Early Optical Observations of GRB 150910A: Bright Jet Optical Afterglow and X-Ray Dipole Radiation from a Magnetar Central Engine

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Abstract

Gamma-ray burst (GRB) 150910A was detected by Swift/Burst Alert Telescope (BAT), and then rapidly observed by Swift/XRT, Swift/Ultraviolet-Optical Telescope, and ground-based telescopes. We report Lick Observatory spectroscopic and photometric observations of GRB 150910A, and we investigate the physical origins of both the optical and X-ray afterglows, incorporating data obtained with BAT and XRT. The light curves show that the jet-emission episode lasts \( \sim 360 \) s with a sharp pulse from BAT to XRT (Episode I). In Episode II, the optical emission has a smooth onset bump followed by a normal decay \((\alpha_{R,2} \approx -1.36)\), as predicted in the standard external shock model, while the X-ray emission exhibits a plateau \((\alpha_{X,1} \approx -0.36)\) followed by a steep decay \((\alpha_{X,2} \approx -2.12)\). The light curves show obvious chromatic behavior with an excess in the X-ray flux. Our results suggest that GRB 150910A is an unusual GRB driven by a newly born magnetar with its extremely energetic magnetic dipole (MD) wind in Episode II, which overwhelmingly dominates the observed early X-ray plateau. The radiative efficiency of the jet prompt emission is \( \eta_{\text{j}} \approx 11\% \). The MD wind emission was detected in both the BAT and XRT bands, making it the brightest among the current sample of MD winds seen by XRT. We infer the initial spin period \((P_0)\) and the surface polar cap magnetic field strength \((B_p)\) of the magnetar as \(1.02 \times 10^{15} \text{ G} \leq B_p \leq 1.80 \times 10^{15} \text{ G}\) and \(1 \text{ ms} \leq P_0 \leq 1.77 \text{ ms}\), and the radiative efficiency of the wind is \( \eta_{\text{w}} \geq 32\% \).

Unified Astronomy Thesaurus concepts: Gamma-ray bursts (629); Magnetars (992); Non-thermal radiation sources (1119)

1. Introduction

Gamma-ray bursts (GRBs) are the most luminous explosions in the universe. Long-duration GRBs have been proposed to originate from core collapse of massive stars (e.g., Woosley 1993; Paczyński 1998; MacFadyen & Woosley 1999; Kumar & Zhang 2015; Dai et al. 2017; Mészáros & Zhang 2015; Dai et al. 2017; Mészáros et al. 2019). The collapse produces a rapidly spinning and strongly magnetized neutron star (millisecond magnetar) or a black hole.

In the millisecond magnetar scenario as the central engine of long GRBs, the magnetar could lose its rotational energy to produce a Poynting-flux-dominated outflow and power the GRB ejecta, with \( E_{\text{rot}} = (1/2)I\Omega_0^2 \approx (2 \times 10^{52}) M_{1.4} R_{\odot}^2 P_0^{-3} \) erg, where \( I \) is the magnetar’s moment of inertia, \( \Omega_0 = 2\pi/P_0 \) is its initial angular frequency, and \( M_{1.4} = M/(1.4 M_\odot) \). During the period of jet magnetic dissipation, or shock collision, it could produce the prompt gamma-ray emission of GRBs. The residual rotational energy may generate a steady wind to produce a plateau-like phase in the early afterglow (i.e., X-ray plateau). After the characteristic spin-down timescale \( \tau \) of the magnetar, its radiation luminosity evolves as \( L \propto (1 + t/\tau)^{-\alpha} \) (e.g., Dai & Lu 1998; Zhang & Mészáros 2001; Liang et al. 2007; Troja et al. 2007; Lü & Zhang 2014; Metzger & Piro 2014; Du et al. 2016; Lasky & Glampedakis 2016; Chen et al. 2017), where \( \alpha \) is, respectively, \(-1\) and \(-2\) in the gravitational wave (GW) and magnetic dipole (MD) radiation dominated scenarios (Lü et al. 2018), and \( \alpha < -3 \) indicates that the magnetar may have collapsed to a black hole prior to spin-down.

Observed properties of GRBs and their early-time afterglows indicate the different structures for the central engine. Analyses of GRB light curves based on large samples (Nousek et al. 2006; O’Brien et al. 2006; Liang et al. 2007; Lü & Zhang 2014; Lü et al. 2015; Wang et al. 2015, 2018) show that a significant fraction of X-ray afterglow light curves share common plateau features, and some exhibit rapid decay with \( \alpha \leq 2\) (e.g., Liang et al. 2007; Troja et al. 2007; Lyons et al. 2010; Lü & Zhang 2014). Zou et al. (2019) found that the jet and MD wind radiation can be separated in a fraction of Swift GRBs, also indicating that the shallow-decaying segment observed in the early-time X-ray afterglow light curves may be dominated by the MD radiation wind of a newly born magnetar, which may serve as central engine of these GRBs.

GRB 150910A is an interesting GRB with an X-ray plateau in the early-time afterglow light curves, which apparently exceeds the predictions of standard external shock models. We suggest that the phase of prompt gamma-ray emission may be
from jet radiation, and the X-ray plateau phase is mainly due to energy injection from the MD wind radiation of a millisecond magnetar in its early spin-down stage. The smooth onset feature observed in the optical afterglow light curves may be dominated by jet afterglow.

This paper reports our observations of a very bright optical afterglow of GRB 150910A and detailed modeling of the optical and X-ray afterglow light curves. Our observations and data analysis are presented in Sections 2 and 3, respectively. Analysis of the jet properties and constraints on the central engine are presented in Section 4. A discussion of the results is given in Sections 5, and 6 summarizes our conclusions. We assume a concordance cosmology of \( H_0 = 69.6 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_M = 0.286, \) and \( \Omega_{\Lambda} = 0.714 \) throughout the paper.

2. Observations and Data Reduction

The Burst Alert Telescope (BAT) onboard the Neil Gehrels Swift Observatory (Swift; Gehrels et al. 2004) triggered GRB 150910A at 09:04:48 (UT dates are used throughout this paper) on 2015 September 10 \((T_0)\) in image mode (Pagani et al. 2015). Typical of image-triggered GRBs (such as GRB 060218; Campana et al. 2006), its real-time light curve shows as long-lasting flickering. The XRT and the Ultraviolet-Optical Telescope (UVOT) onboard Swift began observing the X-ray and optical afterglows 145 s and 153 s, respectively, after the BAT trigger (Pagani et al. 2015).

The bright optical counterpart of GRB 150910A was detected by several ground-based telescopes, such as the 1 m telescope located at Nanshan, Xinjiang (Xu et al. 2015), the 10.4 m GTC (Pagani et al. 2015), the Russian-SAO RAS 1 m telescope (Moskvitin & Goranskij 2015), the 2.2 m MPG telescope at ESO La Silla Observatory (Schmidl et al. 2015), the Nordic Optical Telescope (Cano et al. 2015), the 1 m telescope of Tien Shan Astronomical Observatory (Mazaeva et al. 2015), and the Palomar 60 inch (P60) robotic telescope (Perley & Cenko 2015).

Our optical follow-up campaign of GRB 150910A was carried out using the 0.76 m Katzman Automatic Imaging Telescope (KAIT) at Lick Observatory, beginning at \( \sim T_0 + 1000 \text{ s} \) and ending \( \sim 1.75 \text{ hr} \) after the Swift/BAT trigger time (Zheng & Filippenko 2015). The optical counterpart was clearly detected in the \( V, R, \) and \( Clear \) (close to \( R \); see Li et al. 2003) bands. KAIT data were reduced using our image-reduction pipeline (Ganeshalingam et al. 2010; Stahl et al. 2019). Point-spread-function photometry was applied using DAOPHOT (Stetson 1987) from the Interactive Data Language (IDL) Astronomy User’s Library. The multiband data were calibrated to local Pan-STARRS1 stars, whose magnitudes were transformed into the Landolt (1992) system using the empirical prescription presented by Tonry et al. (2012, Equation (6)).

Additional photometric data were obtained with the 1 m Nickel telescope at Lick Observatory during the second night, \( \sim 0.911 \text{ days} \) after the trigger, with an exposure time of \( 5 \times 600 \text{ s} \) in the \( R \) band. The optical counterpart was detected in the coadded image and was measured with the method above. The afterglow light curves of GRB 150910A are shown in Figure 1.

We also obtained a late-time deep image of the site of GRB 150910A with the Low-Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) mounted on the 10 m Keck I telescope on 2015 October 10. Two 300 s images were obtained and then coadded in each of the \( V \) and \( R \) filters. Unfortunately, the optical counterpart was not detected in either band (see Figure 2). An upper limit was derived for each coadded image. All of our optical photometry is reported in Table 1.

Spectroscopic observations of the optical afterglow of GRB 150910A were performed with the Kast double spectrograph (Miller & Stone 1993) on the Shane 3 m telescope at Lick Observatory, starting \( \sim 1.1 \text{ hr} \) after the burst (Zheng et al. 2015). Exposures of 1200 and 2400 s were obtained covering the 3500–10000 Å wavelength range, with the long slit at or near the parallactic angle (Filippenko 1982) to minimize differential light losses caused by atmospheric dispersion. Spectra were reduced using standard techniques for charge-coupled device processing and spectrum extraction, specifically the KastShiv\(^\text{11}\) pipeline. Low-order polynomial fits to calibration-lamp spectra were used to determine the wavelength scale, and small adjustments derived from night-sky lines in the target frames were applied. Flux calibration and telluric-band removal were done with our own IDL routines; details are described by Silverman & Filippenko (2012) and Shivvers et al. (2019).

The spectrum (Figure 3) exhibits a blue continuum. We detect absorption lines from Mg II \( \lambda \lambda 2796, 2803 \) and Fe II \( \lambda \lambda 2344, 2374, 2383 \) at a common redshift of \( z = 1.3585 \), as well as additional lines further to the blue (as marked in Figure 3). We suggest this to be the redshift of the GRB.

We derived the X-ray light curve and spectrum of GRB 150910A observed with BAT. To present the optical light curve with broad temporal coverage we also include photometric data reported in the GCN Circulars (as listed in Table 1). Its XRT light curve is taken from the website of the

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9 http://idlastro.gsfc.nasa.gov/
10 http://archive.stsci.edu/panstarrs/search.php
11 https://github.com/ishivvers/TheKastShiv
Swift burst analyzer (Evans et al. 2010). In order to make a joint X-ray light curve in the XRT band (0.3–10 keV) from the BAT trigger time to late epochs, the light curve of the prompt X-ray emission of a GRB is derived by extrapolating the BAT spectrum to the XRT band (O’Brien et al. 2006; Evans et al. 2007, 2009).

3. Data Analysis

Figure 1 shows our optical afterglow light curve together with the X-ray light curve in the 0.3–10 keV band derived from the XRT and BAT data. Note that GRB 150910A was triggered in image-trigger mode. A weak gamma-ray signal was detected much prior to the BAT trigger time and lasted up to ∼T0 + 800 s, as shown in the inset of Figure 1. Therefore, we illustrate the joint light curves by setting a zero time of the burst at T0=220 s.

The time-integrated spectrum collected with BAT from T0 = 220 to T0 + 800 s can be adequately fit with a single power-law function. The derived photon index is Γ1 = 1.42 ± 0.12. The fluence in the 15–150 keV band is F = (4.8 ± 0.4) × 10−6 erg cm−2. The peak photon energy (Ep) of the u0 spectrum should be above the BAT energy band. We determine the Ep value by using an empirical estimate as log Ep = (2.76 ± 0.07) − (3.61 ± 0.26)log Γ1 and obtain Ep ≈ 162 keV. We take the spectral indices of the Band function α1 = −1 and α2 = −2.3, and make the K-correction for the fluence in the 1−107 keV band (e.g., Bloom et al. 2001). We find K = 1.29. The BAT light curve peaks at ∼T0 + 83 s, and the 1 s peak photon flux measured from T + 82.89 s in the 15–150 keV band is P = 1.1 ± 0.4 ph cm−2 s−1 (Pagani et al. 2015). All of the quoted uncertainties are at the 90% confidence level. With a redshift of z = 1.36, we obtain the burst isotropic gamma-ray energy as Eiso γ = (2.39 ± 0.19) × 1052 erg and a peak luminosity of Liso γ = 1.03 × 1051 erg s−1.

The X-ray light curve with temporal coverage from T0−220 to T0 + 800 s derived from the data observed with BAT and XRT shows two distinct episodes. The first episode (Episode I) lasts from the beginning of the BAT observation (T0−220) to ∼T0 + 140 s, ending with a steep decay segment. The second episode (Episode II) is dominated by a long-lasting, steady emission component, which was simultaneously detected with both the BAT and XRT and rapidly decayed at around 10 ks after the BAT trigger. An empirical fit with a smooth broken power-law model of F = F0[(t/T0)α1 + (t/T0)α2]1/2 to the light curve of the Episode II yields αX,1 = −0.36 ± 0.03 and αX,2 = −2.12 ± 0.02, and T0 = 4.73 ks by fixing the sharpness parameter ω at 3 (e.g., Liang et al. 2007), as shown in Table 2.

Comparison of the temporal slopes between the optical and X-ray light curves of GRB 150910A throughout Episode II reveals an apparent mismatch. The optical emission has a smooth onset bump followed by a normal decay, as predicted by the standard external shock model. The X-ray emission exhibits a plateau followed by a steep decay. The light curves exhibit obvious chromatic behavior with an X-ray excess (as shown in Figure 1), which may indicate that they have different physical origins (Wang et al. 2015).

To investigate this chromatic behavior, we perform a spectral analysis of Episode II. The joint spectrum observed with BAT and XRT from T0 + 140 to T0 + T0 is extracted. We use the Xspec package to fit the spectrum with an absorbed single power law by fixing the equivalent hydrogen column density of our Milky Way in the burst direction as NHMW = 5.43 × 1020 cm−2. We obtain an NH value in the host galaxy as NHhost ≈ (1.3 ± 1.2) × 1021 cm−2 and a photon index of Γ = −1.53 ± 0.03 (as shown in Figure 4). Therefore, the X-ray and gamma-ray radiation of Episode II should be from the same

Figure 2. Keck LRIS images of GRB 150910A in the V (left) and I (right) bands taken on 2015 October 10. The optical counterpart was not detected; its position is marked with a green circle.
| $T-T_d$ (mid, s) | Exp (s) | Mag | $a$ | Filter | Telescope, GCN Circ., References |
|-----------------|--------|-----|-----|--------|----------------------------------|
| 228             | 73     | 19.90 | 0.01 | W      | UVOT,18270, (1)                  |
| 229             | 72     | 19.93 | 0.01 | W      | UVOT,18270, (1)                  |
| 602             | 9.5    | 17.09 | 0.01 | W      | UVOT,18270, (1)                  |
| 775             | 9.5    | 16.67 | 0.01 | W      | UVOT,18270, (1)                  |
| 941             | 73     | 16.30 | 0.01 | W      | UVOT,18270, (1)                  |
| 578             | 9.5    | 17.56 | 0.01 | b      | UVOT,18270, (1)                  |
| 751             | 9.5    | 16.87 | 0.01 | b      | UVOT,18270, (1)                  |
| 1815            | 10     | 16.81 | 0.12 | V      | KAIT                             |
| 1915            | 10     | 16.82 | 0.13 | V      | KAIT                             |
| 2014            | 10     | 16.96 | 0.14 | V      | KAIT                             |
| 2112            | 10     | 16.83 | 0.12 | V      | KAIT                             |
| 2212            | 10     | 17.08 | 0.16 | V      | KAIT                             |
| 2312            | 10     | 17.01 | 0.15 | V      | KAIT                             |
| 2412            | 10     | 17.36 | 0.17 | V      | KAIT                             |
| 2510            | 10     | 17.05 | 0.17 | V      | KAIT                             |
| 2614            | 10     | 17.06 | 0.18 | V      | KAIT                             |
| 2714            | 10     | 17.15 | 0.17 | V      | KAIT                             |
| 2814            | 10     | 17.07 | 0.12 | V      | KAIT                             |
| 2914            | 10     | 17.66 | 0.14 | V      | KAIT                             |
| 3013            | 10     | 17.52 | 0.20 | V      | KAIT                             |
| 3113            | 10     | 17.38 | 0.22 | V      | KAIT                             |
| 2.583,936       | 2 × 300| >24.30| ...  | V      | Keck                             |
| 1849            | 10     | 15.74 | 0.08 | I      | KAIT                             |
| 1947            | 10     | 15.78 | 0.08 | I      | KAIT                             |
| 2045            | 10     | 15.85 | 0.08 | I      | KAIT                             |
| 2145            | 10     | 15.99 | 0.09 | I      | KAIT                             |
| 2245            | 10     | 16.04 | 0.09 | I      | KAIT                             |
| 2345            | 10     | 16.10 | 0.12 | I      | KAIT                             |
| 2445            | 10     | 16.10 | 0.09 | I      | KAIT                             |
| 2549            | 10     | 16.19 | 0.12 | I      | KAIT                             |
| 2648            | 10     | 16.27 | 0.08 | I      | KAIT                             |
| 2748            | 10     | 16.28 | 0.10 | I      | KAIT                             |
| 2848            | 10     | 16.60 | 0.13 | I      | KAIT                             |
| 2946            | 10     | 16.51 | 0.11 | I      | KAIT                             |
| 3046            | 10     | 16.38 | 0.09 | I      | KAIT                             |
| 3144            | 10     | 16.54 | 0.11 | I      | KAIT                             |
| 3209            | 10     | 16.67 | 0.16 | I      | KAIT                             |
| 3276            | 10     | 16.82 | 0.13 | I      | KAIT                             |
| 3342            | 10     | 16.76 | 0.11 | I      | KAIT                             |
| 3409            | 10     | 16.95 | 0.14 | I      | KAIT                             |
| 3476            | 10     | 16.89 | 0.12 | I      | KAIT                             |
| 3541            | 10     | 16.74 | 0.13 | I      | KAIT                             |
| 3608            | 10     | 16.86 | 0.14 | I      | KAIT                             |
| 3674            | 10     | 16.93 | 0.13 | I      | KAIT                             |
| 3739            | 10     | 16.78 | 0.13 | I      | KAIT                             |
| 3806            | 10     | 17.01 | 0.14 | I      | KAIT                             |
| 3873            | 10     | 16.97 | 0.13 | I      | KAIT                             |
| 3940            | 10     | 16.97 | 0.19 | I      | KAIT                             |
| 4007            | 10     | 16.99 | 0.17 | I      | KAIT                             |
| 4080            | 10     | 17.09 | 0.11 | I      | KAIT                             |
| 4146            | 10     | 17.17 | 0.15 | I      | KAIT                             |
| 4213            | 10     | 17.15 | 0.11 | I      | KAIT                             |
| 4280            | 10     | 17.20 | 0.14 | I      | KAIT                             |
| 4516            | 10     | 16.99 | 0.16 | I      | KAIT                             |
| 4583            | 10     | 17.16 | 0.19 | I      | KAIT                             |
| 4650            | 10     | 17.11 | 0.15 | I      | KAIT                             |
| 4717            | 10     | 17.29 | 0.17 | I      | KAIT                             |
| 4783            | 10     | 17.21 | 0.16 | I      | KAIT                             |
| 4850            | 10     | 17.25 | 0.15 | I      | KAIT                             |
| 4915            | 10     | 17.16 | 0.11 | I      | KAIT                             |
| 4982            | 10     | 17.31 | 0.16 | I      | KAIT                             |
| 5048            | 10     | 17.62 | 0.21 | I      | KAIT                             |
| 5115            | 10     | 17.35 | 0.24 | I      | KAIT                             |
| 5182            | 10     | 17.62 | 0.18 | I      | KAIT                             |
| 5249            | 10     | 17.14 | 0.26 | I      | KAIT                             |
| 5316            | 10     | 17.34 | 0.19 | I      | KAIT                             |
| 5382            | 10     | 17.16 | 0.14 | I      | KAIT                             |
| 5845            | 10     | 17.30 | 0.21 | I      | KAIT                             |
| 5912            | 10     | 17.48 | 0.16 | I      | KAIT                             |
| 5979            | 10     | 17.31 | 0.16 | I      | KAIT                             |
| 6046            | 10     | 17.52 | 0.20 | I      | KAIT                             |
| 6112            | 10     | 17.48 | 0.22 | I      | KAIT                             |
| 6177            | 10     | 17.47 | 0.24 | I      | KAIT                             |
| 6244            | 10     | 17.78 | 0.30 | I      | KAIT                             |

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Table 1
Optical Afterglow Photometry Log of GRB 150910A

(Continued)
Table 1 (Continued)

| $t - T_0$ (mid, s) | Exp (s) | Mag$^a$ | $\sigma^a$ | Filter | Telescope, GCN Circ., References |
|--------------------|---------|---------|------------|--------|---------------------------------|
| 6144               | 10      | 17.93   | 0.09       | Clear  | KAIT, RAS,18275, (6)            |
| 6211               | 10      | 18.03   | 0.07       | Clear  | KAIT                            |
| 6278               | 10      | 18.11   | 0.11       | Clear  | KAIT                            |
| 12,104             | 270     | 18.40   | 0.10       | R      | MITSuME,18267, (2)              |
| 17,676             | 300     | 19.40   | 0.20       | R      | Nanshan,18269, (3)              |
| 18,504             | 300     | 19.55   | 0.20       | R      | Nanshan,18269, (3)              |
| 19,116             | 300     | 19.30   | 0.20       | R      | Nanshan,18269, (3)              |
| 36,985             | 1650    | 20.18   | 0.05       | R      | TSHAO,18281, (4)                |
| 39,492             | 150     | 20.09   | 0.23       | R      | T100,18314, (5)                 |
| 39,726             | 900     | 20.20   | 0.05       | R      | SAO                             |
| 39,816             | 150     | 20.18   | 0.25       | R      | T100,18314, (5)                 |
| 44,905             | 2760    | 20.46   | 0.07       | R      | Mt-Ter-kol,18306, (7)           |
| 45,131             | 990     | 20.25   | 0.14       | R      | Chuguev,18287, (8)              |
| 48,412             | 900     | 20.57   | 0.05       | R      | SAO                             |
| 56,660             | 900     | 20.78   | 0.05       | R      | SAO                             |
| 57,959             | 780     | 20.90   | 0.07       | R      | Mt-Ter-kol,18320, (9)           |
| 78,752             | 5 × 600 | 21.17   | 0.09       | R      | Nickel                           |
| 104,998            | 2400    | 21.80   | 0.20       | R      | MITSuME,18288, (10)             |
| 118,903            | 600     | 21.69   | 0.12       | R      | CrAO,18556, (11)                |
| 119,882            | 2400    | 21.87   | 0.10       | R      | TSHAO,18319, (12)               |
| 123,068            | 600     | 21.82   | 0.10       | R      | CrAO,18556, (9)                 |
| 192,376            | 1620    | 22.30   | 0.40       | R      | TSHAO,18319, (12)               |
| 121,150            | 600     | 22.48   | 0.15       | B      | CrAO,18556, (9)                 |
| 124,727            | 960     | 22.09   | 0.10       | B      | CrAO,18556, (9)                 |

Notes. To complete our analysis, we adopt additional photometric data published in the GCN Circulars listed below.

$^a$ Not corrected for Galactic foreground reddening. The reference time $T_0$ is the Swift BAT burst trigger time. "$T - T_0$" is the middle time (s) for each observation. "Exposure" is the exposure time (s) for each observation. "$\sigma$" means the uncertainty in the magnitude.

References. (1) McCauley & Pagani (2015), (2) Kuroda et al. (2015a), (3) Xu et al. (2015), (4) Mazaeva et al. (2015), (5) Sonbas et al. (2015), (6) Moskvitin & Goranskij (2015), (7) Andreev et al. (2015), (8) Krugly et al. (2015), (9) Volnova et al. (2015a), (10) Kuroda et al. (2015b), (11) Rumyantsev et al. (2015), (12) Volnova et al. (2015b).

Figure 3. Optical spectrum of GRB 150910A obtained with the 3 m Shane telescope at Lick Observatory.

Episode II are consistent with the prediction of a newly born magnetar (e.g., Zhang & Meszaros 2001). Therefore, we propose that GRB 150910A is typical of GRBs driven by a newly born magnetar. The prompt gamma-rays and X-rays observed in Episode I would be from the jet radiation, and the late-time gamma-rays and X-rays observed in Episode II would be dominated by the MD wind of a newly born magnetar via an internal energy dissipation process. The early-time optical bump might be attributed to the afterglow of the jet when it propagates into the circumburst medium.

4. Properties of the Jet and Central Engine

If the prompt gamma-ray emission and optical afterglow are produced from the jet, as suggested above, we can fit the optical afterglow data with the standard external shock model (Sari et al. 1999; Fan & Piran 2006). We adopt the Markov Chain Monte Carlo technique to evaluate the likelihoods of the model parameters. For details of model and fitting strategy, please refer to Fan & Xu (2006) and Zhong et al. (2016). We fit only the optical data. The observed X-ray data place an upper limit to the X-ray afterglow.

The fitting results for GRB 150910A are illustrated in Figure 1. Our best fit yields the following model parameters: the initial Lorentz factor of the jet $\Gamma_0 = 200\pm 34$, the internal energy partitions of the electrons $\epsilon_e = (6.0\pm 0.2) \times 10^{-2}$ and of the magnetic field $\epsilon_B = (1.8\pm 0.1) \times 10^{-4}$, the circumburst medium density $n = 2.57\pm 0.5$ cm$^{-3}$, the isotropic kinetic jet energy $E_{K,\text{iso}} = (2.0\pm 0.1) \times 10^{53}$ erg, and the power-law index of emitting electrons $p = 2.79\pm 0.07$. The efficiency of the GRB jet is $\eta = E_{\gamma,\text{iso}}/(E_{K,\text{iso}} + E_{\gamma,\text{iso}}) = 11\%$, being similar to typical GRBs (e.g., Zhang et al. 2006). In Episode II, the photon index of the optical emission ($\Gamma = (p + 1)/2 = 1.9$) is quite different from that of the X-ray emission ($\Gamma \approx 1.56$ and 1.65). Figure 5 shows that extrapolation of the afterglow model from optical to X-rays undershoots the observed X-ray flux, consistent with the X-ray flux excess in Figure 1.

The injected kinetic luminosity to the MD wind from the spin-down of a magnetar evolves as $L_k \propto (1 + t/\tau)^{-\alpha}$, where $\tau$ is the characteristic spin-down timescale of the magnetar (e.g., Zhang & Meszaros 2001). The $\alpha$ value depends on the spin-down energy lost via the MD wind or the GW radiation.
the evolution of the injected kinetic luminosity from the spin-down of a newly born magnetar in the case that the spin-down energy lost is dominated by electromagnetic emission—that is, $L_k \propto (1 + t/\tau)^{-2}$. We estimate the initial spin period ($P_0$) and the surface polar cap magnetic field strength ($B_p$) of the magnetar in GRB 150910A (e.g., Zhang & Mészáros 2001),

$$B_{p,15} = 2.05(I_{45} R_6^{-3} (L_{b,49}/\eta_e)^{-1/2} \tau_5^{-1}) G,$$

$$P_{0,-3} = 1.42(I_{45}^{1/2} (L_{b,49}/\eta_e)^{-1/2} \tau_5^{-1/2}) s,$$

where $R$ and $I$ are, respectively, the neutron star radius and moment of inertia, $\eta_e$ is the radiative efficiency of the MD wind, and the convention $Q = 10^4 Q_e$ is adopted in cgs units. One can infer the relations $B_p - P_0$ and $B_p - P_0^2$,

$$B_{p,15} = 1.44 I_{45}^{1/2} R_6^{-3} \tau_5^{-1/2} P_{0,-3} G,$$

$$B_{p,15} = 1.02 R_6^{-3} (L_{b,49}/\eta_e)^{1/2} P_{0,-3}^2 G.$$ 

Our above analysis yields $\tau = t_p/(1 + z) = 2007 s$ and $L_b = 3.19 \times 10^{48}$ erg s$^{-1}$. By taking $I_{45} = 1$, $R_6 = 1$, and a lower limit of $P_0$ for a neutron star as $P_{0,-3} \gtrsim 1$ (e.g., Lattimer & Prakash 2004), we have $B_{p,15} \gtrsim 1.02$ and $\eta_e \geq 32\%$ (point A in Figure 6). Since $\eta_e \leq 1$, we also have $B_{p,15} \lesssim 1.80$ and $P_{0,-3} \lesssim 1.77$ (point B in Figure 6). Thus, we obtain tight constraints on $B_p$ and $P_0$ as $1.02 \lesssim B_{p,15} \lesssim 1.80$ and $1 \lesssim P_{0,-3} \lesssim 1.77$ (the range between points A and B in Figure 6).

### 5. Discussion

Our analysis shows that the optical observations of GRB 150910A are well explained with the external shock model. The early-time optical bump is then attributed to the deceleration of the jet by the ambient medium. Such a feature may also be interpreted with the line-of-sight effect for a uniform jet with a sharp edge (Panaitescu & Vestrand 2008; Guidorzi et al. 2009; Margutti et al. 2010). In this scenario, the optical light curve may peak at a time when the jet Lorentz factor satisfies $\Gamma = 1/(\theta_v - \theta_j)$, where $\theta_v$ and $\theta_j$ are the viewing angle and the jet opening angle, respectively. By analyzing a sample of optical light curves with an onset bump feature, Liang et al. (2010) argued that such a feature would result from the jet deceleration and that $\Gamma_0$ of the jet should be robustly estimated with the peak time of the optical bump. We examine whether GRB 150910A follows the same empirical
Figure 6. Initial spin period $P_0$ vs. surface polar cap magnetic field strength $B_p$ distributions, which are constrained by the radiation efficiency of the magnetic dipole wind. The black and red dashed lines correspond to efficiencies of 32\% and 100\%, respectively. The vertical black dotted line is the lower limit of the spin period of a neutron star (Lattimer & Prakash 2004). The labels “A” and “B” indicate the lower and upper limits of $(P_0, B_p)$ with (1 ms, 1.02 \times 10^{15} \) G and (1.77 ms, 1.80 \times 10^{15} \) G, respectively. The range between A to B is the available parameter space for GRB 150910A.

Figure 7. GRB 150910A (marked with a red star) shares the same empirical relation $L_{p,\text{iiso}}-E_{p,z}-\Gamma_0$ with typical GRBs (black circles; data from Liang et al. 2015). The solid and dashed lines are the least-squares fit and its 95\% confidence levels, respectively. $L_{p,\text{iiso}}$ is the peak of the isotropic luminosity, and $L_{n,\text{s}}$ is derived from three-parameter correlations $L_{p,\text{iiso}}-E_{p,z}-\Gamma_0$ by Liang et al. (2015).

$E_{\text{peak}}$ vs. $B_p$ relation determined for typical GRBs (Liang et al. 2015), where $E_{p,z}$ is the peak energy in the cosmological rest frame. Figure 7 illustrates this consistency, likely suggesting that the derived $\Gamma_0$ is the initial Lorentz factor of the fireball and the onset bump may be due to the deceleration of the fireball, as in typical long GRBs.

The X-ray plateau of GRB 150910A was simultaneously observed in the BAT and XRT bands. We calculate the energy of the MD wind as $L_{\text{wind}}=L_{\text{wind}} \times \tau \approx 6.40 \times 10^{51} \text{ erg}$, where $L_{\text{wind}}$ is the observed wind luminosity in the BAT+XRT band. Figure 8 shows GRB 150910A in the $E_{\text{wind}}-E_{\text{jet}}$ plane in comparison with a sample of GRBs whose early XRT light curves are dominated by MD radiation (Zou et al. 2019). One can observe that the MD wind of GRB 150910A is the most energetic one among these GRBs. However, it still follows the $P_0-E_{\text{jet}}$ relation reported by Zou et al. (2019).

Such a jet-wind coexisting system may explain the observed diverse temporal features in the optical and X-ray afterglow light curves. Comprehensive analysis of both the optical and X-ray afterglow light curves reveals that the light-curve diversity may be due to the competition among radiation components (e.g., Li et al. 2012; Liang et al. 2013). The optical afterglows and the single power-law decaying X-ray afterglows may be dominated by the jet afterglows, and the X-ray emission in the shallow-decaying segment of the canonical XRT light curves may be dominated by MD radiation (e.g., Zou et al. 2019). GRB 150910A is unusual with its extremely energetic wind, which overwhelmingly dominates the observed early X-ray plateau. The MD radiation decays as roughly $L_k \propto t^{-2}$ after the characteristic spin-down timescale $\tau$, and $\tau$ is typically thousands of seconds. In addition, the X-ray afterglow usually decays as roughly $L_0 \propto t^{-1.7}$ prior to the jet break. The observed jet-break time is usually at several days (e.g., Liang et al. 2008). Therefore, the observed X-ray emission at late epoch (several hours after the GRB trigger) may be dominated by the jet afterglow, where they will have the same decay slopes in both X-ray and optical light curves. Wang et al. (2015) found that a large fraction of optical and X-ray afterglows can still be explained with the external shock model. For GRB 150910A, the temporal slopes of the X-ray and optical light curves fall at the same rate until after $10^5$ s (as shown in Figure 1).

6. Conclusions

We report our optical spectroscopic and photometric observations of the optical afterglow of GRB 150910A, and we investigate the physical origins of both the optical and X-ray afterglows, incorporating data obtained with the Swift BAT and XRT. We show that the gamma-ray and X-ray emission of this GRB can be separated into the jet-emission episode (Episode I) and the magnetar MD wind radiation episode (Episode II). The jet-emission episode is observed with BAT more than 200 s prior to its trigger.

Modeling the $R$-band optical light curve with the standard external shock model, we obtain jet parameters of $\Gamma_{0,5} = 200^{+44}_{-34}$, $\epsilon_e = 0.06 \pm 0.002$, $\epsilon_B = (1.8 \pm 0.1) \times 10^{-4}$, $n = 2.57 \pm 0.5 \text{ cm}^{-3}$, and $\epsilon_{K,\text{iiso}} = (2.0 \pm 0.1) \times 10^{55} \text{ erg}$. The radiative efficiency of the jet prompt emission is $\eta_{j,5} \approx 11\%$. This GRB follows the $L_{p,\text{iiso}}-E_{p,z}-\Gamma_0$ relation derived for typical GRBs that have a clear detection of an onset bump in their early-time optical afterglow light curves.

The MD wind emission was detected in both the BAT and XRT bands, making GRB 150910A the brightest among the current sample of MD winds detected by the XRT. We infer the parameters of the magnetar as $1.02 \times 10^{15} \text{ G} \leq B_p \leq 1.80 \times 10^{15} \text{ G}$ and $1 \text{ ms} \leq P_0 \leq 1.77 \text{ ms}$, and the lower limit of the radiation efficiency of the wind as $\eta_{w,5} \geq 32\%$. It also satisfies the $P_0-E_{\text{jet}}$ relation of GRBs in which a shallow-decay segment was detected in their early-time XRT light curves.
Figure 8. Correlations of $P_{90}$–$E_{jet,iso}$ (left panel) and $E_{wind}$–$E_{jet,iso}$ (right panel); GRB 150910A is marked with a red star. The solid and dashed lines are the least-squares fit and its 95% confidence levels, respectively. The sample of Zou et al. (2019) (black point) also presented here.

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