An external-shock model for gamma-ray burst afterglow 130427A

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ABSTRACT

The complex multiwavelength emission of gamma-ray burst (GRB) afterglow 130427A (monitored in the radio up to 10 d, in the optical and X-ray until 50 d, and at GeV energies until 1 d) can be accounted for by a hybrid reverse–forward shock synchrotron model, with inverse-Compton emerging only above a few GeV. The high ratio of the early optical to late radio flux requires that the ambient medium is a wind and that the forward-shock synchrotron spectrum peaks in the optical at about 10 ks. The latter has two consequences: the wind must be very tenuous and the optical emission before 10 ks must arise from the reverse-shock, as suggested also by the bright optical flash that Raptor has monitored during the prompt emission phase (<100 s). The Very Large Array radio emission is from the reverse-shock, the Swift X-ray emission is mostly from the forward-shock, but the both shocks give comparable contributions to the Fermi GeV emission. The weak wind implies a large blast-wave radius (8 L\(_{\odot}\)/day pc), which requires a very tenuous circumstellar medium, suggesting that the massive stellar progenitor of GRB 130427A resided in a superbubble.

Key words: radiation mechanisms: non-thermal – relativistic processes – shock waves.

1 INTRODUCTION

Gamma-ray burst (GRB) 130427A may well be the burst with the most comprehensive afterglow follow-up, its multiwavelength monitoring covering radio, optical, X-ray and gamma-ray frequencies, and extending from seconds to tens of days after trigger. The X-ray prompt emission (up to 100 s) was accompanied by the second brightest optical flash, monitored by Raptor (Vestrand et al. 2013), with the optical afterglow light curve displaying a steepening at 300 s and a flattening at 10 ks. The Swift X-ray light curve (X-ray light-curve repository – Evans et al. 2009) is consistent with a single power law from 500 s to 5 Ms. The Fermi-Large Area Telescope (LAT) gamma-ray light curve (Tam et al. 2013) displays a peak at 10–20 s, simultaneous with the optical flash peak, and a steepening at 550–800 s (Zhu et al. 2013). The Very Large Array (VLA) radio light curves (Laskar et al. 2013) display a slow decay at 1–10 d.

With such a rich data set, GRB afterglow 130427A demands a theoretical interpretation, done here in the framework of the external-shock model (Mészáros & Rees 1997) where some relativistic ejecta, produced by the black hole resulting from the core-collapse of a massive star, drive a forward-shock into the ambient medium while the ejecta are energized by the reverse-shock. The synchrotron and inverse-Compton emissions from both shocks are calculated assuming that electrons and magnetic field acquire a certain fraction of the post-shock energy. The shock-accelerated electrons are assumed to have a power-law distribution with energy (hence the synchrotron and inverse-Compton spectra are also power laws), with a break at the cooling energy (where the radiative-loss time-scale equals the shock age).

Analytical treatments for the forward-shock emission have been provided by Mészáros & Rees (1997), Sari, Piran & Narayan (1998), Waxman, Kulkarni & Frail (1998), Granot, Piran & Sari (1999), Wijers & Galama (1999), Chevalier & Li (2000), Panaitescu & Kumar (2000), and for the reverse-shock by Kobayashi (2000). Both shocks have been studied with one-dimensional hydrodynamical codes by Panaitescu & Mészáros (1998) and Kobayashi & Sari (2000), the former focusing on the two-shock synchrotron and inverse-Compton emission, the latter on the dynamics of the shocks.

To model the multiwavelength emission of GRB afterglow 130427A, we employ a one-dimensional code that follows the ejecta–medium interaction, with the dynamics of each shock calculated from conservation of energy and using the shock jump-conditions (Blandford & McKee 1976). After the onset of deceleration, the dynamics of the forward-shock is determined by the ejecta initial energy, injected energy (Rees & Mészáros 1998) and ambient medium density. The dynamics of the reverse-shock is determined by that of the shocked fluid and two properties of the incoming ejecta: their energy and Lorentz factor. Here, we consider that the ejecta add energy to the blast-wave as a power law in observer time and that they have a single Lorentz factor. The self-absorption and cooling frequencies of the synchrotron spectrum and the inverse-Compton parameter are calculated self-consistently from the electron distribution and the magnetic field strength (Panaitescu & Mészáros 2000). Radiative losses are also calculated from the electron distribution, but they are negligible for the following best-fitting
models. The emissions from both shocks are integrated over their motion and over the angle at which the fluid moves relative to the direction towards the observer. More details about this numerical model and its application to the multiband X-ray light curves of the GRS 1915+105 afterglows are given in Panaitescu (2005).

2 REVERSE–FORWARD (EXTERNAL) SHOCK MODEL

2.1 Closure relations for forward-shock light curves suggest a homogeneous medium

The choice of the model features that may accommodate the temporal decay of the broad-band emission of GRB afterglow 130427A starts with the X-ray light curve because its temporal decay index \( F \propto t^{-\alpha} \) and spectral slope \( F_\nu \propto \nu^{-\beta} \) are the best determined: \( \alpha = 1.36 \pm 0.01 \) at 20 ks–5 Ms (Fig. 1) and \( \beta = 0.79 \pm 0.16 \) at mean time 24 ks (Kennea et al. 2013). These lead to \( \alpha_x = 1.5 \beta_x = 0.18 \pm 0.24 \), which is compatible with the value expected (zero) for the synchrotron emission from the forward-shock inter-

acting with a homogeneous medium and for the X-ray being below the cooling frequency \( \nu_x \) of the synchrotron spectrum.

As the optical flux also decays at that time, the optical must be above the peak energy \( \nu_p \) of the synchrotron spectrum: hence, optical and X-ray are in the same spectral regime: \( \nu_p < \nu_{\text{syn}}(2 \text{eV}) < \nu_{\text{x}}(10 \text{keV}) < \nu_x \). Consequently, the intrinsic afterglow optical flux can be calculated from the X-ray flux: \( F_o = F_x (\nu_x / \nu_o)^{\alpha_x} \). For instance, the observed \( F_{10-100}\text{keV}(54 \text{ks}) = 1.4 \mu\text{Jy} \) implies that \( F_{2-10\text{eV}}(54 \text{ks}) = 1.2 \mu\text{Jy} \), which is a factor 2.5 larger than the measured \( F_{2-10\text{eV}}(53 \text{ks}) = 0.47 \mu\text{Jy} \), requiring \( A_H = 1 \text{ mag} \) of dust extinction in the host galaxy.

The 10 keV–100 MeV spectral slope \( \beta_x \) (3 ks) \( \approx 0.89 \pm 0.09 \) \( \gtrsim \beta_x \) indicates that \( \nu_x \) is well above 10 keV. That the LAT flux decays slower than in the X-ray (\( \alpha_x = 1.22 \pm 0.09 \) at 500 s–50 ks) indicates that \( \nu_x \) is below the LAT range (otherwise, for \( \nu_x > 100 \text{ MeV} \), the model expectation is \( \alpha_x = \alpha_x \) and that the electron radiative cooling is dominated by inverse-Compton scatterings (otherwise, for synchrotron-dominated electron cooling, \( \nu_x \propto t^{-1/2} \) and \( \alpha_x - \alpha_x = -0.3 \cdot (d \log \nu_d / d \log t) = 1/4 \), incompatible with the observed \( \alpha_x \approx \alpha_x \)). More exactly, for a Compton-dominated electron cooling, the decay index of the synchrotron flux above \( \nu_x \) is \( \alpha = 3p/4 - 1/(4 - p) = 1.27 \), which matches well the observed \( \alpha_x \), with \( p = (4\alpha_x + 3)/3 \approx 2.8 \) being the exponent of the power-law distribution of electrons with energy \( \text{dN}/(\text{d} E \propto \nu^{-p} \)) that is required by the forward-shock model, given the measured flux decay index \( \alpha_x \) below the cooling frequency.

In summary, the optical, X-ray, and gamma-ray fluxes of GRB afterglow 130427A, their decay indices and the X-ray spectral slope, require that \( \nu_p < \nu_o < \nu_x < \nu_x \), if the afterglow emission is synchrotron from the forward-shock.

2.2 External medium is not homogeneous

Under the assumption that the two microphysical parameters of the forward-shock (\( \epsilon_B \) and \( \epsilon_i \)) that quantify the post-shock fractional energy in the magnetic field and in electrons are constant, the forward-shock synchrotron light curve at any frequency below the optical can be easily calculated from the optical light curve, using the expected evolution of the synchrotron peak flux \( F_p \) (const) and peak energy \( \nu_p \propto t^{-3/2} \) for a homogeneous medium. If \( \nu_p \) crosses the optical at some time \( t_o \), yielding an optical flux \( F_o \), then the radio flux at frequency \( \nu, < \nu_x \) is

\[
F(t) = F_p (\nu/\nu_p)^{1/\gamma} = F_p(t_o)(t/t_o)^{1/\gamma} (\nu/\nu_p)^{1/\gamma} \propto t^{1/2}.
\]

Here, \( F_p(t_o) \approx 5 (t_o/10 \text{ks})^{-\gamma} \text{ mJy} \) is the intrinsic optical light curve after 10 ks (corrected for the above-inferred host extinction \( A_H = 1 \text{ mag} \)) and \( \gamma = 1.36 \) (the forward-shock model requires that \( \gamma = \gamma_x \)). The largest \( t_o \) required by equation (1) arises from the radio measurement with the highest \( \nu/\nu_p^{1/2} F_p \): taking the \( F_{10-100\text{GHz}}(9.7 \text{ d}) = 0.43 \mu\text{Jy} \) measurement as an upper limit for the forward-shock radio flux, implies \( t_o \gtrsim 23 \text{ ks} \).

This means that, for the forward-shock emission (that accommodates the observed optical flux) not to exceed the measured radio fluxes, the synchrotron peak should cross the optical at 23 ks. Conversely, if the synchrotron peak crossed the optical before 23 ks, then the synchrotron flux from the forward-shock would violate VLA measurements. That may be avoided if the magnetic field parameter \( \epsilon_B \) decreases (roughly as \( t^{-1/2} \)), and if energy injection in the forward-shock is allowed (to match the optical and X-ray flux decays at 1–10 d, which are faster when \( \epsilon_B \) decreases), but this scenario requires fine-tuning and we do not pursue it.

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**Figure 1.** Multiwavelength light curves for GRB 130427A and the synchrotron forward-shock/homogeneous-medium model best fit to the radio, optical after 10 ks, X-ray after 50 ks and gamma-ray measurements (the second X-ray pulse at 100–400 s is not included in the fit). Numbers adjacent to light curves give the local power-law flux decay index (and its 1σ uncertainty). Solid lines are for a model excluding radio measurements; the peak of the synchrotron spectrum crosses the \( R \) band (2 eV) at 10 ks and the model overpredicts some of the VLA radio measurements at 1–10 d and 1–90 GHz (as expected from equation 1). The parameters of this model are: ejecta initial kinetic energy \( E_0 = 3.10^{53} \text{ erg} \), ejecta initial Lorentz factor \( \Gamma_0 = 850 \) (to yield a 20 ks peak for the 100 MeV flux, when the ejecta deceleration begins), ambient medium density \( n = 2.10^{-3} \text{ cm}^{-3} \), magnetic-field parameter \( \epsilon_B = 10^{-4} \), electron minimum-energy parameter \( \epsilon_i = 0.11 \), index of electron power-law distribution with energy \( p = 2.5 \), host dust-extinction \( A_V = 1.3 \). Dashed lines are for a model including the radio measurements, which forces the peak of the synchrotron spectrum to be higher (crossing the optical at 20 ks). This model still overpredicts some radio measurements as well as the gamma-ray flux measured by LAT during the prompt phase. Its parameters are similar to the solid lines model, the most notable difference being \( \epsilon_i = 0.23 \).
2.3 Wind-like medium and forward-shock emission for the late optical afterglow

The closure relation $\alpha_1 - 1.5 \beta_1 = 0.18 \pm 0.24$ is also compatible with the forward-shock model expectation for a wind-like medium (with an $n \propto r^{-2}$ particle density distribution with radius) and for X-ray below the cooling frequency, provided that there is an energy injection in the forward-shock that slows its deceleration and the decay of the afterglow X-ray flux. If that energy injection is parametrized as $E \propto t$ in observer time (a power-law flux decay requires that the dynamics of the forward-shock is a power law in observer time), then $\alpha_1 - 1.5 \beta_1 = [1 + (\beta_1 + 1) t]/2$, from where $e = 3 - 2(\alpha_1 + 1)/(\beta_1 + 1) = 0.36 \pm 0.23$.

Numerically, we find that the best fit to the X-ray emission after 500 s (including all the GeV data and the optical after 10 ks) has $e = 0.30$ and that forward-shock energy should increase by a factor $E_0/E_0 = 3$ until $t_o \simeq 1$ Ms, to account for the observed X-ray flux decay. That means that the energy added to the forward-shock mitigates its deceleration after $t_i = t_o(E_0/E_i)^{1/e} = 20$ ks.

It is important to note that the forward-shock interacting with a wind-like medium does not produce more radio emission than measured because the synchrotron peak flux decreases as $F_o \propto t^{-1/2}$ (instead of being constant, as for a homogeneous medium). The evolution of the synchrotron peak energy is the same as for a homogeneous medium ($\nu_o \propto t^{-3/2}$); hence, the radio flux expected from the optical emission is

$$F_o(t) = F_o(\nu_o/\nu_0)^{1/2} = F_o(t_o)(\nu_o/\nu_o)^{1/3} \propto t^0.$$ (2)

Then, $F_o(t_o) \simeq 2(\nu_o/10^{18} \text{ Hz})^{-1.36}$ mJy and $F_{36\text{GHz}}(9.7 \text{ d}) = 0.43$ mJy require that the time when the synchrotron peak crosses the optical is $t_o \gtrless 3$ ks. That brief flattening seen in the optical light curve at 10 ks could be due to $\nu_o$ crossing the optical and is compatible with $t_o \gtrless 3$ ks.

The best fit to the optical data after 10 ks, the X-ray after 500 s, and all GeV measurements, with the forward-shock emission and for a wind-like medium is shown in Fig. 2, with a sequence of spectra shown in Fig. 3. The $\chi^2$ is 5.7 for 135 dof of that best fit makes it statistically unacceptable; the GeV fit has the largest $\chi^2 = 7.1$ for 9 points, closely followed by the optical fit's $\chi^2 = 6.3$ for 39 points, with the largest contribution to the fit's $\chi^2$ arising from the X-ray data, $\Delta \chi^2 = 392$ for 79 points. The model light curves follow well all flux trends and relative intensities except the brightness of the prompt emission until 50 s, but cannot describe well the early GeV light curve and cannot capture the fluctuations in the X-ray and optical measurements (after 10 ks, optical data are from different instruments).

2.4 A very tenuous wind

Compared to the parameters inferred for other afterglows by modelling their multwavlength emission, the wind density of the best fit shown in Fig. 2 is very small, but not unprecedented (Chevalier, Li & Fransson 2004). Its parameter, $A = 0.003$, corresponds to a stellar mass-loss rate to terminal wind-velocity ratio $(M/v)$ that is 300 smaller than for a typical Wolf–Rayet (WR) star (as the progenitor of long bursts with an associated Type Ic supernovae), for which $M = 10^{-5} M \odot \text{ yr}^{-1}$ and $v = 10^8 \text{ cm s}^{-1}$. The reason for that low density is the requirement that the synchrotron peak crosses the optical after 3 ks and matches the optical flux detected at that time. For $z = 0.34$ and for the fluid moving directly towards the observer, the forward-shock synchrotron peak energy and peak flux are

$$h \nu_\beta(10 \text{ ks}) = 0.5 E_{54}^{1/2} \epsilon_{B,-5}^{1/2} \epsilon_{i,-1}^{1/2} \text{ eV}$$ (3)

$$F_\gamma(10 \text{ ks}) = 240 E_{54}^{1/2} \epsilon_{B,-5}^{1/2} \epsilon_{i,-1}^{1/2} \text{ mJy}.$$ (4)

Imposing that $\nu_o(10 \text{ ks}) = \nu_o = 2$ eV and $F_\gamma(10 \text{ ks}) = F_o(10 \text{ ks}) = 2 \text{ mJy}$ yields

$$E_{54}^{1/2} \epsilon_{B,-5}^{1/2} \epsilon_{i,-1}^{1/2} = 0.011 \ , \ E_{54}^{1/2} \epsilon_{B,-5}^2 A = 2.6 \times 10^{-5}.$$ (5)

Taking the ratio of these two equations leads to $A = 2.3 \times 10^{-3} \epsilon_{i,-1}$. The $\epsilon_i$ parameter that quantifies the typical electron energy corresponds to a total electron energy that is a fraction $\epsilon_i = (p - 1)/(p - 2)\epsilon_e$ of the post-shock energy. Equi-partition with...
...the medium density around the star, we find that \( p \beta \) and \( e \) are fixed at \( \sim \pm \) (cooling frequency, for electrons \( \chi \nu \) yr life-time for a wind with \( 1 / \Gamma_1 / 25 \) s spectrum) and can account for the higher energy LAT emission until about 10 ks, after which the inverse-Compton flux is too low.

Interestingly, a hardening of the LAT spectrum above several GeV was identified by Tam et al. (2013), from \( \beta_{\gamma}^{(\text{high})} \) and \( \beta_{\gamma}^{(\text{low})} \). For the best-fitting parameters given in Fig. 2, the forward-shock has \( \Gamma(1 \text{ ks}) = 240 \) and \( \Gamma(1 \text{ ks}) \), so the maximal synchrotron energy is \( h\nu_c(1 \text{ ks}) \approx 600 \text{ MeV} \) (see synchrotron spectrum cut-off in Fig. 3). At earlier times, that cut-off is higher, but the inverse-Compton emission from the forward-shock takes over above 2 GeV (as shown by the \( t = 75 \text{ s} \) spectrum) and can account for the higher energy LAT emission until about 10 ks, after which the inverse-Compton flux is too low.

2.6 Reverse-shock emission for the radio and early optical afterglow

The estimation of the expected radio emission given in equation (2) led to the conclusion that the forward-shock cannot account for the optical afterglow emission prior to \( \sim 10 \) ks. Also, the flat radio light curve arising from the forward-shock interacting with a wind cannot account for the radio emission at 1–10 d, which is slowly decaying. Both these emissions are attributed to the reverse-shock (see also Laskar et al. 2013), as discussed below. We note that, after 10 ks, the existence of a reverse-shock is required by the energy injection into the forward-shock required by the measured decay index of the X-ray flux.

The radio data are contemporaneous with the higher energy (optical, X-ray and gamma-ray) afterglow emission accommodated by the forward-shock, thus, for the calculation of the reverse-shock emission, the dynamical parameters \( E_0 \), \( E_{\gamma}^{(\text{high})} \), \( \epsilon \), and \( \alpha \) are fixed at the values determined from the forward-shock best fit. The free parameters of the reverse-shock are the Lorentz factor \( \Gamma_i \) of the incoming ejecta (which sets the post-shock energy density) and the three microphysical parameters \( (\epsilon_B, \epsilon_i, \epsilon_p) \) that determine the synchrotron spectrum. The best fit obtained with the reverse-shock emission to the 1–10 d radio data is shown in Figs 2 and 3. Unfortunately, it has a large \( \chi^2 \) for 25 dof, because it under-estimates the radio flux above 50 GHz. As shown in Fig. 3, those radio data cannot be explained by the forward-shock either, if its microphysical parameters are constant. Requiring the same microphysical parameters for both the reverse and forward shocks yields a much worse radio data fit, with \( \chi^2 \).
The best fit to the early optical emission with a reverse-shock model includes also the earlier X-ray data and all GeV data, to ensure that the reverse-shock emission does not exceed what was observed. Again, the dynamical parameters $E_{\alpha}$ and $A$ are fixed to the values obtained for the forward-shock, but the energy $E^{(r)}$ carried by the incoming ejecta arriving at the blast-wave prior to 10 ks is only weakly constrained by the forward-shock fit to the optical and X-ray data after 10 ks, which sets an upper limit $E^{(r)} < E_0$. With free micro-parameters, the best fit with the reverse-shock to the early afterglow has $\chi^2_{\nu} = 5.4$ for 136 dof, as it fails to account for the GeV prompt emission prior to 100 s, although it explains well the early optical data and the X-ray data at 0.5–3 ks. We note that the reverse-shock magnetic parameter $\epsilon_B$ prior to 10 ks (from fitting the early optical afterglow) is 100 times larger than after 10 ks (from modelling for the radio emission). If the reverse-shock microphysical parameters were held constant across 10 ks, then the fit to the radio emission would have a $\chi^2_{\nu}$ twice larger; thus, a decrease in $\epsilon_B$ at 10 ks is required. That may mean that the ejecta arriving at the blast-wave later are less magnetized.

2.7 Other models with a more complicated afterglow medium structure

As discussed in Section 2.3, to reconcile the radio and optical fluxes of afterglow 130427A requires that the peak of the forward-shock synchrotron crosses the optical after 3 ks. In turn, that requires (Section 2.4) a very weak stellar wind, about 300 less tenuous ($M_{\cdot\cdot\cdot}/v_{\infty} = 0.004$) than for the average Galactic WR star. Then, the forward-shock radius is $R_{\odot}(3\,\text{ks}) = 1.5\,\text{pc}$, while the wind bubble radius should be $R_{\odot} = 12(v_{\infty}/n_0)^{1/3}\,\text{pc}$. Thus, if the circumstellar medium is sufficiently dense, it is possible that $R_{\odot}(3\,\text{ks}) = R_{\odot}$. Alternatively, if the stellar wind had the average density, the wind termination shock could be encountered by the forward-shock at 3 ks, provided that the burst is embedded in a hot, highly pressurized environment (Chevalier et al. 2004). At frequencies below the cooling break, the afterglow light curve should display a flattening when the forward-shock crosses the wind termination shock, transiting from the $r^{-2}$ free wind to the quasi-homogeneous shocked wind.

To be self-consistent, the interpretation of the 3 ks optical light-curve flattening as the blast-wave encountering the wind termination shock should attribute the entire afterglow emission to the same shock. Then, the peak of the synchrotron spectrum must be below optical at all times when a decaying optical flux is measured, a model which overproduces radio emission, if the optical afterglow originates in the forward-shock (as shown in Section 2.3). The subsequent steepening of the optical light curve at 20 ks cannot originate in the ambient medium stratification because, outside the termination shock, the shocked wind and circumstellar medium are still homogeneous. Instead, that light-curve steepening should be attributed to the cooling frequency falling below the optical, which yields a steepening of the power-law flux decay by $\delta \alpha = 1/4$ (consistent with that measured for the optical light curve of 130427A at 20 ks), and a softening of the optical spectrum by $\delta \beta = 1/2$ (consistent with the reddening reported by Perley et al. 2013, after 10 ks).

The fortuitous temporal coincidence of the cooling frequency falling below optical just after the blast-wave arrives at the free-wind termination shock is not required if the discontinuity in the ambient medium structure that yields the 3 ks optical light-curve flattening is caused by an internal interaction within an unsteady stellar wind or by the interaction between the winds of two stars. In the former scenario, considered analytically by Chevalier & Imamura (1983) and in the context of GRB afterglows by Ramirez-Ruiz et al. (2005), a stronger wind produced by the WR star prior to its core-collapse interacts with a slower wind ejected previously. In the latter scenario, proposed by Mimica & Giannios (2011) to be the source for more diverse afterglow light curves, the GRB progenitor is in a dense stellar cluster, where the mean distance between stars is below 1 pc, and the WR wind interacts with the weaker wind of a nearby O star or a later type. In either scenario, after the interaction with the shocked wind(s), which yields a light-curve flattening, the blast-wave goes into an $r^{-2}$ wind, which is the earlier WR wind or the wind of the nearby star, producing a light-curve steepening, with the flux decay index $\alpha$ returning to the value it had during the interaction with the free WR wind. Only the dense cluster scenario provides a natural explanation for the very weak wind inferred here from modelling the afterglow 130427A: the wind of a B star located within 1 pc of the GRB progenitor. However, this scenario cannot explain why that weak wind extends over tens of pcs (as required by the duration of the afterglow, Section 2.4) despite the more powerful winds of nearby, earlier type stars.

Thus, the 3 ks flattening and 20 ks steepening seen in the optical light curve of 130427A could originate from a forward-shock interacting with the more complex ambient medium resulting from an internal wind interaction provided that microphysical parameters evolve such that this model does not exceed the 1–10 d radio measurements. Alternatively, radio emission is not overproduced if the entire afterglow emission arises from the reverse-shock, and the optical light-curve flattening and steepening could result from the changing dynamics of the reverse-shock when the shocked-wind shell is crossed. Such light-curve features could also be due to variations in the density and Lorentz factor of the incoming ejecta, without any need for a non-uniform ambient medium.

However, a model where the entire afterglow emission arises from the same shock (reverse or forward) does not provide a natural explanation for the colour evolution displayed by 130427A, which becomes bluer after 3 ks (Vestrand et al. 2013), when the optical light-curve flattens, and redder after 10 ks (Perley et al. 2013), when the optical light-curve steepens. In contrast, the hybrid reverse–forward shock model explains naturally both the 3 ks spectral hardening, as due to the harder (below the synchrotron peak energy) forward-shock emission emerging from under the softer reverse-shock emission, and the following spectral softening, caused by the peak energy of the forward-shock synchrotron spectrum falling below optical.

3 CONCLUSIONS

The closure relations expected between the forward-shock synchrotron flux decay index and spectral slope suggest a homogeneous ambient medium for GRB afterglow 130427A. Although long GRBs arise from massive stars that drive powerful winds, a homogeneous medium is possible if the afterglow emission is produced in the shocked wind. However, this afterglow’s (10 ks) optical flux to (1–10 d) radio flux ratio and its slowly decaying radio light curves disfavour that type of ambient medium. Instead, for an unevolving constant magnetic field parameter, the synchrotron spectrum peak flux is constant and the radio emission should have been brighter and slowly rising. With some fine-tuning of the evolutions of those micro-parameters, it may be possible to reduce the forward-shock model radio flux below measurements, while still accounting for the observed optical and X-ray light-curves.
A wind-like medium ($\rho \propto r^{-2}$) is the more natural expectation for a massive star as the GRB progenitor. The forward-shock emission still cannot account for the radio data because the expected radio light-curve is flat; however, a wind-like medium yields a decreasing synchrotron spectrum peak flux, making it easier to keep the forward-shock radio emission below radio measurements. To explain the optical and X-ray flux decay after 10 ks with the forward-shock synchrotron emission, a moderate energy injection into the forward-shock is required, increasing the shock energy by a factor 4 from 10 ks to 1 Ms. The agent of that energy injection should be some ejecta that arrive at the forward-shock at that time, which provides a natural explanation for the afterglow radio emission: the reverse-shock that crosses the incoming ejecta.

The reverse-shock must have been operating at even earlier times because the high early-optical to late-radio flux ratio precludes a forward-shock origin of the optical afterglow emission prior to 10 ks. Such a reverse-to-forward shock switch for the origin of the optical emission, occurring at few ks, is supported by the optical afterglow becoming bluer\(^1\) at that time (Vestrand et al. 2013), when the forward-shock emission, with a spectrum $F_\nu \propto \nu^{1/3}$ in the optical, begins to dominate the softer reverse-shock emission, with a spectrum $F_\nu \propto \nu^{-1/2}$. As the peak of the forward-shock synchrotron spectrum falls below optical at about 10 ks, the optical afterglow should become redder after 10 ks, as was observed by Perley et al. (2013).

However, for the reverse-shock to explain the 100 s to few ks optical afterglow and the 1–10 d radio afterglow emission, the properties of the reverse-shock (microphysical parameters, kinetic energy and Lorentz factor of the incoming ejecta) must change around 10 ks. Furthermore, Vestrand et al. (2013) have shown that the reverse-shock can also account for the optical flash (up to 100 s) and the GeV light-curve peak, but for microphysical different than after that peak.

For this hybrid reverse–forward shock model, we find that the X-ray flux of GRB afterglow 130427A is accounted mostly by the forward-shock emission, from the tail of the first GRB pulse (50–100 s) up to 5 Ms, excluding the second GRB pulse at 100–500 s. The reverse-shock may have had a significant contribution to the early X-ray emission, at 500 s–2 ks. Both shocks give comparable GeV emissions. As shown in Fig. 2, the radio emission from the forward-shock is expected to overshone that from the reverse-shock at 30 d (or somewhat later, if energy injection continues after 1 Ms), yielding a flat flux $\lesssim 0.1$ mJy until $\sim 200$ d, when the peak of the synchrotron spectrum falls below 10 GHz. If that flat radio flux is not seen, then the magnetic field parameter $\epsilon_B$ of the forward-shock must be decreasing, so that the peak flux of the forward-shock synchrotron spectrum falls off faster than the $F_\nu \propto r^{-1/2}$ expected for $\epsilon_B = \text{const.}$

The relative dimness of the radio afterglow suggests that the peak of the synchrotron spectrum has crossed the optical range at 10 ks. An immediate consequence is that the wind-like ambient medium is a factor 20 less dense than the most tenuous wind measured for Galactic WR stars. We cannot provide a good argument for why GRB 130427A’s progenitor had such a low mass-loss rate to wind-speed ratio ($M/\nu = 4 \times 10^{-11} (M_\odot \text{yr}^{-1})/(\text{km s}^{-1})$), but note that, owing to the weak wind, the afterglow remains highly relativistic and travels $\sim 100$ pc until the last observation epoch (50 d).

For such a large afterglow radius to remain inside the free WR wind (i.e. within the wind termination shock), the GRB progenitor must have been embedded in a very tenuous medium, suggesting a super-bubble blown by preceding supernovae and stellar winds.

Owing to tenuous ambient medium, the afterglow transverse size, $2R_\perp = 2Gc\tau \sim 0.1(t/1 \text{ d})^{1/2} \text{ pc}$, is unusually large, and implies a source apparent diameter of $\theta = 0.63 (t/100 \text{ d})^{1/2}$ mas, which may be resolved with radio interferometry.

If the GeV emission of GRB afterglow 130427A arises from the forward-shock, then the up-scattering of the synchrotron emission occurred at the onset of the KN regime, where the reduction of the electron scattering cross-section lowers the Compton parameter, increases the synchrotron cooling-break frequency, and increases the synchrotron flux above that break (i.e. in the LAT range). Furthermore, LAT must have measured the forward-shock inverse-Compton emission at photon energies above a few GeV.

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\(^1\)This feature, accompanied by a flattening of the optical flux decay, was previously observed in two other GRB afterglows: 061126 (Perley et al. 2008) and 080319B (Woźniak et al. 2009).

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