GRB 090417B: a Dark Gamma-Ray Burst

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ABSTRACT

GRB 090417B was an unusually long gamma-ray burst with a T_{90} *duration of at least 2131 s and a multi-peaked light curve at energies of 15–150 keV. It was an optically dark burst and has been convincingly associated with a bright star-forming galaxy at a redshift of* $z = 0.345$ *that is broadly similar to the Milky Way. This is one of the few cases where a host galaxy has been clearly identified for a dark gamma-ray burst and thus is an ideal candidate for studying the origin of dark bursts. We find that the dark nature of GRB 090417B can not be explained by high redshift, incomplete observations, or unusual physics in the production of the afterglow. The* Swift/*XRT* X-ray *data are consistent with the afterglow being obscured by a dense, localized sheet of dust approximately 30–80 pc from the burst along the line of sight. Assuming the standard relativistic fireball model for the afterglow we find that the optical flux is at least 2.5 mag fainter than predicted by the* X-ray *flux. We are able to explain the lack of an optical afterglow, and the evolution of the* X-ray *spectrum, by assuming localized dust along the line of sight. Our results suggest that this dust imparts an extinction of* $A_V >\approx 12$ *mag, which is sufficient to explain the missing optical flux. GRB 090417B is an example of a gamma-ray burst that is dark due to the localized dust structure in its host galaxy.*

Introduction

Dark bursts are an enduring mystery in the lore of gamma-ray burst (GRB) studies. Historically only about one quarter of localized GRBs have had optical afterglows detected, and even with the rapid follow-up observations made possible by the near-real-time positions provided by *Swift* ≈25%–40% of GRBs are still dark (Fynbo et al. 2009). There have been several proposed explanations for these dark bursts.

1. Several studies have suggested that the host galaxies of dark GRBs are dustier than those of optically-bright GRBs. However, there is a significant overlap in the N_H distribution between hosts of dark and bright GRBs, so it is not clear if extinction is the sole parameter responsible for the darkness of these bursts.

2. Some dark GRBs occur at very high redshift (such as GRB 090423 with z = 8.2, Salvaterra et al. 2009; Tanvir et al. 2009), so the Lyman break (or Lyman-alpha forest) is redward of the optical band resulting in the optical flux being absorbed. However, Fynbo et al. (2009) found that <≈24% of all GRBs have z >≈ 6, less than the percentage of dark GRBs, so high redshift is not responsible for all dark GRBs.

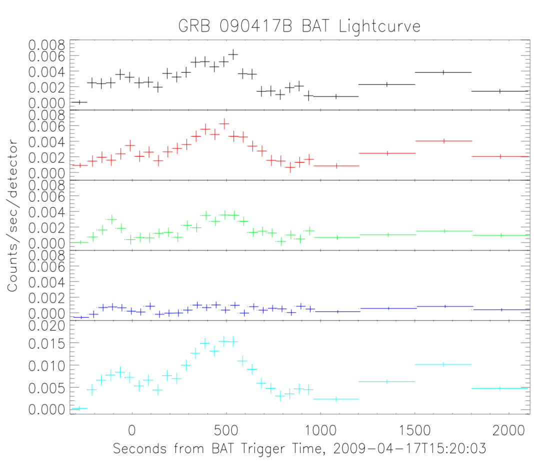
3. Afterglow radiation from dark GRBs may not be due to synchrotron processes. If this is the case then the relationship between the optical and *X*-ray spectrum may not be as expected from the relativistic fireball model. This could result in the physics of the afterglow producing afterglows that are intrinsically underluminous at optical wavelengths compared to what is expected from a synchrotron spectrum. However, to date the *X*-ray properties of dark bursts have been broadly the same as those of bright bursts, so there is no evidence for the afterglow physics being different.

GRB 090417B was a long–soft GRB detected by *Swift* at 13:17:23 UT on 2009 Apr 17. *Swift* slewed immediately to this burst. XRT and UVOT observations began about 380 s after the trigger. Several ground-based observatories observed the field of the *X*-ray afterglow, but no optical or infrared afterglow was found. The SDSS galaxy J135846.65+470104.5 (z= 0.345) is located 1.08" from the centre of the XRT error circle.

Observations

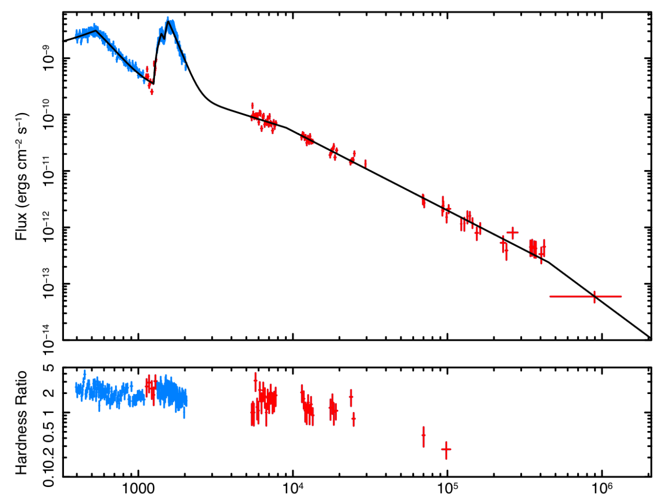
BAT—Prompt Emission

The BAT observed GRB 090417B for ≈2130 s, until observations were interrupted by an Earth limb constraint. The burst duration was T_{90} > 2130 s in the 15–150 keV band. This is one of the longest known prompt emissions. The BAT light curve was very smooth with three broad peaks.



XRT—*X*-Ray Data

The XRT observed GRB 090417B from 387 s to 15 days. There were two strong flares at 530 and 1410 s. The light curve decayed as a doubly-broken power law with $\alpha_1 = 0.86$, $t_1 = 9100$ s, $\alpha_s = 1.40$, $t_s \approx 5.2$ days, and $\alpha_3 \approx 2$. The spectrum evolves from $\Gamma = 0.2$ before 2055 s to $\Gamma = 2.0$ between 1.4 and 19 hr. After this the spectrum became unusually soft with $\Gamma = 3.8$. The fitted hydrogen column density in the host is $\approx 2 \times 10^{22}$ cm^{-2}.



UVOT & NOT—Host Galaxy

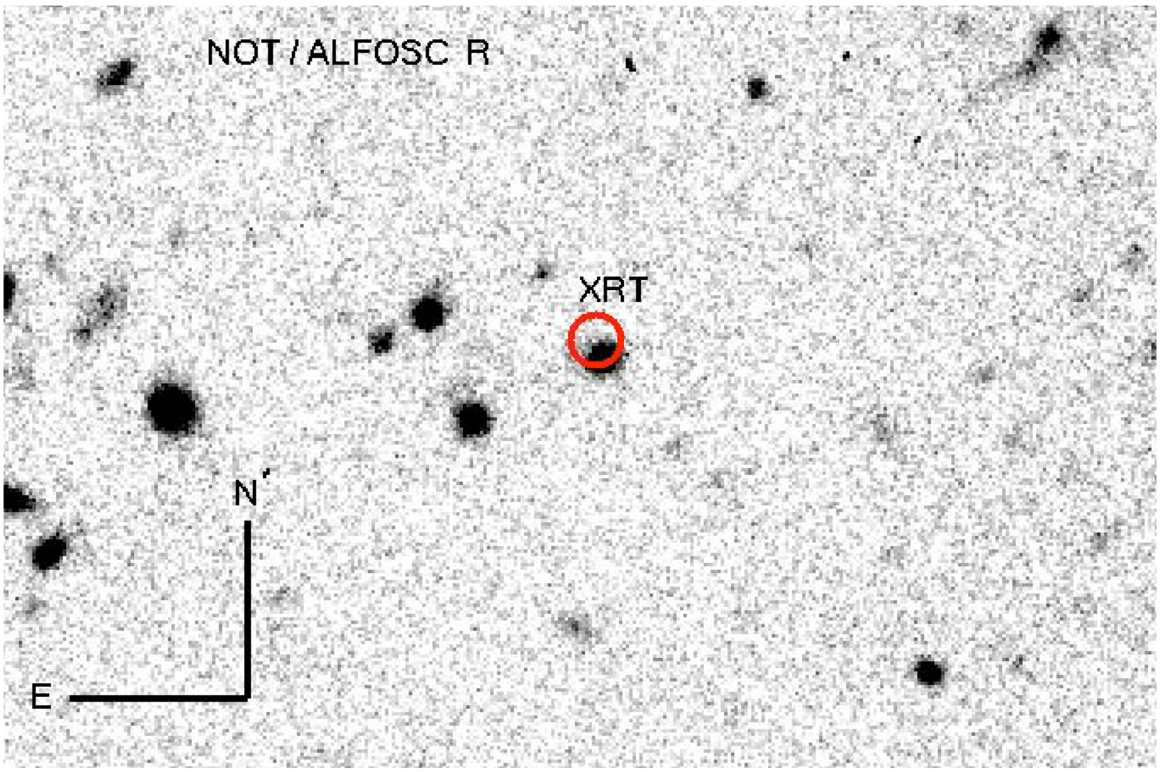
The UVOT observed GRB 090417B starting at 378 s, but did not find an optical or ultraviolet afterglow. The SDSS galaxy was observed and the photometry is given below.

The Nordic Optical Telescope observed the host on 17–18 Apr 2009 and found $B = 23.25 \pm 0.13$, $R = 21.34 \pm 0.03$, and $i = 20.82 \pm 0.07$.

Filter	Exposure	Mag	Err
v	1237	>20.9	⋯
b	862	>21.4	⋯
u	22 554	23.09	0.38
uvw1	10 850	23.12	0.56
uvm2	15 942	22.49	0.29
uvw2	30 827	22.69	0.19
white	841	>22.2	⋯

The Host Galaxy

Is SDSS J135846.65+470104.5 the host galaxy of GRB 090417B? The methodology of Bloom et al. (2002) yields a probability of a chance alignment between this galaxy and the XRT position of $P_{\text{ch}} \approx 10^{-3}$, which is one of the most secure identifications of a host galaxy of a dark GRB. The luminosity and size of this galaxy is consistent with the hosts of optically-bright GRBs (Fruchter et al. 2006). Unpublished *Chandra* data (PI: Andy Levan) indicate that the *X-r*ay afterglow is near the nucleus of the SDSS galaxy, and has an X-ray luminosity consistent with the observed late-time decay of the XRT light curve. Therefore, we are confident that this is the host galaxy of GRB 090417B.



Dust in the Host Galaxy

We combined UVOT, NOT, SDSS, and other published photometry of SDSS J135846.65+470104.5 to create a combined ultraviolet/optical/infrared spectral energy distribution of the galaxy. We assumed that the intrinsic spectrum of the galaxy can be approximated by a power law at these wavelengths and used XSpec to estimate the amount of internal extinction in the host. We tested extinction laws for the Milky Way, Large Magellanic Cloud, and Small Magellanic Cloud and found that a Milky Way extinction law gave the best fit, suggesting that the dust properties of the host are broadly similar to those of the dust in the Milky Way. The fitted extinction is A_V = 3.5 mag, somewhat higher than is typical for the host galaxies of optically-bright GRBs.

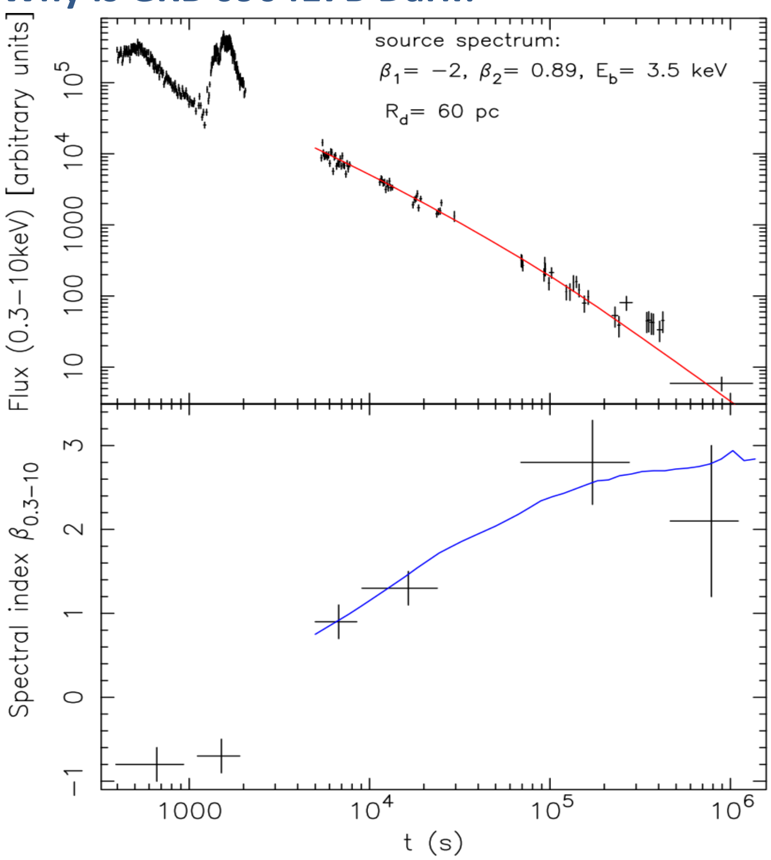
Luminosity

The rest-frame absolute magnitude of the host galaxy is $(M^*_B)_{AB} \approx -20.3$, which gives it a luminosity of approximately $1.3\mathcal{L}^*_B$. This makes the galaxy comparable in luminosity to the Milky Way.

Star-Formation Rate

The relationships of Madau et al. (1998) yield an estimated star-formation rate of at least 1 $\mathcal{M}_\odot$ yr^{-1}, and perhaps as high as 10^2–10^4 $\mathcal{M}_\odot$ yr^{-1} when corrected for the observed extinction in the host. However, the large, and uncertain, host extinction makes our estimated star-formation rate somewhat uncertain.

Why is GRB 090417B Dark?



The fit of the dust scattering model to the X-ray light curve (top) and spectral evolution (bottom).

GRB 090417B is a Dark Burst

The spectral slope in the X ray regime at 11 hr is $\beta_X = 1.3$ while the slope between the optical and X-ray bands is $\beta_X < -1.9$. This makes GRB 090417B a dark burst by the definitions of Jakobsson et al (2004) and van der Holst et al. (2009). The observed X-ray flux at 11 hr predicts that the afterglow should have a UVOT u-band magnitude of $u <\approx 21.7$. The combine host + afterglow magnitude at this time was $u = 23.09$.

The Early Afterglow

The X-ray decay and spectrum before ≈8 hr are consistent with a relativistic fireball expanding into an external medium. We can not determine the density structure of this medium. The cooling frequency is below the XRT band between 2.5 and 8 hr after the burst.

Dust Scattering

The late-time (after about 19 hr) softening of the X-ray spectrum can not be explained using a synchrotron spectrum. We found that the dust scattering model of Shao & Dai (2007) and Shen et al. (2009) is able to explain this unusual spectral behaviour. Their model can reproduce the XRT light curve and spectral evolution if there is a sheet of dust approximately 30–80 pc from the burst. This dust provides an extinction of $A_V \approx 15\text{–}40$ magnitudes, which would explain the lack of an optical or infrared afterglow for GRB 090417B. The neutral hydrogen column density in the host from the X-ray spectrum corresponds to $A_V = 11$mag, which agrees with the dust scattering model.

Localized Dust

Our result suggests that GRB 090417B is dark because of localized dust along the line of sight to the burst, and not because the progenitor was located in a concentration of dust. Such dense dust clouds are not unusual in large $\mathcal{L}^*$ galaxies and may explain a significant number of dark GRBs.

Conclusions

- GRB 090417B was a dark gamma-ray burst.
- The host galaxy was SDSS J135846.65+470104.5, an $\mathcal{L}^*$ galaxy similar to the Milky Way at $z = 0.345$.
- The host is dusty with an overall V-band extinction of $A_V = 3.5$ mag.
- Before ≈19 hr the X-ray light curve and spectrum is consistent with a relativistic fireball.
- After ≈19 hr the X-ray spectrum becomes significantly softer and is consistent with the dust scattering model of Shao & Dai (2007) and Shen et al. (2009).
- The dust scattering model predicts a sheet of dust with $A_V \approx 15\text{–}40$ mag located 30–80 pc from the burst along the line of sight.
- Predicted extinction is consistent with the neutral hydrogen column density in the host.

- GRB 090417B was dark due to dense, localized dust along the line of sight.

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