Astro2020 Science White Paper

Prompt Emission Polarimetry of Gamma-Ray Bursts

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☒ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

Principal Author:
Name: Mark L. McConnell
Institution: University of New Hampshire / Southwest Research Institute
Email: mark.mcconnell@unh.edu
Phone: 603-862-2047

Co-authors: (names and institutions)
Marco Ajello, Clemson University, majello@g.clemson.edu
Matthew Baring, Rice University, baring@rice.edu
Peter Bloser, Los Alamos National Laboratory, pbloser@lanl.gov
Tanmoy Chattopadhyay, Pennsylvania State University, txc344@psu.edu
R.M. Curado da Silva, LIP, Portugal, rui.silva@coimbra.lip.pt
Sylvain Guirec, George Washington University / NASA GSFC, sylvain.guiriec@gmail.com
Dieter Hartmann, Clemson University, hdieter@g.clemson.edu
Hui Li, Los Alamos National Laboratory, hli@lanl.gov
Alex Lowell, University of California - San Diego, alex.lowell.ssl@gmail.com
Chanda Prescod-Weinstein, University of New Hampshire, Chanda.Prescod-Weinstein@unh.edu
Bindu Rani, NASA / Goddard Space Flight Center, bindu.rani@nasa.gov
Vincent Tatischeff, French National Centre for Scientific Research (CNRS), vincent.tatischeff@csnsm.in2p3.fr
John Tomsick, University of California - Berkeley, jtomsick@ssl.berkeley.edu
Alexander van der Horst, George Washington University, ajvanderhorst@email.gwu.edu
Tom Vestrand, Los Alamos National Laboratory, vestrand@lanl.gov
Zorawar Wadiasingh, NASA / Goddard Space Flight Center, zwadiasingh@gmail.com
Silvia Zane, University College London, s.zane@ucl.ac.uk
Bing Zhang, University of Nevada - Las Vegas, zhang@physics.unlv.edu
Haocheng Zhang, Purdue University, phitlip2007@gmail.com

1 Overview

The nature of astrophysical jets is a central theme in many areas of astrophysical research. Jets form and propagate under conditions covering a wide range of size and mass scales in a variety of astrophysical systems, including proto-stars, white dwarfs, neutron stars, stellar-mass black holes, and supermassive black holes. Jets are typically observed as an outflow along the rotation axis of an accretion disk and result from the conversion of inflowing energy into axially directed energy, by mechanisms not yet thoroughly understood, though probably intimately connected to MHD physics.

Many aspects of astrophysical jets (launching, energization, propagation, composition, and emission) can be studied by measuring the polarization of the prompt emission from γ-ray bursts (GRBs). Theoretically associated with the formation of stellar- mass black holes, GRBs are among the most distant objects observed. The instantaneous electromagnetic intensity released during a typical GRB is eclipsed only by the Big Bang. The intense prompt emission is short-lived, typically lasting < 100 s and is believed to be associated with the formation of an ultra-relativistic jet. Extensive observational and theoretical studies in recent years have largely focused on time histories, spectra, and spatial distributions. Theoretical models show that a more complete understanding of the inner structure of GRBs, including the geometry and physical processes close to the central engine, can only be achieved by γ-ray polarimetry. Studies of ultra-relativistic GRB jets could broaden our understanding of one of the most ubiquitous phenomena in the Universe. After years of investigating time variability and spectra, now is the time to study GRBs in a new and revolutionary way using γ-ray polarimetry. NASA's 2014 Astrophysics Roadmap ("Enduring Quests, Daring Visions") echoed the sentiment that X-ray and γ-ray polarimetry should be a goal of future missions.

2 Approach

A complete picture of the GRB phenomena requires an understanding of the prompt emission from the inner part of the jet closest to where the black hole is formed. We have only a limited understanding of the inner jet, as it depends on the short-lived, high-energy prompt emission, which is difficult to study given the unpredictable nature of these sources. GRBs have spectra that typically peak in the 50–300 keV range, are isotropically distributed on the sky, and have durations from < 1 s to 100s of seconds [31]. 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.) with the resulting gravitational wave signal. Regardless of the progenitor, a generic fireball shock model [21, 30, 33] 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, corresponding to the observed GRB prompt emission. Eventually, the outflow is decelerated by the circumburst medium that leads to a long-lasting forward shock, producing well-studied afterglow emission at longer wavelengths.

Prompt emission spectra of GRBs are typically well fit with empirical models [4], many of which are based on the so-called Band function [2], consisting of a broken power-law with a smooth break at a characteristic energy, commonly referred to as "E-peak" (E_p). Variations on the Band function include: 1) a Band function plus a high-energy, power-law tail [1, 15, 18]; 2) a Band function plus a low-energy blackbody component, likely due to thermal emission from an expanding photosphere [36]; and 3) a Band function with a high-energy cutoff. These empirical fits do not yield physical insight. As an example, they often result in spectral fits that are inconsistent with a pure, optically thin synchrotron emission spectrum [9, 34].

Attempts to fit spectra with physics-based emission models, such as synchrotron (often expected to be the dominant emission mechanism) require an additional low-energy ($< E_p$) blackbody component. This is generally interpreted to be evidence of photospheric emission [5, 4]. From such spectral analyses, kinematic shock models are equally as likely as magnetically dominated jets and leave open questions about the composition, structure, energy dissipation mechanisms, and radiation mechanisms. These questions can only be probed by polarization measurements of the prompt emission [14].

Initial measurements derived from gamma ray missions not specifically designed for polarimetry suggest that prompt GRB emission is polarized at levels between 30 and 100% [8, 16, 20, 29, 35, 41, 42, 43, 44], and that the polarization angle varies during a burst [44]. More recent measurements based on Compton events in the CZTI instrument on the AstroSat mission [7, 6] and from the POLAR instrument on the Tiangong-2 space laboratory [47] have provided additional data. The POLAR data suggest lower polarization levels than some earlier measurements and also provides evidence of variable polarization levels during a GRB. With such a wide range of results, most of limited significance, a consistent picture of GRB polarization [28] remains elusive. High-sensitivity polarization measurements will be required to substantially advance our understanding of GRBs.

3 Science Objectives

Current models for GRB polarization are classified as either intrinsic or geometric [10, 24, 40]. Intrinsic models assume a globally-ordered magnetic field in the emission region so that electron synchrotron emission in this field gives a net linear polarization [17, 27, 40]. In this case, the polarization properties are derived from the intrinsic characteristics of the jet and reflect the distribution function of the electrons. Shocked electrons develop a power-law distribution that produces Band function-like photon spectra. High polarization values ($\Pi > 20\%$) are predicted for a broad range of viewing angles, with maximum values reaching $\Pi \sim 70\%$. These models suggest a highly magnetized jet composition (dominated by Poynting flux), with reconnection as the most probable dissipation mechanism and synchrotron radiation as the emission mechanism. Geometric models predict a dependence on the degree of polarization with viewing angle relative to the jet axis. The magnetic field structure is presumed to be approximately random in the emission region, so that no net polarization is detected if the viewing angle is along the jet axis. If the viewing direction is near the edge of the jet, a high degree of polarization may be observed due to loss of emission symmetry [24, 37]. These models assume a matter-dominated outflow and internal shocks as the most likely dissipation mechanism. Possible radiation mechanisms include both synchrotron and inverse Compton (IC) processes. Geometric models involving synchrotron emission predict Π as high as $\sim 40\%$. Inverse Compton models, also known as Compton drag models [24], achieve $\Pi \sim 85\%$. In general, geometric models predict $\Pi < 20\%$ for most viewing angles. The energy dependence of Π can serve to discriminate between the IC and synchrotron mechanisms (see below).

These observational differences provide an opportunity to probe the physics of GRB jets, since several of the science objectives can be addressed by determining which of these models is most dominant.

The measurements outlined above can collectively be used to achieve the following science objectives, which may provide different results for different types of GRBs (i.e., long vs. short):

Determine the jet magnetic field structure. Magnetic B-fields are thought to play a significant role in both launching and collimating the jet, but the precise details are not yet understood. Lower polarization values would indicate that the B-fields are oriented at random [40], suggesting that they have been generated within shocks [22, 38, 39]. Higher polarization values would indicate an ordered structure, suggesting that the B-fields have been carried outward from the central engine by the ejecta. Time variable polarization may be indicative of an evolving magnetic field structure (e.g., from ordered to disordered).

Determine the jet composition (matter vs. Poynting flux). Kinetic energy can be transported away from the central engine by matter, dominated by ions, or by B-fields, as a Poynting flow. This in turn is determined by conditions at the very base of the jet, before the outflow has become optically thin. For matter-dominated GRB jets, a bright photospheric emission is expected [3, 13, 32], while for Poynting flux-dominated outflows, the photosphere emission is suppressed [46, 45].

Determine the jet energy dissipation process (internal shocks or reconnection). If GRB jet composition is matter-dominated, the dissipation is likely through mildly relativistic internal shocks near or above the photosphere, with particle acceleration taking place via the first order Fermi mechanism. This process can generate the observed time variability in the prompt GRB emission, but the radiative efficiency and associated polarization is quite low. On the other hand, if the energy of the jet outflow is dominated by B-fields (Poynting-flux), the energy dissipation mechanism is through magnetic reconnection, and particles are accelerated during reconnection events [46]. The radiative efficiency and associated polarization of this process is much higher than that of internal shocks.

Determine the prompt emission mechanism(s). It is generally believed that synchrotron emission of relativistic electrons contributes significantly to the spectrum. In addition, the contribution of the thermal blackbody emission from the expanding photosphere [36] also appears to play an important role. Contrary to what might be expected, this photospheric emission is not completely depolarized; skin-depth/limb effects increase polarization above zero. A likely third mechanism is the inverse Compton scattering of thermal or synchrotron seed photons near the photosphere [3, 23, 25, 46].

4 Key Measurements

The optimal energy range for GRB polarization measurements is that which encompasses the typical values for E_p, which is nominally from 50–500 keV. This corresponds not only to the energy range where most of the energy is emitted; it also corresponds to the range where energy-dependent measurements are most useful for elucidating the emission mechanism(s). To place the polarization

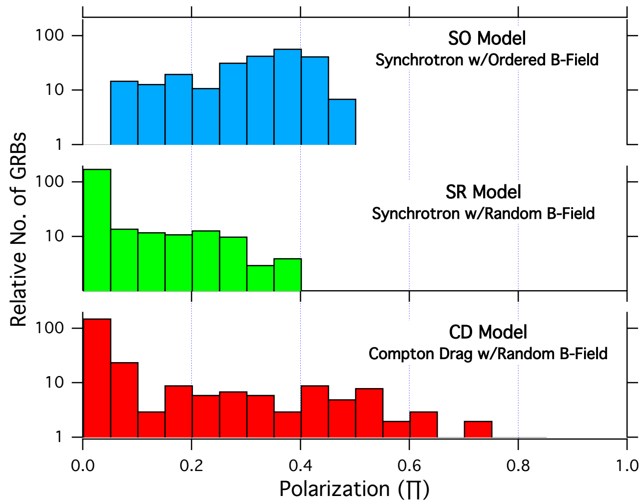

Figure 1: Distribution of predicted polarization values as measured in the 50–500 keV energy range for three different models. (Distributions are based on data from [39].)

measurements in proper context, the GRB spectrum must be measured over an energy range that is characteristic of the full source spectrum. For GRBs, this is typically from ∼30 keV up to at least 1 MeV. The energy resolution should be sufficient ($< 20\%$) to provide an accurate determination of the E_p value, which is necessary for the 2-D distribution studies.

The full set of science objectives can be addressed with the following studies:

Distribution of GRB Polarization Levels. As an example of what could be measured, Figure 1 shows the distribution of expected polarization values for each of three principal models : 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). Distinguishing between these models provides a direct diagnostic of the B-field structure, energy dissipation process, and radiation mechanism of GRB jets. The fraction of bursts with measured polarization above some given value can be used to distinguish these three models. For example, the fraction of bursts exhibiting $\Pi > 30\%$ is significantly smaller in the geometric models than in the intrinsic model. The observation of bursts with higher polarization ($\Pi > 45\%$) would favor the CD model.

2-D Distribution of GRB Polarization Levels. A more powerful diagnostic is the distribution of Π as a function of spectral E_p. Toma et al. [39] have studied the distribution of polarization values (assuming random viewing angles) in this parameter space for the three models described above. These distributions (Figure 2) indicate a more distinctive structures in this parameter space. The correlation between E_p and Π for the SO model is particularly striking. The true distribution depends on the relative admixture of these models. Sensitive measurements of polarization, coupled with spectral measurements to determine E_p, are used to identify the dominant model and to place constraints on the relative contributions from additional models.

Energy dependence of GRB Polarization. The nature of the GRB radiation mechanism(s) is also

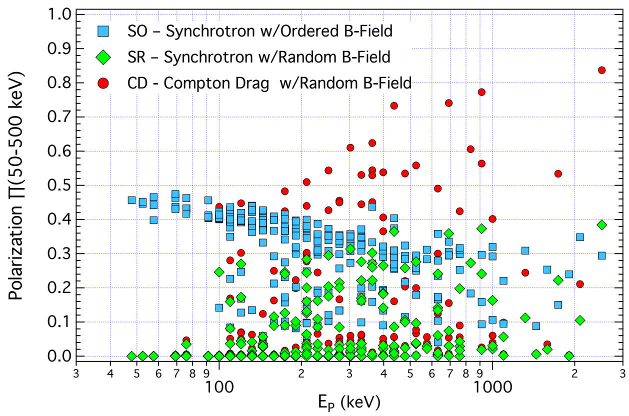

Figure 2: Distribution of predicted polarization values (as measured in the 50–500 keV energy range) as a function of E_p for different three models. [Figure adapted from [39].]

derived from the energy- dependence of the polarization, as different emission mechanisms are distinguished by their polarization signatures [12, 26]. For example, the contribution of a photospheric component is expected to decrease the net polarization in the energy range near typical values of E_p where the thermal spectrum is most pronounced [19]. This requires the ability to resolve energy-dependent differences in polarization on the order of 5%.

Temporal dependence of GRB Polarization. The temporal evolution of polarization properties (both fraction and angle) also carries essential information with which to diagnose the GRB mechanism. For example, in the Internal-Collision- induced MAgnetic Reconnection and Turbulence (ICMART) model of GRBs [46, 11], each broad pulse in the GRB light curve is related to one event that destroys the ordered magnetic fields through reconnection to produce radiation. In this case, a decrease of the polarization with time is expected across each broad pulse.

5 Summary

Some of the existing data suggest relatively high levels of polarization in GRBs, indicative of an ordered magnetic field within the jet structure. Other data suggest relatively low levels (or perhaps varying levels) of polarization. High-significance data on a large number of GRBs will be required before a consistent picture can be developed. An instrument designed for GRB polarimetry must have a very large FoV (preferably covering close to 2π steradian) in order to capture a number of GRB events and must have sufficient sensitivity for measuring polarization levels well below 10% in some of the larger GRBs. A mission designed to measure at least 30-50 GRBs with a Minimum Detectable Polarization (MDP) of $< 30\%$ would contribute much to our understanding of the GRB phenomenon. This would provide sufficient sensitivity to distinguish between GRB models and (for the brighter GRBs) to study the time evolution of the polarization parameters.

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