Status and prospects for polarimetry in high energy astrophysics

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Abstract

The recent detection of linear polarization from GRB120206 has piqued the interest of the community in this relatively unexplored avenue of research. Here, we review the current status and prospects for polarimetry at hard X-ray and soft γ-ray energies. After reviewing the basic principles of making polarization measurements at these energies, we give an overview of the most recent results and present a brief survey of current and planned experiments that are capable of making polarization measurements in the energy range between 30 keV and 30 MeV.

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1 Introduction

For many years, astronomers have generally been slow to accept the idea that polarimetry could be a useful tool for MeV astronomy. This has been both because of the experimental difficulty in making such a measurement and because the levels of polarization were expected to be quite low. Even at lower energies (1–10 keV), where source fluxes are considerably greater, the astronomical community has been slow to embrace the potential value of polarimetry. All this may have changed, however, with the recent detection of γ-ray polarization from GRB021206. This paper provides a brief overview of the experimental status and future prospects of polarimetry at energies above ~ 30 keV, an energy range that encompasses the nuclear line region.

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2 Polarimetry techniques

At these energies, there are three physical processes that can be exploited for the sake of measuring linear polarization. These are: the photoelectric effect, Compton scattering (and its low-energy equivalent, Thomson scattering), and electron-positron pair production. In each case, the byproducts of the initial photon interaction (photoelectron, scattered photon, or electron-positron pair) have angular distributions that go as $\cos^2\theta$. A measurement of the angular distribution of these secondaries provides a measure of not only the direction but also the magnitude of the linear polarization of the incident flux. The phase of the distribution is directly related to the direction of the incident polarization. The amplitude of the modulation in the angular distribution is directly related to the magnitude of the incident polarization. Much of the technical challenge for experimentalists arises from the difficulty in measuring these distributions.

At energies below ~ 30 keV, either photoelectric or Thomson scattering methods are typically employed for polarization measurements. Polarimeters based on the photoelectric effect are designed to track the direction of the photoelectron that results from the absorption of the incident photon. In this case, the photoelectron tends to be emitted *parallel* to the incident electric field vector. Thomson scattering detectors employ passive low-Z scattering elements (composed of Li or Be) surrounded by a position-sensitive detector that can measure the angular distribution of the scattered photons. In this case, the incident photons will tend to scatter *perpendicular* to the incident electric field vector.

For energies between roughly 30 keV and several MeV, Compton polarimetry methods are commonly used. As in the case of Thomson scattering, the Compton scattered photons tend to scatter at right angles to the incident electric field vector. The magnitude of the modulation of this distribution is maximized for Compton scattering angles near 90°, providing an important constraint for instrument designs.

At higher energies (above ~ 2 MeV), pair production begins to play an increasingly important role in photon interactions. The pair production process is sensitive to the polarization of the incident photon in that the plane of pair production tends to lie parallel to the incident electric field vector. This aspect of the pair production process can be utilized for making polarization measurements at higher energies.

3 Recent results from RHESSI

Although originally designed as a hard X-ray solar imager, the Ramaty High Energy Solar Spectroscopic Imager (RHESSI; Lin et al., 2002) has proven itself to be a valuable polarimeter. Two recent results demonstrate how RHESSI can do polarimetry utilizing two different techniques. Both techniques make use of RHESSI's 9-element Ge spectrometer array (Figure 1; Smith et al., 2002). For polarization measurements at low energies (20 – 100 keV), a small block of passive Be (strategically located within the Ge array) is used to scatter photons into the rear segments of adjacent Ge detectors (McConnell et al., 2002). The polarization of a transient event (such as a solar flare) can be determined by a careful analysis of the counting rates in the Ge detectors that are closest to the Be scattering block. This mode is limited to a small FoV ($\sim 1^\circ$) by the collimation of the Be scattering element through the front of the telescope assembly. At higher energies, scattering events between the Ge detectors within the spectrometer array can be used to measure polarization. The lack of significant amounts of shielding surrounding the Ge array means that this mode is sensitive to events over a much larger area of the sky. In both cases, the rotation of the RHESSI spacecraft (required for imaging with RHESSI's rotation modulation collimators) greatly facilitates effective polarization measurements by reducing systematic uncertainties and providing a more uniform sampling in the azimuthal direction.

The low energy polarimetry mode has recently been demonstrated by McConnell et al. (2003a) with a result from the solar flare of 23-July-2002 that indicated a 20–40 keV polarization of 27(±7)% (Figure 2). The high energy polarimetry mode of RHESSI has also been recently demonstrated with a result from GRB 021206 (Coburn and Boggs, 2003) that indicates polarization at a level of 80(±20)% in the 150 keV – 2 MeV energy range (Figure 3). These results dramatically demonstrate the scientific potential of high energy polarimetry.

4 Prospects for hard X-ray polarimetry (30–300 keV)

Polarimetry in this energy band typically requires low-Z scattering elements (coupled with high-Z photon absorbers) for achieving the best result. Unfortunately, instruments that operate in this energy band are usually not constructed using position sensitive low-Z material, but rather they are designed with high-Z materials to maximize photon absorption. Consequently, there is a need in this regime for dedicated instrumentation. One dedicated design, referred to as GRAPE, has been developed by McConnell et al. (2003b). Based on Compton scattering from a low-Z plastic scintillator into a high-Z inorganic

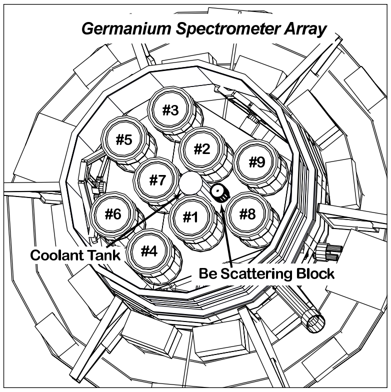

Fig. 1. The spectrometer array of RHESSI showing the layout of the nine Ge detectors and the location of the Be scattering block.

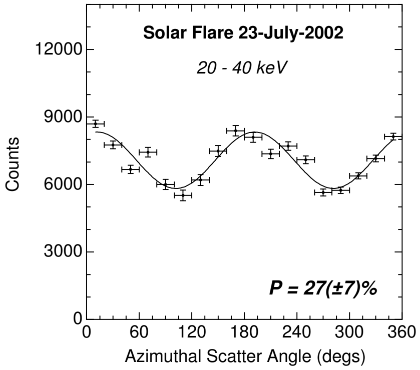

Fig. 2. The polarization result derived from RHESSI data in the 20–40 keV energy range for the X4.3 class solar flare of 23-July-2002 (McConnell et al., 2003a).

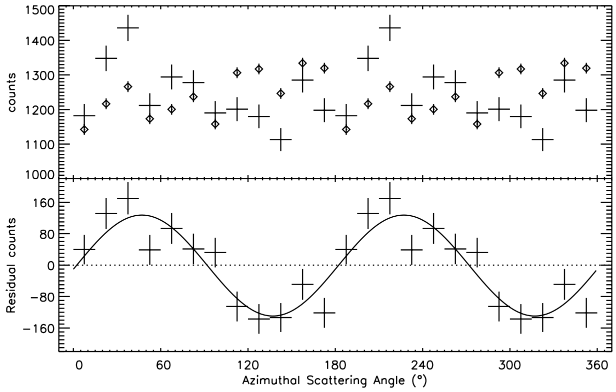

Fig. 3. The polarization signal derived from RHESSI data in the 150 keV – 2 MeV energy range for GRB021206 (Coburn and Boggs, 2003). The top panel shows the measured distribution (crosses) along with the simulated distribution for an unpolarized source (diamonds). The bottom panel shows the difference of the two distributions.

scintillator (CsI or $LaBr_3$), an early GRAPE design has been demonstrated in the laboratory (Figure 4). Its very wide FoV also makes it ideal for studying the polarization of γ-ray bursts. A more recent version of the GRAPE concept (Figure 5) permits large area arrays, perhaps to serve as a detection plane for a coded mask imaging polarimeter. A group at Yamagata University has also been working on designs that are optimized for this energy band (e.g., Tomita et al., 1996).

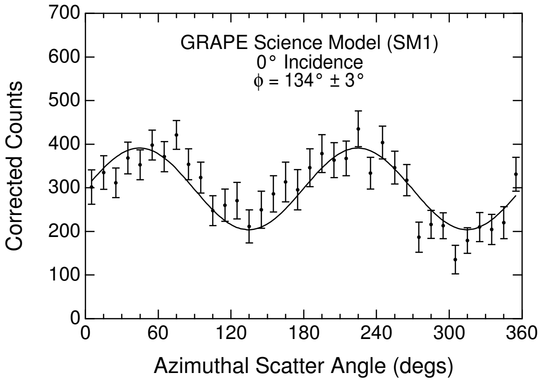

Fig. 4. Laboratory data from the first GRAPE prototype, a design based on the use of a 5-inch position-sensitive PMT (PSPMT) for readout. These data were taken using a partially polarized beam at 288 keV.

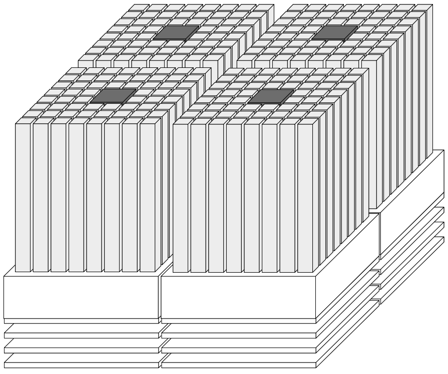

Fig. 5. A more recent GRAPE concept utilizes a flat-panel MAPMT for readout, shown here in a tiled configuration.

5 Prospects for soft γ-ray polarimetry (300 keV – 10 MeV)

At higher energies, Compton polarimeters based on the use of high-Z scattering elements (coupled with high-Z absorbers) becomes viable. For example, the Ge double scatter approach used by RHESSI becomes most effective at energies above $\sim$ 300 keV. Multiple scatter events in high-Z coded mask detection planes also offer possibilities for polarimetry. The use of a Ge strip detector has been demonstrated in this energy range (Kroeger et al., 1999). An imaging polarimeter based on the use of CdTe is being developed by Caroli et al. (2000). In principle, both the IBIS and SPI instruments on INTEGRAL are capable of polarimetry in this energy band (Lei, Dean and Hills, 1997). Unfortunately, the lack of rotation makes the polarization analysis of these data difficult and telemetry limitations may limit the capabilities of IBIS. In principle, the CdZnTe detection plane of the Swift BAT instrument (Barthelmy, 2000) might make for a good polarimeter, but the packaging design of the detectors and associated electronics results in a loss of the necessary multiple scatter event information.

This energy range is also the domain of Compton telescopes. A properly configured Compton telescope can serve as a very powerful polarimeter. The one Compton telescope that has flown in orbit, the COMPTEL instrument on CGRO (Schönfelder et al., 1993), was very limited in its ability to do polarimetry. This was due both to its inability to precisely measure the interaction sites and also to a very poor Compton scattering geometry that required scatter angles $< 90°$. Although some efforts have been made to study polarization with COMPTEL data, no successful results have so far been obtained (Lei et al., 1996).

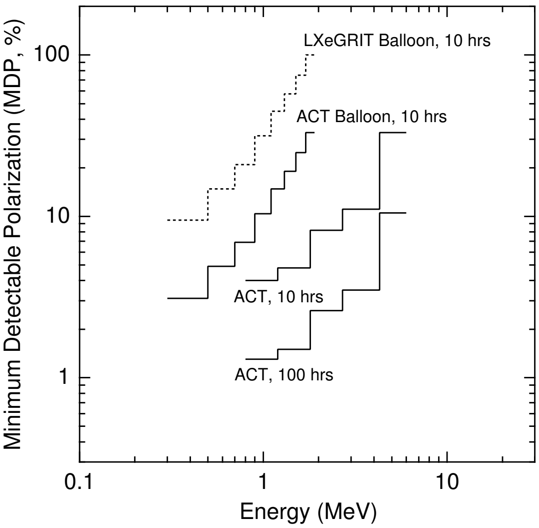

Fig. 6. The polarization sensitivity for a proposed design of the Advanced Compton Telescope (ACT; Kurfess and Kroeger, 2001) as compared to the LXeGRIT balloon telescope (Aprile et al., 1984).

Compton telescope designs that are currently being studied offer a much more favorable geometry for polarization measurements. With the elimination of time-of-light measurements, recent designs are much more compact. This results in significantly improved detection efficiency and a significantly larger FoV. It also provides a far more optimized well-tye geometry for Compton polarimetry. The next generation of Compton telescopes are therefore likely to offer substantial improvements in polarization sensitivity. Recent Compton telescope designs can be characterized as those that attempt to track the scattered electron, such as TIGRE (O'Neill et al., 1996) and MEGA (Kanbach et al., 2001), and those that don't, such as LXeGRIT (Aprile et al., 1984) and NCT (Boggs et al., 2001). One concept for the Advanced Compton Telescope (ACT) involves a large (1 m^2) stack of Si strip detectors that is used to track multiple Compton intertactions (Kurfess and Kroeger, 2001). An estimate of the polarization sensitivity of such a design is shown in Figure 6.

6 Prospects for high energy γ-ray polarimetry (2 MeV – 10 GeV)

The potential utility of pair production for measuring polarization has been recognized for some time (e.g., Maximon and Olsen, 1962). Unfortunately, effective polarization measurements with pair production telescopes are limited by the effects of multiple coulomb scattering, which makes it difficult to define the plane of pair production. Efforts to measure polarization both with COS-B (Mattox, Mayer-Hasselwander, and Strong, 1990) and with CGRO/EGRET

(Mattox, 1991) have been unsuccessful, largely for this reason. It also appears that GLAST will suffer from similar difficulties, making polarization measurements with GLAST unlikely. A recent design for an effective pair production polarimeter involves the use of gas micro-well detectors for tracking the electron-positron pair with minimal scattering (Bloser et al., 2003). Even for this optimized design, however, pair production polarization measurements will only be effective for the brightest sources.

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