Extremely Soft X-ray Flash as the indicator of off-axis orphan GRB afterglow

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Abstract

Toward unification of GRBs and X-ray Flashes (XRFs), we verified the off-axis jet model and examined a discovery of off-axis orphan GRB afterglows. The XRF sample was selected on the basis of the following three factors: (1) a constraint on the lower peak energy of the prompt spectrum, (2) redshift measurements, and (3) multicolor observations of an earlier (or brightening) phase. XRF020903 was the only sample selected basis of these criteria. An off-axis jet model with a large observing angle (0.21 rad, which is twice the jet opening half-angle), can naturally describe the achromatic brightening and the prompt X-ray spectral properties. This result indicates the existence of off-axis orphan GRB afterglow light curves. Events with a larger viewing angle (>2 times of the jet opening angle) could be discovered using Subaru Hyper-Suprime-Cam (HSC), LSST, and SKA.

Key words: Gamma-Ray Bursts — Off-axis orphan GRB afterglow — X-ray Flash

1. Introduction

GRBs are believed to be caused by jet collimation and ultra-relativistic motion. As identical to that of AGN classification, a unified picture of GRBs and massive stellar explosions is expected. Along to the observing angle of GRB jet, four astronomical phenomena should exist; (A) classical GRBs, (B) X-ray flash (XRFs), (C) off-axis orphan GRB afterglows, and (D) supernova. However, no direct, unambiguous, observational evidence exists. Toward establishment of the unification model, (1) demostration of off-axis origin of XRFs and (2) discovery of off-axis orphan GRB afterglows are required.

XRFs exhibit that X-ray temporal and spectral properties in the prompt phase do not show any differences relative to those of GRBs, except for the considerably lower energy values of the peak of the νF_ν spectrum in the observer's frame. The majority of *HETE-2* samples (nine out of 16 XRFs) show a low energy of spectral peak energy $E^{obs}_{peak} < 20$ keV. The number of XRFs detected by *HETE-2* was comparable and relatively larger than that of GRBs indicating that XRFs represent a large portion of the entire GRB population. To explain the aforementioned prompt observational properties, three models have been proposed for XRFs: a high redshift origin; the off-axis jet model, which is equivalent to the unification scenario of AGN galaxies; and intrinsic properties (e.g., a subenergetic or inefficient fireball), which may also produce on-axis orphan afterglows.

Off-axis orphan afterglows occur as a natural prediction of GRB jets and ultra-relativistic motion. However, no direct, unambiguous, observational evidence exists. We therefore verify the off-axis jet model and to provide feedback to ongoing and planned optical time domain surveys of Subaru Hyper-Suprime-Cam (HSC) and LSST (Urata et al. 2015).

2. XRF020903

We considered possible XRFs for our study and quickly realized XRF 020903 was the only event that has (1) either a measurement or an upper bound on the peak energy of the prompt spectrum E^{src}_{peak}, (2) a measured redshift, and (3) multicolor afterglow observations adequately cover the early afterglow phase when achromatic brightening of the afterglow might occur.This was one of the XRFs detected by *HETE-2* and the first events for which an optical afterglow was detected and a spectroscopic redshift ($z = 0.251$) was determined. The prompt emission had the lowest intrinsic spectral peak energy E^{src}_{peak} of $3.3^{+1.8}_{-1.0}$ keV among all the XRF samples. We collected data for the XRF 020903 afterglow by using

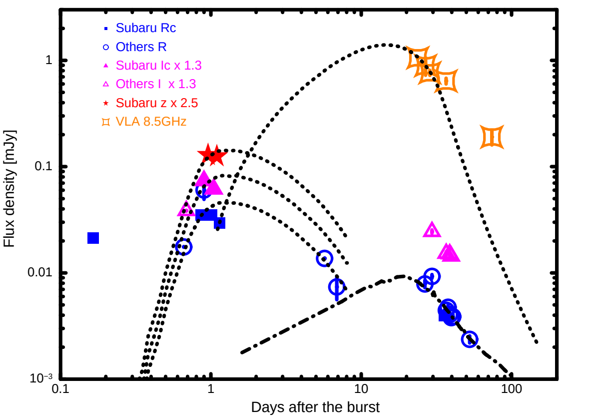

Fig. 1. Multi-frequency light curves of XRF020903 afterglow. The dotted lines show the off-axis jet model functions.

Subaru archive data and photometric results obtained from literature. To perform accurate optical photometry by removing contamination from the host galaxy, we also employed Pan-STARRS1 data.

Figure 1 shows the optical and radio (8.5 GHz) light curves. The optical (Rc and Ic) light curves show a clear rapid rebrightening between 0.7 and 0.9 days. The equivalent rising power law index α ($F_\nu \propto t^\alpha$) are ~ 2.6 in the Rc and ~ 2.3 in the Ic band. There is another late-phase rebrightening peaking at ~ 20 days in the R band light curve, which was interpreted as the associated supernova component. The SED at 0.7 and 0.9 day is well fitted by the power-law function as $f(\nu) \propto \nu^{-\beta}$. We obtained the β at 0.695 day as 1.48 ± 0.06. Similarly, we obtained a β as 1.43 ± 0.08 at 0.899 day, which is consistent with the value for 0.695 day. These results imply that the rebrightening is achromatic.

To perform light curves and SEDs modeling for XRF020903, we employed the boxfit code. Figure 1 shows the best-fit model functions that describe the achromatic rebrightening, optical temporal evolution, and radio brightness. There are two notable features. The first is the jet opening half angle θ_{jet} of 0.1 rad, which is consistent with those of classical hard GRBs. The second is the large observing angle ($\theta_{obs} \sim 0.21$ rad), which corresponds to $\theta_{obs} \sim 2\theta_{jet}$.

We verified the observed small values of E^{src}_{peak} and E_{iso} by adopting a simple model with a top-hat profile of the prompt emission of a relativistic jet. The parameters $E^{src}_{peak}(\theta_{obs})$ and $E_{iso}(\theta_{obs})$ were analytically derived as functions of θ_{obs}, θ_{jet}, and γ. By fixing θ_{obs} and θ_{jet} as 0.21 and 0.1 rad, respectively, we evaluated γ, E^{src}_{peak}, and E_{iso} observed from the on-axis of the jet ($E^{src}_{peak}(0)$ and $E_{iso}(0)$). These expected values were consistent with those of classical hard GRBs, and the observed small values of E^{src}_{peak} and E_{iso} of XRF 020903 could be naturally explained by the off-axis jet model.

3. Prospect with Optical Surveys

We expected off-axis orphan GRB afterglow light curves at $z = 0.5$ along with three viewing angles on the basis of the XRF020903 result (Figure 2 top). To detect these light curves, especially afterglows with a larger viewing angle ($\theta_{obs} > 2\theta_{jet}$), an 8-m class telescope with wide-field imagers, such as the LSST and Subaru/HSC, is required. Off-axis orphan GRB afterglows up to $\sim 3\theta_{jet}$ can be discovered by performing time-domain surveys with an 8-m class telescope. Because such optical time-domain surveys also detect numerous other optical transients (e.g. Urata et al. 2012), we presented expected radio afterglow light curves for the confirmation and determination of burst parameters. Radio light curves can be monitored using ALMA and JVLA with reasonable exposure (Figure 2 bottom).

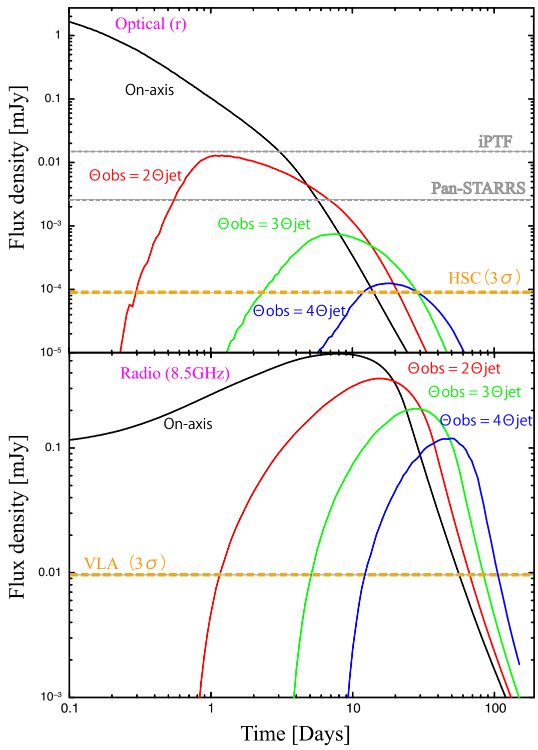

Fig. 2. Expected off-axis GRB afterglow with observing angles of $2\theta_{jet}$ (red), $3\theta_{jet}$ (green), and $4\theta_{jet}$ (blue) at typical redshift of $z = 0.5$.

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References

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