Naked-eye optical flash from gamma-ray burst 080319B:
Tracing the decaying neutrons in the outflow

Yi-Zhong Fan*

Niels Bohr International Academy, Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen, Denmark
Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China

Bing Zhang

Department of Physics and Astronomy, University of Nevada, Las Vegas, Nevada 89154, USA

Da-Ming Wei

Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China
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For an unsteady baryonic gamma-ray burst (GRB) outflow, the fast and slow proton shells collide with each other and produce energetic soft gamma-ray emission. If the outflow has a significant neutron component, the ultrarelativistic neutrons initially expand freely until decaying at a larger radius. The late-time proton shells ejected from the GRB central engine, after powering the regular internal shocks, will sweep these β-decay products and give rise to very bright UV/optical emission. The naked-eye optical flash from GRB 080319B, an energetic explosion in the distant Universe, can be well explained in this way.

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There were four gamma-ray bursts (GRBs) detected on 19 March, 2008. Among them, GRB 080319B was most noticeable due to its huge isotropic energy and its extremely bright prompt optical emission that could have been seen with the naked eye [1]. For a redshift $z = 0.937$, the detected peak optical emission had a visual magnitude ~ 5.3 that corresponds to an optical luminosity $\geq 5 \times 10^{50}$ erg s^{-1}. The simultaneous soft γ-ray emission had a luminosity $L_\gamma \sim 4 \times 10^{52}$ erg s^{-1}. The optical flux is significantly above the spectral extrapolation of the GRB emission into the optical band [1], suggesting that the optical and the gamma-ray emissions originate from different emission sites or belong to different spectral components at the same emission site. The light curves in the two bands show some similarities but do not trace each other exactly [1]. This suggests that the emissions from the two bands are somewhat related to each other.

For the energetic outflow of GRB 080319B, if not strongly magnetized, a significant neutron component is unavoidable [2–5]. The average Lorentz factor of the outflow before getting decelerated by a stellar wind medium is very high. A lower limit can be set by the Lorentz factor of the forward shock at ~ 70 s, when the x-ray afterglow began to decline normally, i.e., $\Gamma > 500 E_{\mathrm{k},55}^{1/4} A_{*,-2}^{-1/4} \times (t/70 \text{ s})^{-1/4} [(1 + z)/2]^{1/4}$, where $E_\mathrm{k} \sim 10^{55}$ erg is the isotropic-equivalent energy of the outflow and $A_* \sim 0.01$ is the stellar wind parameter of the progenitor [1]. The current data then suggest an initial Lorentz factor of the outflow $\Gamma \sim 10^3$. For an unsteady baryonic outflow, the GRB is powered by the interaction of proton shells with

variable Lorentz factors, i.e., internal shocks [6–10]. In order to convert a significant fraction of the initial kinetic energy into internal energy and then to γ-ray radiation, the difference in Lorentz factors between the shells should be substantial (i.e., the Lorentz factors $\eta_f \gg \eta_s$, hereafter the subscripts "f" and "s" denote "fast" and "slow," respectively) and their masses should satisfy $M_f = f M_s$, with $f > \eta_s/\eta_f$. The merged new proton shell moves with a Lorentz factor $\Gamma_\mathrm{m} \approx \sqrt{f \eta_f \eta_s}$ [8]. For $\eta_f \sim$ a few $\times 10^4$ and $f \sim 0.1$, $\eta_s \sim$ a few $\times 100$ is needed to get a $\Gamma_\mathrm{m}(\sim \Gamma) \sim 10^3$.

The dynamics of a neutron-rich outflow is governed by the dimensionless entropy $\eta = L/(\dot{M} c^2)$ at r_0, where $\dot{M}$ is the mass loading rate, L is the isotropic luminosity of the ejecta, and r_0 is the radius of the central engine. Whether or not the proton and the neutron components decouple from each other depends on whether η is above or below the critical value $\eta_\mathrm{cr} \simeq 10^3 L_{54}^{1/4} r_{0,7}^{-1/4} [(1 + \xi)/2]^{-1/4}$, where ξ is the ratio of the number density of neutrons to protons [11]. The convention $Q_x = Q/10^x$ is adopted in this work in cgs units. For $\eta < \eta_\mathrm{cr}$, the neutron and proton components (denoted by the subscripts n and p, respectively) are still coupled with each other by nuclear elastic scattering at a radius $\sim \eta r_0$, i.e., at the end of the fireball acceleration. Thus for slow shells one usually has $\eta_{n,s} = \eta_{p,s}$. For $\eta > \eta_\mathrm{cr}$, the n and p components decouple at a radius $\sim \eta_{n,f} r_0$ where the nuclear elastic scattering becomes too weak to accelerate the neutrons, where $\eta_{n,f} \sim 10^3 L_{54}^{1/4} r_{0,7}^{-1/4} [(1 + \xi)/2]^{-1/4} (\eta_{p,f}/\eta_\mathrm{cr})^{-1/3}$ [11]. For the observed information of GRB 080319B, we take $\eta_{p,s} = \eta_{n,s}(\sim \eta_{n,f}) \sim$ a few hundred, $\eta_{p,f} \sim$ a few $\times 10^4$, $M_{p,s} \sim 10 M_{p,f}$, and

*yizhong@nbi.dk

$\xi \sim 1$. Hereafter Γ_n denotes the generic Lorentz factor of the neutron shell regardless of whether it is relatively slow or fast. Below, we show that with these parameters both the soft γ-ray and optical emission can be interpreted.

First, we discuss the regular internal shocks powered by the collisions of the fast and slow proton shells at a radius $R_{int} \sim 2\Gamma_m^2 c \delta t/(1+z) \sim 3 \times 10^{14} \, cm \Gamma_{m,3}^2 \delta t_{-2}[2/(1+z)]cm$, where δt is the typical variability time scale of the prompt γ-ray light curve. The electrons are accelerated by the internal reverse shock to a typical Lorentz factor [8] $\sim 5 \times 10^3(\epsilon_e/0.3)(\eta_{p,f}/2 \times 10^4)\Gamma_{m,3}^{-1}$, and the magnetic field generated in the shocks can be estimated as $\sim 4 \times 10^3 \, Gauss(3\epsilon_B/\epsilon_e)^{1/2}L_{\gamma,52.6}^{1/2}R_{int,14.5}^{-1}\Gamma_{m,3}^{-1}$, where ϵ_e and ϵ_B are the fractions of the shock energy distributed to electrons and magnetic fields, respectively. The typical synchrotron emission frequency of these electrons in the internal reverse shock is $\sim 1.4 \times 10^{20}$ Hz, matching the observation. The internal forward shock can accelerate electrons only to a typical Lorentz factor ~ 300, and the emission is in the soft x-ray band.

The neutrons have negligible interaction with the protons before decaying into protons, electrons, and electron neutrinos. The β-decay radius reads

$$R_\beta \approx 1.1 \times 10^{16} \, cm \Gamma_{n,2.6}. \tag{1}$$

A pair of fast/slow proton shells ejected at late times would merge into a proton shell with a Lorentz factor $\sim \Gamma_m$ in the inner internal shocks and then catch up with the decay trail of the neutron shells ejected earlier at a radius $R_{cat} \approx 2\Gamma_n^2 c \delta T/(1+z)$, where δT is the ejection time lag between the earlier neutron shell and the later proton shell. As long as $R_{cat} \gtrsim R_\beta$, which requires $\delta T \gtrsim 1.1(1+z)\Gamma_{n,2.6}^{-1}$ s, there will be a substantial number of β-decay products that would be swept orderly by the later proton shell at a radius of $\sim 2R_\beta$. These "secondary internal shocks" are unable to give rise to energetic x-ray and γ-ray emissions for the following reasons. (i) They are generated at a radius much larger than R_{int}, so that the magnetic fields are much weaker than those in the regular internal shocks. (ii) They have much lower efficiency than the inner ones at R_{int} because of the smaller Lorentz contrast between the merged proton shell and the neutron shell. For the same reason, the total energy converted into internal energy and then into radiation is lower by a factor of >10 than that of the regular internal shocks.

We first look at the interaction between a proton shell formed in the inner internal shocks and the decay trail of a series of identical neutron shells. The number density of the decay products being swept by the proton shell reads [12] $n \approx \frac{\Gamma_n M_n}{2\pi R^2 m_n R_\beta}$, where m_n is the neutron rest mass and $M_n \propto \exp(-R/R_\beta)$ is the rest mass of the neutron shell that undergoes β decay. The minimum Lorentz factor of

the shocked electrons can be estimated as [8] $\gamma_{e,m} \approx 55(\frac{\epsilon_e}{0.3})\frac{3(p-2)}{(p-1)}(\frac{\gamma_{rel}-1}{0.3})$, where p is the power-law index of the accelerated electrons and $\gamma_{rel} \approx (\Gamma/\Gamma_n + \Gamma_n/\Gamma)/2$ is the Lorentz factor of the trailing fast-moving proton shell with a Lorentz factor Γ relative to the neutron shell. The magnetic field strength B' can be estimated as [13]

$$B' \sim 60 \, Gauss\epsilon_{B,-1}^{1/2}(\gamma_{rel}^2 - 1)^{1/2}N_{n,51.5}^{1/2}R_{16}^{-1}$$
$$\times R_{\beta,16}^{-1/2}\Gamma_{n,2.6}^{1/2}\exp(-R/2R_\beta), \tag{2}$$

where the neutron number N_n of one shell is estimated by $N_n \sim \xi L \delta t/[(1+z)\Gamma_m m_n c^2] \sim 3.3 \times 10^{51} \xi L_{54} \delta t_{-2} \Gamma_{m,3}^{-1}$. Since this secondary internal shock region is permeated by gamma-ray photons produced from the "inner" internal shocks from the late-time ejected proton shells, the electrons in the secondary internal shock region suffer Compton cooling by these prompt γ rays[14]. The corresponding cooling Lorentz factor reads

$$\gamma_{e,c} \sim 180\Gamma_3^3 R_{16}L_{\gamma,52.7}^{-1}. \tag{3}$$

So the synchrotron radiation energy of the shocked electrons peaks at a frequency

$$\nu_p \sim 1.4 \times 10^{15} \, Hz\Gamma_3 B_2'\frac{\min\{\gamma_{e,c}^2, \gamma_{e,m}^2\}}{10^4}. \tag{4}$$

The detected maximum specific spectral flux can be estimated as [13]

$$F_{\nu_{max}} \sim 50 \, JyN_{e,53}\Gamma_3 B_2', \tag{5}$$

where $N_e \sim N_n \delta t_\beta/\delta t \simeq 2 \times 10^{53} \xi L_{54}\Gamma_{m,3}^{-1}\Gamma_3^{-2}R_{\beta,16}$ and $\delta t_\beta \approx (1+z)R_\beta/\Gamma^2 c \sim 0.6 \, s(\frac{1+z}{2})R_{\beta,16}\Gamma_3^{-2}$. This flux is bright enough to well exceed the spectral extrapolation of the gamma-ray emission and to interpret the observed naked-eye optical flash. Notice that we have introduced the number of proton shells ($\sim \delta t_\beta/\delta t$) ejected during the time span of δt_β to account for the total emission output [12]. Since $F_{\nu_{max}} \propto N_e B' \propto \xi^{3/2}$, $\xi \sim 1$ is highly needed to reproduce the prompt optical emission with a flux ~ 20 Jy.

Following the standard approach [15], we estimate the synchrotron self-absorption frequency

$$\nu_a \sim 2 \times 10^{14} \, Hz\frac{100}{\min\{\gamma_{e,c}, \gamma_{e,m}\}}N_{n,51.5}^{3/5}R_{16}^{-6/5}B_2'^{2/5}\Gamma_3.$$
$$\tag{6}$$

We can see that for the standard parameters, in particular, the large neutron decay radius $R_{16} \sim 1$ and the small $B_2' < 1$, one has $\nu_a < \nu_p$. This is the main reason that the optical flash of this burst is so bright. The lack of bright optical flash in most other bursts may be attributed to their smaller

TABLE I. Physical parameters that reproduce the prompt emission of GRB 080319B.

Quantity	Slow shell	Fast shell
Lorentz factor of protons	~ 400	$\sim 2 \times 10^4$
Lorentz factor of neutrons	~ 400	~ 500
Isotropic luminosity (erg/s)	$\sim 2 \times 10^{53}$	$\sim 10^{54}$
Mass ratio of neutrons to protons	~ 1	~ 1
Entropy per baryon (s/k)	$\sim 1.2 \times 10^5$	$\sim 4 \times 10^6$

Lorentz factors, which give a smaller neutron decay radius, stronger magnetic fields, and, hence, a higher self-absorption frequency than optical. In addition, smaller Γ and R_β would suppress the optical emission also by reducing $\gamma_{e,c}$, as shown in Eq. (3).

Until now, we have shown that with reasonable parameters (see Table I for a summary) the neutron-rich internal shocks can power both the energetic soft γ-ray flare and the extremely bright optical flash of GRB 080319B. The thermodynamic entropy per baryon of the initial ejecta can be estimated as $s/k \sim \eta m_n c^2/(kT)$ [4,16], where k is Boltzmann's constant and $T \sim 5$ MeV$r_{0.7}^{-1/2} L_{54}^{1/4}$ is the temperature of the initial fireball. For the fast and slow shells, we have $s/k \sim (4 \times 10^6, 1.2 \times 10^5)$, respectively.

Since the neutron shells are originally coupled to the early proton shells, they carry the essential variability information of the early proton outflows. When the decay products are swept by a later injected proton shell, the resultant optical light curve generally follow the variability pattern of the gamma-ray light curve yet does not strictly trace the gamma-ray light curve. The time delay between the optical and gamma-ray peaks can be estimated as $\sim 2.2[(1+z)/2]\Gamma_{n,2.6}^{-1}$ s, matching the time lag ~ 3 s found in the correlation analysis of prompt γ-ray and optical light curves [17]. Being at a larger emission radius $\sim R_\beta$, the optical variability is also smoothed by the geometric effect in a time scale $\sim \delta t_\beta \gg \delta t$, generally consistent with the fact that the optical light curve is much smoother than the gamma-ray light curve [18]. The contamination from a bright external reverse shock optical emission component [1] introduces a bright background and also contributes to the smoothing.

In the synchrotron-self-Compton (SSC) internal shock model [1,17], one requires a large emission radius ($\sim 10^{16}$ cm) to avoid self-absorption and also requires a large $\epsilon_e/\epsilon_B(>10^3)$ to interpret the huge energy contrast between the optical and the γ-ray emission. In that scenario, one predicts a very bright prompt GeV emission component with luminosity $\geq 4 \times 10^{53}$ erg s^{-1}, which may suffer an energy crisis [19]. In our scenario, the SSC component of the prompt GeV emission is most likely weaker because our standard model parameters demand $\epsilon_e \sim \epsilon_B$. GeV emission can also arise from the prompt γ-ray cooling in the shocked region at $\sim R_\beta$. However, as mentioned before, the total energy of the shocks at $\sim R_\beta$ is much smaller than that of the inner internal shocks. So the high energy emission would not be enhanced significantly. Prompt UV/optical photons will cool the forward shock electrons effectively and give rise to GeV-TeV emission with luminosity $\sim 10^{52}$ erg s^{-1}. However, such a component, appearing as a plateau, should last 2 more times longer than the prompt optical emission and thus can be easily distinguished [20].

In summary, we show in this work that an outflow, containing comparable amounts of protons and neutrons (i.e., $\xi \sim 1$) and having an averaged Lorentz factor $\sim 10^3$ and a huge isotropic luminosity $L \sim 10^{54}$ erg s^{-1}, can power an energetic soft γ-ray burst and a naked-eye optical flash in GRB 080319B (see Table II for a summary). In our scenario, the prompt optical light curve will be much smoother than that of the prompt γ-ray emission, and the peaks in optical band will lag behind the γ-ray peaks by a few seconds; both are well consistent with the data [17,18] and are hard to be interpreted in other models that invoke a similar emission radius for both prompt gamma-ray and optical emissions [1,17,21].

TABLE II. General features of the neutron-rich internal shock model for GRB 080319B.

Quantity	Regular internal shocks	Secondary internal shocks
Slow material	Slow protons from central engine	β-decay products of neutrons
Shock radius	$\sim 10^{14}$–10^{15} cm	$\sim R_\beta \sim 10^{16}$ cm
Shock strength	Ultrarelativistic	Subrelativistic
Typical emission	γ rays	Ultraviolet/optical photons
Emission flux	$\sim 10^{-5}$ erg/s/cm^2	~ 50 Jy (in optical band)
Variability time scale	$\delta t \sim 0.01$–0.1 s	$\delta t_\beta \sim 1$ s

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