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Polarized Emission from Gamma-Ray Burst Jets

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Abstract: I review how polarization signals have been discussed in the research field of Gamma-Ray Bursts (GRBs). I mainly discuss two subjects in which polarimetry enables us to study the nature of relativistic jets. (1) Jet breaks: Gamma-ray bursts are produced in ultra-relativistic jets. Due to the relativistic beaming effect, the emission can be modeled in a spherical model at early times. However, as the jet gradually slows down, we begin to see the edge of the jet together with polarized signals at some point. (2) Optical flash: later time afterglow is known to be insensitive to the properties of the original ejecta from the GRB central engine. However, a short-lived, reverse shock emission would enable us to study the nature of of GRB jets. I also briefly discuss the recent detection of optical circular polarization in GRB afterglow.

Keywords: polarization; relativistic jets; relativistic shocks; gamma-ray bursts

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1. Introduction

Gamma-ray bursts (GRBs) are the brightest objects in the universe, produced by the deceleration of ultra-relativistic jets with Lorentz factors $\Gamma \gtrsim 100$. The core-collapses of massive stars and the mergers of binary compact stellar objects such as neutron stars and black holes (BHs) are the possible progenitors [1,2]. In both cases accretion onto a compact object is likely to power the relativistic outflow and the same physical processes are involved. The outflow energy is first dissipated by internal shocks (or another form of internal dissipation) which produce highly variable, prompt γ-rays. Later, the interaction of the outflow with the ambient medium produces a blast wave which expands and produces the subsequent afterglow at lower frequencies (i.e., X-ray, optical and radio) [3,4]. Relativistic motion is an essential ingredient in the GRB model, and understanding the formation process of the outflow (i.e., acceleration and collimation process) is a major focus of international research efforts in the context of GRBs (and other astrophysical jets). GRB outflows are conventionally assumed to be a baryonic jet. However, recent polarization measurements imply that magnetic fields play a role in the jet acceleration [5–8].

Relativistic outflows and possibly magnetic acceleration are features that GRBs and active galactic nuclei (AGN) have in common. GRB "jets" are bipolar outflow with a opening angle θ_j. Unlike other astrophysical jets, GRB jets are transient (i.e., explosive events). The matter and energy are highly concentrated in an extremely thin layer at the forefront of the "jet". The width of the high density region in the direction of motion is orders of magnitude smaller than the radius where the high density layer is. A "flying pancake" is a better description for GRB jets [3]. Another unique feature of GRB jets is the size of the visible region which is much smaller than the jet opening angle θ_j. Due to the relativistic beaming effect, we can see only a small portion of the jet, i.e., $1/\Gamma \ll \theta_j \sim 5$ deg. The relativistic beaming effect plays an important role when the polarization signals are discussed below.

2. Jet Breaks

Although GRBs originate from highly collimated jets, the prompt γ-rays and early afterglow are well described by a spherical model due to the relativistic beaming. If we are on-axis for the jet and the jet's Lorentz factor Γ is larger than the inverse of the jet opening angle θ_j, the emission from a spherically expanding shell and a jet would be similar to each other. However, as the jet propagates through the ambient medium, the Lorentz factor gradually decreases, and we eventually notice that it is jet emission [9]. When Γ drops below θ_j^{-1}, we begin to see the edge of the jet, and we expect a break in the light curve of the afterglow at this stage (i.e., a jet break). Before the break (and even after the break if the sideway expansion is not significant), the outflow is well described by a relativistic blast wave [10] with an "isotropic" explosion energy E, which is estimated from the prompt γ-ray luminosity assuming isotropic emission. Using a spherical adiabatic estimate $\Gamma(t) \sim 6(E_{52}/n)^{1/8} t_{day}^{-3/8}$, this break should take place at

$$t_j \sim 6.2(E_{52}/n)^{1/3}(\theta_j/0.1)^{8/3}\ \mathrm{hr}, \tag{1}$$

where E_{52} is the isotropic energy of the jet in units of 10^{52} ergs and n is the ambient medium particle density in cm^{-3}. Such a jet break has been observed for many GRB afterglow around days after GRB triggers. The jet opening angle distribution peaks around 5 degree for long GRBs (i.e., the γ duration T_{90} is more than 2 s), and it is less constrained for short GRBs ($T_{90} < 2$ s) [2].

A large polarization degree usually implies the synchrotron process and some asymmetry in the emission region. Highly polarized emission is expected to be associated with a jet break [11–13]. At any point in a shock front, there is a preferred direction (i.e., the radial direction) in which the shock moves. The magnetic field might not be completely isotropic in the shock region, the field strength parallel to the shock plane could be significantly different from that in the plane normal direction [14]. In such a case, We might observe a linearly polarized emission even if the magnetic field is isotropic in the shock plane.

As we have discussed, we can observe only a small portion of a relativistic jet (or the shock front) due to the relativistic beaming effect, which is a small area (i.e., thin disk) around the line-of-sight with angular scale of $1/\Gamma$. First we consider the disk emission in its comoving frame. Even if the magnetic field is isotropic (i.e., totally random) when the disk is seen face-on, there are some degree of alignment and the emission can be highly polarized if the disk is seen edge-on. However, our line-of-sight is supposed to be perpendicular to the disk (i.e., face-on). How can we see the polarized, edge-on emission? This is where the special relativistic effect, i.e., the relativistic aberration of photons plays a role [12]. In the lab frame, the disk is propagating with the Lorentz factor Γ. Photons emitted at $\theta' = \pi/2$ (edge-on) in the comoving frame are observed at $\theta \sim 1/\Gamma$ (almost face-on) in the lab frame. Therefore, the visible region (the disk) is expected to be highly polarized at the edge. However, since the region is symmetric (i.e., disk), the net polarization degree is still zero.

At later times, as the shock slows down, a larger area becomes visible. A jet break in the afterglow light curve is expected when we begin to see the edge of the jet. Since it is unlikely that the observer is directed exactly at the center of the jet, we would see a part of the edge (i.e., arc), rather than the entire, circular edge of the jet at the same time. Most photons come from the direction toward the center of the jet, and the visible region is not symmetric anymore. The net polarization becomes non-zero. If the jet is homogeneous, the light curve of the degree of polarization is expected to have two maxima, with the polarization position angle changing by 90 degree between the first and the second maximum [11,13]. Since GRBs are located at cosmological distances, they are basically point sources. We can not resolve the images of jets. However, the evolution of the polarization degree and polarization angle is known to be sensitive to the angular structure of jets (e.g., energy distribution). Polarization curves will be very important to solve the jet structure [15].

3. Early Afterglow and Magnetic Fields in GRB Jets

The nature of the jets and the role of magnetic fields in GRBs are not well understood yet. In a baryon-dominated jet, only weak, tangled fields are expected to be generated in situ by shock instabilities [14]. In an alternative model, the rotation of a BH-accretion disk system might cause a helical outgoing Magnetohydrodynamic (MHD) wave which accelerates material frozen into the field lines. In a magnetic jet, globally ordered magnetic fields are expected to present [16]. As we discuss below, by measuring the degree of linear polarization in early-time emission, we should be able to distinguish the competing models.

When the GRB outflow collides on the ambient medium, a transient shock called the reverse shock is generated inside the flow itself. The short-lived, reverse shock emission so-called "optical flash" is a key element in early afterglow studies [17,18]. The outflow from the GRB central engine (e.g., a BH accretion disk system) initially propagates with a constant velocity, but it eventually sweeps a large volume of the ambient medium, and it is decelerated. The interaction between the outflow and the ambient medium (or the energy transfer from the original ejecta to the ambient medium) is described by two shocks: a forward shock propagating into the ambient medium and a reverse shock propagating into the ejecta. The optical flash is emitted only during the reverse shock is crossing the ejecta. Once the reverse shock has crossed the ejecta, no new electrons are shocked anymore. Since the ejecta is a very thin structure (i.e., the pancake), the emission is short-lived. The shock crossing time coincides with the deceleration time at which most energy of the ejecta is given to the ambient medium,

$$t_\times = \left(\frac{3E}{32\pi\Gamma^8 n m_p c^5}\right)^{1/3} \sim 90\, E_{52}^{1/3} n^{-1/3} \left(\frac{\Gamma}{100}\right)^{-8/3} \text{sec}, \tag{2}$$

where m_p is the proton mass. At this shock crossing time, the two shocked regions separated by the contact discontinuity have the same bulk Lorentz factor and internal energy density e. The typical frequency of synchrotron emission is proportional to the Lorentz boost and the magnetic field and to the electron's random Lorentz factor squared. The first two factors, i.e., the Lorentz boost and the magnetic field proportional to e, are the same for the two shocked regions, while the random Lorentz factor is different by a factor of Γ (the two shocked regions contain the same amount of the internal energy, but the ejecta is heavier by a factor of Γ. The internal energy is distributed to a larger number of electrons. Then, the effective temperature is lower by a factor of Γ). The typical frequency of the reverse shock emission is lower by a factor of Γ^2, compared to that of the forward shock emission. If the forward shock emits X-rays, the reverse shock should emit in the optical band [19].

The interaction between the ejecta and the ambient medium also depends on the magnetization of the ejecta [20,21]. If the ejecta is magnetized, the reverse shock component would become much brighter than the forward shock component. However, if the magnetization is too high $\sigma \gtrsim 0.1$ where σ is the ratio of magnetic to kinetic energy flux, the magnetic pressure suppresses the formation of a reverse shock and consequently the reverse shock component. The forward- and reverse- shock modeling of afterglow indicates that the ejecta might be endowed with primordial magnetic fields at the central engine [22,23].

After the shock crossing $t > t_\times$, the forward shock region becomes a blast wave and it carries most of the system energy. The reverse shocked ejecta is adiabatically cooled and the reverse shock emission rapidly declined as $L \sim t^{-2}$. Since the blast wave is the shocked ambient medium, the blast wave emission (i.e., late time afterglow) does not depend on the magnetization of the original ejecta. In order to distinguish between the baryon-dominated jet and magnetized jet models, it is essential to carry out afterglow observations at early times and catch the optical flash (the exception in late afterglow is radio flares. The ejecta and consequently shocked electrons in the ejecta are adiabatically cooled, and the radiation comes to the radio band around 1 day after GRB triggers. If the original ejecta contains large scale magnetic fields, radio flares should be polarized [24–26]).

The forward- and reverse- shock modeling of early afterglow and early afterglow polarimetry are complementary. The former is sensitive to the strength of magnetic fields in the ejecta, while the latter depends on the length scales and geometry of the magnetic fields. We have been observing early afterglow by using the RINGO polarimeters. RINGO and RINGO2 are optical polarimeters on the Liverpool telescope which is the world-largest robotic telescope. We can measure the polarization degree of optical afterglow as early as just a few mins after GRB triggers [6,8,27,28]. The polarimeters use a rotating polaroid that rotates once per second. The original polarimeter, RINGO uses deviating optics to spread the time-dependent polarized signal into rings. For RINGO2, a fast readout camera is used to capture this signal as it changes in time. Synchronized with the rotation of the polaroid, eight exposures are obtained per second and the combination of the images allows us to determine the polarization of sources.

Nineteen GRB afterglow observations were carried out with RINGO2 between 2010 and 2012 [28]. We performed polarimetric analysis for 9 bright events out of the 19 events, and the polarization degrees (or limits) and polarization angle were measured. For three events: GRB 101112A, GRB110205A and GRB120308A, we detected polarization signals in their early optical afterglow. We also constructed the light curves of the bright events by using RINGO2 and RATCam data in order to evaluate the decay indexes of the afterglow. The combination of our photometric and polarimetric data clear indicates that the events for which polarization were detected have a reverse shock emission dominated phase in the early afterglow.

- **GRB 101112A:** Around the peak of the afterglow, 6% polarization degree was detected. Since the onset of the afterglow $t_p \sim 299$ s is well separated from the end of the prompt gamma-ray emission $T_{90} \sim 9.2$ s, this is a thin shell case where the reverse shock is mildly relativistic in the comoving frame of the outflow [18]. The observed rising of the emission $t^{4.2}$ is faster than that for the forward shock emission t^3, and it implies that the reverse shock emission contributed around the peak.
- **GRB 110205A:** A polarization degree of 13% was detected in the rising phase. The peak at $t_p \sim 1027$ s ($\gg T_{90} = 249$ s) is considered to be the onset-of the afterglow. The rapid rise $t^{4.6}$ and decay $t^{-1.5}$ indicate that the reverse shock emission significantly contributed to the optical band around the peak.
- **GRB 120308A:** we detected a very high polarization degree $P = 28\%$ around the peak at $t_p = 298$ s (see Figure 1), and the very rapid rise t^5 and decay $t^{-2.4}$ are a clear signature of the reverse shock. It has been demonstrated that this light curve is best described by the combination of the two components, one from a reverse and the other from a forward shock [8].

We also note that polarization signals were detected in multiple epochs for GRB 101112A and GRB120308A. Interestingly, the polarization angle was constant in time within the error limits in both cases. Since the amplification of magnetic fields by the rotation of a BH-accretion disk system is expected in the magnetic GRB jet model, the outflow would be thread with globally ordered magnetic fields. Since the radial field decays faster than the tangential one, the large scale magnetic field is likely to be dominated by a toroidal component. Although internal dissipation processes preceding the onset of afterglow can distort the toroidal field [29,30], the visible region with angular scale $\sim 1/\Gamma$ might have a rather uniform magnetic field. In such a case, the polarization (electric) vector is expected to point toward the jet axis. The constant polarization angle results are consistent with this model.

Since the energy in the original ejecta is quickly transferred to the ambient medium and emission originates from a blast wave, we expect low degrees of linear polarization and negligible circular polarization at late times. We recently detected circularly polarized optical light in the afterglow of GRB 121024A, which was measured 0.15 days after the burst [31]. This might be due to anisotropic electron pitch angle distributions (however, see also [32]). If so, new models are required to produce the complex microphysics of realistic shocks in relativistic jets.

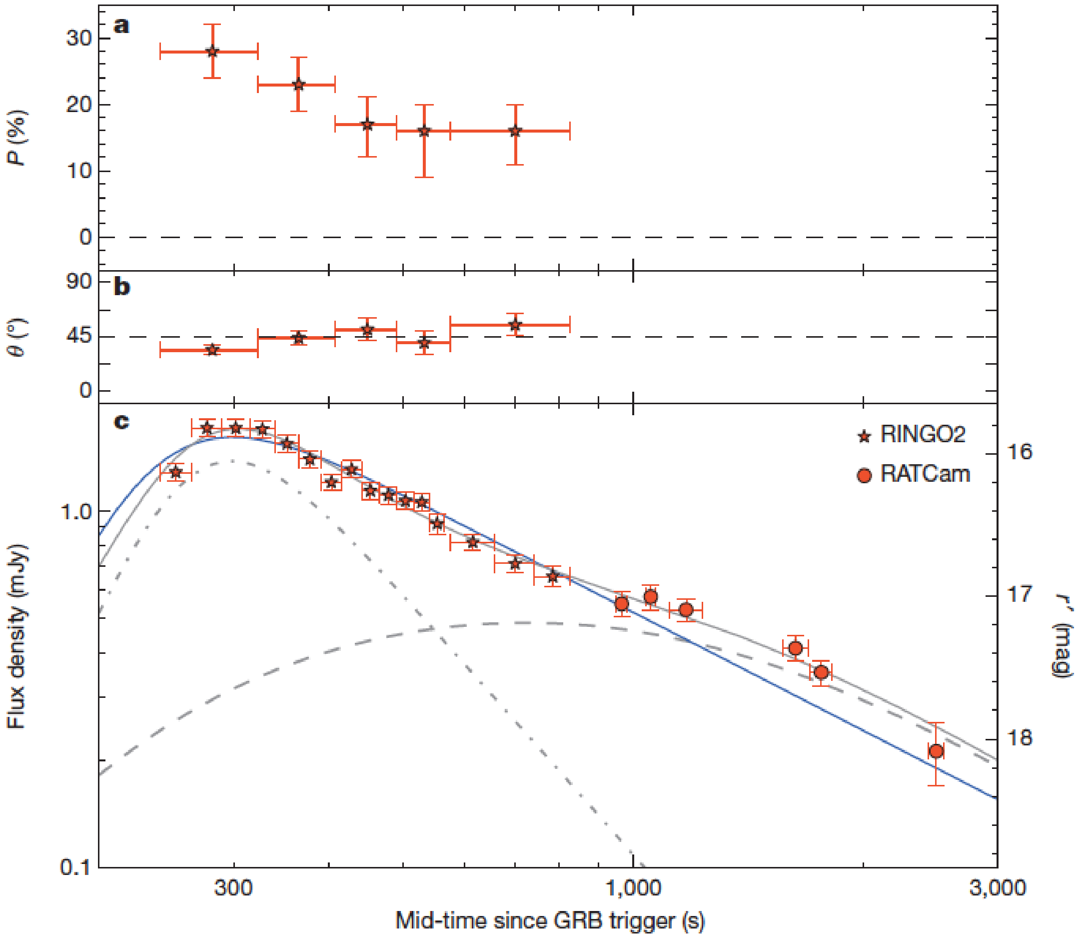

Figure 1. Evolution of optical polarization and brightness in GRB120308A. Evolution of (**a**) polarization degree P and (**b**) position angle θ. (**c**) Light curve. Model fits using one peak (blue solid line) or two peaks (broken grey line for each component). Figure from [8].

4. Discussion and Conclusions

I have briefly reviewed how polarization signals had been discussed in GRB studies. Although we can see only a small portion of GRB jets at early times due to the relativistic beaming effect, as the outflow decelerates, a larger region becomes visible at later times for the observer. When the Lorentz factor becomes comparable to the inverse of the jet opening angle, we expect a peculiar behavior in the evolution of the polarization degree and polarization angle. The exact evolution is sensitive to the angular structure of jets. Polarization curves around jet breaks would be a powerful means to solve the jet structure.

Since the later time afterglow is radiated from a shocked ambient medium (i.e., a blast wave), rather than the original ejecta from the central engine which powers GRB events, it is essential to detect the reverse shock emission (i.e., optical flash) in order to study the energy content of the GRB jets (i.e., magnetized vs baryonic). The forward- and reverse- shock modeling of afterglow and polarization measurements of early afterglow both indicate magnetized outflow. Magnetic fields are very likely to play a significant role in the GRB jet formation.

Recently, circularly polarized signals were detected in the optical afterglow of GRB 121024A. The circular polarization degree itself and the ratio between the circular and linear polarization degree are much higher than the theoretically expected values. Additional observations would be needed to understand the origin of the circular polarization.

Binary compact stellar objects are leading candidates for short GRB progenitors, they are also the primary targets for gravitational wave observatory such as LIGO and Virgo. Various electromagnetic (EM) signals should be associated with these GW events [33,34]. Measuring the degree of polarization of the electromagnetic emission provides unique constraints on the geometry of the system (the polarization of GWs also might provide constraints on the geometry in future [35]).

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References

1. Woosley, S.E.; Bloom, J.S. The Supernova Gamma-Ray Burst Connection. *Ann. Rev. Astron. Astrophys.* **2006**, *44*, 507–556.
2. Berger, E. Short-Duration Gamma-Ray Bursts. *Ann. Rev. Astron. Astrophys.* **2014**, *52*, 43–105.
3. Piran, T. The physics of gamma-ray bursts. *Rev. Mod. Phys.* **2004**, *76*, 1143–1210.
4. Zhang, B.; Meszaros, P. Gamma-Ray Bursts: Progress, problems & prospects. *Int. J. Mod. Phys.* **2004**, *19*, 2385–2472.
5. Götz, D.; Laurent, P.; Lebrun, F.; Daigne, F.; Bošnjak, Z. Variable Polarization Measured in the Prompt Emission of GRB 041219A Using IBIS on Board INTEGRAL. *Astrophys. J.* **2009**, *695*, L208–L212.
6. Steele, I.A.; Mundell, C.G.; Smith, R.J.; Kobayashi, S.; Guidorzi, C. Ten per cent polarized optical emission from GRB090102. *Nature* **2009**, *462*, 767–769.
7. Yonetoku, D.; Murakami, T.; Gunji, S.; Mihara, T.; Toma, K. Detection of Gamma-Ray Polarization in Prompt Emission of GRB 100826A. *Astrophys. J.* **2011**, *743*, L30.
8. Mundell, C.G.; Kopač, D.; Arnold, D.M.; Steele, I.A.; Gomboc, A.; Kobayashi, S.; Harrison, R.M.; Smith, R.J.; Guidorzi, C.; Virgili, F.J.; et al. Highly polarized light from stable ordered magnetic fields in GRB 120308A. *Nature* **2013**, *504*, 119–121.
9. Sari, R.; Piran, T.; Halpern, J.P. Jets in Gamma-Ray Bursts. *Astrophys. J.* **1999**, *519*, L17–L20.
10. Blandford, R.D.; McKee, C.F. Fluid dynamics of relativistic blast waves. *Phys. Fluids* **1976**, *19*, 1130–1138.
11. Sari, R. Linear Polarization and Proper Motion in the Afterglow of Beamed Gamma-Ray Bursts. *Astrophys. J.* **1999**, *524*, L43–L46.
12. Ghisellini, G.; Lazzati, D. Polarization light curves and position angle variation of beamed gamma-ray bursts. *Mon. Not. R. Astron. Soc.* **1999**, *309*, L7–L11.
13. Lazzati, D. Polarization in the prompt emission of gamma-ray bursts and their afterglows. *New J. Phys.* **2006**, *8*, 131.
14. Medvedev, M.V.; Loeb, A. Generation of Magnetic Fields in the Relativistic Shock of Gamma-Ray Burst Sources. *Astrophys. J.* **1999**, *526*, 697–706.
15. Rossi, E.M.; Lazzati, D.; Salmonson, J.D.; Ghisellini, G. The polarization of afterglow emission reveals γ-ray bursts jet structure. *Mon. Not. R. Astron. Soc.* **2004**, *354*, 86–100.
16. Komissarov, S.S.; Vlahakis, N.; Königl, A.; Barkov, M.V. Magnetic acceleration of ultrarelativistic jets in gamma-ray burst sources. *Mon. Not. R. Astron. Soc.* **2009**, *394*, 1182–1212.
17. Sari, R.; Piran, T. Predictions for the Very Early Afterglow and the Optical Flash. *Astrophys. J.* **1999**, *520*, 641–649.
18. Kobayashi, S. Light Curves of Gamma-Ray Burst Optical Flashes. *Astrophys. J.* **2000**, *545*, 807–812.
19. Kobayashi, S.; Zhang, B. GRB 021004: Reverse Shock Emission. *Astrophys. J.* **2003**, *582*, L75–L78.
20. Zhang, B.; Kobayashi, S. Gamma-Ray Burst Early Afterglows: Reverse Shock Emission from an Arbitrarily Magnetized Ejecta. *Astrophys. J.* **2005**, *628*, 315–334.
21. Zhang, B.; Kobayashi, S.; Mészáros, P. Gamma-Ray Burst Early Optical Afterglows: Implications for the Initial Lorentz Factor and the Central Engine. *Astrophys. J.* **2003**, *595*, 950–954.

22. Gomboc, A.; Kobayashi, S.; Guidorzi, C.; Melandri, A.; Mangano, V.; Sbarufatti, B.; Mundell, C.G.; Schady, P.; Smith, R.J.; Updike, A.C.; et al. Multiwavelength Analysis of the Intriguing GRB 061126: The Reverse Shock Scenario and Magnetization. *Astrophys. J.* **2008**, *687*, 443–455.
23. Harrison, R.; Kobayashi, S. Magnetization Degree of Gamma-Ray Burst Fireballs: Numerical Study. *Astrophys. J.* **2013**, *772*, 101.
24. Sari, R.; Piran, T. GRB 990123: The Optical Flash and the Fireball Model. *Astrophys. J.* **1999**, *517*, L109–L112.
25. Kobayashi, S.; Sari, R. Optical Flashes and Radio Flares in Gamma-Ray Burst Afterglow: Numerical Study. *Astrophys. J.* **1999**, *542*, 819–828.
26. Granot, J.; Taylor, G.B. Radio Flares and the Magnetic Field Structure in Gamma-Ray Burst Outflows. *Astrophys. J.* **2005**, *625*, 263-270.
27. Mundell, C.G.; Steele, I.A.; Smith, R.J.; Kobayashi, S.; Melandri, A.; Guidorzi, C.; Gomboc, A.; Mottram, C.J.; Clarke, D.; Monfardini, A.; et al. Early optical polarization of a gamma ray burst afterglow. *Science* **2007**, *315*, 1822–1824.
28. Steele, I.A.; Kopač, D.; Arnold, D.M.; Smith, R.J.; Kobayashi, S.; Jermak, H.E.; Mundell, C.G.; Gomboc, A.; Guidorzi, C.; Melandri, A.; et al. Polarimetry and Photometry of Gamma-Ray Bursts with RINGO2. *Astrophys. J.* **2017**, *843*, 143.
29. Troja, E.; Lipunov, V.M.; Mundell, C.G.; Butler, N.R.; Watson, A.M.; Kobayashi, S.; Cenko, S.B.; Marshall, F.E.; Ricci, R.; Fruchter, A.; et al. Significant and variable linear polarization during the prompt optical flash of GRB 160625B. *Nature* **2017**, *547*, 425–427.
30. Zhang, B.; Yan, H. The Internal-collision-induced Magnetic Reconnection and Turbulence (ICMART) Model of Gamma-ray Bursts. *Astrophys. J.* **2011**, *726*, 90.
31. Wiersema, K.; Covino, S.; Toma, K.; van der Horst, A.J.; Varela, K.; Min, M.; Greiner, J.; Starling, R.L.; Tanvir, N.R.; Wijers, R.A.; et al. Circular polarization in the optical afterglow of GRB 121024A. *Nature* **2014**, *509*, 201–204.
32. Nava, L.; Nakar, E.; Piran, T. Linear and circular polarization in ultra-relativistic synchrotron sources—implications to GRB afterglows. *Mon. Not. R. Astron. Soc.* **2015**, *455*, 1594–1606.
33. Metzger, B.D.; Berger, E. What is the Most Promising Electromagnetic Counterpart of a Neutron Star Binary Merger? *Astrophys. J.* **2012**, *746*, 48.
34. Lamb, G.; Kobayashi, S. Electromagnetic Counterparts to Structured Jets from Gravitational Wave Detected Mergers. *Mon. Not. R. Astron. Soc.* **2017**, in press.
35. Kobayashi, S.; Mészáros, P. Polarized Gravitational Waves from Gamma-Ray Bursts. *Astrophys. J.* **2003**, *585*, L89–L92.