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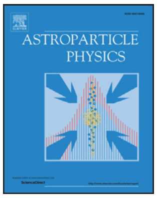

Science prospects for SPHiNX – A small satellite GRB polarimetry mission

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ABSTRACT

Gamma-ray bursts (GRBs) are exceptionally bright electromagnetic events occurring daily on the sky. The prompt emission is dominated by X-/γ-rays. Since their discovery over 50 years ago, GRBs are primarily studied through spectral and temporal measurements. The properties of the emission jets and underlying processes are not well understood. A promising way forward is the development of missions capable of characterising the linear polarisation of the high-energy emission. For this reason, the SPHiNX mission has been developed for a small-satellite platform. The polarisation properties of incident high-energy radiation (50–600 keV) are determined by reconstructing Compton scattering interactions in a segmented array of plastic and $Gd_3Al_2Ga_3O_{12}$(Ce) (GAGG(Ce)) scintillators. During a two-year mission, $\sim$200 GRBs will be observed, with $\sim$50 yielding measurements where the polarisation fraction is determined with a relative error $\leq$10%. This is a significant improvement compared to contemporary missions. This performance, combined with the ability to reconstruct GRB localisation and spectral properties, will allow discrimination between leading classes of emission models.

1. Introduction

Gamma-ray bursts (GRBs) are the brightest electromagnetic events in the universe, occurring randomly on the sky approximately daily [1,2]. The emission is characterised by two epochs – the prompt phase, lasting for seconds to minutes and dominated by X-/γ-rays, and the afterglow, lasting for days and emitting at lower energies. The afterglow is relatively well understood [3]. Many aspects of the prompt phase remain unknown, but the fireball model [4] is a generally accepted scenario, where the GRB is formed during the collapse of a massive object into a black hole. Recent observations of gravitational waves [5] in coincidence with a short GRB (typical prompt duration <2 s) have shown that the progenitor is a merger of two neutron stars. Neutron star-black hole mergers can also result in short GRBs. For long GRBs (typical prompt duration up to 100 s), the progenitor is instead connected to broad line type 1c supernovae [6]. Understanding the GRB prompt emission mechanism holds the key to using GRBs as probes of the early universe and of extreme physics such as relativistic jets, relativistic magneto-hydrodynamics, aberration of light, relativistic shock waves, and Lorentz invariance violation [7,8].

During the process of collapse and merger, two highly relativistic jets of plasma are emitted along the rotational axis of the black hole. A GRB is observed if one of the jets is directed to earth. Energy dissipation within the outflow (e.g., internal shocks or magnetic reconnection) gives rise to the prompt emission (keV–MeV). The prompt energy spectrum is featureless and is often well described by a smoothly broken power-law with a break at a peak energy, E_p, typically occurring in the range from a few tens to several hundred keV. The Band function is often used, smoothly connecting a low-energy power-law, with spectral index α (the photon flux $N_E \propto E^{\alpha}$, where E is the energy) to a high-energy power-law with spectral index β [9]. There is a large spread in the measured values of α, β and E_p [2], with a typical GRB having $\alpha = -1$, $\beta = -2.5$ and $E_p = 200$ keV. As the jet interacts with the surrounding medium it is decelerated producing a forward external shock, the emission from which forms the afterglow.

GRB detectors typically measure the energy distribution (spectra) and the arrival time (light-curve) of the GRB photons. Even though large samples of bursts have been observed, the properties of the jets and the underlying emission process remain poorly

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understood. The study of GRB jets is inherently difficult since images cannot be produced due to the large observing distance. Measurements of the linear polarisation properties of the detected photons address this problem. Linear polarisation is described using two parameters: (*i*) the polarisation fraction (PF, %) describing the magnitude of beam polarisation; and, (*ii*) the polarisation angle (PA, degrees) which defines the orientation of the electric field vector of the incident photon beam relative to, e.g., celestial north.

Despite the scientific value of GRB polarimetry, there is a lack of reliable observational data [10]. Between 2010 and 2012, the GAP polarimeter on-board the IKAROS spacecraft measured the polarisation of three bright GRBs in the 70–300 keV energy band [11,12]. The measurements indicated high PF values, and for the brightest burst, polarisation parameters were determined in two time bins revealing a 90° change in PA. The measurements had weak statistical significance and additional observations with more sensitive missions are required. POLAR is a gamma-ray polarimeter mission (50–500 keV) launched with the Chinese Tiangong-2 space station in 2016 [13]. After $\sim$6 months of operations, data-taking ceased due to instrument malfunction. Polarisation data is expected for some of the $\sim$50 observed GRBs [14]. The AstroSat mission was launched in 2015. The CZTI instrument is a general purpose coded aperture spectrometer for X-ray observations which can be used for polarimetry. During the first year of operations, 47 GRBs were detected and polarisation parameters determined for 11 of the brightest bursts [15]. High PF values were observed for the majority of GRBs, albeit with relatively large uncertainties, as discussed in Section 6.6. Observations have also been reported from instruments not designed for polarimetry, e.g., the INTEGRAL [16,17] and RHESSI [18] missions. Since no polarimetric calibration was performed prior to observations, it is difficult to ascertain the reliability of the reported results [19–21].

This paper describes the Satellite Polarimeter for High eNergy X-rays (SPHiNX) – a satellite-borne instrument for hard X-ray polarimetric studies of GRBs. The instrument design is optimised for polarimetry and with a large field-of-view, $\sim 120^\circ$ opening angle, and collecting area, ~ 800 cm^2, a large sample of $\sim$200 GRBs will be provided during the two year mission. The light-curve and spectral shape will be determined for all GRBs. Polarisation parameters will be reconstructed in the energy range 50–600 keV for $\sim$50 GRBs. The arrival time of X-rays will be determined with an absolute timing accuracy of 1 ms to allow correlation with other missions. These instrument characteristics will allow discrimination between different classes of GRB emission models.

This paper is organised as follows. In Section 2, the scientific motivation for the mission is presented. An overview of the mission parameters and constraints is presented in Section 3. The instrument design is described in Section 4 and the operational and calibration strategy is outlined in Section 5. The simulated instrument characteristics and scientific performance are discussed in Section 6. An outlook is presented in Section 7.

2. Scientific motivation

The objectives of the SPHiNX mission are to identify the properties of GRB jets, and to identify the mechanism behind the high-energy emission. It is not known whether the emission is produced far down in the jet where the densities are high and the photons and plasma are closely connected (photospheric emission) or whether the emission is produced at large distances from the progenitor, where turbulence and shocks are responsible for the energy release (optically thin emission). Likewise, the magnetisation of the jet is a fully open question which depends on how the jet is formed and launched. Finally, it is unclear whether the jets are symmetric, if they are wide or narrow, or if they have a varying lateral profile. These jet characteristics are encoded into the energy spectrum and polarisation properties of the observed emission. The resulting three measurement goals, summarised in Table 1, are described in the remainder of this section. These goals drive the design of the mission and the polarimeter, as outlined in Sections 3–5. Section 6 describes the ability of SPHiNX to discriminate between different classes of GRB prompt emission models.

2.1. Geometric structure of GRB jets

GRB jets are commonly modelled as axisymmetric structures, where the observed emission can only be polarised parallel or perpendicular to the sky projection of the jet axis [22]. A key prediction of the axisymmetric jet scenario is that PA will either change by 90° during the prompt GRB emission, or remain invariant. Other possibilities for the geometric structure include jets with internal structure, such as fragmented jets, or mini-jets within the larger jet [23]. The mini-jet brightness is expected to change during the prompt emission, leading to pulsed emission from different parts of the jet. As the emission at a given time is dominated by the brightest mini-jet, PA is expected to fluctuate in a random fashion.

2.2. Magnetisation of GRB jets

Depending on the details of the jet launching mechanism, the plasma may be highly magnetised close to the central black hole. In this case, as the jets are launched, the magnetic fields are advected outwards, resulting in an ordered magnetic-field structure across the entire jet. Such a jet will produce synchrotron emission as electrons gyrate in the magnetic fields. Due to relativistic aberration of light, the observer can only see a small patch of the jet emission region. Within this patch, the magnetic field is ordered, and, as a consequence, most observed GRBs will be highly polarised. The maximum PF is expected to be $\sim$50%, while a typical value for most observers is $\sim$40% [24]. Some jet launching mechanisms instead predict low magnetisation of the jet [25]. Shocks within the jet can still produce weak magnetic fields, but the direction of the field lines will vary randomly on small scales. This causes much of the observed jet patch polarisation signal to average out for on-axis observers. Observers that have the jet edge within their field-of-view can still see a substantial PF due to the asymmetric shape of the observed patch. In the weakly magnetised scenario, the distribution of PF will thus peak at 0%, but a tail extends to high PF values due to viewing angle effects.

2.3. High-energy emission mechanism

Different mechanisms can dominate the GRB prompt phase emission. Depending primarily on the dimensionless entropy and the magnetisation of the outflow, the emission can stem from the photosphere, internal shocks, magnetic reconnection, or the external shock [26,27]. The high-energy emission is thus typically attributed to synchrotron radiation [28,29] or emission from the photosphere [30–32]. The Compton drag model is also considered [33], but is not as well established. If the jets are highly magnetised, synchrotron emission is expected to dominate which will be revealed through a measurement of PF. If the jet has low magnetisation, discrimination is still possible by characterising the tail of the PF distribution.

For synchrotron models, softer emission is expected to be more polarised, resulting in a correlation between α and PF. Furthermore, the allowed values of α are restricted to $\alpha \leq -\frac{2}{3}$ [34]. For photospheric emission the spectrum can be significantly harder, with α approaching unity. Two mechanisms can broaden the spectrum away from a black-body: energy dissipation below the photosphere and geometric effects [35]. In both scenarios, polarised emission is expected for observers viewing the jet off-axis. The