New Astronomy Reviews 000 (2016) 1–21

Contents lists available at ScienceDirect

New Astronomy Reviews

journal homepage: www.elsevier.com/locate/newastrev

High energy polarimetry of prompt GRB emission

Mark L. McConnell[a,b,*]

[a] Space Science Center, University of New Hampshire, Durham, NH 03824, USA
[b] Department of Earth, Oceans, and Space, Southwest Research Institute, Durham, NH 03824, USA

ARTICLE INFO

Article history:
Accepted 20 November 2016
Available online xxx

Keywords:
Gamma-rays
Instrumentation
Polarimetry
Polarization
Gamma-ray bursts,

ABSTRACT

[Evidence] of polarized γ-ray emission (> 50 keV) from Gamma-Ray Bursts (GRBs) has been accumulated in recent years. Measurements have been reported with levels in the range of 30–80%, typically with limited statistical significance. No clear picture has yet emerged with regards to the polarization properties of GRBs. Taken at face value, the data suggest that most GRBs have a relatively large level of polarization (typically, > 50%), which may suggest synchrotron emission associated with an ordered magnetic field structure within the GRB jet. But these results are far from conclusive. Here, we review the observations that have been made, concentrating especially on the instrumental issues and the lessons that might be learned from these data.

Contents

* Corresponding author.
E-mail address: mark.mcconnell@unh.edu

http://dx.doi.org/10.1016/j.newar.2016.11.001

1. Introduction

The process by which some stellar-mass black holes are thought to form (either from the final stages of a highly evolved, massive star or the merger of two compact objects) results in a release of energy that exceeds anything observed in the Universe since the Big Bang itself. This energy release results in the formation of two oppositely directed jets, which can observationally manifest itself as a Gamma Ray Burst (GRB) and its afterglow emission. The initial burst of γ-rays, the so-called prompt emission, lasts from a fraction of a second up to a few hundred seconds and is thought to originate in the innermost region of the jets. The longer-lasting afterglow emission, lasting from days to weeks, is believed to originate in the outer part of the jet. This emission has been well studied across the entire electromagnetic spectrum, providing a better understanding of the late stages of the jet evolution, as it interacts with the surrounding medium. However, a complete picture of the GRB phenomena also requires an understanding of the inner part of the jet, closest to where the black hole is formed. At this time, we have only a limited understanding of the inner jet, as it depends on the short-lived, high-energy prompt emission, which is far more difficult to study given the random nature of these sources. Theoretical modeling argues that a more complete understanding of the inner structure of GRBs, including the geometry and physical processes close to the central engine, requires the exploitation of X-ray and γ-ray polarimetry. Efforts to measure the high energy polarization have so far met with limited success. As several efforts are currently underway to collect more definitive measurements, it is worthwhile to review the available results in the context of past experimental efforts.

2. GRB theory

GRBs are distributed isotropically across the sky with an occurrence rate of roughly one every day, as observed by both *CGRO/BATSE* and *Fermi/GBM* (Paciesas et al., 1999; 2012). Burst durations range from < 10 ms up to several hundred seconds (Paciesas et al., 1999). Long-duration bursts (> 2 s) are believed to be associated with the death of massive stars, whereas short-duration bursts (< 2 s) are believed to be associated with the merger of compact star binaries (neutron star-neutron star, neutron star-black hole, etc.). Regardless of the progenitor, a generic “fireball” shock model (e.g., Piran, 2005; Mészáros, 2006) suggests that a relativistic jet is launched from the center of the explosion. The “internal” dissipation within the fireball (e.g., via internal shocks or internal magnetic dissipation processes) leads to emission in the X-ray and γ-ray band, which corresponds to the observed prompt emission. Observationally, the canonical prompt emission spectrum can often be empirically fit by the so-called *Band function* (Band et al., 1993), consisting of a broken power-law with a smooth break at a characteristic energy, commonly referred to as *E-peak* (E_p). The E_p value corresponds to the peak of the spectrum when plotted in terms of energy output per decade of energy ($E^2 N_E$). The observed distribution of E_p values range from ~ 10 keV up to at least 1 MeV, with a broad peak near 200 keV. As there is no physical basis for this spectral model, the precise nature of the emission is not well determined. Although synchrotron emission is believed to play a significant role (e.g., Rees and Mészáros, 1994), many aspects of the emission can also be explained by inverse Compton emission (e.g., Eichler and Levinson, 2003; Shaviv and Dar, 1995). Additionally, thermal emission from an expanding photosphere appears to be an important component in some GRBs (e.g., Lundman et al., 2014). Eventually, the outflowing jet is decelerated by the circumburst medium, which leads to a long-lasting forward shock. Emission from the external shock is believed to be responsible for the afterglow following the burst. Much has been learned about these afterglows, but little progress has been made in understanding the physical origin of the prompt emission.

Although polarimetry of the prompt γ-ray emission is expected to provide useful insights, current measurements furnish only very limited constraints for theoretical modeling of the prompt emission. Consequently, there are a large number of models that seek to explain the available polarization measurements. These models can often be characterized as falling into one of two general classes of models: intrinsic and extrinsic (Waxman, 2003; Lazzati, 2006).

Intrinsic models invoke a globally ordered magnetic field in the emission region, with electron synchrotron emission yielding a net linear polarization (e.g., Waxman, 2003; Lyutikov, 2003; Granot, 2003). In this case, the polarization properties are derived from the intrinsic characteristics (i.e., the magnetic field geometry) of the jet. The model applies for most observer viewing-angle geometries, with typical levels of polarization (Π) ranging from ~ 20% up to ~ 60%. These models are characterized by a highly magnetized jet composition, reconnection as the most possible dissipation mechanism, and synchrotron radiation as the emission mechanism.

Geometric models models require an optimistic viewing direction (or geometry) to observe a high degree of polarization. The magnetic field structure is random in the emission region, so that no net polarization is detected if the viewing angle is along the jet beam (regardless of radiation mechanism). However, if the viewing direction is near the edge of the jet, in particular about $1/\Gamma$ outside the jet cone (where Γ is the bulk Lorentz factor of the outflow), a high polarization degree results due to loss of emission symmetry (e.g., Shaviv and Dar, 1995; Lazzati et al., 2004). This model is characterized by a matter-dominated outflow and shocks as the most likely dissipation mechanism. Both synchrotron and inverse Compton can be the radiation mechanisms. The typical polarization is $\Pi < 20\%$ for most viewing angles, although synchrotron emission can produce Π as high as ~ 70%, and inverse Compton models (also known as Compton drag models; Lazzati et al., 2004) can achieve $\Pi \sim 100\%$ under optimistic geometries.

A statistical study of GRB polarization properties could differentiate between the two classes of models (intrinsic vs. geometric) and, in some cases, distinguish between models within a class, providing a direct diagnostic of the magnetic field structure, radiation mechanism, and geometric configuration of GRB jets. The distribution of polarization values (assuming random viewing angles) has been studied for three generalized models that characterize the jet physics (Toma et al., 2009). The three principle models include: (a) an intrinsic model for synchrotron emission with ordered B-fields (SO); (b) a geometric model for synchrotron emission in random B-fields (SR); and (c) a geometric model for Compton-drag (CD).

Each model predicts a different value for the maximum possible polarization ($\Pi_{\rm max}$), so the largest observed values of Π already constrains the models. For example, the fraction of bursts exhibiting a high Π is significantly smaller in the geometric models than in the intrinsic models. A more powerful diagnostic is the distri-