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Reply to Lyutikov's comments on Zhang & Kobayashi (2005)

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ABSTRACT

Lyutikov (astro-ph/0503505) raised a valid point that for shock deceleration of a highly magnetized outflow, the fate of the magnetic fields after shock crossing should be considered. However, his comment that the deceleration radius should be defined by the total energy rather than by the baryonic kinetic energy is incorrect. As strictly derived from the shock jump conditions in Zhang & Kobayashi (2005), during the reverse shock crossing process the magnetic energy is not tapped. As a result, the fireball deceleration radius is defined by the baryonic energy only. The magnetic energy is expected to be transferred to the circumburst medium after the reverse shock disappears. The evolution of the system then mimicks a continuously-fed fireball. As a result, Lyutikov's naive conclusion that the forward shock dynamics is independent on the ejecta content is also incorrect. The shock deceleration dynamics and the reverse shock calculation presented in Zhang & Kobayashi (2005) are robust and correct.

In our recent paper Zhang & Kobayashi (2005, hereafter ZK05), we calculated the gamma-ray burst (GRB) reverse shock emission when a highly relativistic outflow with a wide range of magnetization parameter σ interacts with a constant density medium (ISM). We found that throughout the period when the reverse shock crosses the ejecta, the lab-frame Poynting flux energy is essentially unchanged. Considering a fireball with a total energy $E = E_{K,0} + E_{P,0} = E_{K,0}(1+\sigma)$, where $E_{K,0} = \gamma_0 M_0 c^2$ is the initial baryonic kinetic energy in the ejecta and $E_{P,0}$ is the initial Poynting flux energy, we drew the conclusion that the radius at which the fireball collects $1/\Gamma_0$ of the initial fireball rest mass, i.e.

$$R_\gamma \sim R_{dec} \sim \left(\frac{E_{K,0}}{\gamma_0^2 n m_p c^2}\right)^{1/3} , \tag{1}$$

defines the radius for fireball deceleration in the "thin shell" regime (Eq.[41] in ZK05) when a reverse shock exists. This is smaller than the conventional deceleration radius (defined by E, in the $\sigma = 0$ limit) by a factor $(1+\sigma)^{1/3}$. As a result, the forward shock bolometric emission level right after this deceleration radius is correspondingly fainter by a factor of $(1+\sigma)$ comparing to $\sigma = 0$ case.

In a recent astro-ph comment by Lyutikov (2005), he raised a valid point that the fate of magnetic fields after shock crossing, which has been ignored in the version 2 of our paper posted in astro-ph, should be considered. The Poynting energy ($E_{P,0}$) should be eventually transferred to the ISM. We have incorporated this comment in our final version to appear in ApJ (version 3 in astro-ph), and discussed the possibility of transferring $E_{P,0}$ to the ISM after the shock crossing stage.

However, there exist severe errors in Lyutikov's comments, which would mislead the readers if not corrected.

The major error in Lyutikov (2005) is that he defines deceleration using the total energy E regardless of the σ value. This gives

$$R_{dec}^L \sim \left(\frac{E}{\gamma_0^2 n m_p c^2}\right)^{1/3} = R_{dec}(1+\sigma)^{1/3} . \tag{2}$$

Such a definition is *purely based on his intuition without investigating the rigorous shock jump conditions carefully.* The consequence of adopting such *an assumption* unfortunately leads to self-contradictory results in the high-σ regime. We now elaborate it in the following.

There are several characteristic radii when discussing the deceleration of a fireball by ISM through reverse shocks (Sari & Piran 1995). Besides R_γ, the relevant ones also include R_Δ, the radius at which the reverse shock crosses the ejecta shell, and R_N, the radius at which the reverse shock upstream and downstream becomes relativistic to each other. When σ increases, a reverse shock forms when the forward shock pressure exceeds the magnetic pressure in the outflow (Eqs.[31] and [43] in ZK05). The critical radii discussed above may deviate from the values in the $\sigma = 0$ limit. A detailed analysis shows that for a fixed total energy E, R_N does not depend on σ, and R_Δ is roughly smaller by a factor $\sigma^{1/2}$ (Eqs [36] and [38] in ZK05). The relations among these critical radii are characterized by Eqs. (46) or (51) in ZK05. One can then categorize various parameter regimes in the $T/t_\gamma - \sigma$ plane as long as the reverse shock forming condition is satisfied (see Fig.4 of ZK05), where T is the duration of the burst, t_γ is a typical time scale defined by the total energy E and the initial Lorentz factor γ_0 (Eq.[48] in ZK05, where γ_0 was denoted as γ_4).

Regardless of the σ value, as long as T is long enough (Region (I) in ZK05), one should be in the regime of $R_N < R_\gamma < R_\Delta$, i.e. the so-called thick shell regime (cf. Sari & Piran 1995 for the case in the $\sigma = 0$ limit). In this regime, the reverse shock upstream and downstream becomes relativistic with each other before the reverse shock crosses the shell. As a result, the ejecta is significanly decelerated after one shock crossing. In this regime R_Δ defines the radius of fireball deceleration. R_γ is no longer meaningful.

As T becomes smaller, one enters the thin shell regime. In this regime, shock crossing only mildly decelerates the shell, and the shell starts to decelerate significantly when it feels a large enough inertia from the ISM (at R_{dec}). In this regime $R_{dec} \le R_N$ should be satisfied. In the $\sigma = 0$ limit, this naturally happens when $T < t_\gamma$. When a higher σ value is considered, one still gets a consistent picture when R_{dec} is defined as R_γ (Eq.[1]), and the transition naturally happens at $T < t_\gamma Q(\sigma)$, where $Q(\sigma)$ is a function of σ ($\propto \sigma^{2/3}$ at large σ). However, if one uses the un-justified deceleration radius defined by Lyutikov, R^L_{dec} (Eq.[2]), one reaches an unphysical regime $R_N < R_\Delta < R^L_{dec}$ when $\sigma^{2/3} \le T/t_\gamma \le \sigma^2$ is satisified. In such a regime, the reverse shock upstream and downstream becomes relativistic first (at R_N), so that after the reverse shock crosses the shell (at R_Δ), the shell should be significantly decelerated. However, the fireball has not reached R^L_{dec} yet - the radius Lyutikov expects the fireball to decelerate. This conclusion is obviously absurd, which already invalids his definition. Below we will explicitly analyze the inconsistency in Lyutikov's argument.

Defining R_γ as R_{dec} in the thin shell regime by ZK05 *is not an assumption.* It stems from solid energy conservation physics and rigorous shock jump conditions. Let us analyze the deceleration process in detail.

(1) Before the shock crossing process is over, the system contains four regions separated by two shocks and one contact continuity. One can write the energy conservation during the process. Assuming that the ISM mass collected by the fireball at the end of shock crossing is $M_{\rm ISM}$, The total energy of the whole system before the shock crossing is $\gamma_0 M_0 c^2 + E_{P,0} + M_{\rm ISM} c^2$. After shock crossing, the total energy of the system is $\gamma(\gamma_{34} M_0 + \gamma M_{\rm ISM})c^2 + E_P$, where γ is the bulk Lorentz factor at the end of shock crossing, γ_{34} is the reverse shock Lorentz factor which is ~ 1 in the thin shell case we are discussing, the term $\gamma M_{\rm ISM} c^2$ takes into account the rest ISM mass and its thermal energy (which is $(\gamma - 1) M_{\rm ISM} c^2$), and E_P is the lab-frame Poynting energy after the shock crossing. The energy conservation for the whole system then reads

$$(\gamma_0 - \gamma) M_0 c^2 + (E_{P,0} - E_P) = (\gamma^2 - 1) M_{\rm ISM} c^2 \ . \tag{3}$$

According to Eq.(40) of ZK05, strict shock jump condition analysis gives $E_{P,0} \simeq E_P$ in the high-σ regime.

The physical reason is that during the shock crossing the magnetic fields are compressed so that their comoving energy increases. In the meantime, the whole system is decelerated, so that the lab frame Poynting energy $E_P = \gamma U'_B$ (where U'_B is the comoving magnetic energy) remains essentially unchanged. This means that the term $(E_{P,0} - E_P)$ drops out from the Eq.(3). The remaining equation is the standard fireball deceleration equation with an effective fireball energy $E_{K,0}$. The fireball starts to decelerate when $M_{\rm ISM} \sim M_0/\gamma_0$ is satisfied, at the radius defined by R_γ (eq.[1]), not at R^L_{dec} defined by Lyutikov (eq.[2]).

(2) What is the status of the ejecta beyond R_γ? What happens after the reverse shock disappears? Is R^L_{dec} meaningful at all?

Again one can write down the energy conservation of the whole system during the process. Let's simply re-define γ_0, M_0, $E_{P,0}$ as the bulk Lorentz factor, effective mass and Poynting energy at R_γ (Eq.[1]), and γ, E_P are the Lorentz factor and Poynting energy at a later radius R. We also re-define $M_{\rm ISM}$ as the ISM mass collected during the process (from R_γ to R). Then the energy conservation can be still expressed as equation (3). We show below that γ must be significantly smaller than γ_0. In other words, the fireball is decelerated beyond R_γ.

If multi-crossing of the reverse shock still happens beyond R_γ, the $(E_{P,0} - E_P)$ term still drops out from the energy conservation equation, so that the fireball must be decelerating. The energy transfer process only happens when the reverse shock disappears.

During the energy transfer epoch (after the reverse shock disappears), fireball deceleration is still going on. This is manifested by the argument below. First, it is obvious that one should always have $(E_{P,0} - E_P) \geq 0$, i.e. the Poynting energy should only decrease and gets transferred to the medium. Next, the lab frame Poynting energy could be written as

$$E_P = \gamma U'_B = \gamma V' \frac{B'^2}{8\pi} = \gamma \frac{R^3}{\gamma} \frac{B'^2}{8\pi} = R^3 \frac{B'^2}{8\pi} \ , \tag{4}$$

where V' is the comoving volumn, which can be expressed as R^3/γ in the spreading phase (which is the case in the Regime III of Fig.4 of ZK05). For the non-spreading case, a similar conclusion could be also drawn.

If the GRB outflow does not decelerate from R_γ to R^L_{dec}, as Lyutikov hopes, one would maintain a forward shock with a constant thermal pressure in the shocked region. The magnetic pressure $B'^2/8\pi$ behind the contact discontinuity should keep constant in order to maintain hydrodynamical equilibrium. Eq.(4) then leads to an absurd conclusion, i.e. the lab-frame Poynting energy increases with time (by a huge factor). This again invalidates *the assumption of Lyutikov* that the outflow decelerates at R^L_{dec}.

Then how is the Poynting energy transferred to the ISM eventually? This is an interesting problem and needs further detailed investigation. The treatment in ZK05 (ignoring this effect) is a reasonable approximation shortly after the reverse shock peak, but will become less rigorous when the reverse shock disappears because of the energy transfer from the Poynting energy to the ISM. According to the energy conservation equation (3), one can see that the dynamics depends on how the term $(E_{P,0} - E_P)$ evolves with γ. In any case, the system would mimick a continuously-fed fireball, with the Poynting energy gradually injected into the system. Physically, $B'^2/8\pi$ is related to the pressure at the contact discontinuity during the deceleration phase. Right after the shock crossing (at or beyond R_γ for thin shells and at R_Δ for thick shells), the pressure is balanced at the contact discontinuity, and there is no net energy transfer from the Poynting energy to the ISM kinetic energy. As the system decelerates, the magnetic pressure behind the contact discontinuity becomes stronger than the thermal pressure in front, so it does work to the shocked region in front of the contact discontinuity. This makes the system decelerates less significantly than it would have been without such a magnetic pushing. Such a process keeps going on, until most of the Poynting energy is transferred to the ISM. The late afterglow of a high-σ flow could be comparable to that of a low-σ flow, but in the early afterglow phase, the afterglow level is significantly lower. The crucial point here is that energy transfer phase is separated from the reverse shock deceleration phase, so that the bolometric reverse shock emission peak epoch is separated from the bolometric forward shock emission peak epoch. Detailed deceleration process is under investigation. One thing is clear: nothing special happens at the radius R_{dec}^L.

It is now evident that another statement in Lyutikov (2005), i.e. "energy in the forward shock is determined by the total energy and is virtually independent of the content of the ejecta", is also incorrect. According to the above analysis, the higher the σ, the more prominant the injection process would be. Different σ leads to different deceleration dynamics and different afterglow lightcurves. The "universal" dynamics $\gamma \propto R^{-3/2}$ suggested by Lyutikov (notice he used $\propto t^{-3/2}$ so that his t is not the observer's time) is only valid when the energy transfer process is over, i.e. when essentially all the energy of the system is given to the ISM. However, the energy transfer is a complicated process, and it obviously varies when σ varies. The naive treatment of Lyutikov (2005, and his previous work) lacks solid physical justification.

In conclusion, the dynamics of shock deceleration of a magnetized, relativistic outflow presented in ZK05 is robust. The calculations of the reverse shock emission (which is the main subject of our paper as reflected from the title) are correct. The forward shock emission after the reverse shock disappears is not treated in detail, and will be studied more carefully in a future work. We thank Lyutikov[1] for pointing out the flaw in our previous version of ignoring the fate of the magnetic fields after shock crossing, and we have added a relevant discussion in the final version of the paper to appear in ApJ (version 3 in astro-ph). Yet, the flaw does not influence the bulk of the rigorous calculations presented in the paper. In contrast, the main arguments presented in Lyutikov (2005) are incorrect, as has been explicitly explained in this reply.

REFERENCES

Lyutikov, M. 2005, astro-ph/0503505

Sari, R. & Piran, T. 1995, ApJ, 455, L143

Zhang, B. & Kobayashi, S. 2005, ApJ, in press (astro-ph/0404140, version 3) (ZK05)

[1]There have been extensive email discussions between Lyutikov and us about the subject. Later we decided to temporarily withdraw the paper from ApJ to add in a discussion about the caveat of the forward shock calculation in our paper, and we planned to update the astro-ph version after the paper is finalized. We have also acknowledged Lyutikov for his critical comments, and let him know that we are preparing the final version and will send it to him for comments when it is completed. It is to our surprise that Lyutikov still decided to expose his incorrect opinion at astro-ph. Although astro-ph might be a chat board to exchange ideas, we believe that refereed journals are more appropriate places to lay out scientific view points. We will not reply to any further comments on this subject in astro-ph.

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