Abstract. Polarimetry of Gamma-Ray Burst (GRB) afterglows in the last few years has been considered one of the most effective tool to probe the geometry, energetic, dynamics and the environment of GRBs. We report some of the most recent results and discuss their implications and future perspectives.

INTRODUCTION

Polarimetry has always been a niche observational technique. It may be difficult to apply, requiring special care for the instruments, data reduction and analysis. Indeed, for real astronomical sources, where often the polarisation degree is fairly small at the level of a few per cent, the signal to noise required to derive useful information has to be very high. However, the amount of information that can be extracted by a polarised flux is also very high, since polarisation is an expected feature of a large number of physical phenomena of astronomical interest. This is particularly true for unresolved sources as GRB afterglows, where polarimetry offers one of the best opportunity to infer on the real geometry of the system. In particular, time resolved polarimetry can in principle give fundamental hints on the jet luminosity structure and on the evolution of the expanding fireball. This would provide reliable tools to discriminate among different scenarios. Finally, it has been recently realised that polarimetry of GRB afterglows can offer a direct way to study the physical condition of the Inter-Stellar Medium (ISM) around the GRB progenitor. GRB polarimetry, thus, becomes a powerful probe for gas and dust in cosmological environments, a valuable research field by itself.

In the following of this contribution we want to briefly comment on the most recent advancement in the field and discuss the likely future perspectives that are now open by the advent of the GRB dedicated Swift satellite with its unprecedented rapid localisation capabilities [1].

SYNCHROTRON AND BEAMING?

The first pioneeristic attempts, culminated with the successful observation of a $\sim 1.7\%$ polarisation level in GRB 990510 [2,3], were driven by the hypothesis that the afterglow
emission were due to synchrotron radiation [4, 5, 6]. GRB 990510 was also a perfect case for testing the hypothesis of a geometrically beamed fireball. Indeed, the detection of an achromatic break in the optical light curve [7, 8], together with the observed degree of polarisation, gave support to this scenario. Shortly after this result, it was realised that a jetted ultra-relativistic outflow would produce a characteristic time evolution of the polarisation degree and position angle [9, 10]. The detailed shape of the polarisation curves depends on the dynamical evolution. Testing this model against data is thus a powerful diagnosis of the geometry and dynamics of the fireball.

A large number of polarimetric observations has been carried out since GRB 990510. A review of these data has been compiled by Covino et al. [11] and Björnsson [12]. However, until recently, the detection of a low level of polarisation required strong observational efforts. This prevented a satisfactory time coverage of the afterglow decay and, in turn, a convincing test for the model predictions.

HOMOGENEOUS, STRUCTURED AND MAGNETISED JETS

Lacking strong observational constraints, an improvement of the reference models was achieved considering more physical descriptions for the GRB afterglow jets. In the basic model the energy distribution is homogeneous, making the jet a single entity. More complex beam and magnetic field patterns (Fig. 1), reflecting a physically more plausible scenario, were studied in several papers [13, 14, 15] showing that the light curve is barely affected by this parameter, while the polarisation and position angle evolution changes substantially, providing a further diagnostic tool Fig. 2.

The universal structured jet model predicts that the maximum of the polarisation curve is at the time of the break in the light curve. The position angle remains constant throughout the afterglow evolution. On the contrary, the homogeneous jet model requires two maxima before and after the light curve break and, more importantly, the position angle shows a sudden rotation of 90° between the two maxima, roughly simultaneously.
FIGURE 2. Light curve and polarisation evolution for different jet structures. SJ stands for structured jet, HJ homogeneous jet, GJ for Gaussian jet. The figure shows the similarity of the predicted light curves for the various models while the polarisation changes considerably. Negative polarisation degrees mark a 90° rotation for the position angle. From Rossi et al. [15].

to the break time of the light curve. At early and late time the polarisation should be essentially zero (Fig.2).

This last result is substantially modified if it is assumed that a large-scale magnetic field is driving the fireball expansion. The topics has been widely discussed in the context of polarimetry by Granot & Königl [13], Lazzati et al. [14] and [15]. Magnetised jets can be both homogeneous and structured. We do not discuss here the details of this recent research branch. However, we note that, at early times, a large-scale ordered magnetic field produces a non negligible degree of polarisation, contrary to the purely hydrodynamical models. Polarimetry may therefore be the most powerful available diagnostic tool to investigate the fireball energy content and its early dynamical evolution.

Dust Induced Polarisation

The observed low polarisation level from GRB afterglows is often comparable to the expected polarisation induced by dust. Dust grains are known to behave like a dichroic, possibly birefringent, medium [16]. Significant amounts of dust are expected to lie close to the GRB site, as a consequence of the observation of a supernova (SN) component in
FIGURE 3. Assuming as a reference a typical polarisation curve with a homogeneous jet, the presence of some dust along the line of sight deeply modify the observed time evolution if the dust-induced polarisation is comparable to the intrinsic one, as it seems to be the rule for GRB afterglow at least at rather late time after the high-energy event [11]. Depending on the relation between the position angle of the dust-induced polarisation and of the intrinsic GRB afterglow polarisation, the typical shape of the curve can be removed or even enhanced. From Lazzati et al. [16].

a few GRBs. The measured polarisation will be modified by the propagation of radiation through dusty media. This effect is, contrary to the intrinsic afterglow polarisation, wavelength dependent. The different wavelength dependence open the interesting possibility to study the polarisation signature from the afterglow to study the physical characteristics of dust in cosmological environments: probably the only way to study dust close to star formation regions at high redshift. Even assuming that dust properties close to GRB formation sites are comparable to what we know in the Milky Way (MW), it is important to take into account this component once information from time evolution polarimetry are derived. The superposition of the intrinsic time evolution to dust-induced components for the GRB host galaxy and the MW may substantially alter the expected behavior (Fig. 3).

OBSERVATIONS VS. THEORY

So far, a rather satisfactory coverage of the polarisation evolution of a GRB afterglow has been obtained for three events only: GRB 021004 [17, 16, 18, 19], GRB 030329 [20, 21], and GRB 020813 [22, 14]. However, firm conclusions from the analysis could have been derived for the last case only. GRB 021004 and GRB 030329 showed some remarkable similarities given that their light curves were characterised by a large number of “bumps” or rebrightenings. Several different possibilities has been proposed to model the irregularities in the light curve invoking clumping in the external medium [23]: a more complex and not axi-symmetric energy distribution in the fireball [18] or delayed energy injections [19]. It was soon clear [16] that the standard models for polar-
Polarisation could not be applied in these conditions, since they are all derived in cylindrical symmetry. Even for GRB 030329, for which a remarkable dataset was obtained \cite{20}, no convincing explanation of the polarization and light-curve erratic behaviors has so far been obtained. It is not clear yet to what extent GRB 021004 and GRB 030329 belong to the same population of long GRBs. It is argued however that the failed detection of this erratic behavior in other afterglows (such as GRB 020813) is not due to a coarser sampling of the light curve.

GRB 020813 was the best case for model testing. Its light curve was remarkably smooth \cite{24}, in several optical/infrared bands, and a break in the light curve was clearly singled out. A few polarimetric observations have been carried out providing for the first time polarisation data before and after the light curve break time \cite{22}. Lazzati et al. \cite{14} applied to this event a more quantitative approach not limited, as usually done in the past, to the bare qualitative search of features in the polarisation curve (i.e. rotation of the position angle, etc.). A formal analysis was carried out, taking into account the GRB host galaxy and MW dust induced polarisation and the intrinsic GRB afterglow polarisation. All current jet models were considered, including homogeneous and structured jets, with and without a coherent magnetic field. The dataset, did not allow us to strictly derive a best fitting model. The main result was to rule out the basic homogeneous jets model at a confidence larger than $3\sigma$, mainly because of the lack of the predicted $90^\circ$ position angle rotation. Again the role of the MW dust induced polarisation is significant. All magnetized models and structured jets fit satisfactorily the data, the ambiguity being mainly due to the lack of early time measurement, i.e. where magnetised or not magnetised models mostly differ (see Fig. 4).

The debate is still far from being settled. Recently, for GRB 030226 Klose et al. \cite{25}
a quite low upper limits (∼ 1%) was reported, in rather strict coincidence with the break
time, therefore close to the maximum for the polarisation curve if we assume a structured
jet model. With one only measurement it is difficult to draw firm conclusions, since this
null polarisation measurement may well be due to dust induced polarisation superposed
destructively to the intrinsic, if any, GRB afterglow polarisation.

It is finally worth, even though tautological, to report that, as soon as Swift will be
fully operational, distributing routinely prompt localisations, a new era will be open
even for GRB polarimetry. It will allow us to carry out more stringent tests to the
available models and therefore strictly constraint geometry, energetics and dynamics
of the fireball.

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