deduce from the infrared that the interaction started at least ≈ 7 months before the main outburst, and that the interaction expelled dust with a velocity of $v_{\rm d} \simeq 35$ km s^{-1}.

In this short study I further analyze the new event ZTF SLRN-2020. I place it on the energy-time diagram of ILOTs and compare it with predictions of previous studies and discuss the common properties and differences from the two earlier ILOTs powered by star-planet interaction (section 2). I then suggest (section 3) that the slowly expanding dust was launched from an accretion disk around the planet. I do not study other theoretical aspects that were worked out by earlier studies (e.g., Bear, Kashi, & Soker 2011; Metzger, Giannios, &

[1] I refer to all gravitational-powered transients as ILOTs, not including supernova nor dwarf novae (e.g., Berger et al. 2009; Kashi & Soker 2016; Muthukrishna et al. 2019). Other researchers use other terms (e.g., Jencson et al. (2019); Pastorello et al. (2019); Pastorello & Fraser (2019). The ILOT class includes in it the subclass of Red Novae and some similar sub-classes.

Spiegel 2012; Gurevich, Bear, & Soker 2022; O'Connor et al. 2023). I summarize in section 4.

2. COMPARING ZTF SLRN-2020 WITH OTHER STAR-PLANET ILOTS

I consider the duration of the star-planet ILOTs and their total energy that includes the radiated energy and the kinetic energy of the ejecta.

The total radiated energy of ZTF SLRN-2020 is $E_{\rm rad} \simeq 6.5 \times 10^{41}(d/4~{\rm kpc})^2$ erg, and the decline time by three magnitudes is about 200 days (De et al. 2023). De et al. (2023) consider two limits for the duration of the event. Its lightcurve plateau duration, $\simeq 26$ days, and the time it radiated 90% of its the total radiated energy, 103 ± 20 days. The total radiate energy divided by the luminosity during the plateau $L_{\rm p} \simeq 1.1 \times 10^{35}(d/4~{\rm kpc})^2$ erg (De et al. 2023) gives a timescale of $\simeq 70$ days. I take the range to include all these timescales, namely, from 26 days to 200 days. I mark these two end with yellow-red stars on Fig. 1. Fig. 1 that is adapted from Kashi & Soker (2017) presents many ILOTs in a plane of their total energy versus their typical timescale. Note that the energy is the total energy, including radiation and kinetic energy.

When there is no information on the kinetic energy the structure of this diagram assumes that the total energy is ten times the radiated energy. This estimate gives here a total energy of $E \simeq 6.5 \times 10^{42}$ (for a distance of $d = 4$ kpc) for ZTF SLRN-2020. De et al. (2023) crudely estimate an ejecta mass and velocity $M_{\rm ej} \approx 3 \times 10^{-5} M_\odot$ and $v_{\rm ej} \approx 100~{\rm km~s^{-1}}$. This gives a kinetic energy of $E_{\rm ej} \approx 3 \times 10^{42}$ erg. I mark the location of ZTF SLRN-2020 on Fig. 1 with $E \simeq 6.5 \times 10^{42}$ and the range of timescales by the two yellow-filled blue circles and a line concocting them.

Kashi et al. (2019) analyzed the ILOT ASASSN-13db that was observed by Sicilia-Aguilar et al. (2017). The total duration of high emission lasted ≈ 800 day, ending with a decline that lasted ≈ 55 day. The total radiated energy during the (more or less) plateau of ≈ 800 days is $E_{\rm rad} \approx 2 \times 10^{41}$ erg. The total energy of the event is about an order of magnitude larger. Kashi et al. (2019) scale it with $\approx 10^{42}$ erg. I take it here to be ten times lager at $E \simeq 2 \times 10^{42}$. I mark this energy with the span of the timescale of 55 to 800 days. This timescale range is not the uncertainty in observations, but rather the unclear way by which the event timescale should be defined, i.e., should we take only the decline phase by three magnitudes or so, or the entire duration, or the plateau duration, etc.

From the locations of the three ILOTs (Red Novae) claimed to be powered by star-planet interaction, ASASSN-15qi, ASASSN-13db, and ZTF SLRN-2020, on the Energy-Time diagram we can learn the following. (1) V838 Mon is much above their location, and it was not powered by a star-planet interaction, contrary to the claim by Retter & Marom (2003). (2) The three star-planet ILOTs occupy a relatively well define area in the energy-time diagram that is clearly below those that are thought to be powered by stellar-binary systems. (3) The star-plant ILOTs have typical timescales that are much longer than the dynamical time of the star, by about two orders of magnitude and more. This might suggest a powering process that is much longer than the dynamical time scale. An accretion disk that is formed by the planet might have this property (e.g., Bear, Kashi, & Soker 2011). (4) The timescale of the star-planet ILOTs is not necessarily well defined, as a plateau phase in their lightcurve might be very long. Nonetheless, their decline phase might have a similar behavior as regular ILOTs (e.g., Kashi et al. 2019). (5) The recently added star-planet ILOT, ZTF SLRN-202 (De et al. 2023), does not seem to be a young system as the other two are. Despite that it occupies the same general area of the other two star-planet ILOTs and close to the area that Kashi & Soker (2017) mark to be due to star-planet interaction in young planetary systems (green lines on the lower left of the diagram). This suggests that there are common powering processes to these three ILOTs. A common properties might results from accretion disks that launch jets. I turn to study this possibility.

3. THE ROLES OF JETS

Observations and theoretical arguments suggest that jets play major roles in many ILOTs (Red Novae). Observations of ILOTs that have a spatially resolved ejecta show the ILOTs to possess bipolar structures that strongly hint at shaping by jets. These include the Great Eruption of Eta Carinae (Davidson, & Humphreys 1997), a luminous blue variable (LBV) with its bipolar Homunculus nebula, V4332 Sgr that has a bipolar structure (Kaminski et al. 2018), and Nova 1670 (CK Vulpeculae) with a 350-years old bipolar nebula (Shara et al. 1985) that has an S-morphology (Kaminski et al. 2020; Kamiński et al. 2021), a morphological type that must be shaped by jets.

Theoretically, jets are very efficient in powering ILOTs and more efficient than equatorial ejecta (Soker 2020; for powering by equatorial ejecta see, e.g., Pejcha et al. 2016a,b; Metzger, & Pejcha 2017). Specific studies show that jets can account for the lightcurves of at least some ILOTs (e.g., Soker 2020; Soker & Kaplan 2021). These studies were aiming at ILOTs powered by stellar binary

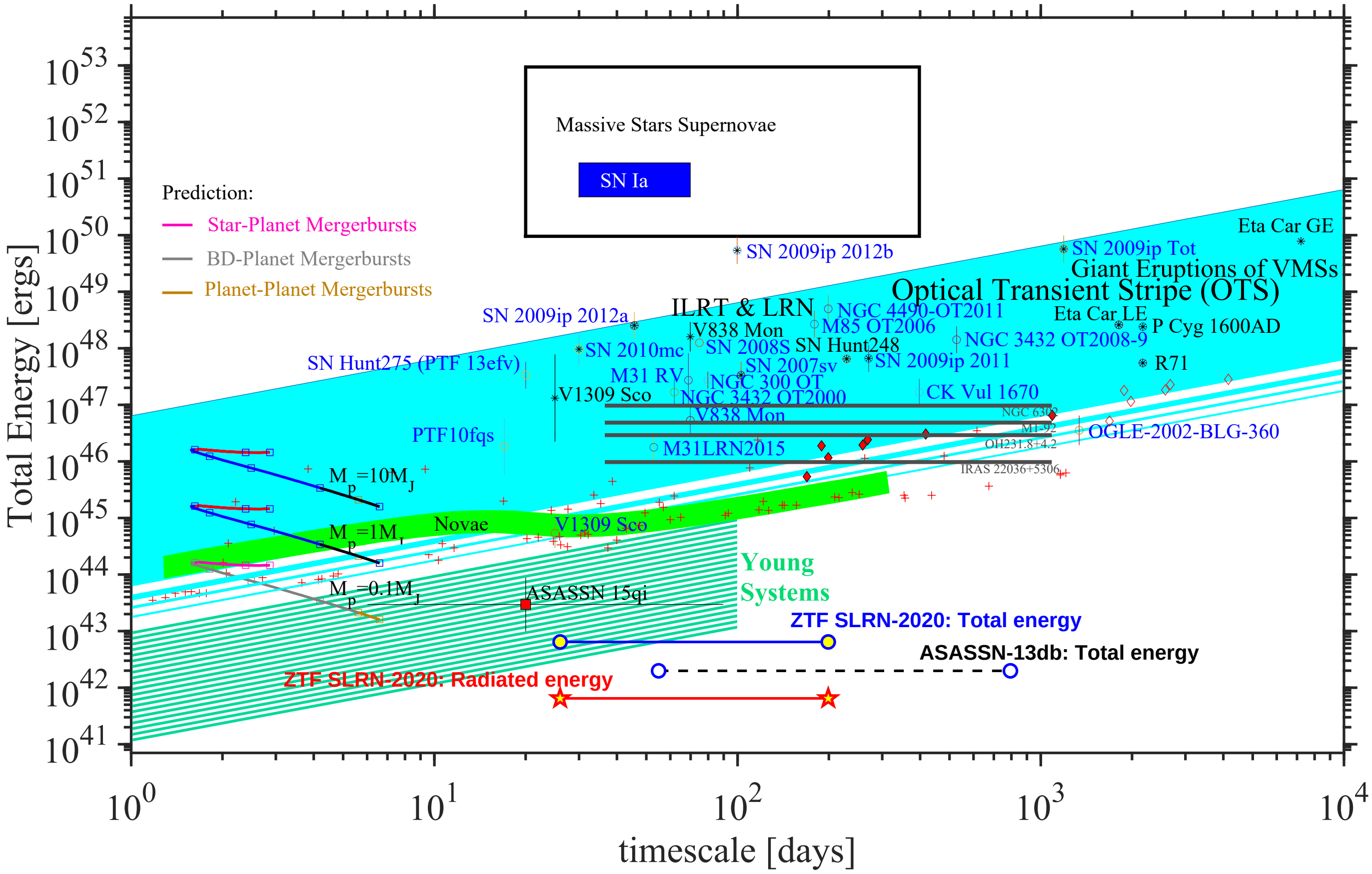

Figure 1. Observed transient events on the energy time diagram adapted from Kashi & Soker (2017) (where more details can be found). Blue empty circles represent the total (radiated plus kinetic) energy of the observed transients as a function of the duration of their eruptions, i.e., usually the time for the visible luminosity to decrease by 3 magnitudes. The three lines on the left are theoretical estimates for ILOTs powered by planet-brown dwarf (BD) interaction (Bear, Kashi, & Soker 2011). Kashi & Soker (2017) place the ILOT ASASSN-15qi (observational data from Herczeg et al. 2016) and argued it was powered by a star-planet interaction. I added ASASSN-13db (observational data from Sicilia-Aguilar et al. 2017) with its estimated total energy that Kashi et al. (2019) claimed to have been powered by a star engulfing planet debris, and ZTF SLRN-2020 from De et al. (2023) who argued it was powered by a star engulfing a planet. Both the radiated energy (yellow-filled red stars) and the crudely estimated total energy (radiation + kinetic; two yellow-filled blue circles) are shown with the timescale range of ZTF SLRN-2020 (see text). The timescale range is not due to uncertain observations, but rather in the way that one defines the timescale, total duration or decline rate. The lower-left part (hatched in green) is the extension that Kashi & Soker (2017) made to include young star-planet systems. The new observations suggest that old star-planet systems also populate this region. Abbreviation: BD: brown dwarf; GE: Great Eruption; ILRT: intermediate luminosity red transient; LRT: luminous red transient; SN: supernova; VMSs: very massive stars;

interaction. I turn to suggest that the planet in ZTF SLRN-2020 also launched jets (or disk-wind).

I consider the following parameters that De et al. (2023) infer for the planetary system ZTF SLRN-2020. A stellar mass of $M_1 \simeq 1 M_\odot$, a stellar radius of $R_1 \simeq 1-4 M_\odot$, and a planet mass of $M_{\rm p} \simeq 0.01 M_\odot$. For the planet to expel mass from the system or to accrete mass it should orbit very close to the stellar surface. For a solar mass and an orbit at $a = 2 R_\odot$ the orbital velocity is $v_{\rm orb} = 310 {~\rm km} {~\rm s}^{-1}$. The radius of the planet of the above mass is $R_{\rm p} \simeq 0.1 R_\odot$ (e.g., Bashi et al. 2017), and so the escape velocity from the planet is $v_{\rm p,es} \simeq 200 {~\rm km} {~\rm s}^{-1}$.

The ILOT ZTF SLRN-2020 had months of pre-outburst activity, including mass loss (De et al. 2023). I consider a process by which the planet accreted mass and launched jets (or a bipolar disk wind). As is the case with stellar winds, the typical terminal velocity of jets is about the escape velocity from the object that launches the jets. The properties of jets might change over short timescales relative to their total activity time period. Some parts in the jets during some jet-launching episodes might have terminal velocities that are larger than the escape velocity, i.e., $v_{\rm jet,m} = \beta v_{\rm p,es}$ with $\beta > 1$. For the parameters I take above, the escape velocity from the star at the location of planet is

$v_{1,\rm e} = 2^{1/2} v_{\rm orb} \simeq 440~{\rm km~s^{-1}}$. Because the jets are launched perpendicular to the orbital plane, the terminal velocity of the fastest parts of the jets relative to the star is

$$v_{\rm jet,m,1} = \sqrt{(\beta v_{\rm p,es})^2 + v_{\rm orb}^2}. \quad (1)$$

These segments of the jets escapes the system if $v_{\rm jet,m,1} > v_{1,\rm es}$, which reads $\beta > v_{\rm orb}/v_{\rm e,p} \simeq 1.5$. The property of this system that the escape velocity from the planet is of the same order of magnitude as the escape velocity from the system implies that some jets segments can reach the escape velocity, but not by much. These jet segments barely escape the star. If they do, their final outflow velocity from the system is much smaller than the escape velocity from the system.

I suggest that this explains the slow outflow velocity of the dust $\approx 35~{\rm km~s^{-1}} \ll {\rm v_{orb}}$. Because the outflow velocity from the planet of the escaping gas/dust, which is perpendicular to the orbital plane, is about equal to the orbital velocity, the outflow direction of the escaping dust/gas in this case is about $\theta_{\rm j} \approx 45^\circ$ to the equatorial plane. This forms a bipolar outflow morphology, in addition to possible concentration of outflowing gas/dues in the equatorial plane.

The accreted mass onto the planet forms an outer layer around the planet. When the planet spirals-in closer to the stellar surface, the planet might lose this material back to the star, hence forming an accretion disk around the star. This accretion disk might launch much faster jets. These jets might play a role in powering the main outburst, as was suggested for ILOTs power by stellar binary systems.

If we take the lowest mass range of masses that De et al. (2023) discuss for the planet in ZTF SLRN-2020, $M_{\rm p} \simeq 10^{-4} M_\odot$, then we are in a different regime. The average density of such planets is $< 1~{\rm g~cm^{-1}}$ and they might be tidally disrupted by a sun like star on the main sequence. This brings the scenario to be much more similar to what Kashi & Soker (2017) suggested for the young system ASASSN-15qi and Kashi et al. (2019) suggested for the young system ASASSN-13db. However, De et al. (2023) consider the tidal disruption of the planet to be unlikely.

4. SUMMARY

The goal of this study is to group the newly analyzed (De et al. 2023) star-planet ILOT (Red Nova) ZTF SLRN-2020 with the two other star-planet ILOTs, ASASSN-15qi (Kashi & Soker 2017) and ASASSN-13db (Kashi et al. 2019). I added ASASSN-13db and ZTF SLRN-2020 to the energy-time diagram of ILOTs (Fig. 1). These three star-planet ILOTs occupy a well defined area in that diagram, below all other ILOTs and below classical novae. They are in the general area that was marked as ILOTs in young star-planet interactions. The new event ZTF SLRN-2020 is not a young system, but nonetheless located in the same area. This might points to a similar powering mechanism.

I suggested (section 3) that one of the common ingredients might be the launching of jets by the star. For the ILOT ASASSN-15qi that occurred in a young planetary system Kashi & Soker (2017) suggested that the star tidally disrupted the planet, forming an accretion disk that launched the jets during the event. In the star-planet ILOT ZTF SLRN-2020 the star engulfed the planet rather than tidally disrupted the planet (De et al. 2023). I suggested that the planet accreted some mass from the star in the months before the main outburst. At the early phase of the outburst as the planet spiralled-in close to the star the star tidally removed the accreted mass. This formed an accretion disk around the star that launched jets. This suggested process must be confirmed by three-dimensional hydrodynamical simulations.

I also suggested that the planet launched jets as it accreted mass. These formed the slowly expanding outflowing dust. The jets that the planet launched form a concentrated outflow at $\approx 45^\circ$ to the equatorial plane. The jets that the star might have launched are perpendicular to the equatorial plane. Overall, I expect the outflow from ZTF SLRN-2020 to form a bipolar nebula, as other ILOTs have, e.g., Nova 1670 (CK Vulpeculae; Kaminski et al. 2020; Kamiński et al. 2021; section 3).

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