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The Onset of Cosmic Ray Acceleration at Supernovae: From Shock Breakout to the First Decades

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We demonstrate, for the first time, that CR acceleration can start significantly before shock breakout for some supernovae surrounded with optically thick winds. Diffusive shock acceleration notably requires the presence of a collisionless shock (CS). It is usually thought that the shock is initially radiation-dominated, and that the CS only forms in the optically thin layers of the wind. However, we show analytically and numerically, that a CS forms deep inside the thick layers of the wind for some astrophysically-relevant progenitors, such as possibly SN 2008D.
An observational consequence is that secondary TeV neutrinos can reach the observer up to ~ 10 hours before the first photons from shock breakout, enabling one to study the otherwise inaccessible optically thick layers of such winds [1].

We also investigate the beginning of cosmic ray (CR) acceleration at supernovae, from the first day to the first few decades following the explosion. We show that supernovae occuring in dense winds should accelerate CR protons to energies $E >$ PeV [2]. We present a study of the maximum CR energy.

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1. Introduction

Following core collapse in a massive star, a shock wave is launched. Inside the optically thick layers of the star, the shock is radiation-dominated, i.e. the radiation pressure in the downstream exceeds the fluid pressure [3]. Once the radiation-dominated shock (RDS) reaches the optically thin outer layers, photon escape ahead of the shock. This flash of photons corresponds to shock breakout (SB), e.g. [4, 5]. A few of them have been observed [6, 7, 8, 9, 10]. At SB, the RDS disappears and a collisionless shock (CS) later forms, e.g. [5, 11]. Diffusive shock acceleration may then become possible. A thorough understanding of the CS formation time is then crucial to study the onset of cosmic ray (CR) acceleration, when very high energies may be reached [2].

Some Wolf-Rayet (WR) stars, blue and red supergiants (RSG) may explode in optically thick winds. Ref. [12] demonstrated that a CS must appear during or on the time scale of SB, when the RDS reaches the optically thin layers of the wind, at an optical depth $\tau \sim c/u_{\rm s} = \beta_{\rm s}^{-1}$ from the surface [13]. We demonstrate here that the formation of a CS occurs *significantly before* SB for *some* progenitors in *thick* winds. This redefines the onset of CR acceleration with respect to SB, since it can start in such cases significantly before SB. Supernova SN 2008D may have been an event in which a CS is formed before SB, assuming a progenitor with the parameters derived in [14].

Finally, we show that supernovae occuring in dense winds are likely to accelerate CRs to $\sim$ PeV energies during the first few years or decades following the explosion.

2. Collisionless shocks before breakout from optically thick winds

For progenitors surrounded with optically thin winds, the flash of photons at SB accelerates the low density circumstellar medium to a velocity about $\propto r^{-2}$ (r is the distance to the center of the progenitor). The shocked outer layers of the star then push supersonically into the more slowly moving circumstellar material at larger r, which leads to the formation of a collisionless shock. We verified, with the 1D spherical radiation-hydrodynamics code presented in [1], that a CS forms after SB for a progenitor in an optically thin wind. In this case, the RDS stalls when entering optically thin material.

However, in some situations, the RDS can also stall inside optically thick material, and lead to the formation of a CS. We find that this happens for some supernovae exploding in optically thick winds. For thick winds, shock breakout occurs at a radius $r_{\rm br}$, which is larger than the radius of the star r_*. When the progenitor is surrounded with a very dense wind, such as for Type IIn SNe, the RDS survives the transition from the core to the thick wind at $r = r_*$. On the contrary, we find that when the wind is only moderately thick, the RDS stalls when exiting the hydrostatic core at $r = r_*$, and a CS forms in the wind at $r_* < r < r_{\rm br}$, *before* SB.

Let us consider two concentric shells in the thick wind, with respective radii $r_1(t)$ and $r_2(t)$, and velocities $u_1 = u_{\rm s}$ and u_2, see Fig. 1. They are chosen such that $r_1(t=0) = r_*$, and $r_* < r_2(t=0) < r_* + \lambda_2/\beta_{\rm s}$, where λ_2 is the photon mean free path in the wind at $r \simeq r_*$. In the limiting case where all photons that have accelerated the shell at r_1 also pass through the shell at r_2 (no absorption), the velocity reached by the latter shell cannot exceed $u_2 \leq u_1\,(r_*/r_2(0))^2 + \kappa E_{\rm em}/4\pi c r_2^2(0)$, where κ is the opacity and $E_{\rm em} \simeq \int_{r_*}^{r_2(0)} 4\pi r^2\, \frac{1}{2\kappa\lambda_2} u_{\rm s}^2\, dr$ is an upper limit on the energy that can be radiated

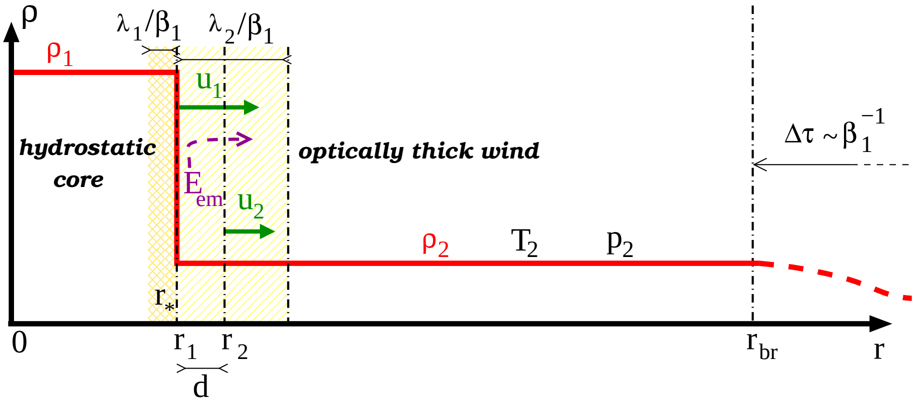

Figure 1: Toy model: The stellar core of radius $r_* = r_1(t=0)$ and density ρ_1 is surrounded with an optically thick wind with $\rho_2 = 1/\kappa\lambda_2 < \rho_1$. The RDS, with velocity $\sim u_1$ leaves the core at $t=0$. Shock breakout occurs at $r_{\rm br} \gg r_*$. A CS forms when the shell at $r_1(t)$ catches up supersonically that at $r_2(t)$, which can happen at $r \ll r_{\rm br}$, see text.

through the shell at r_2 by the fluid between r_1 and r_2. If $E_{\rm em}$ is sufficiently large, it can compensate for the $(r_*/r_2(0))^2$ factor : u_2 then remains $\geq u_1$ and the RDS survives in the wind. If the wind between the two shells cannot radiate enough photons through the shell at r_2 to compensate for the dilution of photons due to shock curvature, then the shell at r_1 can catch up and hit supersonically the shell at r_2, at a radius $r < r_{\rm br}$. A CS then forms before SB. One can show that this happens when [1]: $\beta_{\rm s} \lesssim 10\,\lambda_2/r_*$. For a r^{-2} wind, this condition becomes :

$$\beta_{\rm s} \lesssim 0.1 \left(\frac{u_{\rm w}}{10\,{\rm km/s}}\right)\left(\frac{r_*}{10^{13}\,{\rm cm}}\right)\left(\frac{5\cdot 10^{-4}\,{\rm M_\odot/yr}}{\dot{M}}\right)\,, \tag{2.1}$$

where $u_{\rm w}$ and $\dot{M}$ are respectively the wind velocity and the mass-loss rate of the progenitor. Wolf-Rayet stars and red supergiants with relatively large $\dot{M}$ before the explosion are good candidates, but not progenitors of Type IIn SNe. Very interestingly, SN 2008D marginally satisfies this inequality with the parameters deduced in [14]. For progenitors with wind densities $\propto r^{-2}$, this corresponds $r_{\rm br} \approx 10\,r_*$. However, this scenario can also be satisfied for progenitors with $r_{\rm br}/r_* \gg 10$, if, for example, the wind density profile is flatter than r^{-2} at $r < r_{\rm br}$, due to a change in the mass-loss rate with time.

We verified the above statements with our radiation-hydrodynamics code. Fig. 2 shows the formation of a CS before breakout for a red supergiant exploding in a thick wind, see caption for details. Once formed, the CS continues to propagate to $r \gg r_{\rm br}$.

3. Particle acceleration and high-energy neutrinos before and after shock breakout

Assuming conservatively a magnetic field strength at the CS similar to that at the stellar surface, $B_{\rm s} \sim 10\,{\rm G}$ [15], and wind densities $\rho \sim 10^{-11\,(-9)}\,{\rm g\,cm^{-3}}$, the CS is super-Alfvénic. Once it is formed, CR acceleration may start. Coulomb losses for suprathermal particles are sufficiently small here and do not prevent them from entering diffusive shock acceleration and being accelerated. However, for WRs with $\dot{M} \gtrsim 10^{-3}\,{\rm M_\odot\,yr^{-1}}$, such losses start to inhibit CR acceleration

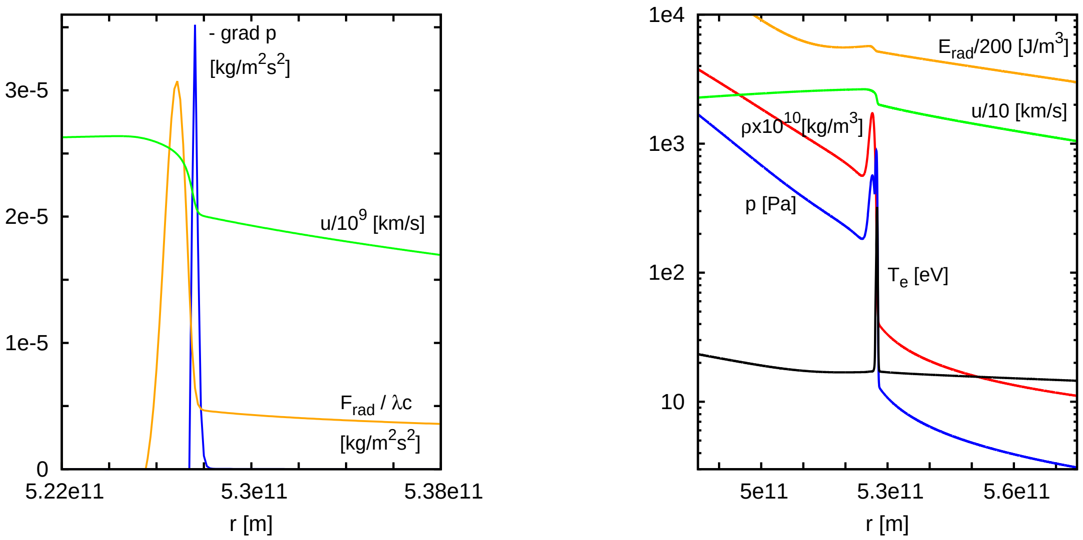

Figure 2: Simulation of a RSG explosion in a thick wind *before* breakout. Zoom around the downstream of the radiation-dominated transition of the shock, where a discontinuity (CS) can be seen around $r \approx 5.28 \times 10^{11}$ m $\approx 1.6\,r_* \approx r_{\rm br}/2$. *Left panel:* Most of the fluid acceleration $d(\rho u)/dt$ is due to the radiation, except in a thin zone at the CS, where the fluid contribution dominates. *Right panel:* Peaks in p and in the electron temperature $T_{\rm e}$ appear in the CS immediate downstream. $T_{\rm rad}$ follows $T_{\rm e}$ except in the peak region.

before SB. Some findings of [16] and [12] can be transposed to our study, yet we deal here with a shock propagating in denser regions of the wind. Assuming Bohm diffusion for CRs at the CS [17], and equal dwell times in the downstream and the upstream, one finds a typical acceleration time

$$\tau_{\rm CR} \approx \frac{8E_{\rm CR}}{3eB_{\rm s}u_{\rm s}^2} \approx 30\,{\rm s}\left(\frac{E_{\rm CR}}{10\,{\rm TeV}}\right)\left(\frac{B_{\rm s}}{10\,{\rm G}}\right)^{-1}\left(\frac{\beta_{\rm s}}{0.1}\right)^{-2} \tag{3.1}$$

for protons. This time can be optimistic when the discontinuity in velocity at the shock is still small due to smoothing by radiation. However, magnetic field amplification at the shock due to the non-resonant hybrid (NRH) instability [18] plays a role in the opposite direction by diminishing $\tau_{\rm CR}$ and thereby facilitating CR acceleration.

Let us note that 10 TeV energies are reachable before breakout because $\tau_{\rm CR} \ll (r_{\rm br} - r_*)/u_{\rm s} \approx$ several hours (resp. minutes) for RSG (resp. WR) progenitors with $\beta_{\rm s} = 0.1$ and $r_{\rm br}/r_* \approx 10$. For such RSGs, $\tau_{\rm CR}$(at 10 TeV) is smaller than energy loss times from pion production through inelastic pp and $p\gamma$ collisions. The typical life time of a CR proton due to pp collisions is

$$\tau_{\rm pp} \approx 4\,{\rm min}\left(\frac{u_{\rm w}}{10\,{\rm km/s}}\right)\left(\frac{r}{10^{13}\,{\rm cm}}\right)^2\left(\frac{\dot{M}}{5\cdot 10^{-4}\,{\rm M}_\odot/{\rm yr}}\right)^{-1}. \tag{3.2}$$

The background ~ 10 eV photons in the thick wind are not sufficiently energetic to trigger pion production through inelastic $p\gamma$ scattering. For 10 TeV CRs, $\gtrsim 10$ keV photons are required to exceed the threshold for pion production. Photons with such energies can be produced by the radiative CS. However, the number density of target photons n_γ must be much less than $\rho u_{\rm s}^2/h\nu$ [12].

We find for the typical life time of a CR proton due to $p\gamma$ collisions :

$$\tau_{\mathrm{p}\gamma} \gtrsim 2\,\mathrm{min}\left(\frac{u_{\mathrm{w}}}{10\,\mathrm{km/s}}\right)\left(\frac{r}{10^{13}\,\mathrm{cm}}\right)^{2}\left(\frac{\dot{M}}{5\cdot10^{-4}\,\mathrm{M}_{\odot}/\mathrm{yr}}\right)^{-1}\left(\frac{\beta_{\mathrm{s}}}{0.1}\right)^{-2}\left(\frac{E_{\mathrm{CR}}}{10\,\mathrm{TeV}}\right)^{-1}. \tag{3.3}$$

$e^{\pm}$ pair creation due to $p\gamma$ interactions does not yield a stronger constraint.

In the case of Wolf-Rayet progenitors with the above parameters, $\tau_{\mathrm{pp,p}\gamma} \gtrsim 3\,\mathrm{s}$. Consequently, TeV energies may be reached for WRs.

Secondary $\gtrsim 100\,\mathrm{GeV} - 1\,\mathrm{TeV}$ neutrinos (from notably $\pi^{\pm}$ decay) can then reach the observer before the first photons from breakout, when the CS forms before SB. The time interval between the arrival of the first neutrinos and photons is approximately

$$\Delta t_{\nu\gamma} \approx \frac{r_{\mathrm{br}} - r_{*}}{c}\left(\frac{1}{\beta_{\mathrm{s}}} - 1\right) \approx 8\,\mathrm{hr}\ (\mathrm{resp.}\ 5\,\mathrm{min}) \tag{3.4}$$

for RSGs (resp. WRs) with the above parameters, $r_{\mathrm{br}}/r_{*} = 10$ and $\beta_{\mathrm{s}} = 0.1$. Assuming that 5 % of the energy processed by the shock is channelled into CRs, we typically find for a source at distance l, and a processed mass between r_{*} and r_{br} of $\approx 10^{-5}\,\mathrm{M}_{\odot}$, that $\sim 10^{3}\,(3\,\mathrm{kpc}/l)^{2}$ neutrinos with $\sim$TeV energies would be detectable before SB by IceCube or KM3NeT. One could record a few of such neutrinos for an event in the Magellanic Clouds.

4. Particle acceleration at later times: First decades of a SN in a dense wind

In this Section, we study CR acceleration at later times, after SB. Once the CS reaches a radius r greater than a few r_{br}, effects on the circumstellar wind from the flash of photons realeased at SB can be neglected.

It has been suggested since a long time that supernovae occuring in stellar wind cavities may accelerate CRs to very high energies [19], and that radio supernovae may be sources of gamma-rays [20]. Here, we study CR acceleration at SNe occuring in dense circumstellar winds, taking into account our latest understanding of magnetic field amplification at the shock. We find that, after a few days and during the first few weeks or decades following the explosion, cosmic rays accelerated at the shock may reach $\gtrsim$ PeV energies.

Magnetic field amplification is (constantly) driven by the escape of the highest energy CRs in the upstream of the collisionless shock [2]. The growth rate of the fastest growing mode of the NRH instability is equal to $\gamma_{\max} = 0.5\, j_{\mathrm{CR}}\sqrt{\mu_0/\rho}$, where $j_{\mathrm{CR}} \simeq 0.03\,\rho u_{\mathrm{s}}^{3} e/E_{\mathrm{CR}}$ is the CR current density which drives it, and the instability growth time is $\tau_{\mathrm{NRH}} \approx 5\gamma_{\max}^{-1}$, see Reference [2] for more details. The condition for magnetic field amplification is then

$$\mathscr{Q}_{\mathrm{CR}} = \int j_{\mathrm{CR}}\,\mathrm{d}t = 10\sqrt{\frac{\rho}{\mu_0}}\,, \tag{4.1}$$

where $\mathscr{Q}_{\mathrm{CR}}$ is the total electric charge of CRs passing through *a unit surface area* upstream of the shock, before the shock arrives.

Let us now assume a spherical supernova shock wave at radius $r(t)$, accelerating CRs to a maximum energy $E_{\mathrm{CR}}(r)$. The condition for CRs to be confined when the shock wave reaches radius R reads :

$$\int_0^R \frac{0.03\rho(r)u_{\mathrm{s}}^2(r)e}{E_{\mathrm{CR}}(r)} r^2\mathrm{d}r = 10R^2\sqrt{\frac{\rho(R)}{\mu_0}}\,. \tag{4.2}$$

For a stellar mass-loss rate $\dot{M}$ and wind velocity u_{w}, one has $\rho(R) = \dot{M}/4\pi u_{\mathrm{w}} R^2$. Differentiating Eqn. (4.2) with respect to R, one finds the following value for the maximum energy of CRs that can be acelerated at a supernova shock wave propagating in a circumstellar wind with density $\rho \propto r^{-2}$:

$$E_{\mathrm{CR}} \approx 7\ \mathrm{PeV} \left(\frac{u_{\mathrm{s}}}{30\,000\,\mathrm{km\,s^{-1}}}\right)^2 \left(\frac{\dot{M}}{10^{-5}\,\mathrm{M_{\odot}\,yr^{-1}}}\right)^{1/2} \left(\frac{u_{\mathrm{w}}}{10\,\mathrm{km\,s^{-1}}}\right)^{-1/2}\,. \tag{4.3}$$

This shows that CRs with PeV energies (if not even with energies beyond that of the knee, $\approx 4\,\mathrm{PeV}$) should be accelerated during the first few weeks or decades following the explosion of stars occuring in dense circumstellar winds. A similar conclusion is reached by [21].

It is interesting to note that the large magnetic field strengths inferred for radio supernovae (see e.g. Reference [22]) may be a hint at strong magnetic field amplification due to the NRH instability from CR protons (and nuclei) being accelerated at the (forward) shock. Reference [23] studied radio supernova SN 1993J in detail and showed that the values of magnetic fields inferred from the radio data are roughly compatible with those expected from the NRH instability. It also found that SN 1993J should have been a PeVatron for about a decade.

5. Conclusions

During a core-collapse supernova, a radiation-dominated shock propagates through the progenitor star. If the surrounding wind is optically thin, this shock stalls when it reaches the outer layers of the stellar core and a collisionless shock forms in the wind.

For supernovae occuring in optically thick winds, the formation of a CS should also occur no later than during or on the time scale of shock breakout – from the 'outer' layers of the optically thick part of the wind.

We have demonstrated here that for some astrophysically-relevant progenitors surrounded with thick winds, a collisionless shock forms well before breakout, providing new ways to study invisible layers of their winds and to constrain stellar evolution theories. In such cases, the RDS has been found to stall when entering the optically thick part of the wind, notably because of shock curvature.

We have discussed, in Section 3, the onset of particle acceleration at the CS. For example, we predict that for some red supergiants surrounded with thick winds, a fraction of secondary high-energy neutrinos from CRs can arrive ~ 10 hours before photons from shock breakout.

We find that the CS forms after the RDS exits the core, and before breakout, for progenitors with shock velocities $\lesssim 0.1\mathrm{c}\,(\frac{u_{\mathrm{w}}}{10\mathrm{km/s}})(\frac{\dot{M}}{5\cdot 10^{-4}\mathrm{M_{\odot}/yr}})^{-1}(\frac{r_*}{10^{13}\mathrm{cm}})$, where u_{w}, $\dot{M}$ and r_* respectively denote the wind velocity, mass-loss rate and radius of the hydrostatic core. The wind has to be sufficiently dense to be optically thick but not excessively. Progenitors of Type IIn supernovae are expected to have too dense winds to form CS when the RDS leave their cores. However, Wolf-Rayet stars or red supergiants with either dense winds or enhanced mass-loss prior to the explosion are better candidates. For example, Type Ibc supernova SN 2008D/XRF 080109 has been interpreted by [14] as the explosion in a moderately thick wind of a WR star, undergoing an enhanced mass-loss during its last $\lesssim 10$ days. Interestingly, the parameters inferred by [14] for SN 2008D make it marginally consistent with the above condition.

In Section 4, we have studied CR acceleration at significantly later times: From weeks to decades after SN shock breakout. We have shown that for SNe occuring in dense circumstellar winds, CRs can be accelerated up to a few PeV, if not beyond the knee, for sufficiently fast shocks in sufficiently dense winds: $\sim 7\,\mathrm{PeV}\left(\frac{u_{\mathrm{s}}}{30\,000\,\mathrm{km\,s^{-1}}}\right)^{2}\left(\frac{\dot{M}}{10^{-5}\,\mathrm{M_{\odot}\,yr^{-1}}}\right)^{1/2}\left(\frac{u_{\mathrm{w}}}{10\,\mathrm{km\,s^{-1}}}\right)^{-1/2}$. Studying CR acceleration in dense winds is important, because it should lead to a better understanding of the knee in the CR spectrum, see e.g. [24] and [2].

More generally, supernovae occurring in dense winds are promising targets for multi-messenger studies. The detection of their UVs, X-rays, γ-rays and TeV neutrinos will allow one to test a wide variety of physical and astrophysical phenomena in extreme conditions, such as particle acceleration, magnetic field amplification and shock physics.

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