Pre-explosion, explosion, and post-explosion jets in supernova SN 2019zrk

Noam Soker

Department of Physics, Technion, Haifa, 3200003, Israel; soker@physics.technion.ac.il

ABSTRACT

I analyse some properties of the luminous transient event SN 2019zrk and conclude that jets were the main powering sources of the pre-explosion outburst (pre-cursor) and ejection of a massive circumstellar matter (CSM), of the very energetic explosion itself, and of the post-explosion bump in the light curve. The pre-explosion energy source is mainly a companion (main sequence, Wolf-Rayet, neutron star or black hole) star that accreted mass and launched jets. I find that the fast expansion of the CSM after acceleration by the explosion ejecta requires the explosion energy to be $\gtrsim 10^{52}$ erg. Only jet-driven explosions can supply this energy in such SN 2009ip-like transients. I conclude that ejecta-CSM interaction is extremely unlikely to power the bright bump at about 110 days after explosion. Instead, I show by applying a jet-driven bump toy-model that post-explosion jets are the most likely explanation for the bump. I leave open the question of whether the explosion itself (main outburst) was a core collapse supernova (CCSN) or a common envelope jets supernova (CEJSN). In this study I further connect peculiar transient events, here 2009ip-like transient events, to CCSNe by arguing that jets drive all events, from regular CCSNe through superluminous CCSNe and to many other peculiar and super-energetic transient events, including CEJSNe. Jet-powering cannot be ignored when analyzing all these types of transients.

Keywords: supernovae: general – supernovae: individual: SN 2019zrk, SN 2009ip – circumstellar matter - stars: jets

1. INTRODUCTION

The SN 2009ip-like (2009ip-like) class includes several transients that show prominent pre-cursor with a light curve that has relatively fast rise and decline to peak luminosity, bumps during the decline phase, and cannot be explained by regular core collapse supernovae (CCSNe). Either there are extra ingredients in a CCSN scenario, or they are descendants of different evolutionary routes. In addition to SN 2009ip (e.g., Smith et al. 2010; Fraser et al. 2013; Mauerhan et al. 2013; Pastorello et al. 2013; Graham et al. 2014; Smith et al. 2022), some other class members that show (most of) these properties are SN 2010mc (e.g., Ofek et al. 2013; Smith, Mauerhan, & Prieto 2014), SN 2013gc (Reguitti et al. 2019), LSQ13zm (Tartaglia et al. 2016), SN 2015bh (e.g., Elias-Rosa et al. 2016; Thöne et al. 2017), SN 2016bdu (e.g., Pastorello et al. 2018), and AT 2016jbu (e.g., Bose et al. 2017; Kilpatrick et al. 2018; Brennan et al. 2022a).

In this study I will refer to the main luminosity peak as ‘explosion’, to the pre-cursor as the pre-explosion phase, and to the late decline phase of the light curve as the post-explosion phase. I note though that the ‘explosion’ is not necessarily a terminal explosion that ends the evolution, e.g., of a binary system, neither it implies the collapse of the core, although this might be the case.

Most researchers agree that these events involve a massive circumstellar matter (CSM). However, there is no consensus on some basic ingredients of 2009ip-like events. One issue in disagreement is the powering of the main events. One view (e.g., Smith, Mauerhan, & Prieto 2014 for SN 2009ip) is that, at least in some cases, the precursor (pre-explosion outburst) is a CCSN event and that the main peak of the light curve (the ‘explosion’) results from ejecta-CSM interaction. Another class of possibilities is that the explosion is a CCSN while the pre-explosion activity results from either an instability of the CCSN progenitor or from a binary interaction (section 2). Another model for SN 2009ip was the merger of a massive star with a luminous blue variable (LBV) star (Soker & Kashi 2013), and much of the energy results from accretion onto the main sequence star. Then there is the possibility that the explosion is driven by the accretion power onto a neutron star (NS) or onto a black hole (BH) companions that spiral-in in a common envelope evolution (CEE) inside the RSG envelope (e.g., Gilkis, Soker, & Kashi 2019), or deep to the RSG core (e.g., Chevalier 2012; Schröder et al. 2020).
Another issue is the role that jets play in 2009ip-like events. Jets can be launched by the newly born NS or BH at the center of the collapsing core, or by a NS/BH that experience a CEE with a RSG and/or its core. Transient events that are powered mainly by jets that a NS/BH launches inside the envelope or the core of a RSG are termed common envelope jets supernovae (CEJSNe; for some recent studies that emphasise the role of jets see, e.g., Gilkis, Soker, & Kashi 2019; Soker et al. 2019; Grichener & Soker 2019a; López-Cámara et al. 2019, 2020; Akashi & Soker 2021; Grichener & Soker 2021; Grichener, Cohen, & Soker 2021; Schreier et al. 2021; Soker 2021; Hillel, Schreier, & Soker 2022, and for studies of NS/BH merger with the RSG core that do not emphasize jets see, e.g., Fryer & Woosley 1998; Chevalier 2012; Schröder et al. 2020). Strictly speaking, if the NS/BH does not enter the core the event is a CEJSN impostor, but in this study I will use CEJSN to refer to impostors as well. The diversity of outflow properties and light-curves that CEJSNe allow (see above papers) have made them attractive scenarios for some rare peculiar explosions. These include among others the peculiar gamma ray burst (GRB) 101225A (Thöne et al. 2011), iPTF14hls (Soker & Glikis 2018), AT2018cow and other fast blue optical transients (Soker et al. 2019; Metzger 2022; Soker & Gilkis 2018), and the luminous radio transient event VT J121001+495647 (Dong et al. 2021). It is possible that some 2009ip-like events are also CEJSNe (e.g., Gilkis, Soker, & Kashi 2019; Schröder et al. 2020). In any case, I argue that jets seem to play a crucial role in some or all phases of 2009ip-like events.

In this study I argue that jets must play the major roles in the pre-explosion (section 2), in the explosion (section 3), and in the post-explosion (section 4) powering of the 2009ip-like event SN 2019zrk.

Fransson et al. (2022) present a thorough observational study of SN 2019zrk (for an early study see Strotjohann et al. 2021). It reached a maximum magnitude of $M_r = -19.2$ and showed expansion velocities of up to $v_{\text{ex}} \approx 16,000 \text{ km s}^{-1}$. Its light curve is complex, with precursor (pre-explosion emission) and bumps in its light curve. I will analyse and model the sharp and relatively bright bump centred at $t = 110 \text{ d}$ in section 4. The total radiate energy during the main outburst (which I also refer to as explosion) is $E_{\text{rad,ex}} \approx 5 \times 10^{49} \text{ erg}$. Fransson et al. (2022) point out that like the case with SN 2009ip (Margutti et al. 2014) the total radiated energy can be much larger due to substantial contribution from UV and X-rays.

By its peak magnitude of $M_r = -19.2$ SN 2019zrk is a luminous supernovae (see definition by Gomez et al. 2022). In earlier papers I argued that luminous supernovae (Soker 2022b), and more so super supernovae which have $M_r < -20$ (Soker & Glikis 2017), are most likely powered by jets, even if an energetic magnetar supply energy as well (e.g., Soker 2016a, 2017a). Reichert et al. (2022) conduct magneto-hydrodynamic simulations of jets in CCSNe and further support jet-powering of superluminous CCSNe. This discussion further motivates me to consider jet-powering of SN 2019zrk. In my summary (section 5) I will connect 2009ip-like events to other luminous and superluminous CCSNe.

## 2. PRE-EXPLOSION JETS AND MERGER-DRIVEN MASS LOSS

Like other systems in the 2009ip-like class, SN 2019zrk also displays an energetic pre-cursor, i.e., pre-explosion outburst(s). Such outbursts have some similarities with other types of outbursts of the heterogeneous class of intermediate luminosity optical transients (ILOTs; other names include gap objects; luminous red novae; intermediate luminosity red transients), e.g., as Smith et al. (2010) and Soker & Kashi (2013) discussed for SN 2009ip and Brennan et al. (2022b) discussed for AT 2016jbu.

Fransson et al. (2022) find the merger scenario to be the most promising to explain the properties of SN 2019zrk. It is not clear whether they refer to a main sequence companion that enters the envelope of a RSG as Soker & Kashi (2013) and Kashi, Soker, & Moskovitz (2013) discussed for SN 2009ip, or whether they refer to a NS (or even a BH) companion that enters the RSG envelope as Gilkis, Soker, & Kashi (2019) suggested already for SN2009ip. In both cases jets play critical roles as these points pointed out.

Let me elaborate on this by referring to two problems that Fransson et al. (2022) mention in their discussion of SN 2019zrk. Both of these have already been solved with jets.

Fransson et al. (2022) claim that a possible problem for the merger model might be the large velocity observed in the precursor of SN 2009ip, $\approx 12,000 \text{ km s}^{-1}$ (Foley et al. 2011; Pastorello et al. 2013). I disagree, because even for a main sequence companion that launches jets at $\approx 2000 - 3000 \text{ km s}^{-1}$ the interaction of the jets with the CSM can accelerate gas to velocities of $\gtrsim 10,000 \text{ km s}^{-1}$, as Tsebrenko & Soker (2013) showed for parameters that fit SN 2009ip and Akashi & Kashi (2020) showed for the parameters that fit the Great Eruption of Eta Carinae (an energetic ILOT event). For a NS/BH companion that might launch very fast jets, as in the CEJSN scenario, this is not a problem at all, as Gilkis, Soker, & Kashi (2019) argued for SN 2009ip.
The second problem that Fransson et al. (2022) mention relates to the formation of a massive CSM just before the explosion. Fransson et al. (2022) write that the energy that core-convection-driven waves (e.g., Quataert & Shiode 2012; Wu & Fuller 2021) carry to the envelope of massive RSG stars is too low to explain the ejection of a pre-explosion massive CSM. Mcley & Soker (2014) already solved this problem. Mcley & Soker (2014) found indeed that the main outcome of energy that the waves deposit to the RSG envelope is envelope expansion rather than mass ejection. They concluded that pre-explosion outbursts result from the accretion energy that a binary companion releases as it accretes mass from the extended envelope. Daniël & Soker (2019) studied this process for a NS companion that accretes mass from the inflated envelope and launches jets.

Fransson et al. (2022) conclude that "... we believe that the low mass alternative, involving a merger, is the one with the least problems." I accept this, and add that jets constitute the main powering of the outflow. Of course, the energy source is the accretion onto the NS companion, as with all CEJSNe. This basic idea goes back to Soker & Kashi (2013) and Kashi, Soker, & Moskovitz (2013) who discussed merger with a main sequence companion (also Soker & Kashi 2016 for accretion and jets in SN 2015bh). However, for the more luminous SN 2019zrk I prefer the CEJSSN scenario, where the companion that enters a CEE with the RSG is a NS as Gilkis, Soker, & Kashi (2019) suggested already for SN2009ip. Schröder et al. (2020) consider the CEJSSN scenario for SN 1998S, which is a 09-like SN.

My main point in this section is that jets powered the pre-explosion outburst (pre-cursor) of SN 2019zrk, as I schematically show in the second panel of Fig. 1. I suggest that this outburst was preceded by a longer CEE phase (first panel of Fig. 1).

3. EXPLOSION JETS

In this section I show that both the CSM model that Fransson et al. (2022) consider and an alternative CSM model that I discuss here require that jets power the explosion (main outburst) of SN 2019zrk.

The spectra of SN 2019zrk (figure 6 of Fransson et al. 2022) at early times $t \lesssim 45$ day are composed from a blue continuum with superimposed narrow emission lines with faint broad wings that Fransson et al. (2022) attribute to electron scattering. At $t \approx 45$ day and later the spectra show a broad and asymmetric line profile of Hα. Fransson et al. (2022) conclude that the Hα emission is decoupled from the thermalization photosphere.

To explain the transition from narrow to broad Hα emission lines at $t \approx 45$ days Fransson et al. (2022) build a flow model where the CSM is optically thick during the early time period. They then estimate the CSM mass in front of the shock at 50 days to be $M_{\text{CSM,F22}} = 0.96 M_\odot$, where ‘F22’ marks quantities as Fransson et al. (2022) deduce. Such a CSM mass has a severe demand on the explosion energy. Because the line widths even at $t = 110$ days show a velocity of $v_{\text{ex}} \approx 16,000$ km s$^{-1}$, the explosion ejecta must accelerate the hydrogen-rich shell to these velocities. Since very little energy relative to the explosion energy is radiated away, I consider energy conservation. Consider an ejecta shell of mass $M_\text{f}$ at the front of the ejecta moving with a velocity of $v_\text{ej}$ and colliding with the shell of mass $M_{\text{CSM}}$. The collision accelerates the CSM to velocity $v_{\text{ex}}$. Energy conservation reads

$$\frac{1}{2} M_\text{f} v_{\text{ej}}^2 \simeq \frac{1}{2} (M_\text{f} + M_{\text{CSM}}) v_{\text{ex}}^2. \quad (1)$$

The collision will take place at radius $v_\text{ej} \times 50$ days, the distance of the front of the ejecta, rather than at $v_{\text{ex}} \times 50$ days as Fransson et al. (2022) take. The demand of optically thick CSM implies that the CSM mass now is $M_{\text{CSM}} = M_{\text{CSM,F22}} v_\text{ej} / v_{\text{ex}}$. Substituting this mass in equation (1) and demanding minimum possible ejecta energy to obey energy conservation I find the ejecta velocity to be $v_\text{ej} = 2^{1/2} v_{\text{ex}}$, where here $v_{\text{ex}} = 16,000$ kms$^{-1}$, and $M_\text{f} = 2 M_{\text{CSM,F22}} = 1.92 M_\odot$. The constraint on the total energy of the ejecta under the condition of optically thick CSM is then

$$E_{\text{ej},\text{tot}} > 2 \times 10^{52} \left( \frac{f_{E,\text{f}}}{0.5} \right)^{-1} \left( \frac{f_\text{k}}{1} \right)^{-1} \left( \frac{M_{\text{CSM,F22}}}{0.96 M_\odot} \right) \text{erg}, \quad (2)$$

where $f_{E,\text{f}}$ is the fraction of the energy that the front of the ejecta that collides with the CSM has relative to the entire ejecta, and $f_\text{k}$ is the fraction of energy that ends as kinetic energy rather than thermal energy during the collision. This minimum energy requires the CSM mass to be twice as large as what Fransson et al. (2022) find. The energy is not likely to be at its minimum, and the total ejecta energy is likely to be much larger.

The conclusion from this discussion is that the model that Fransson et al. (2022) build for the CSM demands an extremely energetic explosion with an explosion energy of $E_{\text{ej},\text{tot}} \simeq \text{several } \times 10^{52}$ erg. Only jets can supply this energy as the neutrino-driven mechanism is limited to explosions energies of $\lesssim 3 \times 10^{51}$ erg (e.g. Ertl et al. 2016; Sukhbold et al. 2016).

Another problem is as follows. In many cases the collision of the ejecta with the CSM is applied to explain bright supernovae. But for the above parameters the collision channelled a negligible amount of energy to radiation. The total observed radiated energy at $t > 50$ days
Onset of a strong binary interaction.
A compact companion strongly interacted with the RSG progenitor of SN 2019zrk for \(\approx 1\) year and at \(\approx 20 - 30\) years before explosion. The interaction was a common envelope phase that ejected a thin shell with a velocity of \(\approx 100\) km/sec.
The compact companion might be a main sequence star, a neutron star, or a black hole.

Precursor.
At about 100 days before the explosion the companion was very close to the core and another strong interaction phase removed the rest of the hydrogen-rich gas. The companion accreted mass through an accretion disk and launched jets that powered the precursor (pre-explosion outburst). The companion spun-up the core.

Explosion.
Because of the fast-rotating pre-collapse core the hydrogen-poor CCSN was driven by energetic jets that powered an energetic explosion. Narrow H\(\alpha\) lines originated from the optically thin clumpy-thin shell and possibly from a dense and massive slowly expanding equatorial outflow. We are away from the equatorial plane.

Late evolution.
At \(\approx 45\) day the ejecta collided with the clumpy-thin shell and formed the wide H\(\alpha\) lines. Later jets set two mini-explosions at \(t \approx 100\) day that powered the sharp bump.

Figure 1. A schematic description (not to scale) of the scenario that I propose in this study where the final explosion is a CCSN. Similar energetic transient events might be powered by CEJSNe, namely, where a NS/BH companion enters the core, destroys the core and launches energetic jets.
is < 2 × 10^{49} \text{ erg}. The acceleration of the CSM requires a minimum energy of 0.5M_{\text{CSM, F22}}v_{\text{ex}}^2 = 2.4 × 10^{51} \text{ erg}. Namely, the very energetic collision channels < 1% of the collision energy to radiation. This is a very small ratio that requires an explanation considering that the shell optical depth is ≈ 1 at collision time in the model of Fransson et al. (2022) and that collision takes place at a very large radius (hence the gas suffers little adiabatic cooling in the following several weeks).

As a plausible alternative, I propose a model with a much lower-mass CSM. I propose that the photosphere up to t ≈ 45 days was hydrogen-free. The narrow emission lines result from the CSM that has been ionised from the explosion time on, as in the model of Fransson et al. (2022). But I do not require this CSM to be optically thick. Therefore, its mass might be much smaller, namely, I require that the mass that the ejecta collided with in the first ∼ 110 days is M_{\text{CSM}} < 1M_\odot. The CSM resides in a dense shell in the zone r > v_{\text{ej}} × 50 days. The velocity of the ejecta can be larger than the maximum observed velocity, v_{\text{ej}} > v_{\text{ex}} = 16,000 \text{ km s}^{-1}, but after the ejecta-CSM collision the velocity is v_{\text{ex}} ≈ 16,000 \text{ km s}^{-1}. The hydrogen shell is sufficiently dense to have a strong Hα emission.

Let me give one example of a set of plausible physical values. Consider the front of the ejecta that collides with the CSM to expand with a velocity of v_{\text{ej}} ≈ 20,000 \text{ km s}^{-1} and have a mass of M_{\text{ej, front}}. Here I apply momentum conservation as I require that the CSM is accelerated in a very short time, before the shocked CSM and shocked ejecta have time to adiabatically cool and channel thermal energy to kinetic energy. Using energy conservation will require less ejecta energy even. To accelerate the CSM shell of mass M_{\text{CSM}} to v_{\text{ex}} = 16,000 \text{ km s}^{-1} the requirement from momentum conservation is M_{\text{ej, front}} = 4M_{\text{CSM}}. The energy that the front of the ejecta carry is E_{\text{ej, front}} ≈ 3.2 × 10^{51} (M_{\text{CSM}}/0.2M_\odot) \text{ erg}. The energy that is dissipated to thermal energy during the collision is E_{\text{dis}} = 0.2E_{\text{ej, front}}.

This very fast ejecta front that collides with the CSM might crudely carry fifth of the ejecta mass and a larger fraction of its energy. For example, for an ejecta density of ρ_{\text{ej}} ∝ r^{-1} (e.g., Suzuki & Maeda 2019) the fraction of mass in the velocity range of 18,000 km s^{-1} to the maximum value of v_{\text{ej}} = 20,000 that I expect to collide with the CSM during the time period t = 40 days (just before the time of the first spectrum with wide lines) to t = 80 days (just before the time of the first spectrum with wide lines) carry a fraction of 0.19 of the total ejecta mass. It carry a fraction of ≈ 35% of the ejecta energy. Overall, the constrain on the ejecta mass and energy under the assumption of v_{\text{ej}} ≈ 20,000 km s^{-1} and the observations of v_{\text{ex}} ≈ 16,000 km s^{-1} are

\[ M_{\text{ej}} \approx 4 \left( \frac{M_{\text{CSM}}}{0.2M_\odot} \right) M_\odot, \]  

and

\[ E_{\text{ej}} \approx 10^{52} \left( \frac{M_{\text{CSM}}}{0.2M_\odot} \right) \text{ erg}, \]

respectively. These values are not unique. I only point out the possibility of an event of lower mass and energy than what the model of Fransson et al. (2022) requires. In section 4 I will consider parameters that are between these two models.

The maximum Hα luminosity is \( L_{\text{Hα}}(\text{obs}, m) \approx 2 \times 10^{41} \text{ erg s}^{-1} \) (Fransson et al. 2022). To account for this luminosity I need to constrain the properties of the hydrogen-rich shell that I place at a radius of \( R_s = 20,000 \text{ km s}^{-1} \times 45 \text{ day} = 7.8 \times 10^{15} \text{ cm} \), where the ejecta collides with it after ∼ 45 day. I scale the shell width with ∆r = 0.05R_s, and the compression of the hydrogen-rich gas beyond the shock by β = 7. The expected maximum luminosity of this shell for Case B recombination at a temperature of 10^4 K is

\[ L_{\text{Hα}} \approx 3 \times 10^{41} \left( \frac{M_{\text{CSM}}}{0.2M_\odot} \right)^2 \times \left( \frac{\Delta r}{0.05R_s} \right)^{-1} \left( \frac{\beta}{7} \right) \text{ erg s}^{-1}. \]

Such a shell can account for the observed maximum Hα luminosity. However, before the collision of the ejecta with the shell the shell is not compressed but the observed Hα luminosity is already \( L_{\text{Hα}}(\text{obs}) \approx 1.5 \times 10^{41} \text{ erg s}^{-1} \) (Fransson et al. 2022). Therefore, to account for the Hα luminosity at early time as well the shell must be denser. Either it is more massive with \( M_{\text{CSM}} \approx 0.4M_\odot \) and/or it is clumpy with dense clumps. Even for a mass of \( M_{\text{CSM}} \approx 0.4M_\odot \) the optical depth of such a shell is \( \tau \approx 0.33 \). Therefore, it is indeed optically thin. I prefer to consider a very clumpy shell with a mass of \( M_{\text{CSM}} \approx 0.2 - 0.3M_\odot \). Future hydrodynamical simulations that include radiative transfer should explore such a flow structure.

I also note that the Hα to Hβ luminosity ratio at early times is larger than a simple Case B recombination. This points to a more complicated flow structure. For example, there might be very low-mass ejecta at very high velocities, namely very large energy but very small momentum, that collides with the dense shell at very early times. This collision adds to the excitation of hydrogen in the shell but does not accelerate it much, in particular if the shell is composed of dense clumps. Another possibility is that there is a massive hydrogen-rich equatorial
slow outflow, i.e., in the equatorial plane of the system (e.g., SN 1987A) that is more or less on the plane of the sky (see below) starting close to the star. Therefore the collision of the fast ejecta with this equatorial outflow takes place at early times. Part of the Hα emission is due to the collision of the very fast (and optically thin) ejecta with this dense equatorial outflow.

I emphasize again that I differ from Fransson et al. (2022) mainly in that I do not demand the CSM to be optically thick in the first ~ 50 days. This leads to a model with lower explosion energy and lower ejecta mass. The question then is where is the heavy hydrogen-rich envelope? In this scenario it is either concentrated in an equatorial dense outflow (as I mentioned above; see Fig. 1), or it was expelled at a much earlier time. Better, both effects. Namely, some of the hydrogen-rich envelope was expelled as the NS interacted with the envelope before it entered a CEE. Only after thousands of years or more the NS entered a CEE with the RSG progenitor.

The main conclusion of this section is that the explosion energy is \( E_{ej} \gtrsim 10^{52} \), and that only jets can supply this explosion energy, whether in a CCSN event or in a CEJNS event.

4. POST-EXPLOSION JETS

4.1. The bump in the declining phase

In this section I consider the sharp bump that lasts from \( t \approx 95 \) days and reach a peak luminosity at \( t_{\text{bump}} \approx 110 \) days, and then declines on a similar time scale. I take the observed timescale of the bump to be \( t_{b,\text{obs}} = 15 \) days. Fransson et al. (2022) find the total extra radiated energy in this bump to be \( E_{\text{rad,b}} \approx 1.8 \times 10^{48} \text{ erg} \). For a later application I take the ‘typical maximum luminosity’ of the bump to be \( L_{b,\text{obs}} = E_{\text{rad,b}}/t_{b,\text{obs}} \approx 1.4 \times 10^{42} \text{ erg s}^{-1} \).

A key observation to this discussion is that the spectra at \( t = 83 \) days (pre-bump) and at \( t = 109 \) days (bump) are very similar.

4.2. Limitations of CSM powering

Fransson et al. (2022) attribute the powering of the bump to the collision of the ejecta with a CSM density enhancement at \( t \approx 110 \) days, and at \( R_{\text{EC}} = t_{\text{bump}}v_{\text{ex}} \approx 1.5 \times 10^{16} \). The similarity of the spectra at \( t = 83 \) days and at \( t = 109 \) days shows that the extra heating must affect both the photosphere and the Hα emitting gas in a similar manner. For example, an increase in the Hα emission due to the compression of the emitting region will not affect the photosphere, hence this cannot be an explanation to the bump.

At \( t \approx 110 \) days the photosphere is at \( R_{\text{ph}} = 2.3 \times 10^{15} \text{ cm} \approx 0.15R_{\text{EC}} \) (Fransson et al. 2022). From geometrical considerations the fraction of the energy that the ejecta-CSM interaction radiates at \( R_{\text{EC}} \) that reaches the photosphere is (e.g., Chevalier & Fransson 1994)

\[
\begin{align*}
  f_{\text{ph}} &= \frac{1}{2} \left( 1 - \sqrt{1 - \frac{R^2_{\text{ph}}}{R^2_{\text{EC}}}} \right) \\
  &= \frac{1}{4} \frac{R_{\text{ph}}}{R_{\text{EC}}} \left( \frac{R_{\text{ph}}}{0.15R_{\text{EC}}} \right)^2.
\end{align*}
\]

The ejecta-CSM collision is very inefficient in powering the bump. The total dissipated energy in the collision should be

\[
E_{\text{EC}} \approx 10^{51} \left( \frac{E_{\text{rad,b}}}{1.5 \times 10^{48} \text{ erg}} \right) \left( \frac{f_{\text{EC,rad}}}{0.5} \right)^{-1} \times \left( \frac{f_{\text{ph,rad}}}{0.5} \right)^{-1} \text{ erg},
\]

where \( f_{\text{EC,rad}} \) is the fraction of energy that ends in radiation in the ejecta-CSM collision and \( f_{\text{ph,rad}} \) is the fraction of the radiation of the photosphere that ends in the visible (observed band). For example, some X-ray radiation from the collision region might simple be reflected by the photosphere and will not contribute to the increase in the visible luminosity.

Although the amount of energy that equation (7) gives is possible to release in the collision, e.g., if the ejecta collides with a CSM extra mass of \( \approx 0.2M_\odot \), it seems to be an extreme case because the collision should take place within 15 days.

The larger problem is that this collision has no marks on the spectrum (because the spectra at \( t = 83 \) days and at \( t = 109 \) days are basically identical). The CSM and ejecta are shocked to X-ray emitting temperatures in such a collision of a relative velocity of \( \gtrsim 10^4 \text{ km s}^{-1} \). However, to be efficient in radiating the energy in about 15 days the shell should cool to low temperatures where it emits in the visible. Otherwise, \( f_{\text{EC,rad}} \ll 0.5 \) and the demand on the collision energy is much larger. Therefore, in such a case the cooling shell will affect the spectrum.

My conclusion is that it is extremely unlikely that ejecta-CSM collision powered the bump at \( t_{\text{bump}} \approx 110 \) days. I turn to a powering by jets from the central NS, either a newly born NS in a CCSN or an old NS in a CEJNS event.

4.3. Powering the bump with jets

I use the toy model that Kaplan & Soker (2020) built to estimate the timescale and luminosity of a jet-driven
bump in the light curve of CCSNe. I refer to this interaction in the last panel of Fig. 1.

The toy model assumes that the two opposite jets that the central NS (or a BH) launches are active for a very short time. The toy model assumes then that the interaction of the jets with the ejecta lasts for a very short time. Kaplan & Soker (2020) term the short interaction of each of the two jets with the ejecta as an off-center ‘mini-explosion’. The jet-ejecta interaction shocks a zone around the interaction region, the ‘cocoon’ (one cocoon per each of the two jets). By a simple analytical derivation Kaplan & Soker (2020) find the following expressions for the typical time scale (rise time) of the bump and for the extra luminosity of the bump

\[ t_{\text{toy,b}} = 56 \left( \frac{\epsilon_{E}}{0.01} \right)^{-1/4} \left( \frac{\epsilon_{V}}{0.067} \right)^{3/4} \left( \frac{\kappa_{c}}{0.38 \, \text{cm}^2 \, \text{g}^{-1}} \right) \left( \frac{M_{\text{SN}}}{10 M_{\odot}} \right)^{3/4} \frac{1}{d} \]  

(8)

and

\[ L_{\text{toy,b}} = 4.2 \times 10^{41} \left( \frac{\epsilon_{E}}{0.01} \right)^{-1} \left( \frac{\epsilon_{V}}{0.067} \right)^{-1} \left( \frac{\kappa_{c}}{0.38 \, \text{cm}^2 \, \text{g}^{-1}} \right) \left( \frac{M_{\text{SN}}}{10 M_{\odot}} \right)^{-3/2} \left( \frac{t_{1.0}}{100 \, \text{d}} \right) \]  

(9)

respectively. In the above expressions \( \epsilon_{E} \equiv E_{1j}/E_{\text{SN}} \), where \( E_{1j} \) is the energy that one jet deposits into one cocoon, \( E_{\text{SN}} \) is the total energy of the ejecta (mainly kinetic energy at late times), \( M_{\text{SN}} \) is the total ejecta mass, \( \epsilon_{V} \equiv M_{\text{co}}/M_{\text{SN}} \), where \( M_{\text{co}} \) is the mass in one cocoon, \( \alpha_{j} \) is the half opening angle of each jet, \( \kappa_{c} \) is the opacity, and \( \beta \) is the ratio of the radius at which the ‘mini-explosion’ occurs to the ejecta outer radius. For the jet-ejecta interaction time (the time of the mini-explosion) I scale in this study with \( t_{1.0} = 100 \) days.

According to the properties of the bump of SN 2019zkp (section 4.1) I also use the following constraints on some toy model variables. For the rise time of the bump and its total radiated extra energy I get

\[ t_{\text{toy,b}} = 15 \, \text{d} \]  

(10)

and

\[ L_{\text{toy,b}} = E_{\text{rad,b}} \simeq 1.8 \times 10^{48} \, \text{erg} \]  

(11)

respectively. I assume that the front of the ejecta moves at a faster velocity than the observed velocity after ejecta-CSM collision of \( v_{\text{ex}} \simeq 1.6 \times 10^{4} \, \text{km} \, \text{s}^{-1} \) (section 3), and take

\[ E_{\text{SN}} = 0.3 M_{\text{SN}} (2 \times 10^{4} \, \text{km} \, \text{s}^{-1})^{2} = 2.39 \times 10^{52} \left( \frac{M_{\text{SN}}}{10 M_{\odot}} \right) \, \text{erg} \]  

(12)

Since by the time of the bump the photosphere has already moved deep into the ejecta (section 4.2) I take a lower value of the radius of jet–ejecta interaction, i.e., I take \( \beta = 0.1 \) instead of \( \beta = 0.5 \). For the same reason I take a lower value of the mass of the ejecta that the jet interacts with \( \epsilon_{V} < 0.067 \), i.e., I scale here with \( \epsilon_{V} = 0.01 \). For lack of further information I leave the variables \( \kappa_{c} \) and \( \sin \alpha_{j} \) as in the scaling of Kaplan & Soker (2020).

I emphasize that the set of the toy model parameters is not unique. My goal is to demonstrate that a jet-powered bump can work for reasonable physical values.

From equations (8), (10) and (12) I find with the above value of \( \beta \) and \( \epsilon_{V} \)

\[ 2 \simeq \left( \frac{\epsilon_{E}}{0.01} \right)^{-1/4} \left( \frac{\epsilon_{V}}{0.01} \right)^{3/4} \left( \frac{\kappa_{c}}{0.38 \, \text{cm}^2 \, \text{g}^{-1}} \right)^{1/2} \left( \frac{M_{\text{SN}}}{10 M_{\odot}} \right)^{1/2} \]  

(13)

while from equations (9) - (12) I find

\[ 0.06 \simeq \left( \frac{\epsilon_{E}}{0.01} \right)^{-1} \left( \frac{\epsilon_{V}}{0.01} \right)^{-1} \left( \frac{\kappa_{c}}{0.38 \, \text{cm}^2 \, \text{g}^{-1}} \right)^{-1} \left( \frac{t_{1.0}}{100 \, \text{d}} \right) \]  

(14)

The solution of equations (13) and (14) for the last two parameters of the toy model reads

\[ \epsilon_{E} \simeq 6 \times 10^{-4} \quad \text{and} \quad M_{\text{SN}} \simeq 10 M_{\odot} \]  

(15)

I emphasise again that this is not a unique solution, but rather presents a plausible set of values. For these values and using equation (12) the two jets together carry an energy of

\[ E_{2j} \simeq 2.9 \times 10^{59} \, \text{erg} \simeq 16 E_{\text{rad,b}}. \]  

(16)

About 6% of the total energy of the two post-explosion jets that power the bump ends in the bump extra radiation.

The modelling procedure of bumps with mini-explosions assumes that the cocoon and jets do not breakout from the photosphere. Namely, the very hot cocoon stays inside the photosphere. This implies that the mini-explosion does not lead to UV/X-ray burst. The main effect is to heat somewhat the polar caps of the photosphere (along the jets’ axis), and by that to increase the luminosity. Much more energetic jets might lead to strong shock-breakout and UV/X-ray burst. Namely, the hot cocoon reaches the photosphere. In that case the interaction is no longer a mini-explosion. On the other extreme of mini-explosions that are powered by weak and brief jets there are very strong jets that might last for a long time. Such very energetic jets might power peculiar superluminous supernova like...
SN 2018cow and similar transients, whether in CEJSN (e.g., Soker et al. 2019; Metzger 2022; Soker 2022a) or in CCSNe (e.g., Kashiyama & Quataert 2015; Tsuna, Kashiyama, & Shigeyama 2021; Gottlieb, Tchekhovskoy, & Margutti 2022b; Guarini, Tamborra, & Margutti 2022).

My main conclusion from this entire section is that it is much more likely that jets powered the sharp bump in the light curve of SN 2019zrk at $t \simeq 110$ days than an ejecta-CSM interaction.

5. SUMMARY

I analysed some properties of the 2009ip-like transient SN 2019zrk (Strotjohann et al. 2021; Fransson et al. 2022), and applied jets to account for its pre-explosion, explosion, and post-explosion powering (Fig. 1).

In section 2 I presented my view that an interaction with a binary companion is the most likely explanation to the ejection of a massive CSM. The energy source of the mass ejection is mainly the accretion onto a companion, which might be a main sequence star, a WR star, or a NS/BH, and jets carry the accretion energy to the RSG envelope and by that ejecting the massive CSM. As well, jets are most likely to have powered the pre-explosion outburst (pre-cursor), as with some other ILOTs (other names include gap objects; luminous red novae; intermediate luminosity red transients).

In section 3 I considered two models for the CSM. In the first the CSM is optically thick in the first $\simeq 45$ days as Fransson et al. (2022) suggested. I found that the total ejecta (explosion) energy should be $E_{ej, tot} \simeq several \times 10^{52}$ erg (equation 2). In the second model that I discussed here the CSM is of lower mass and it is optically thin from early times. The absence of wide hydrogen lines at early times is because the ejecta is hydrogen-poor. In that case the explosion energy is $E_{ej, tot} \approx 10^{52}$ erg (equation 4). In both cases the explosion must be driven by jets because neutrino-driven explosion models cannot supply this energy.

In section 4 I analysed the powering of the short and bright (sharp) bump in the declining light curve of SN 2019zrk at $t_{bump} \simeq 110$ days. I concluded that ejecta-CSM interaction is extremely unlikely to power such a sharp bump (section 4.2). Instead, I used a toy model from the literature to present one set of parameters (not unique) for jets that might power such a bump (section 4.3). I concluded that late (post-explosion) jets are the most likely explanation for the bump of SN 2019zrk, and possibly sharp bumps in the declining lightcurves of other CCSNe, like the two bumps in the lightcurve of SN 2019tsf that Zenati et al. (2022) study in a recent paper. Late sources of accreted mass that might lead to late jet-launching include fallback after the explosion (e.g., Della Valle et al. 2006; Moriya et al. 2010; Akashi & Soker 2022; Pellegrino et al. 2022), feeding the young NS (or BH) by an inflated main sequence companion (e.g., Ogata, Hirai, & Hijikawa 2021; Hober, Bear, & Soker 2022), and the feeding of a pre-existing NS/BH by the CCSN ejecta (e.g., Fryer, Rueda, & Ruffini 2014; Becerra et al. 2015, 2019; Akashi & Soker 2020). At this time I leave all possibilities open for SN 2019zrk, as it is not clear whether it was a CCSN event or a CEJSN event.

The powering of both the pre-explosion outburst, which is similar to outbursts of some ILOTs (luminous red novae; intermediate-luminosity red transients), and late bumps by jets might be the case also in ILOTs. Some ILOTs are known to be powered by jets because of their bipolar morphology, e.g., Nova 1670 (CK Vulpeculae; Kamiński et al. 2021). I therefore raise the possibility that the sharp bump in the light curve of the luminous red novae (ILOT) AT 2021biy at about 330 to 400 days post maximum (Cai et al. 2022) was powered by jets.

On a broader scope, this study further connects peculiar transient events, specifically here 2009ip-like transient events, with CCSNe by further arguing that jets drive all these events, from regular CCSNe through superluminous CCSNe and to many other peculiar and super-energetic transient events (section 1; see Soker 2022c for a review). In recent years a number of research groups presented the view that jets power not only energetic and peculiar CCSNe, but also regular CCSNe (e.g., Soker 2010; Papish, Nordhaus, & Soker 2015; Izzo et al. 2019; Piran et al. 2019). In the majority of the CCSNe that do not have pre-collapse rapid rotation the accretion disk that launches the jets is a stochastic intermittent accretion disk that launches jitting jets (e.g., Papish & Soker 2011; Shishkin & Soker 2022). The source of the stochastic angular momentum is the pre-collapse convection motion in the core (e.g., Gilkis & Soker 2014; Quataert et al. 2019; Shishkin & Soker 2021).

This study strengthens the call to include jet-powering in the analysis of all luminous transient events of massive stars (excluding pair instability supernova; Rakavy & Shaviv 1967), whether CCSNe or CEJSNe, and most likely in analysing most CCSNe even if are not luminous.

ACKNOWLEDGMENTS

I thank Amit Kashi and an anonymous referee for useful comments. This research was supported by a grant from the Israel Science Foundation (769/20).

DATA AVAILABILITY
The data underlying this article will be shared on reasonable request to the corresponding author.

REFERENCES

Akashi M., Soker N., 2020, ApJ, 901, 53. doi:10.3847/1538-4357/abad35
Akashi M., Soker N., 2021, ApJ, 923, 55. doi:10.3847/1538-4357/ac2d2b
Akashi M., Soker N., 2022, ApJ, 930, 59. doi:10.3847/1538-4357/ac6102
Akashi M., Kashi A., 2020, MNRAS, 494, 3186. doi:10.1093/mnras/staa1014
Becerra L., Cipolletta F., Fryer C. L., Rueda J. A., Ruffini R., 2015, ApJ, 812, 100. doi:10.1088/0004-637X/812/2/100
Becerra L., Ellinger C. L., Fryer C. L., Rueda J. A., Ruffini R., 2019, ApJ, 871, 14. doi:10.3847/1538-4357/aaf6b3
Bose S., Monard L. A. G., Seidel M. K., Dong S., Hisao E., Shappee B. J., Bond H. E., et al., 2017, ATel, 9937
Brennan S. J., Fraser M., Pastorello A., Kotak R., Stevance H. F., Chen T.-W., et al., 2022a, MNRAS, 513, 5666. doi:10.1093/mnras/stac1228
Cai Y.-Z., Pastorello A., Fraser M., Wang X.-F., Filippenko A. V., Reguitti A., Patra K. C., et al., 2022, arXiv:2207.00734
Chevalier R. A., 2012, ApJL, 752, L2. doi:10.1088/2041-8205/752/1/L2
Chevalier R. A., Fransson C., 1994, ApJ, 420, 268. doi:10.1086/173557
Danieli B., Soker N., 2019, MNRAS, 482, 2277. doi:10.1093/mnras/sty2892
Della Valle M., Chincarini G., Panagia N., Tagliaferri G., Malesani D., Testa V., Fugazza D., et al., 2006, Natur, 444, 1050. doi:10.1038/nature05374
Dong D. Z., Hallinan G., Nakar E., Ho A. Y. Q., Hughes A. K., Hotokezaka K., Myers S. T., et al., 2021, Sci, 373, 1125. doi:10.1126/science.abc6037
Elias-Rosa N., Pastorello A., Benetti S., Cappellaro E., Taubenberger S., Terraner G., Fraser M., et al., 2016, MNRAS, 463, 3894. doi:10.1093/mnras/stw2253
Erft T., Janka H.-T., Woosley S. E., Sukhbold T., Ugliano M., 2016, ApJ, 818, 124. doi:10.3847/0004-637X/818/2/124
Foley R. J., Berger E., Fox O., Levesque E. M., Challis P. J., Ivans I. I., Rhoads J. E., et al., 2011, ApJ, 732, 32. doi:10.1088/0004-637X/732/1/32
Fransson C., Sollerman J., Strotjohann N. L., Yang S., Schulze S., Barbarino C., Kool E. C., et al., 2022, arXiv:2206.06497
Fryer C. L., Rueda J. A., Ruffini R., 2014, ApJL, 793, L36. doi:10.1088/2041-8205/793/2/L36
Gilkis A., Soker, N. 1998, ApJL, 502, L9
Gilkis A., Soker, N. 2014, MNRAS, 439, 4011
Gilkis A., Soker N., Kashi A., 2019, MNRAS, 482, 4233. doi:10.1093/mnras/sty3008
Gottlieb O., Tchekhovskoy A., Margutti R., 2022b, MNRAS, 513, 3810. doi:10.1093/mnras/stac910
Graham M. L., Sand D. J., Valenti S., Howell D. A., Parrent J., Hallford M., Zaritsky D., et al., 2014, ApJ, 787, 163. doi:10.1088/0004-637X/787/2/163
Grichener A., Cohen C., Soker N., 2021, ApJ, 922, 61. doi:10.3847/1538-4357/ac23dd
Grichener, A. & Soker, N. 2019, ApJ, 878, 24. doi:10.3847/1538-4357/ab1d5d
Grichener A., Soker N., 2021, MNRAS, 507, 1651. doi:10.1093/mnras/stab2233
Guarini E., Tamborra I., Margutti R., 2022, ApJ, 935, 157. doi:10.3847/1538-4357/ac7fa0
Hillel S., Schreier R., Soker N., 2022, MNRAS, 514, 3212. doi:10.1093/mnras/stac1341
Hober O., Bear E., Soker N., 2022, arXiv, arXiv:2205.11059
Izzo L., de Ugarte Postigo A., Maeda K., Thöne C. C., Kann D. A., Della Valle M., Sagues-Carracedo A., et al., 2019, Natur, 565, 324. doi:10.1038/s41586-018-0826-3
Kamiński T., Steffen W., Bujarrabal V., Tylenda R., Menten K. M., Hajduk M., 2021, A&A, 646, A1. doi:10.1051/0004-6361/202039634
Kaplan N., Soker N., 2020, MNRAS, 492, 3013. doi:10.1093/mnras/staa020
Kashi A., Soker N., Moskovitz N., 2013, MNRAS, 436, 2484. doi:10.1093/mnras/stt1742
Kashiyama K., Quataert E., 2015, MNRAS, 451, 2656. doi:10.1093/mnras/stv1164
Kilpatrick C. D., Foley R. J., Drout M. R., Pan Y.-C., Panter F. H., Coulter D. A., Filippenko A. V., et al., 2018, MNRAS, 473, 4805. doi:10.1093/mnras/stx2675
Thöne C. C., de Ugarte Postigo A., Fryer C. L., Page K. L., Gorosabel J., Aloy M. A., Perley D. A., et al., 2011, Natur, 480, 72. doi:10.1038/nature10611

Thöne C. C., de Ugarte Postigo A., Leloudas G., Gall C., Cano Z., Maeda K., Schulze S., et al., 2017, A&A, 599, A129. doi:10.1051/0004-6361/201629968

Tsebrenko D., Soker N., 2013, ApJL, 777, L35. doi:10.1088/2041-8205/777/2/L35

Tsuna D., Kashiyama K., Shigeyama T., 2021, ApJL, 922, L34. doi:10.3847/2041-8213/ac3997

Wu S., Fuller J., 2021, ApJ, 906, 3. doi:10.3847/1538-4357/abc87c

Zenati Y., Wang Q., Bobrick A., DeMarchi L., Glanz H., Rozner M., Rest A., Metzger B. D., et al., 2022, arXiv, arXiv:2207.07146