Study on the X-ray Re-brightening Signature of GRB 220117A: Postprint

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Abstract

The Swift/XRT detected the X-ray afterglow of long burst GRB 220117A, which began to rebrighten 300 seconds after triggering and followed a single power-law decay segment after thousands of seconds of orbital observation gap. This segment is different from the shallow decay segment (plateau) and flare, and may belong to a giant X-ray bump. We investigated this segment by the fall-back accretion model and found that the model can interpret this segment with reasonable parameter values. Within this physical model scenario, the fall-back accretion rate reaches a peak value $ sim 1.70 times10^{-5} M_{ odot} rm s^{-1}$ around 300s in the central engine frame, which is compatible with the late mass supply rate of some **low-metallicity** massive progenitor stars. **The initial black hole (BH) spin is** $a_0 = 0.64^{+0.24}_{-0.26}$ and imply this re-brightening signature requires a larger black hole(BH) spin. The total accretion mass during the fall-back process is $M_{rmacc} = (3.09pm0.02)times10^{-2}M_{odot}$. The jet energy from the fall-back accretion is $(9.77pm0.65)times10^{52}rmergs$, with a ratio of 0.066 to the isotropic-equivalent radiation energies of GRB prompt phase in the $1-10^4$ keV band. The fall-back radius r_p corresponding to the peak time of fall-back t_p is $(3.16pm0.05)times10^{10}rmcm$, which is consistent with the typical radius of Wolf–Rayet stars. In summary, our results provide additional support for the origin of the long burst from the core collapse of Wolf-Rayet stars, and its late central engine activity is likely due to the fall-back accretion process.

Full Text

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Study on X-ray Re-brightening Signature of GRB 220117A

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Abstract

The Swift/XRT detected the X-ray afterglow of long burst GRB 220117A, which began to rebrighten 300 seconds after triggering and followed a single power-law decay segment after thousands of seconds of orbital observation gap. This segment is different from the shallow decay segment (plateau) and flare, and may belong to a giant X-ray bump. We investigated this segment using the fall-back accretion model and found that the model can interpret this segment with reasonable parameter values. Within this physical model scenario, the fall-back accretion rate reaches a peak value 1.70×10^{-5}M s^{-1} around 300s in the central engine frame, which is compatible with the late mass supply rate of some low-metallicity massive progenitor stars. The initial black hole (BH) spin is $a_0 = 0.64^{+0.24}{}_{0\cdot26}$, implying that this re-brightening signature requires a larger BH spin. The total accretion mass during the fall-back process is M cc = (3.09\$±0.02)×10$^{\{-2\}M\odot.Thejetenergyfromthefall-backaccretionis(9.77\pm0.65)\times10}$\{52\}$ergs, witharatioof0.066totheiso$ $equivalentradiationenergiesoftheGRBpromptphaseinthe$1–10^\{4\}\$ keV band. The fall-back radius r corresponding to the peak time of fall-back t is (3.16\$±0.05)×10^\{10\}\$cm, which is consistent with the typical radius of Wolf–Rayet stars. In summary, our results provide additional support for the origin of long bursts from the core collapse of Wolf-Rayet stars, and suggest that its late central engine activity is likely due to the fall-back accretion process.

Key words: gamma-ray bursts; accretion; black hole

1 Introduction

Gamma-ray bursts (GRBs) are the brightest electromagnetic events that have occurred in the universe since the Big Bang, consisting of two emission phases: the prompt emission (with initial prompt soft γ-ray emission) and afterglow emission (with long-term broadband emission). The prompt emission is generally considered to be related to internal dissipation within the jet, such as internal shock dissipation or magnetic dissipation. Afterglow emission is usually considered to arise from external shocks (especially forward shocks) generated by the interaction between jets and the interstellar medium (see [?] for a review). In general, the end of the prompt emission phase means the cessation of the GRB's central engine. However, observations from the Swift satellite indicate that many GRB central engines have extended activity times, mainly manifested as shallow decay segments (plateaus) ([?]; [?]; [?]; [?]), flares ([?]; [?]; [?]), and giant bumps ([?]; [?]; [?]; [?]; [?], [?]) in the X-ray light curves following the prompt emission.

The Swift/XRT detected the X-ray afterglow of long burst GRB 220117A, which began to rebrighten 300 s after triggering, suggesting that this GRB has an extended central engine activity time. In addition, this signature is different from the X-ray shallow decay segment (plateau) and flare, and may belong to a giant X-ray bump. Due to the absence of an "internal plateau" feature in the X-ray afterglow of GRB 220117A, its central engine may be a hyperaccreting black hole (BH) system. In this physical scenario, the internal dissipation of fall-back accretion energy can interpret the giant X-ray bump. If the fall-back accretion rate or the duration of the fall-back accretion process are large enough, a giant X-ray bump that rapidly rises and decays with a form of $t^{-5\ 3}$ is expected. So far, the giant X-ray bump has been found in the X-ray afterglow of many GRBs and could be well interpreted within the fall-back accretion model ([**?**]; [**?**]; [**?**]; [**?**]).

In this paper, we study the X-ray re-brightening signature of GRB 220117A within the fall-back accretion model. In Section 2, we describe the observations of GRB 220117A and analyze the re-brightening signature. The fall-back accretion model is described in Section 3. In Section 4, we apply the fall-back accretion model to the re-brightening signature. The conclusions and implications of our results are discussed in Section 5. Throughout the paper, the convention $Q = 10^{n} Q$ is adopted in c.g.s. units.

2 GRB 220117A Observations

The BAT triggered and located GRB 220117A at 23:58:21 UT on 2022 January 17. T_{90}(15–350 keV) is 49.81 ± 2.37s. The time-averaged spectrum from T + 14.79s to T + 66.14s is best fitted by a single power law (SPL) function. The power-law index of the time-averaged spectrum is $\Gamma\ = 1.8 \pm 0.18$. The fluence in the 15–150 keV band is $S\ = 1.6 \pm 0.2 \times 10^{-6}$ergs/cm^2 ([**?**]). XRT observations started at 151.9s after the trigger. The XRT light curve is shown in Figure 1 [Figure 1: see original paper]. The UVOT started collecting data 161s after the trigger. No source was detected by the UVOT at the X-ray afterglow position ([**?**]). Palmerio et al. (2022) observed the afterglow of GRB 220117A using the ESO VLT UT3. From the feature of the Lyman-alpha trough and the Si II 1260 Å line, the redshift was measured as z = 4.961.

For the re-brightening segment and follow-up segment of GRB 220117A, we adopted a smooth broken power law (BPL) function to fit it:

$$f(t) = f_0 \left(\frac{t}{t_b}\right)^{w\alpha_1} \left[\left(\frac{t}{t_b}\right)^{w\alpha_2}\right]^{-1/s}$$

where α_1 and α_2 represent the decay slopes before and after the break, respectively. w describes the sharpness of the break, and here we adopt w = 3 as suggested by [**?**]. The fitting light curve and the best-fitting parameters are shown in Figure 1. Zhao et al. (2019) found that the decay slope of shallow decay segments follows a normal distribution $\alpha_1 = 0.35 \pm 0.35$ based on 13 years of Swift/XRT observation data. It can be inferred that the X-ray re-brightening segment may not be a shallow decay segment.

In addition, we also tested whether the X-ray re-brightening segment and follow-up segment belongs to a flare. Yi et al. (2016) analyzed GRBs with significant flares observed by Swift/XRT from April 2005 to March 2015 and obtained an empirical relationship:

$$\log_{10} T_{\mathrm{dur}} = (-0.35 \pm 0.11) + (1.12 \pm 0.04) \times \log_{10}(T_{\mathrm{peak}})$$

where T is the peak time of the flare. T = T − T is the duration of the flare, where T and T represent the start time and end time of the flare, respectively. T and T of each flare could be easily obtained by fitting the light curve with a smooth BPL function. We find that the duration of the X-ray re-brightening segment and its follow-up decay segment deviates from the duration obtained by the empirical relationship by 2σ. Compared to typical flares, the giant X-ray bump has a relatively longer duration. Therefore, the X-ray re-brightening segment and follow-up segment may belong to a giant X-ray bump.

3 Model Description

In this paper, we intend to use the fall-back accretion model to interpret the X-ray re-brightening segment of GRB 220117A. The physical scenario of the fall-back accretion model is described as follows: the progenitor stars of long GRBs may be massive stars ([?]; [?]; [?]; [?]), and generally have a core-envelope structure. At the end of the massive star's evolution, photodisintegration and electron capture will trigger core collapse and form a super-accreting BH system. The relativistic jet is launched by the super-accreting BH system through extracting gravitational energy from the accreted material or the spin energy of the BH. When the relativistic jet successfully penetrates the envelope, it powers the initial prompt emission and broadband afterglow emission of the GRB. During the process of jet penetration through the progenitor envelope, part of the jet energy is transferred to the envelope, which might help the supernova to explode. The bounding shock responsible for the associated supernova transfers kinetic energy to the envelope materials, and part of the envelope materials would be ejected.

The rest of the envelope materials could fall back into the vicinity of the BH and form an accretion disk ([?], [?]). The accretion disk may power a new relativistic jet through the neutrino-annihilation mechanism ([?]; [?]; [?]; [?]; [?]; [?]; [?], [?]; [?], [?]; [?]) or the Blandford–Znajek (BZ) mechanism ([?]; [?]; [?]; [?], [?]). Compared with the neutrino-annihilation mechanism, the jet powered by the BZ mechanism will be cleaner and more powerful ([?]; [?]; [?]). Therefore, the BZ mechanism is more likely to interpret the late central engine activity of long GRBs. Part of the BZ energy would eventually be injected into the afterglow blast wave. If the injected energy is comparable or even larger than the blast wave kinetic energy, it will generate detectable signatures such as a plateau in the X-ray afterglow ([**?**]). In addition, the remaining energy would undergo internal dissipation, which may generate the observed giant X-ray bump.

The evolution of the fall-back rate of progenitor envelope material can be described by a smooth BPL function as ([**?**]; [**?**]; [**?**]; [**?**]):

$$\dot{M}_{\rm fb} = \dot{M}_p \left[\left(\frac{t-t_0}{t_p-t_0} \right)^{-s/2} + \left(\frac{t-t_0}{t_p-t_0} \right)^{5s/3} \right]^{-1/s}$$

where t$_0$ is the starting time of the fall-back accretion in the central engine frame, $\dot{M}_p$ is the peak fall-back rate, and t is the peak time of the fall-back rate in the central engine frame.

Progenitor envelope material falls back at late times and forms an accretion disk, which will be viscously accreted by the BH. The accretion rate can be obtained as ([**?**]):

$$\dot{M} = \frac{1}{\tau_{\rm vis}} \int_0^t \dot{M}_{\rm fb} e^{-(t-t')/\tau_{\rm vis}} dt'$$

where τ $1/\alpha\Omega$ is the viscous timescale of the accretion disk. α is a standard dimensionless viscosity parameter with values of 0.01–0.1, and Ω is the Keplerian angular velocity of the accretion disk. Due to accretion disk mass M will increase with fall-back from the envelope material and decrease with accretion, we have ([**?**]; [**?**]):

$$\dot{M}_d = \dot{M}_{\rm fb} - \dot{M}.$$

By combining Equations 4 and 5, the accretion rate can be obtained as:

$$\dot{M} = \frac{e^{-t/\tau_{\rm vis}}}{\tau_{\rm vis}} \int_0^t e^{t'/\tau_{\rm vis}} \dot{M}_{\rm fb} dt'.$$

If the viscous timescale is larger than the accretion time, the BH will undergo a slow accretion process. The accretion rate of the BH would be flat when t > τ and then begin to decrease with time (see Figure 7 [Figure 7: see original paper] in [**?**]). On the other hand, the BH will undergo rapid accretion if τ t. The evolution of the accretion rate will follow the fall-back rate, i.e., $\dot{M} = \dot{M}_{\rm fb}$. In this paper, we assume that the BH undergoes a rapid accretion process.

The fall-back accretion can continuously extract the rotational energy of the BH through the BZ mechanism and power a Poynting-dominated jet. Part of the jet energy would undergo internal dissipation, which may generate the observed giant X-ray bump. To connect the observed X-ray luminosity L and BZ power P , it is necessary to introduce an efficiency factor   and jet beaming factor f :

$$\eta_X P_{BZ} = f_b L_X.$$

The power of the BZ mechanism to extract the rotational energy of the BH can be written as ([?]; [?]; [?]; [?], [?], [?]; [?]; [?]; [?]; [?]; [?]):

$$P_{BZ} = 1.7 \times 10^{50} a_\bullet^2 m_{\bullet,15}^2 f(a_\bullet) \text{erg s}^{-1},$$

$$f(a_\bullet) = 1 + \sqrt{1 - a_\bullet^2} - \frac{\sqrt{1 - a_\bullet^2}}{2},$$

$$q = \sqrt{1 - a_\bullet^2}$$

where a • is the dimensionless BH spin parameter, m • = M • /M is the dimensionless BH mass, and B • $,_{15}$ is the strength of the magnetic field near the BH horizon in units of 10^{15}G. From equations 8 and 9, it can be seen that the BZ power mainly depends on the parameters B • , m • , and a • .

In general, the strength of the magnetic field near the BH horizon can be estimated by balancing the magnetic pressure on the BH horizon and ram pressure of the accretion flow at the inner edge of the accretion disk ([?]):

$$B_\bullet = \left(\frac{2\dot{M}c}{r_\bullet^2} \right)^{1/2}$$

where r • = (1 + √(1 - a^2 •))GM • /c^2 is the radius of the BH horizon.

The BZ process extracts rotational energy and angular momentum from the BH, while the accretion process brings energy and angular momentum from the accretion disk into the BH. According to the conservation of energy and angular momentum, the evolution of the BH under these two processes can be written as ([?]):

$$\frac{dM_\bullet c^2}{dt} = \dot{M}c^2 E_{\rm ms} - P_{BZ},$$

$$\frac{dJ_\bullet}{dt} = L_{\rm ms}\dot{M} - T_{BZ}.$$

From these two equations, it can be derived that:

$$\dot{a}_\bullet = \frac{(\dot{M}L_{\rm ms} - T_{BZ})c}{2a_\bullet(\dot{M}c^2 E_{\rm ms} - P_{BZ})GM_\bullet^2}$$

where T is the torque applied to the BH by the BZ process, which can be written as ([**?**]):

$$T_{BZ} = 3.36 \times 10^{45} a_{\bullet}^{2} q^{-1} m_{\bullet,15}^{3} F(a_{\bullet}) \mathrm{g\ cm^{2}s^{-2}}.$$

Here E and L are the specific energy and angular momentum at the radius of the innermost stable circular orbit (ISCO) of the accretion disk, respectively, defined as ([**?**]):

$$E_{\rm ms} = \frac{4\sqrt{R_{\rm isco}} - 3a_{\bullet}}{\sqrt{3}R_{\rm isco}},$$

$$L_{\rm ms} = \frac{GM_{\bullet}}{c}\frac{2(3\sqrt{R_{\rm isco}} - 2a_{\bullet})}{\sqrt{3}R_{\rm isco}},$$

$$R_{\rm isco}(M_{\bullet}, a_{\bullet}) = \frac{GM_{\bullet}}{c^{2}}\left[1 + (1 - a_{\bullet}^{2})^{1/3}\left((1 + a_{\bullet})^{1/3} + (1 - a_{\bullet})^{1/3}\right)\right].$$

4 Model Application to the X-ray Re-brightening Signature of GRB 220117A

In this section, we apply the fall-back accretion model introduced in Section 3 to the X-ray re-brightening segment and follow-up segment of GRB 220117A. We adopt the start time of the re-brightening segment t = t , /(1 + z) and the end time of the follow-up segment t = t , /(1 + z) as the start time and end time of the fall-back accretion in the central engine frame. According to analysis, the initial mass of the BH hardly affects the BZ power. In this section, we adopt M $\bullet$,$_0$ = 3M . In addition, we take f = 0.01 and = 0.01 in our calculation. Finally, we take the dimensionless peak fall-back rate $\dot{m}_p$, the sharpness of the peak s, the peak time of the fall-back rate t , and initial BH spin a$_0$ as our free parameters.

In order to obtain the best-fitting values, a Markov Chain Monte Carlo (MCMC) method is adopted. In our MCMC fitting, the emcee code is used ([**?**]). In the code, we set the boundaries of the four free parameters to log$_{10}$($\dot{m}_p$) [−15, 0], s [0, 10], t [t , t], and a$_0$ [0, 1], respectively.

The fitting result of GRB 220117A's X-ray re-brightening segment and follow-up segment is shown in Figure 2 [Figure 2: see original paper]. In addition, Figure 3 [Figure 3: see original paper] shows the corner plot of the posterior probability distribution of the free parameters. We adopt the median of the free parameter distribution and 1σ error as the fitting results: the dimensionless peak fall-back rate is log$_{10}$($\dot{m}_p$) = −4.77^{+0}.^{54} $_{0\cdot49}$, the sharpness of the peak is s = 0.60^{+0}.^{10} $_{0\cdot09}$, the peak time of the fall-back rate is log$_{10}$(t) = 2.51 ± 0.02, and the initial BH spin is a$_0$ = 0.64^{+0}.^{24} $_{0\cdot26}$. From the fitting results, we calculated that the total mass during the fall-back process is M cc = (3.09\$±0.02)×10^{-2}$M\odot, thestrengthofthemagneticfieldneartheBHhorizonatt_p isB_p,\_\{15\}$ = 0.089 ± 0.0021, the fall-back radius corresponding to t is r = (3.16 ± 0.05) × 10^{10}cm, and the jet energy from the fall-back accretion is (9.77 ± 0.65) × 10^{52}ergs, with a ratio of 0.066 to the isotropic-equivalent radiation energies of the GRB prompt phase in the 1–10^4 keV band.

In conclusion, the fall-back accretion model can interpret the X-ray re-brightening segment and follow-up segment with reasonable parameter values. This signature may require a larger black hole spin (the peak of its posterior probability distribution is $a_0 = 0.64^{+0}.^{24}{}_{0\cdot 26}$). When the fall-back rate reaches its peak, the corresponding fall-back radius is consistent with the typical radius of a Wolf-Rayet star. This result provides further support for the origin of long GRBs from the core collapse of Wolf–Rayet stars, and suggests that its late central engine activity is likely due to the fall-back accretion process.

The fall-back accretion rate reaches a peak value 1.70×10^{-5}M s^{-1} around 300s in the central engine frame. The bounding shock responsible for the associated supernova transfers kinetic energy to the envelope materials, and most of the envelope materials would be ejected. Therefore, it is very necessary to check whether the progenitor of GRB 220117A can provide enough envelope material. The fall-back rate of envelope material can be estimated using pre-SN model data ([**?**]; [**?**]; [**?**]; [**?**]):

$$\dot{M}_{\rm fb} = \frac{\rho}{\bar{\rho} - \rho} \frac{M_r}{t_{\rm ff}}$$

where $\bar{\rho}$ is the average density within radius r, and t   is the free-fall timescale of envelope material with radius r. It can be obtained as:

$$t_{\rm ff}(r) = \sqrt{\frac{3\pi}{32G\bar{\rho}}}$$

where M is the mass within radius r. The value can be obtained by the following equation:

$$M_r = M_{\bullet,0} + \int_0^r 4\pi r^2 \rho dr,$$

where is the density of envelope material at radius r. We set the time and radial coordinate for which the enclosed mass reaches the initial black hole mass as r_0 and 0, respectively. By adopting the progenitor density profile with different metallicities and masses from [**?**], we calculate the evolution of the mass supply rate for these models, which are shown in Figure 4 [Figure 4: see original paper]. We find that low-metallicity massive progenitor stars are compatible with our fitting results.

5 Discussion and Conclusions

The Swift/XRT detected the X-ray afterglow of long burst GRB 220117A, which began to rebrighten 300 seconds after triggering and followed a single power-law decay segment after thousands of seconds of orbital observation gap. The re-brightening segment is different from the shallow decay segment (plateau) and flare, and may belong to a giant X-ray bump. We investigated this segment using the fall-back accretion energy internal dissipation model. We found that the model can interpret this segment with reasonable parameter values. Within this physical model scenario, the fall-back accretion rate reaches a peak value 1.70 $\times 10^{-5}$M s^{-1} around 300s in the central engine frame, which is compatible with the late mass supply rate of some low-metallicity massive progenitor stars. The initial BH spin is $a_0 = 0.64^{+0}.^{24}\ {}_{0\cdot 26}$, implying that this re-brightening signature requires a larger BH spin. The total accretion mass M cc during the fall-back process is 3.09 $\times 10^{-2}$M . The jet energy from the fall-back accretion is (9.77 ± 0.65) $\times 10^{52}$ergs, with a ratio of 0.066 to the isotropic-equivalent radiation energies of the GRB prompt phase in the 1–10^4 keV band. The fall-back radius r corresponding to t is (3.16$±0.05)×10^{10}$cm, which is consistent with the typical radius of Wolf–Rayet stars. In summary, our results provide additional support for the origin of long bursts from the core collapse of Wolf-Rayet stars, and suggest that its late central engine activity is likely due to the fall-back accretion process.

In this paper, we adopted a simple fall-back accretion rate evolution model and did not consider the angular momentum distribution of the progenitor star, so this calculation is approximately valid for a slowly rotating progenitor. In fact, the angular velocities Ω of stars with different radii are different, and the fall-back radius satisfies r Ω^{-2} ([?]). Therefore, the angular momentum distribution of the progenitor star has a great influence on the fall-back accretion rate. In addition, the metallicities and masses of stars will have a certain impact on the fall-back accretion rate of the envelope material. In the future, we will study the fall-back accretion model with different angular momentum distributions, mass distributions, and metallicities.

Super-Eddington accretion makes material on the accretion disk subject to outward radiation pressure that is greater than gravity. Therefore, an outflow (i.e., disk wind) driven by radiation pressure is launched on the surface of the accretion disk, taking away part of the fall-back materials. However, the disk wind is ignored in the fall-back accretion model adopted in this paper. It will cause the accretion rate of the BH to decrease. Because the outflow of the accretion disk is not well understood, a power-law function model is generally adopted to describe the accretion rate at different accretion disk radii. It can be seen that the influence from the outflow of the accretion disk on the accretion rate is highly dependent on the power-law index. In addition, the existence of the accretion disk outflow will also be important for understanding the baryon load of the GRB jet ([?], [?]) and ^{56}Ni synthesis for associated supernovae ([?]). We hope that future general-relativistic magnetohydrodynamic (GRMHD) simulations can help us better understand the accretion disk outflow.

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Note: Figure translations are in progress. See original paper for figures.