Is there anything special about GRB 080319B?

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Gamma-ray bursts (GRBs) are short flashes of gamma rays reaching Earth from deep space. They are usually accompanied by a longer-lived ‘afterglow’ (AG) emission at lower energies. They are the brightest events in the visible universe. On March 19th, 2008, the Swift, Integral and Konus-Wind satellites detected¹,²,³ GRB 0803129B with the largest energy fluence, so far, of a long GRB. Three robotic ground telescopes, detected its extremely intensive optical light emission⁴,⁵,⁶ before the Swift alert, and saw it brightening to a visual peak magnitude 5.4, visible to the naked eye, some 18 s after the start of the burst. Several telescopes continued to follow its AG, which, like its prompt emission, is very puzzling⁷ in the ‘standard’ interpretation⁸ of GRBs. Here we show that the properties of GRB 080319B and its AG are well reproduced by the ‘cannonball’ model⁹ of long GRBs. It was an ordinary GRB, produced by a jet of highly relativistic plasmoids (CBs), ejected in a core-collapse supernova (SN) and viewed, as some others before, particularly close to the CB-emission axis. It still remains to be seen whether GRB 080319B was associated with a SN akin to¹⁰ SN1998bw, the SN type ordinarily associated with GRBs, or with a much more luminous SN.

Swift’s prompt alert sent to the world’s telescopes triggered many follow-up observations. Spectral measurements by the VLT and Hobby-Eberly telescopes determined the GRB’s redshift¹¹,¹² to be $z = 0.937$. In the standard cosmology, this implies a 7.5 Gy look-back time, more than half the age of the Universe, and 6 Gpc luminosity distance, $\sim 6000$ times farther than the most-distant object a human eye can see, the Triangulum galaxy M33 with magnitude 5.7 at a distance of nearly 1 Mpc. At $z=0.973$, the GRB’s peak photon energy, $E_p \approx 1260$ keV, its total equivalent isotropic $\gamma$-ray energy, $E_{iso} \approx 1.32 \times 10^{54}$ erg, and its peak luminosity, $L_p \approx 9.67 \times 10^{52}$ erg cm$^{-2}$, inferred from the Konus-Wind measurements³,

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are amongst the largest measured for GRBs (see Figs. 1a,1b), but are not unique, e.g., GRBs 990123, 050717, and 061007 were quite similar.

In the CB model\(^9\) the prompt $\gamma$-ray and X-ray emission is dominated by inverse Compton scattering (ICS) of photons of the ‘glory’ (the early SN light scattered away from the radial direction by the pre-SN ejecta). Electrons in a CB, partaking of its highly relativistic motion, Compton up-scatter the glory’s photons to $\gamma$-ray energies and collimate them into a narrow beam along the CBs’ direction of motion. This relativistic boosting and beaming results in the simple relations

$$E_{\text{iso}} \propto \delta_0^3; \quad (1+z)^2 L_{\text{iso}} \propto \delta_0^4; \quad (1+z) E_p \propto \gamma_0 \delta_0;$$

where $\gamma_0$ is the bulk-motion Lorentz factor of a CB, $\theta$ is the angle between the line of sight to the CB and its direction of motion, and $\delta_0$ is the Doppler factor, $\delta_0 \approx 2 \gamma_0/(1+\gamma_0^2 \theta^2)$, in an excellent approximation for the relevant large-$\gamma_0$ and small-$\theta$ values. The strong dependence on $\gamma_0$ and $\delta_0$ results in correlations among these observables\(^{13}\). The $[(1+z) E_p, E_{\text{iso}}]$ and $[(1+z) E_p, (1+z)^2 L_p]$ correlations, for GRBs with known $z$, are shown in Figs. 1a,1b. They satisfy the CB-model expectation\(^{13}\) depicted as the thick lines. Note that GRB 080319 is in the expected domain. Other established correlations\(^{13,14}\) are also well satisfied by this GRB.

The ICS spectrum of the scattered glory’s photons is an exponential cut-off power-law with a spectral index, $\Gamma \approx 1$, cut-off energy $\approx E_p$, and a power-law tail\(^9\), in agreement with the spectral index, $\Gamma = 1.01 \pm 0.02$ in the 15-350 keV range, reported \(^1\) by the Swift BAT team, and with the Band function fit to the broader 20 keV - 7 MeV energy range, reported by the Konus-Wind team\(^3\).

For the most probable viewing angles of GRBs, $\theta \approx 1/\gamma_0$, resulting in $\delta_0 \approx \gamma_0$. For small viewing angles, $\theta^2 \ll 1/\gamma_0^2$, implying $\delta_0 \approx 2 \gamma_0$, and local values of $E_p$, $E_{\text{iso}}$ and $L_p$ that are, respectively, 2, 8 and 16 times larger than the mean values for long GRBs, in accordance with the properties\(^3\) of GRB 080319B. From the explicit relation $E_p \approx 0.23 \gamma_0 \delta_0 \epsilon_\gamma/(1+z) \text{ eV}$, with $\epsilon_\gamma \sim 2 \text{ eV}$ the mean energy of the ‘thin-bremsstrahlung’ spectrum of the glory’s photons\(^{14}\), we can estimate $\gamma \sim 1250$ for this GRB, close to the mean\(^9\).

The CBs decelerate by gathering and scattering the ISM particles along their path. The values of $\delta$ and $\gamma$ stay put at $\delta_0$ and $\gamma_0$ until a ‘break’ time $t_b$, reached when the CB has swept in a mass comparable to its initial rest mass\(^{14}\). Beyond $t_b$, the CB begins to decelerate rapidly, and in a constant-density ISM $\gamma \equiv \gamma(t)$ and $\delta \equiv \delta(t)$ approach a $\sim t^{-1/4}$ decline\(^{14}\).

The AG of a GRB is dominated by synchrotron radiation (SR) from the electrons of the interstellar medium (ISM) swept into the CBs and Fermi-accelerated by the CBs’ turbulent magnetic field. The energy flux density, $F_\nu \propto \nu dN_\gamma/d\nu$, of the AG of a single CB, which
takes over the prompt emission during the fast decline phase of the ICS contribution\textsuperscript{14}, is

\[ F_\nu \propto n^{(1+\beta)/2} R^2 \gamma^{3\beta-1} \delta^{\beta+\delta} \nu^{-\beta}, \tag{2} \]

where \( n \) is the ISM density along the CB’s trajectory, \( R \) is the CB’s radius, which initially increases at \( v=O(c) \) and approaches a coasting value in a short time, and \( \beta \equiv \Gamma - 1 \) is the SR spectral index, a function of frequency and time.

An X-ray AG often has a ‘canonical’ shape: before the break time \( t_b \), it has a slowly-changing ‘plateau phase’, beyond which it decays like\textsuperscript{14} \( F_\nu \propto t^{-\alpha_X} \nu^{-\beta_X} \), with a predicted \( \alpha_X = \beta_X + 1/2 \). But when \( t_b \) precedes the start-time of the observations or the end of the prompt ICS-dominated phase, the observed AG has this power-law decline for starters, and there is no observable break\textsuperscript{14}. In all cases, the SR-determined value of \( t = t_b \), is correlated\textsuperscript{14} to the ICS-dictated values of \( E_p, E_{iso} \) and \( L_p \). The correlation is satisfied by GRB 080319B, for which only an upper limit, \( t_b < 70 \) s, can be extracted, as for other very energetic GRBs.

In Fig. 1c we show the X-ray light curve of GRB 080319B measured\textsuperscript{15} with the Swift XRT and its CB-model description, assuming a constant ISM density and approximating the result by a single dominant or average CB. The best-fit parameters are \( \gamma_0 \theta = 0.07 \) and \( t_b = 70 \) s, but the fit is good for a smaller \( t_b \). The AG is reasonably well-fit by a power-law with \( \alpha_X = 1.54 \pm 0.04 \), except around \( 4 \times 10^4 \) s, where it is poorly sampled. As expected\textsuperscript{14} for large \( E_p, E_{iso} \) and \( L_p \), no AG break is observed. The temporal index, \( \alpha_X = \Gamma_X - 1/2 = 1.42 \pm 0.07 \), predicted from the late-time photon spectral index reported\textsuperscript{16} by the Swift XRT team (\( \Gamma_X = 1.92 \pm 0.07 \)), is in agreement with the best-fit temporal index. At \( t \sim 4 \times 10^4 \) s, the data lie below the fit. If not a statistical fluctuation, this may be due to a failure of the constant-density approximation, not surprising at this level of precision. Better optical data in the same time domain may resolve this question.

Although ICS dominates the prompt \( \gamma \)-ray and X-ray emission\textsuperscript{9}, the prompt optical emission is dominated by SR, because its flux density increases with decreasing frequency, \( F_\nu \propto \nu^{-0.5} \), to be compared to the flat (\( \beta \approx 0 \)) energy flux density produced by ICS.

A GRB starts with a succession of prompt pulses. Each pulse corresponds to a CB emitted at a time dictated by the chaotic accretion process that generates them. All properties of prompt individual pulses at \( \gamma \) and X-ray energies are well described\textsuperscript{9} by ICS of the glory’s light, whose photon-number density decreases like the density of the ‘circum-burst’ matter, \( \propto 1/r^2 \). The observations of GRB 080319B started too late to see the X-ray pulses. But pulses were seen at \( \gamma \)-ray and optical frequencies. Even though the optical pulses are SR-generated, their time dependence is akin to that of a \( \gamma \)-ray pulse, dictated in their rise by the exponentially increasing transparency of the CB and the medium, and on their fall
by the medium’s decreasing density. Thus, we fit the optical pulses at a fixed $\bar{\nu}$ by:

$$F_{\bar{\nu}}(t) \propto [e^{-(T/(t-t_0))^{(1+\beta)}}] [1 - e^{-(T/(t-t_0))^{(1+\beta)}}],$$

where $T$ is an adjustable time-width and $t_0$ is the start-time of the pulse. The decline $F_{\nu} \propto (t - t_0)^{-(1+\beta)}$ is that implied by Eq. (2) for $n \propto 1/\nu^2$, and the rise, to which the fits are quite insensitive, is described by the same parameters.

The optical light-curve of Fig. 1d was obtained by fitting each of the three early pulses observed by the TORTORA instrument\(^4\) with Eq. (3). The later-time AG, given by Eq.(2) beyond $t_b \sim 70$ s, is essentially a power-law decline, insensitive to $\gamma_0 \theta$ and $t_b$ but sensitive to $\beta_{opt}$. In the CB model, the index $\beta$ is $\sim 0.5$ below and $\sim 1.1$ above a decreasing ‘bend frequency’, $\nu_b(t) \propto n^{-\gamma_3} \delta$, which usually ‘crosses’ the optical band within $t \sim 1$ day, so that $\beta_{opt} \approx \beta_X$ thereafter. Our best fit to the optical AG results in $\alpha_{opt} = 1.40 \pm 0.04$, which implies a late-time $\beta_{opt} \approx 0.90$, consistent with the late time expectation. So far no late-time spectral information is available to verify this prediction.

When a CB crosses a density enhancement, $\nu_b$ increases due the sudden increase in $n$ and the delay in the consequent CB deceleration. The bend frequency may cross the optical band ‘backwards’: from above, to below it. Such a spectral evolution may have been observed\(^7\) some 5000 s after the onset of the burst. The spectral analysis of the UNLV GRB group\(^{17}\) shows a decreased $\beta_X = 0.70 \pm 0.05$ around that time. The expected $\beta_{opt} \approx \beta_X - 0.5 = 0.2 \pm 0.05$ at that time is consistent with the reported\(^7\) spectral evolution around 5000 s after burst.

In Fig. 2d we also show the contribution of a SN1998bw-like supernova. If, instead, GRB 080319B was produced by a SN akin to SN 2006gy, the most luminous ever detected\(^20\), its measured R-band peak magnitude and its estimated extinction in NGC1260 imply that towards the end of July, 2008 it will reach a J-band peak energy-flux density of $\sim 4.4 \mu$Jy.

To conclude, the properties of GRB 080319B, corrected for red-shift effects, were similar to those of other very luminous GRBs, such as 061007\(^{18}\) and 050717\(^{19}\). We have shown that, in the CB model, it was simply an ordinary GRB viewed from very near axis, as its main properties—the prompt observables and the spectral and temporal evolution of the afterglow—are well reproduced. It remains to be seen whether or not GRB 080319B was generated by a supernova akin to SN1998bw, or by a much more luminous one, such as SN2006gy. A SN similar to SN1998bw, having exploded around March 19th, 2008, at $z = 0.937$, should reach peak luminosity around April 15, 2008. Its brightness, however, will be comparable to that of the fading optical afterglow of GRB 080319B around that time, see Fig. 1d. Such an underlying SN may be detected by the most powerful ground-based telescopes via the change in colours of the optical transient induced by the SN, if the host galaxy of GRB 080319B is
not too bright. The unprecedented possibility that GRB 080319B was produced by a much more luminous SN should not be difficult to verify.

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Figure Captions

Fig. 1
Top left (a): The correlation between the ‘rest frame’ peak photon energy and the isotropic equivalent total γ-ray energy of long GRBs with known redshift. The thick line is the correlation predicted by the CB model\textsuperscript{13}. GRB 080319B is indicated by a large star.

Top Right (b): The ‘rest frame’ peak photon energy plotted versus the isotropic peak γ-ray luminosity of long GRBs with known redshift. The thick line is the correlation predicted by the CB model\textsuperscript{13}. GRB 080319B is indicated by a large star.

Bottom left (c): Comparison between the light-curve of the X-ray afterglow of GRB 080319B measured\textsuperscript{15} with the Swift X-ray telescope (XRT) and its CB model description, Eq. (2). For very luminous GRBs and a constant ISM density, the X-ray light-curve is predicted to have a simple power-law decline. The best fit temporal decline index, $\alpha_X = 1.54 \pm 0.04$ and the reported\textsuperscript{16} late-time spectral index, $\beta_X = 0.92 \pm 0.07$, satisfy, within errors, the asymptotic CB model prediction, $\alpha_X = \beta_X + 1/2$.

Bottom Right (d): R-band light curve of GRB 080319B. Data points are from GCNs quoted in Ref. 7. R-band and V-band data were combined by subtraction of 0.26 magnitudes from the V-band data points. The initial flash is fitted by a sum of three SR pulses with the shape given by Eq. (3), beginning at $t_0 = 4.16, 25.74, 37.38$ s after trigger, and with widths $T = 11.02, 8.68, 4.97$ s, respectively. The AG is taken over by a late temporal decline given\textsuperscript{14} by Eq. (2), with $\alpha = 1.40 \pm 0.04$. Also shown is the contribution to the R-band AG from a SN akin to SN1998bw\textsuperscript{10}, displaced to the GRB’s emission site.
