Simulating the inflation of bubbles by late jets in core collapse supernova ejecta

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ABSTRACT

We conducted three-dimensional hydrodynamical simulations to study the interaction of two late opposite jets with the ejecta of a core collapse supernova (CCSN), and study the bipolar structure that results from this interaction as the jets inflate hot-low-density bubbles. The newly born central object, a neutron star (NS; or a black hole), launches these jets at about 50 to 100 days after explosion. The bubbles cross the photosphere in the polar directions at much earlier times than the regions at the same radii near the equatorial plane. The hot bubbles releases more radiation and the photosphere recedes more rapidly in the tenuous bubble. Our results strengthen earlier claims that were based on toy models that such an interaction might lead to a late peak in the light curve, and that an equatorial observer might see a rapid drop in the light curve. Our results have implications to much earlier jets that explode the star, either jets that the newly born NS launches in a CCSN, or jets that a NS companion that merges with the core of a massive star launches in a common envelope jets supernova (CEJSN) event. Our results add indirect support to the CEJSN scenario for fast blue optical transients, e.g., AT2018cow, ZTF18abkwla, and CSS161010.

Keywords: supernovae: general — supernovae: individual: AT2018cow — stars: jets

1. INTRODUCTION

There are several types of observations that point directly and indirectly at the possible role of jets in, at least some, core collapse supernovae (CCSNe). One observation is a bipolar morphology of the $^{56}$Ni in the Type II-P CCSN SN 2016X (ASASSN-16at; Bose et al. 2019). Jets that drive CCSNe form bipolar morphological features (e.g., Orlando et al. 2016; Bear, & Soker 2018), and therefore might account for this $^{56}$Ni morphology. Other observations include the detection of polarisation and the presence of two protruding small lobes on opposite sides of some CCSN remnants (termed ‘Ears’) (e.g., Wang et al. 2001; Maund et al. 2007; Milisavljevic et al. 2013; González-Casanova et al. 2014; Margutti et al. 2014; Inserra et al. 2016; Mauerhan et al. 2017; Bear et al. 2017; Grichener, & Soker 2017; Garcia et al. 2017; Lopez & Fesen 2018). The degree to which jets play roles in the explosion mechanism and in the evolution of CCSNe is still an open question.

Neutrinos carry most of the energy that the formation of a neutron star (NS) in core-collapse supernovae (CCSNe) liberates, while the CCSN ejecta carry only a small fraction of that energy. Constructing a theoretical mechanism to convert even a small fraction of the released gravitational energy to kinetic energy of the CCSN ejecta is challenging.

In one explosion mechanism neutrinos that heat the in-flowing gas revive the stalled shock and explode the star, i.e., the \textit{delayed neutrino mechanism} (Bethe & Wilson 1985; Bruenn et al. 2016; Janka et al. 2016; Müller 2016; Burrows et al. 2018; Mabanta et al. 2019; Casanova et al. 2020; Couch et al. 2020; Delfan Azari et al. 2020; Iwakami et al. 2020; Kazeroni & Abdikamalov 2020; Kuroda et al. 2020; Powell & Müller 2020; Stockinger et al. 2020).

In a second explosion mechanism, jets that the just-born NS (or black hole) launches drive the explosion. Even if the pre-collapse core is slowly rotating (or not at all), the mass that the NS accretes possesses stochastic angular momentum that forms an intermittent accretion disk (or belt) that launches jets in varying directions and intensities. This is the \textit{jittering jets explosion mechanism} (e.g., Soker 2010; Papish & Soker 2011, 2014; Gilkis & Soker 2014, 2015; Quataert et al. 2019). In not requiring pre-collapse core rotation, therefore it might explain most CCSNe, the jittering jets explosion mechanism fundamentally differs from many other cases of jet-driven CCSNe that require pre-collapse rapid core rotation, and therefore are very rare (e.g.,
form a black hole will probably lead to a super-energetic CCSNe. To the contrary, the collapse of the core to itself as they are active after the formation of the central object and after the unbinding of the ejecta. We are motivated by recent calculations that suggest that late jets might solve some puzzles in rare CCSNe. Kaplan & Soker (2020b) assume a bipolar ejecta morphology, and with a simple modelling calculate the light curve as a result of two opposite low-density bubbles along the polar directions, i.e., a bipolar morphology. Again, they did not simulate the bipolar morphology, but rather assumed it. They find that there is a rapid decline in the light curve for an equatorial observer. This might explain the abrupt decline in the light curve of SN 2018dyon.

We conduct three-dimensional (3D) hydrodynamical simulations to explore the process by which the jets inflate bubbles in the ejecta. In section 2 we describe our numerical setting, in section 3.1 we describe the flow structure and in sections 3.2 and 3.3 we describe the evolution with respect to the photosphere. We summarise the main results in section 4.

2. NUMERICAL SETUP

We use version 4.2.2 of the adaptive-grid refinement (AMR) hydrodynamical FLASH code (Fryxell et al. 2000) in three dimension (3D). As the strong jet-ejecta interaction takes place in optically thick regions, we turn off radiative cooling at any gas temperature. The equation of state includes both radiation pressure and gas pressure with an adiabatic index of $\gamma = 5/3$, due both to ions and electrons, i.e., $P_{\text{tot}} = P_{\text{rad}} + P_{\text{ion}} + P_{\text{elec}}$.

We employ a full 3D AMR using a Cartesian grid $(x, y, z)$ with outflow boundary conditions at all boundary surfaces. We use either regular resolution with 7 refinement levels and a minimum cell size of $\Delta_{\text{cell,m}} = 2.34 \times 10^{13}$ cm, or high resolution with 8 refinement levels and a minimum cell size of $\Delta_{\text{cell,m}} = 1.17 \times 10^{13}$ cm. We inject the two opposite jets along a constant axis, the $z$-axis. The $z = 0$ plane is the equatorial plane of the flow. We simulate the whole space (the two sides of the equatorial plane), with a total size of the Cartesian numerical grid of $(800 \text{ AU})^3$, i.e., $(L_x, L_y, L_z) = \pm 400 \text{ AU}$.

We start with a CCSN ejecta with a mass of $M_{\text{ej}}$ and a kinetic energy if $E_{\text{SN}}$. We take the ejecta a long time after the explosion, such that the initial (when we start the simulation) velocity at each radius is $v(r) = v_{\text{br}}$, where $t_0$ is the time after explosion when we start the simulation. We take the initial density profile from Suzuki & Maeda (2019) (their equation 1-6, with $l = 1$ and $m = 10$), which reads

$$
\rho(r, t_0) = \begin{cases} 
\rho_0 \left( \frac{r}{t_0 v_{\text{br}}} \right)^{-1} & r \leq t_0 v_{\text{br}} \\
\rho_0 \left( \frac{r}{t_0 v_{\text{br}}} \right)^{-10} & r > t_0 v_{\text{br}},
\end{cases}
$$

(1)
where

\[ v_{br} = 1.69 \left( \frac{E_{SN}}{M_{ej}} \right)^{1/2} = 7.58 \times 10^3 \]

\[ \times \left( \frac{E_{SN}}{2 \times 10^{51} \text{ erg}} \right)^{1/2} \left( \frac{M_{ej}}{5M_\odot} \right)^{-1/2} \text{ km s}^{-1}, \]  

(2)

and

\[ \rho_0 = \frac{7M_{ej}}{18\pi v_{br}^2 r_0}. \]

(3)

To avoid numerical difficulties near the center we set an inner sphere at \( r < R_{in} = 10^{14} \text{ cm} \) to have a constant density. Namely, \( \rho(r < R_{in}) = \rho(R_{in}) \). In all cases that we simulate the explosion energy is \( E_{SN} = 2 \times 10^{51} \text{ erg} \) and the ejecta mass is \( M_{ej} = 5M_\odot \).

We launch the two jets in two opposite cones from the inner \( \Delta r_j = 3 \times 10^{14} \text{ cm zone along the } z\text{-axis (}x = y = 0\text{) and within a half opening angle of } \alpha_j = 20^\circ \). Although we expect jets’ velocity of \( v_j \gtrsim 10^5 \text{ km s}^{-1} \), to save computational resources we take \( v_j = 5 \times 10^4 \text{ km s}^{-1} \). At the beginning of the simulation the two opposite cones are filled with the jets material. This implies that the jets are already active for a time period of \( \Delta t_{j,0} = \Delta r_j/v_j = 6 \times 10^4 \text{ s} = 0.694 \text{ days} \). We continue to inject the jets for a time period of \( \Delta t_{j,a} \), such that the jets are active for a total time period of \( \Delta t_j = \Delta t_{j,0} + \Delta t_{j,a} \).

In the high resolution (HR) simulation and in the high energy (HE) simulation we take \( \Delta t_{j,a} = 0.1 \text{ days} \). Overall, the jets are active for \( \Delta t_j = 0.79 \text{ days} \) in these two cases. The mass loss rates into the two jets in these two cases are \( M_{ej} = 8 \times 10^{-4}M_\odot \text{ day}^{-1} \) and \( M_{ej} = 0.02M_\odot \text{ day}^{-1} \), respectively, and the total energies in the two jets are \( E_{2j} = 1.6 \times 10^{49} \text{ erg} = 0.008E_{SN} \) and \( E_{2j} = 4 \times 10^{50} \text{ erg} = 0.2E_{SN} \), respectively.

We also run two long-activity cases where the duration of the jet activity is \( \Delta t_j = 50 \text{ days} \), with a total energy of \( E_{2j} = 1.6 \times 10^{49} \text{ erg} = 0.008E_{SN} \) (LA) and \( E_{2j} = 4 \times 10^{50} \text{ erg} = 0.2E_{SN} \) (LAHE). We summarise the simulations we perform in Table 1.

For numerical reasons (to avoid very low densities) we inject a very weak slow wind in the directions where we numerically inject the jets, the flow structure close to the center includes some numerical effects. The initial temperature of the simulation box and the jets is 10000 K.

We find the radius of the photosphere of the ejecta itself from the relation

\[ \tau = \int_0^r \kappa \rho dr = \frac{2}{3}. \]

(4)

We first check at each relevant time whether the photosphere is at \( r > v_{br} t \). In this case the photosphere is at

| Case     | \( \Delta_{cell,m} \) cm | \( E_{2j} \) erg | \( \Delta t_j \) days | Figures |
|----------|------------------------|-----------------|----------------------|---------|
| HR       | \( 1.17 \times 10^{13} \) | \( 1.6 \times 10^{49} \) | 0.79                  | 1 - 7   |
| HE       | \( 2.34 \times 10^{13} \) | \( 4 \times 10^{50} \) | 0.79                  | 8       |
| LA       | \( 2.34 \times 10^{13} \) | \( 1.6 \times 10^{49} \) | 50                    | 9       |
| LAHE     | \( 2.34 \times 10^{13} \) | \( 4 \times 10^{50} \) | 50                    | 10, 11  |

Table 1. Summary of the distinguish properties of the high-resolution (HR), high-energy (HE), long-activity (LA), and long-activity high-energy (LAHE) simulations that we perform. In the second column we list the minimum cell size in the numerical grid. The third column gives the total energy in the two jets and the fourth column gives the time period of jets’ activity, including \( \Delta t_{j,0} = 0.69 \text{ days} \) before we start the simulation. In all simulations we inject the jets inside a cone with a half opening angle of \( \alpha_j = 20^\circ \) and with a velocity of \( v_j = 5 \times 10^4 \text{ km s}^{-1} \), the explosion energy (kinetic energy of the ejecta) is \( E_{SN} = 2 \times 10^{51} \text{ erg} \), and the ejecta mass is \( M_{ej} = 5M_\odot \).

\[ r_{ph} = r_1 > v_{br} t, \]

where

\[ r_1 = 9.7 \times 10^{14} \left( \frac{\kappa}{0.3 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/9} \left( \frac{E_{SN}}{10^{51} \text{ erg}} \right)^{7/18} \times \left( \frac{M_{ej}}{5M_\odot} \right)^{-5/18} \left( \frac{t}{10^6 \text{ s}} \right)^{7/9} \text{ cm}; \]  

for \( \tau (v_{br} t) > 2/3 \).

If the outer part of the ejecta is optically thin, i.e., \( \tau (v_{br} t) < 2/3 \), we neglect the contribution of the outer part (gas at \( r > v_{br} t \)), and consider only the contribution of the inner part of the power law to the optical depth. This gives the photosphere at \( r_i = r_2 \), where

\[ r_2 = 5.36 \times 10^{14} \left( \frac{E_{SN}}{10^{51} \text{ erg}} \right)^{1/2} \left( \frac{M_{ej}}{5M_\odot} \right)^{-1/2} \left( \frac{t}{10^6 \text{ s}} \right) \]

\[ \times \exp \left[ -5.19 \times 10^{-4} \left( \frac{\kappa}{0.3 \text{ cm}^2 \text{ g}^{-1}} \right)^{-1} \left( \frac{E_{SN}}{10^{51} \text{ erg}} \right) \left( \frac{M_{ej}}{5M_\odot} \right)^{-2} \left( \frac{t}{10^6 \text{ s}} \right)^2 \right] \text{ cm}. \]

3. RESULTS

We have two goals. Firstly, we want to check the general morphology and characteristics of the jet-ejecta interaction (section 3.1), and secondly, to determine the location of the jet-inflated bubbles with respect to the (approximate) photosphere as function of time (sections 3.2 and 3.3).

3.1. The basic flow structure: The HR simulation

We first describe a high-resolution (HR) simulation that we summarise in Table 1. Because high resolution simulations demand large computer resources, we have
only one simulation of high resolution. We present some of the results of this simulation below, and postpone the discussion of other aspects and the presentation of other simulations to sections 3.2 and 3.3. In what follows we measure the time from the explosion (beside in Fig. 6).

In Fig. 1 we present the density in the meridional plane. We take the z-axis along the symmetry axis of the jets. In Fig. 2 we present the map of the velocity relative to the homologous expansion, \( \vec{v}_{\text{rel}} \), from equation (7).

In Figs 3 and 4 we present the variation of four quantities with the distance from the center and along the two lines \( \Lambda_0 \) and \( \Lambda_{23} \), respectively, as we mark on Fig. 1. Figures 1-4 are all at the same time \( t = 154 \) days.

From Figs. 1-4 we identify the following features. We clearly see two low-density regions (in deep blue), one at each side of the equatorial plane, that we refer to as inner-bubbles (IB). These are the post-shock jets' material. In these low-density inner-bubbles the fraction of material that originated from the jets in each numerical cell is \( \gtrsim 50\% \); the rest is ejecta gas that mixed with it. Mixing of jet and ejecta gases takes place in the regions we mark by ‘M’ (pale blue), where the fraction of origin-
We identify shocks at $r \simeq 4.2 \times 10^{15}$ cm and at $r \simeq 3.4 \times 10^{15}$ cm.

The homologous expanding ejecta that the jets did not influence the flow of yet. A dense and a relatively thin shell (DS in Fig. 1) behind the forward shock (S1) bounds from inside the undisturbed ejecta. The dense shells has a bipolar morphology, i.e., two opposite bubbles. Behind the dense shell the density drops to below its value had there were no jets. This has an implication for the light curve as we discuss later (Kaplan & Soker 2020b).

The weak S2 shock that trails the forward shock (Fig. 1) results from an early-time fallback flow that creates a high-pressure region in the center. To follow that evolution, we present in Fig. 6 twelve frames of pressure and velocity maps. Only in this figure the time in each frame is the time from the beginning of the simulation $t_0$, rather than the time from explosion.

The evolution proceeds as follows. The jets empty the center, and for the first day or so the pressure in the center is very low, while regions of high pressure are developing behind the forward shock (the 1.6d frame in Fig. 6). By about few days after jets' injection the high pressure pushes gas back toward the center. We see a back-flow in the frame 3.1d. This back-flow collides with itself near the center and it forms a large high-pressure region. After several days there is an outflow in and near the equatorial plane. In the frame 9.3d we see the full inflow stream, with a maximum back-flow velocity of $v_{\text{back}} \simeq 4 \times 10^4$ km s$^{-1}$. In the frame at 11.3d the pressure in the center reaches its maximum value (yellow color). From frame 12.3d on, the back-flow decreases,

Figure 4. Similar to Fig. 3 but for the line $\Lambda_{23}$ that is at 23° from the symmetry axis as we mark on Fig. 1. We identify shocks at $r \simeq 4.2 \times 10^{15}$ cm and at $r \simeq 3.4 \times 10^{15}$ cm.

Figure 5. The density (in log scale and in units of g cm$^{-3}$) profiles along the radial lines $\Lambda_0$ (vertical) and $\Lambda_{23}$, as we mark on Fig. 1.
Figure 6. Pressure maps with relative velocity (equation 7) arrows at twelve early times after the beginning of the simulation, as we indicate in days. Note that the times we list in the panels are from the beginning of the simulation that occurs at $t_0 = 50$ days. Namely, the twelve frames cover the time period $t = 51.6$ days to $t = 86$ days. The blue, pale blue, green, yellow, and red colours depict the pressure from lowest value to highest value, respectively (for typical values of pressure see Figs. 3 and 4). The arrows depict the relative velocity, with their length proportional to the velocity. The typical value of the maximum relative back-flow velocities is $\approx 4 \times 10^4$ km s$^{-1}$. 
and an outflow in the polar directions develops. In the last frame, 36d, we see a full polar outflow, that later forms the trailing shock S2. We also notice the development of the vortexes near the equatorial plane.

3.2. Evolution and implications on light curves

We neither calculate the effects on the light curve nor we include radiative transfer. Such calculations will have to include, in addition to radiative transfer, recombination of the ejecta, calculation of the opacity at each point, and radioactive nuclei. As well, we assume a constant opacity. For that, the location of the photosphere is a very crude estimate. Nonetheless, it serves our purpose of presenting the general behavior of late jets that interact with the ejecta. The study of the influence of the jets on the light curve is a topic of a follow-up paper.

In Fig. 7 we present density maps at three times for the HR simulation. We calculate the location of the photosphere by equation (6) and for an opacity of $\kappa = 0.03$ in the three panels (solid-black circles) and for $\kappa = 0.1$ in the middle panel (solid-red circle). We ignore the presence of the bipolar structure, and so when the photosphere is inside the bubbles the calculation is very crude. (Calculating the exact location of the photosphere in the bubbles requires the inclusion of recombination and the calculation of the opacity in this complicated geometry.) The dashed-black circle is the location of the break in the power-law density profile that is at $r = v_{\text{br}} t$ (equation 1). At late times the break is outside the numerical grid.

Despite the crude calculation of the location of the photosphere, the evolution in Fig. 7 presents important features. These features result from that the photosphere first reaches, from outside, the polar regions of the bipolar structure. Kaplan & Soker (2020a) and Kaplan & Soker (2020b) discussed these features. They built toy models to estimate some effects on the light curve, but did not calculate the morphology of the jets-ejecta interaction. Our simulations show the geometrical evolution that they assumed, and allow us to present these features in a clearer way.

(1) Energising a peak in the light curve. We learn from Figs. 3 and 4 that the temperatures of the dense shells and the bubbles are higher than those of the undisturbed ejecta. Photons from these hotter regions can diffuse out before even the photosphere recedes to the dense shells. These photons might lead to a peak in the light curve of the CCSN (Kaplan & Soker 2020a). When later the photosphere recedes into the bubbles that are hotter and less dense than the ejecta, the emission might lead to a blue peak (i.e., the extra energy is at shorter wavelength than the rest of the ejecta; Kaplan & Soker 2020b).

Figure 7. Density maps in the meridional plane of the HR simulation at three times, from top to bottom, $t = 62$ days, $t = 96$ days, and $t = 142$ days after explosion. The density scale is according to the color bar in units of $g \text{ cm}^{-3}$. The solid-black circle in each panel marks the photosphere according to our crude estimate by equation (6) and for an opacity of $\kappa = 0.03$, while the solid-red circle in the middle panel is for $\kappa = 0.1$. The dashed circle in the upper panel is the radius where the power-law density profile changes, i.e., $v_{\text{br}} t$ (equations 1 and 2; at later times it is outside the numerical grid).
(2) Rapid light-curve drop for an equatorial observer. An observer in and near the equatorial plane (z = 0) might observe a rapid luminosity decline in the light curve (Kaplan & Soker 2020b) as a result of a faster recession of the photosphere inside the bubbles. At later times an observer near the equatorial plane will not see the photosphere in the polar directions. This reduces the flux the observer measures relative to a spherical explosion. Kaplan & Soker (2020b) assume that the density in the bubbles is lower than in the ejecta. We here show this.

The main result from the one case we analysed in sections 3.1 and 3.2 is a support to the toy models and conclusions of Kaplan & Soker (2020a) and Kaplan & Soker (2020b). We turn to examine other cases with jets.

3.3. Other cases

We conducted a simulation of a case where the jets are 25 times more energetic by having 25 more mass relative to the high-resolution simulation. This simulation is of a lower resolution than that of the HR simulation (Table 1). All other parameters are as in the HR simulation. Because this simulation is of lower resolution, we study in this case only the bipolar structure, and not the bubbles and the other inner regions.

As expected, the bipolar structure grows faster relative to the HR simulation. By the time the front of the dens shells break through the photosphere (on both sides), we clearly see that the density in the bubbles have much lower densities, by about an order of magnitude, relative to the densities in the equatorial plane at the same distances (middle panel of Fig. 8). This implies that the photosphere will recede very rapidly within the bipolar structure (the bubbles), something that will lead to a rapid drop in the light curve for an equatorial observer (Kaplan & Soker 2020b; section 3.2 above).

In Fig. 9 we present the density maps at at three times for a long-activity (LA) simulation where the jets were active for 50 days, starting at \( t_0 = 50 \) days, and the energy is as in the HR simulation. Comparing this figure to Fig. 7, we immediately see that the dense shell is more elongated. In the HR simulation (Fig. 7) the ratio of the length of one bubble (or the dense shell on one side) to its full width at maximum width at \( t = 142 \) days is \( \beta(\text{HR}) = 0.9 \), while in the LA simulation (Fig. 9) this ratio is \( \beta(\text{LA}) = 1.4 \) at the same time. The same holds for the very low-density inner bubbles (deep blue), which are much more extended in the LA simulation. This might imply an even more abrupt drop in the light curve for an equatorial observer than we discussed above (Kaplan & Soker 2020b).

In Fig. 10 we present the density maps at at three times for a long-activity high-energy (LAHE) simulation where the jets were active for 50 days, starting at \( t_0 = \)

\[3.5 \times 10^{-18} \quad 6.5 \times 10^{-17} \quad 1.1 \times 10^{-16} \quad 2.1 \times 10^{-15} \quad 3.7 \times 10^{-15}\]

\[1.6 \times 10^{-17} \quad 1.9 \times 10^{-16} \quad 2.2 \times 10^{-15} \quad 2.7 \times 10^{-14} \quad 3.2 \times 10^{-13}\]

\[6.6 \times 10^{-17} \quad 5.3 \times 10^{-16} \quad 4.2 \times 10^{-15} \quad 3.3 \times 10^{-14} \quad 2.7 \times 10^{-13}\]
Figure 9. Similar to Fig. 7, but for the long-activity (LA) simulation where the jets are active for 50 days. The times of the three frames are also as in Fig. 7, $t = 62, 96, \text{ and } 142$ days.

50 days, and the energy is as in the HE simulation, i.e., 25 times the energy in the HR and LA simulations. In the HE simulation (Fig. 8) the ratio of the length of one bubble to its full width at maximum width at $t = 96$ days is $\beta(\text{HE}) = 1.05$, while in the LAHE simulation (Fig. 10) this ratio is $\beta(\text{LAHE}) = 1.2$ at the same time. The bubbles are of very low density, about an order of magnitude lower, relative to the regions outside the dense shells. As we commented above, this supports the toy model that Kaplan & Soker (2020b) assumed, and therefore supports their suggestion that this might lead to an abrupt drop in the light curve for an equatorial observer when the photosphere enters the bubbles (lower panel of Fig. 10).

The energetic jets in the LAHE simulation, $E_{2j} = 0.2E_{\text{SN}}$, and their long activity time lead to an interaction that forms a deep along the symmetry axis, one at each side, in the outer boundary of each of the two dense shells. This is a feature we have obtained before when simulating jets in planetary nebulae (Akashi & Soker 2016). To further present the complicated flow structure, in Fig. 11 we present the velocity map in the meridional plane of the LAHE simulation.

4. DISCUSSION AND SUMMARY

We conducted four 3D hydrodynamical simulations to study the interaction of late jets, either 50 days or 50 to 100 days after explosion, with the ejecta of a CCSN (table 1). We analysed the interaction flow in the HR simulation, where the jets are active for less than a day (Figs. 1 - 7). We mark the relevant morphological features on Fig. 1. In such a case of short-activity jets, the outcome looks like one explosion at each side of the equatorial plane (what Kaplan & Soker 2020a termed ‘min-explosion’). The morphology at late times is of an almost spherical bubble that is bounded by a dense-shell, one at each side of the equatorial plane (Fig. 7). The same holds for the more energetic HE simulation with a short activity jets (Fig. 8). In cases where the jets are active for a long time, the LA (fig. 9) and the LAHE (Fig. 10) simulations, the bubbles are more elongated.

In Figs. 7 - 10 we presented also the crude photosphere location. These figures represent the qualitative results that the bubbles break out from the photosphere at much earlier times than the regions at the same radii near the equatorial plane. In section 3.2 we discussed two implications of this. The first is a possible peak in the light curve at late times (Kaplan & Soker 2020a). For a polar observer this peak might be blue in some cases (Kaplan & Soker 2020b). The second implication is that after the photosphere rapidly recedes inside the bubble (because of its low density), an equatorial observer does no see the polar photosphere any more (Kaplan & Soker 2020b). This might lead to a rapid light-curve drop for an equatorial observer (Kaplan & Soker 2020b).
Figure 10. Similar to Fig. 8, but for the long-activity high-energy (LAHE) simulation where the jets are active for 50 days and the energy is high (Table 1). The times of the three frames are also as in Fig. 8, $t = 62, 76, \text{and } 96$ days.

2020b). Our results support the toy models that Kaplan & Soker (2020a) and Kaplan & Soker (2020b) assumed, and therefore support their conclusions regarding possible late peaks in the light curve and rare cases of rapid drop in luminosity for an equatorial observer.

Although we simulated late jets from the center, our results on the formation of bipolar hot and low-density bubbles have wider implications. Our results can be extended to jets that explode the star. Namely, very energetic jets at the explosion itself. If the pre-collapse core has only a slow rotation, the explosion will be by jittering jets (assuming the jittering jets explosion mechanism). The jets in each jets-launching episode carry a small fraction of the total explosion energy (section 1). However, if the core has a large amount of angular momentum the jets might maintain a constant axis and lead to a super-energetic CCSN (Gilkis et al. 2016). Energetic jets that maintain a constant axis will form a bipolar structure with a similar morphology to what we have obtained in this study, but that extends to a large distance and occupies a large volume out of that of the ejecta. In a short time, days after explosion, the photosphere might be inside the hot-tenuous bubbles, leading to blue emission that drops within days.

The same process of a strong blue emission followed by a rapid drop might take place when the jets that explode the star are of a NS companion that merges with the core, the so called common envelope jets supernova
(CEJSN). Soker et al. (2019) suggested that the fast blue optical transients (FBOT) AT2018cow (Prentice et al. 2018) was a CEJSN. In the specific CEJSN scenario that Soker et al. (2019) proposed for AT2018cow, the jets clear the polar directions of the giant envelope before the NS companion launches the jets that explodes the star as it accretes mass from the core. They termed this the polar CEJSN scenario. The basic process in the polar CEJSN is the formation of two opposite bubbles in a bipolar structure, similar to the structures that we have obtained in this study, but with very large bubbles. We suggest here the CEJSN scenario to two other FBOTs, ZTF18abvkwla (Ho et al. 2020) and CSS161010 (Coppejans et al. 2020).

We also note that a very close, about $1 - 5R_\odot$, NS companion to an exploding stripped-envelope (Type Ib or Ic) CCSN might launch weak jets that will form a bipolar structure in the inner regions of the ejecta (Soker 2020). This is the subject of a future study.

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