ABSTRACT
The afterglow emission that follows gamma-ray bursts (GRBs) contains valuable information about the circumburst medium and, therefore, about the GRB progenitor. Theoretical studies of GRB blast waves, however, are often limited to simple density profiles for the external medium (mostly constant density and power-law $R^{-2}$ ones). We argue that a large fraction of long-duration GRBs should take place in massive stellar clusters where the circumburst medium is much more complicated. As a case study, we simulate the propagation of a GRB blast wave in a medium shaped by the collision of the winds of O and Wolf–Rayet stars, the typical distance of which is $d \sim 0.1–1$ pc. Assuming a spherical blast wave, the afterglow light curve shows a flattening followed by a shallow break on a time-scale from hours up to a week after the burst, which is a result of the propagation of the blast wave through the shocked wind region. If the blast wave is collimated, the jet break may, in some cases, become very pronounced with the post-break decline of the light curve as steep as $t^{-5}$. Inverse Compton scattering of ultraviolet photons from the nearby star off energetic electrons in the blast wave leads to a bright $\sim$GeV afterglow flare that may be detectable by Fermi.

Key words: hydrodynamics – radiation mechanisms: non-thermal – radiative transfer – shock waves – gamma-ray burst: general.

1 INTRODUCTION
The prompt phase of gamma-ray bursts (GRBs) is followed by a long-lived afterglow emission. The afterglow is believed to be powered by shocks driven by the relativistic outflow into the circumburst medium. Assuming that these external shocks inject ultrarelativistic electrons into the downstream shocked fluid, synchrotron emission from these particles can account for the basic properties of a large number of the afterglow observations (Sari, Piran & Narayan 1998; Wijers & Galama 1999).

Afterglow modelling can provide important information about, among other things, the density profile of the circumburst material, thus constraining the nature of the progenitor. So far, however, typically only very simplistic density profiles have been considered, i.e. the external medium is assumed either to have constant density or to follow a power-law function of spherical distance $R$. Observations are inconclusive about the density profile, i.e. depending on the burst and the analysis more than one or none of the simple density profiles may account for observations (see e.g. Panaitescu & Kumar 2002; Piro et al. 2005; Starling et al. 2008; Curran et al. 2009; Schulze et al. 2011).

At least some long-duration GRBs have been convincingly shown to be associated with the death of massive stars of Wolf–Rayet type (Galama et al. 1998; Hjorth et al. 2003; Mazzali et al. 2003; Stanek et al. 2003). Because Wolf–Rayet stars are characterized by strong winds, a $R^{-2}$ wind-like profile is, at first sight, a natural choice to describe the density distribution surrounding the progenitor. For high enough density of the medium that confines the stellar wind, the termination shock (TS) of the wind may take place sufficiently close to the progenitor to affect the afterglow light curve (Wijers 2001; Chevalier, Li & Fransson 2004; Ramirez-Ruiz et al. 2005; Pe’er & Wijers 2006). However, for ‘standard’ parameters for the wind of the massive star and the density of the environment, the TS is usually too distant to have a bright signature in the afterglow light curve (Eldridge et al. 2006; van Marle et al. 2006).

The actual density profile which decelerates the GRB-driven blast wave could be much more complicated. Massive stars rarely form in isolation; they preferentially reside in dense stellar clusters where tens or even hundreds Wolf–Rayet and O stars are crowded on sub-pc scale regions (e.g. Massey & Hunter 1998). About one-third of the Galactic Wolf–Rayet stars are located in several very massive stellar clusters (e.g. Figer 2004). It is reasonable to expect a fair fraction of GRBs to take place in such dense stellar environment. The interactions of the strong stellar winds in stellar clusters complicate the medium that surrounds the GRB progenitor and, therefore, the blast wave evolution. Furthermore, nearby O stars provide a strong UV photon field that is up-scattered by electrons accelerated at the forward shock and may potentially result in bright GeV afterglow flaring (Giannios 2008).
As a first step towards studying the afterglow appearance in more realistic density profiles, we focus on a blast wave propagating through a medium shaped by colliding stellar winds. Hydrodynamic simulations are used to study the profile from the collision of stellar winds. Follow-up relativistic hydrodynamic simulations are performed in order to study the blast wave propagation through such density profile (Section 2). The fluid dynamics are coupled to a radiative transfer code to calculate the resulting synchrotron and inverse Compton (IC) emission (Sections 3 and 4). We discuss our results in Section 5.

2 A BLAST WAVE IN COMPLEX DENSITY PROFILES

With the number of massive stars \( N_* \sim 100 \) (ranging from a few tens to a few hundreds) crowded on a \( R_c \lesssim 1 \) pc scale of a typical massive stellar cluster (similar to, e.g., Westerlund 1, Arches, Quintuplet or Centre in the Galaxy), the mean distance between O stars is \( d \sim R_c N_*^{1/3} \sim 0.1 \) pc. The blast wave driven by a GRB, still relativistic at these distances, is expected to encounter density bumps while propagating in the cluster. We simulate several density profiles that may be expected in a massive cluster and then study the blast wave propagation through them.

2.1 Colliding winds

In the young stellar cluster under consideration, the gas density is shaped by the interactions of the stellar winds. Since the most massive (O and Wolf–Rayet) stars have the strongest winds, they are going to dominate these interactions. The stars are surrounded by regions of their freely expanding winds that are followed, further out, by regions of shocked gas – result of wind–wind collisions. For a given line of sight from the explosion centre to the observer, the density is likely to be shaped by the few massive stars that happen to lie close to it. For \( N_* \) stars randomly distributed in the cluster, the closest one to the line of sight is located at an angle \( \theta \sim 4(N_*)^{1/2} \sim 2N_*^{1/2} \) rad (where the \( \Lambda \lesssim 10^6 \) notation is adopted). Encountering a star within an angle \( \theta \sim 10^\circ \) from the line of sight is, therefore, the norm in the massive clusters under consideration. As long as the outflow is ultrarelativistic with a bulk Lorentz factor \( \Gamma \gg 1 \), the observer of the GRB afterglow probes the blast–medium interactions that take place within a narrow cone of angle \( \sim 1/\Gamma \) with respect to the line of sight. In the narrow cone, which the observer can see, the closest stellar encounter is the dominant one in determining the relevant density profile.

As a first approach, we limit ourselves to a single massive star (O) located at distance \( d \lesssim 1 \) pc from the explosion centre (P) and at a modest angle \( \theta \lesssim 30^\circ \) with respect to the line that connects the explosion centre to the observer (Fig. 1). We consider the density profile resulting from the collision of the winds of two stars with mass-loss rates \( \dot{M}_P = 10^{-5} M_\odot \) yr\(^{-1} \) and \( \dot{M}_O = 10^{-6} M_\odot \) yr\(^{-1} \), respectively. The \( \dot{M}_P \) is typical for a Wolf–Rayet star assumed to be the GRB progenitor, and \( \dot{M}_O \) is expected for a typical O star (also referred to as the ‘companion’ star). The stellar winds are assumed to be cold and have the same velocity \( v_w = 1000 \) km s\(^{-1} \). We have performed a 2D axisymmetric hydrodynamical simulation of such wind–wind interaction assuming adiabatic behaviour of the gas.\(^1\) We have used the high-resolution shock-capturing scheme

\[^1\] Stevens, Blondin & Pollock (1992) and, more recently, van Marle, Keppens & Meliani (2011) have studied the stellar wind interaction in detail and showed that for the distances \( d \gtrsim 0.1 \) pc of interest here, radiative cooling in the shocked regions is negligible, thus justifying the assumption that the gas is adiabatic.
that by the end of our simulations, the fluid may decelerate to $\Gamma \sim$ several and lateral spreading effects (not taken into account by our simulations) may be modestly important for $\theta \sim 5^\circ$; a value commonly inferred in GRBs (Frail et al. 2001). This point is discussed further in Section 3.1.

Having specified the density profile for the external medium, we only need to choose the (isotropic equivalent) energy of the blast $E$ for the self-similar initial conditions to be well defined. We consider a rather powerful GRB of $E = 10^{54}$ erg. The distance between the stars is set to $d = 2.2 \times 10^{18}$ cm. The blast wave dynamics is followed with relativistic hydrodynamic simulations using the code MRGENESIS described in Mimica et al. (2009b). The simulations have been performed in spherical symmetry with a numerical resolution of 16,000 cells in the blast wave. We have generated five blast wave models.

(i) Three models with external medium density profiles shown in Fig. 2: N05 (cut along a line $5^\circ$ off the line joining centres of two stars), N10 (10$^\circ$) and N20 (20$^\circ$).

(ii) A simulation in an external medium with a wind profile throughout: model WP.

(iii) A simulation in an external medium with a wind profile out to the wind TS at $1.6 \times 10^{18}$ cm (we assume a density jump of factor 4 at the TS and a constant density medium afterwards): model TS.

In Fig. 3, we show the Lorentz factor of the fluid behind the forward shock as a function of distance from the centre of the explosion. The initial evolution of all models is that of a self-similar blast in a $R^{-2}$ wind profile where the Lorentz factor just behind the forward shock $\Gamma \propto R^{-1/2}$ (Blandford & McKee 1976). For models N05, N10 and N20, the self-similar evolution holds until distance $R \sim d$ where the blast encounters the region of the shocked winds. At this stage, the enhancement of the density causes the forward shock to decelerate and a weak reverse shock launches into the blast.\footnote{The dynamics of this reverse shock has been studied by Pe’er & Wijers (2006). We verify using our simulation that the ratio of density and the ratio of the internal energy between shocked and unshocked regions as well as the Lorentz factor of the reverse shock agree within 15 per cent to the theoretical values of equations (12)–(14) in Pe’er & Wijers (2006).}

exit from the shocked wind region, the density drops and the blast rarefies in the front. The density profile has a second bump due to the approach to the companion star. This results in one more drop in the Lorentz factor $\Gamma$, the depth of which depends on the angle $\theta$. These non-self-similar stages of the interaction can only be studied in detail using numerical simulations. At still larger distance, the blast wave relaxes to a self-similar solution determined by the $R^{-2}$ density profile of the companion star. In the model WP the blast wave follows the Blandford & McKee (1976) evolution, while in the model TS it decelerates much faster after encountering the constant density medium behind the TS (e.g. van Eerten et al. 2009).

3 EMISSION

After the hydrodynamical simulations have been performed, we use the spev code (Mimica et al. 2009a) to compute the light curves. The details of how spev is applied to calculate the afterglows from GRBs can be found in the Section 3 of Mimica, Giannios & Aloy (2010). We consider synchrotron emission from the shock-accelerated electrons (Section 3.1) and external IC (EIC) scattering of the photon field from the companion star off the same electrons (Section 3.2).

In this paper we ignore the synchrotron self-Compton process. Section 3 contains qualitative discussion and analytical estimates, while the numerical results are presented in Section 4.

3.1 Synchrotron emission

During the initial self-similar stage of deceleration in the wind of the progenitor of density $\rho = AR^2$, with $A \equiv M_p/4\pi v_w \omega = 5 \times 10^{31} A_s$ g cm$^{-3}$ where $A_s = M_{-5} v_{w,8}^{-1}$, the bulk Lorentz factor of the fluid just behind the shock is

$$\Gamma = \sqrt{\frac{9E}{16\pi A R c^2}} = 60E_{54}^{1/2} R_{17}^{-1/2} A_s^{-1/2}. \quad (1)$$
The observer time evolves as \( t_{\text{obs}} = R/2\Gamma^{2}c \simeq 500R_{17}^{2}A_{4}E_{41}^{-1}s \) (neglecting cosmological redshift effects). For the distance \( d \sim 3 \times 10^{17} \) cm and the energy \( E \sim 10^{53} \) erg, it takes typically a day for the blast wave to reach the shocked wind region (this time-scale can range from hours to a week, depending on the various parameters).

We make standard assumptions in calculating the synchrotron emission from shocked fluid in the blast wave following Sari et al. (1998), i.e. we assume that a fraction \( \epsilon_e \) and \( \epsilon_B \) of the dissipated energy goes into accelerating electrons into a power-law distribution with index \( p \) and amplifying magnetic field, respectively. Throughout this paper, we fix \( \epsilon_e = 0.1, \epsilon_B = 0.005 \) and \( p = 2.5 \). The light curve at the initial self-similar stage is that calculated by Chevalier & Li (2000) that focus on a blast propagating in a \( R^{-2} \) wind profile. At a time \( t_{\text{obs}} \sim d/\Gamma c \) the blast wave encounters the region of the shocked winds, which causes a flattening in the light curve (Fig. 4). This feature has already been discussed in the case of a wind with a TS (Nakar & Granot 2007; van Eerten et al. 2009; see also Eldridge et al. 2006). In our setup, the blast wave crosses the shocked wind region on a short time-scale and transits to a less dense wind of the companion. This transition, a distinct characteristic of colliding stellar winds, leads to a steeper decline of the light curve. More light curves and a discussion are presented in the next section.

In our 1D, spherically symmetric approximation, even the sharp features of the external medium (e.g. shocks, density jumps) result in smooth changes on the afterglow emission. This effect, result (at least in part) of the large lateral extent of the emitting region, has been studied in detail by Nakar & Granot (2007) and van Eerten et al. (2009). However, there is evidence that GRB jets are collimated with opening angles of \( \theta_j \sim 5^\circ \) (e.g. Frail et al. 2001). Here we show that departures from spherical symmetry combined with structured external media introduce interesting novel features to the afterglow light curves.

In addition to modulations of the light curve because of external density profile, deviations from spherical symmetry are also expected to affect the afterglow appearance. A ‘jet break’ in the light curve is expected to occur when \( \Gamma \sim \theta_j^{-1} \) for a smooth density profile (Rhoads 1999). Zhang & MacFadyen (2009) have shown that the main effect of the \( \Gamma \lesssim \theta_j^{-1} \) transition is a steepening in the light curve because of the ‘missing surface’ emitting towards the observer (see, however, Wygoda, Waxman & Frail 2011). With our 1D simulations we cannot treat the transition exactly. However, we can easily include the dominant geometric effect that contributes to the jet break by considering the emission taking place only within an angle \( \theta_j \) with respect to the observer. Such examples are shown in Fig. 5 and discussed in Section 4.1.

3 Currently, combined X-ray (Swift) and optical observations cast some doubt on the presence of truly achromatic breaks. Nevertheless, it is very probable that GRB outflows are collimated, even if the ‘standard’ value of \( \theta_j \) is highly uncertain.
to the line of sight. The emission of the star is assumed to peak at $e_c = 10 c_e$ eV (typical for an O star). Electrons accelerated at the forward shock have a lower cut-off of their distribution at $\gamma_{\text{min}} \simeq (e_c/3)^{1/2} m_p m_e \simeq 1000 e_c$, where equation (1) is used in the last step. The energy of the scattered photons in the central engine frame is

$$e_{\text{sc}} \simeq 2 \gamma^2 e_{\text{min}} = \frac{8 \epsilon^2 - 1 \epsilon_{\text{sc}}^2 e_{\text{sc}}}{d_{18}} A_{2}^2 \text{ GeV.} \quad (2)$$

The detailed numerical results (Section 4.2) identify the expression $e_{\text{sc}}$ as a good estimate for the peak of the $L_{\gamma}$ spectrum of the EIC component. Note that for $e_{\text{sc}} \gtrsim (mc^2)^2/10 e_c \simeq 25/c_e$ GeV, the scattering takes place in the Klein–Nishina regime for all electrons and the last expression is not applicable.

The fluence of the EIC component can be estimated by considering the fraction of the total energy carried by electrons $\epsilon e E$ that is radiated away because of EIC. The closest approach to the companion star is $\sim \delta d$ with the energy density of photons (in the rest frame of the blast wave) being $u_{\gamma} \simeq \Gamma^2 L_{\gamma}/4\pi \delta d^2 c$. The IC cooling time-scale of an electron with $\gamma_{\text{min}}$ is $\tau_{\text{cool}} = 2 \times 10^7/\gamma_{\text{min}} u_{\gamma} \delta d^2$. The energy density of external photons peaks while the blast travels distance $\delta d/\Gamma c$ (in the comoving frame of the blast). The residence time in the intense radiation field is, therefore, $\tau_{\text{res}} \approx \delta d/\Gamma c$. Combining all these, the total (isotropic equivalent) radiated energy of the EIC component is

$$E_{\text{IC}} = \tau_{\text{res}} \epsilon E = 5 \times 10^{40} \epsilon_{\text{sc}}^2 L_{90.5} \frac{d_{18}^2}{\theta_{1}^{-1} d_{18}^4 A_{2}} \text{erg.} \quad (3)$$

The detailed numerical results (see Section 4.2) show that expression for $E_{\text{IC}}$ overestimates the fluence of the EIC component by a factor of, typically, $\sim$ a few. Klein–Nishina corrections contribute mostly to the discrepancy.

The flare peaks at time $t_{\text{peak}} = d/2\Gamma^2 c \simeq 0.5 d_{18}^2 A_{2} A_{e}^{-1}$. Not that for $d \sim 3 \times 10^{17}$ cm, $A_{e} \lesssim 1$, a close encounter with a bright star leads to extraction of a large fraction of the electron energy in the blast through EIC scattering. The emission from such encounter may peak several hours after the burst.

## 4 LIGHT CURVES

In this section we present the light curves produced by the five models introduced in Section 2.2. We first discuss the optical, X-ray light curves resulting from synchrotron emission, and then turn our attention to the $\gamma$-ray emission result of EIC.

### 4.1 Optical/X-ray emission

Fig. 4 shows the optical light curves. Before reaching the progenitor wind TS the light curves are indistinguishable from the one corresponding to a self-similar blast wave propagating in a $R^{-2}$ profile (model WP). From that point on the models begin to diverge depending on whether the blast wave continues propagating into a constant-density environment (TS) or whether it eventually encounters the wind of the companion star (N05, N10 and N20). The latter three models differ in their light curves because the blast wave crosses the wind interaction zone and a companion stellar wind at different angles.

In model N05, the blast wave propagates closest to the companion star and it encounters the densest companion wind. Therefore, it is slowed down more than N10, which in turn decelerates more than N20 (see also Fig. 3). This is seen in Fig. 4 after $t \simeq 3$ d, where N05 is the brightest of the three models, followed by N10 and N20.

Fig. 5 shows the effect of the finite opening angle of the jet. Since we are simulating a 1D spherical blast wave, we model a jet with a half-opening angle $\theta_{1}$ by assuming no contribution to emission from the fluid at angle with respect to the line of sight $>\theta_{1}$. As expected, while $\Gamma \gtrsim \theta_{1}^{-1}$ the jet collimation is not affecting the light curve. For a blast wave propagating in a pure wind-like profile, a rather smooth break appears in the light curve when $\Gamma \sim \theta_{1}^{-1}$. The break can be much sharper if the transition to $\Gamma < \theta_{1}^{-1}$ takes place when the blast wave reaches the shocked wind region. The rapid decline of the Lorentz factor of the blast wave at the density jump is not compensated by the increase of the emitting surface visible to the observer and the flux drops much faster than expected from a jet break in a smooth external medium. Comparing with the thick full and dashed grey lines (which show the temporal decline proportional to $t^{-2}$ and $t^{-3}$, respectively), we see that the combination of the jet break and the interaction of the blast wave with a shocked wind environment can produce steep declines.

Fig. 5 also demonstrates how the break happens at progressively earlier times as $\theta_{1}$ decreases (thick full, thick and dotted lines, respectively). At later times, the light curve decline becomes less steep due to the acceleration of the blast wave as it leaves the shocked region and encounters a less dense companion stellar wind.

Fig. 6 shows the X-ray light curve for the models N05, N10 and N20, as well as for the model N05 assuming a small jet opening angle, to simulate the effect of a jet break. As can be seen, the effect of the traversal of the shocked wind leaves qualitatively similar but less pronounced imprints on the X-rays in comparison to the optical light curve (see Fig. 4). The effect of the jet break (result of a finite jet angle) is, as expected, also an adiabatic one (e.g. not due to electron cooling), appearing simultaneously in the optical and X-rays.

### 4.2 $\gamma$-ray emission

The analytical estimates of Section 3.2 provide the dependence of the photon energy and fluence ($e_{\gamma}$ and $E_{\gamma}$, respectively) of the EIC emission on the various parameters. The actual numerical values of equations (2) and (3) are, however, meant more as rough...
order-of-magnitude estimates than the accurate predictions. In this section we use the numerical simulations to calculate the EIC emission and calibrate the analytics.

Part of the uncertainty of the analytical estimates is connected to the fact that they ignore the blast wave hydrodynamics of the shocked wind regions (instead, the blast wave is assumed to propagate in a freely propagating stellar wind). The numerical simulations are more accurate since they include the effect of the colliding winds on the blast dynamics and the exact calculation of the EIC cooling during the blast encounter (including Klein–Nishina effects) for a power-law injected electron distribution. We compute the EIC emission assuming a monochromatic external point source of radiation (good approximation for the blackbody stellar emission). To compute the emissivity, we use the method described in the section 2.2.1 of Mimica (2004).  

Fig. 7 shows the EIC bolometric light curves and the energy of the spectral peak (in GeV) for the models N05, N10 and N20 (thick, full, dashed and dotted lines, respectively). The EIC emission peaks at time $t_{\text{peak}} \approx 2 \text{d}$ in good agreement to equation (4) (using the value $d_{\text{sh}} = 2.2$) and then gradually declines. The duration of the high-energy flare is $\delta t \sim t_{\text{peak}}$. As expected, the EIC is brighter for the closer encounters (smaller $b$) between the line of sight and the companion star. At maximum of the EIC luminosity, the peak of the $L_{\nu}$ spectrum is $E \approx 2 \text{ GeV}$ independently of $\theta$ in close agreement to equation (2). The spectral peak moves to lower energies as function of time. We have verified that the EIC spectrum has a cut-off at $\approx 25 \text{ GeV}$ because of the Klein–Nishina suppression. The numerically calculated fluence is found to be a factor of $\sim 3$ less that the estimate in equation (3).

The total number of $\gamma$-ray photons emitted in the 0.1–300 GeV energy range [where the effective area of Fermi Large Area Tele-

scope (LAT) peaks] is $N_{\gamma} \approx 8 \times 10^{51}, 2 \times 10^{51}, 6 \times 10^{50}$ for $\theta = 5^\circ, 10^\circ, 20^\circ$, respectively. For an effective area of LAT of $A_{\text{eff}} \sim 10^4 \text{ cm}^2$, the closest encounter can be detected out to a proper distance of $d_p \approx (A_{\text{eff}} N_{\gamma}/4\pi)^{1/2} \approx 2.5 \times 10^{17} \text{ cm}$ or out to a modest redshift of $z \sim 0.3$ for this example.

In addition to the photon field of the companion, the blast wave also encounters the diffuse emission of the stellar cluster. The latter is dominated by that of the most massive stars in the cluster. For $N_\star$, massive stars of luminosity $L_\star$, each distributed isotropically within a cluster of radius $R_\star$, the ambient UVT photon field in the cluster is $U_{\text{UV}} \approx 3 N_\star L_\star/4\pi R_\star^2 c$. Fig. 7 shows the total EIC emission coming from the scattering of the photon field of the companion and the ambient cluster emission for $N_\star = 30, L_\star = 10^{55} \text{ erg s}^{-1}$ and $R_\star = 5 \times 10^{18} \text{ cm}$ (thin lines). Note that the ambient photon field is the dominant source of soft photons for the more distant encounters (with $\theta = 10^\circ, 20^\circ$), while it makes a modest contribution to the $\theta = 5^\circ$ example. The peak of the EIC component is broader in this case. Including both the companion and the diffuse sources of soft photons, the total number of $\gamma$-ray photons emitted in the 0.1–300 GeV energy range increases to $N_{\gamma} \approx 1.4 \times 10^{52}, 8 \times 10^{51}, 3 \times 10^{51}$ for $\theta = 5^\circ, 10^\circ, 20^\circ$, respectively. In this case, the emission can be detected out to $d_p \approx 3.3 \times 10^{17} \text{ cm}$ or out to $z \sim 0.3$–0.4.

5 DISCUSSION

If all, or at least the majority of, long duration GRBs come from the death of massive stars, a fair fraction of them should take place inside young, massive stellar clusters. In such crowded environments, the wind of the progenitor star terminates on sub-pc scales (mainly due to interactions with other stellar winds). The wind–wind interaction regions are characterized by shocks, contact discontinuities and other sharp features in the density profile. The blast wave, result of the GRB jet interacting with the external medium, has a bumpy ride in such environments. In this work we search for the characteristic observational signatures of such blast wave evolution, focusing on the profile shaped by the collision of the wind of the progenitor with that of a nearby massive star or ‘companion’.

5.1 Optical and X-ray emission

As long as the Lorentz factor of the blast $\Gamma \gg 1$ and $\Gamma \gtrsim \theta^{-1}$, one can study the basic features of the blast–external medium interaction assuming spherical symmetry and considering different lines of sight to the observer. We find that, when the blast wave enters the shocked wind region, the optical light curve at first flattens, followed by a steeper decline at later times (Fig. 4). The flattening takes place at observer time $t \approx 0.5d_{17}^{0.5} A_{\text{eff}} E_{51}^{-1/2} \text{d}$ (e.g. see equation 4). When the characteristic synchrotron frequency crosses the observed band, the modulations of the light curve are enhanced. Qualitatively similar (but much less pronounced) effects are in general expected in the X-rays as well (Fig. 6). Our results are in agreement with the generic arguments presented in Nakar & Granot (2007), who show that relativistic blast waves in spherical symmetry do not show sharp features in their light curve even for step-function changes of the external density as function of radius.

Observations with dense sampling until late times and good signal-to-noise ratio are required to detect the relatively smooth changes in the light curves. One recent example is a well-studied optical, X-ray afterglow of GRB 080413B (Filgas et al. 2011), which shows a characteristic flattening in the optical followed by a steeper decline in both optical and X-ray wavelengths that appears to be in agreement with the expectations from our model. Further
examples include GRBs 021004 (see Lazatzi et al. 2002, and references therein), 080710 (Krühler et al. 2009a), 080129 (Greiner et al. 2009a) and 080913 (Greiner et al. 2009b). Finally, there is an interesting GRB 071031 (Krühler et al. 2009b), which shows several bumps in the optical, which might be due to more than one star influencing the afterglow (see, however, the discussion in Section 5.3).

For a wide range of parameters, the blast wave is expected to enter the shocked wind region when $\Gamma \sim \theta^{-1}$. Strictly speaking, our 1D calculations are not directly applicable to this regime since they ignore lateral spreading of the blast. Nevertheless, recent 2D simulations performed by Zhang & MacFadyen (2009) indicate that lateral spreading effects are small at this stage and that the ‘jet breaks’ are mainly a geometric effect. We show that the combination of jet collimation and structured external medium may lead to rather sharp features in the light curve, such as a fast decline of the light curve as steep as $F \propto t^{-4}$ to $F \propto t^{-5}$, which is not expected for the evolution in a smooth external medium (Fig. 5).

5.2 $\gamma$-ray emission

Another characteristic signature of the companion–blast interaction is an IC powered, GeV flare (Giannios 2008). We show that, under optimistic conditions, a large fraction of the energy deposited on the shocked electrons is radiated away during the encounter with the dense UV photon field of the massive star. Such a flare at the energies of tens of GeV may account e.g. for the emission of the GRB 940217 observed hours after the burst with EGRET (Hurley et al. 1994). The LAT instrument on-board to the Fermi satellite is capable of detecting such flaring for bursts out to modest redshift $z \lesssim 1$. Depending of the distance of the companion star, the $\sim$GeV emission will peak on time-scales that range from a few hours up to a few weeks after the burst (Fig. 7). In some cases, the ambient UV photon field of the massive stars in the cluster may be the dominant source of the IC component resulting in slower varying $\gamma$-ray emission. A systematic search for delayed $\gamma$-ray emission from the location of the burst on time-scales of hours to weeks after the burst may be fruitful. The timing and photon energy of such detection will provide invaluable information about the GRB environment.

An additional promising source of seed photons to be IC scattered at the forward shock may be the infrared emission from dust. Though its physical origin is unclear, dust is forming actively in the stellar wind region in many Wolf–Rayet stars (e.g. Crowther 2003). Up to $\sim 10$ per cent of the stellar light can be reprocessed into the infrared that provides an isotropic bath of photons through which the blast propagates. Mid- to near-infrared photons can be scattered into multi-TeV energies by the high-energy tail of the electron distribution while still in the Thomson scattering regime. Such emission, with a $\nu L_\nu$ peak at $\sim$TeV energies, may be detectable by atmospheric Cherenkov telescopes provided that the burst takes place at redshift $z \lesssim 0.5$ (for the TeV photons to avoid attenuation while propagating through the extragalactic background light).

5.3 Other effects

In this paper, we focused on the effect of a single massive star on the circumburst medium density in the cluster where the GRB takes place. This star is most relevant in the early afterglow stages since it lies closest to the line of sight of the observer. Clearly, the collective effect of many stellar winds will dominate the density profile at larger distance (more than a few times the distance to the ‘companion’, corresponding to a time of several hours after the burst). At these scales the external medium is expected to be very inhomogeneous, although on scales much smaller than those relevant for the blast wave emitting towards the observer. At late times, therefore, the afterglow light curve may resemble that expected from a constant density medium. The confining effect of the environment in the cluster can thus naturally limit the extent of the wind of the progenitor and lead to a constant-like density as is commonly suggested by modelling of afterglow observations (e.g. see Schulze et al. 2011). Such interpretation, however, is problematic when a constant density medium is inferred very early (from minutes to few hours) after the burst.

ACKNOWLEDGMENTS

We are grateful to Miguel Angel Aloy, Jose Maria Ibáñez and Jochen Greiner for the constructive criticism and a fruitful discussion. PM acknowledges the support from the European Research Council (grant CAMAP-259276), from the Spanish Ministry of Education and Science (AYA2007-67626-C03-01, AYA2010-21097-C03-01, CSD2007-00050) and from the Valencian Conselleria d’Educació (PROMETEO/2009/103). DG is a Lyman Spitzer, Jr Fellow of the Department of Astrophysical Sciences of Princeton University. The calculations have been performed on the Lluís Vives cluster at the University of Valencia.

REFERENCES

Blandford R. D., McKee C. F., 1976, Phys. Fluids, 19, 1130
Galama T. J. et al., 1998, Nat, 395, 670
Hjorth J. et al., 2003, Nat, 423, 847
Hurley K. et al., 1994, Nat, 372, 652

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