

## On the jet structure and magnetic field configuration of GRB 020813<sup>★</sup>

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**Abstract.** The polarization curve of GRB 020813 is discussed and compared to different models for the structure, evolution and magnetisation properties of the jet and the interstellar medium onto which the fireball impacts. GRB 020813 is best suited for this kind of analysis for the smoothness of its afterglow light curve, ensuring the applicability of current models. The polarization dataset allows us to rule out the standard GRB jet, in which the energy and Lorentz factor have a well defined value inside the jet opening angle and the magnetic field is generated at the shock front. We explore alternative models finding that a structured jet or a jet with a toroidal component of the magnetic field can fit equally well the polarization curve. Stronger conclusions cannot be drawn due to the incomplete sampling of the polarization curve. A more dense sampling, especially at early times, is required to pin down the structure of the jet and the geometry of its magnetic field.

**Key words.** gamma rays: bursts – polarization – radiation mechanisms: non-thermal

### 1. Introduction

The discovery that Gamma-Ray Burst (hereafter GRB) afterglows are linearly polarized is one of the strongest proofs that the photons we observe are synchrotron radiation (Covino et al. 1999; Wijers et al. 1999). Despite that, polarimetric afterglow observations have so far been sparse and discontinuous,

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with only few polarimetric measurements performed on different optical transients (see Covino et al. 2003b for a review). Recently, however, several better sampled linear polarization measurements allowed for the first studies of the evolution of polarization, especially for GRB 021004 (Rol et al. 2003; Lazzati et al. 2003) and GRB 030329 (Greiner et al. 2003).

These studies (Lazzati et al. 2003; Nakar & Oren 2003), coupled with theoretical works (Ghisellini & Lazzati 1999; Sari 1999; Rossi et al. 2004; Granot & Königl 2003) reached two important conclusions. First, polarimetric studies provide unique information on the structure and dynamics of GRB outflows: the polarization, e.g., from a homogeneous jet has a markedly different evolution from that of a structured one, even though their light-curves are barely distinguishable (Rossi et al. 2004). Second, polarization studies are complex and subject to systematic errors. This is due to the combination of the intrinsic weakness of GRB polarization ( $\lesssim 3\%$ , at least at the times at which measurements have so far been possible; Covino et al. 2003b, but see also Bersier et al. 2003 who found a possible polarization flickering at the 10% level) and to the sensitivity of the polarization signal to bright spots on the fireball surface and/or inhomogeneities in the ambient medium (Lazzati et al. 2003; Granot & Königl 2003; Nakar & Oren 2003). In addition, the measured polarized signal is comparable to the polarization induced by the propagation of light through a moderately absorbing interstellar material, making the direct comparison of models with data more difficult (Lazzati et al. 2003).

All these considerations make the dataset obtained for GRB 020813 unique and extremely interesting. GRB 020813 (see the accompanying paper, Gorosabel et al. 2004, for more details) had an extremely smooth light curve (Laursen & Stanek 2003; Gorosabel et al. 2004), successfully fitted by a smoothly broken power-law with an rms scatter of the residuals of  $< 0.01$  mag in the optical filters. This ensures that inhomogeneities in the fireball structure and/or in the surrounding interstellar medium (ISM) are not significant and therefore can not affect the polarization measurement. In addition, the spectropolarimetric measurement of Barth et al. (2003) does not show evidence of a strong colour dependence of the polarization, a signature of the polarization induced by the interstellar medium (Serkowski et al. 1975).

In this paper we compare the polarization evolution of GRB 020813 with existing models from the production of polarized light in spherical and beamed fireballs. Some of these models, which were originally computed in a uniform environment, are extended to the wind case (Sect. 2). We also consider the possible presence of an ordered component of the magnetic field advected from the central source (Sect. 2). The comparison of the models with the data is described in Sect. 3 and we finally discuss our findings in Sect. 4.

## 2. The models

In this section we describe the models we will compare to the polarimetric data of GRB 020813. Although some of the theoretical polarization curves are taken from the literature those associated with magnetised jets are originally calculated for this work.

First, let us consider the magnetic domain model, the first ever considered model for the observation of linear polarization in GRB afterglows (Gruzinov & Waxman 1999). If the shock generated field is able to rearrange rapidly in ordered domains, Gruzinov & Waxman (1999) calculated that an average observer should see about  $\sim 50$  magnetic domains, and therefore if each domain produces a polarization  $p_0$  a net polarization  $\Pi = p_0/\sqrt{N} \sim 0.1(p_0/0.7)(50/N)^{1/2}$  should be observed, where  $p_0 \sim 70\%$  for synchrotron. Deriving a polarization curve for this model is not an easy task, given its intrinsic random character. Nevertheless, a general conclusion can be drawn. Polarization should be variable and variability in the degree of polarization should be associated to variability in the position angle (Gruzinov & Waxman 1999). In particular, a variation of linear polarization by a factor of 2 should be associated to a random re-shuffling of the position angle. This is not what we observe in the data, where only a moderate rotation of a few degrees is associated to the polarization evolution (Gorosabel et al. 2004). We conclude therefore, analogously to what derived by Barth et al. (2003) (see also Greiner et al. 2003 for the case of GRB 030329), that random patches of ordered magnetic field are not producing the observed polarization.

### 2.1. Hydrodynamic Homogeneous Jet

We define a ‘‘Hydrodynamic Homogeneous Jet’’ (HHJ) as a standard top-hat jet in which the energy, which is uniformly distributed within the jet opening angle, is carried by baryons and the magnetic field responsible for the afterglow synchrotron emission is tangled on small scales but overall dominated by either a component orthogonal or parallel to the shock front. Such a field configuration is generated either by compression of a fully tangled magnetic field of by two stream plasma instabilities at the shock front, for example the Weibel instability (Silva et al. 2003). Polarization curves from this class of jets have been computed by various authors (Ghisellini & Lazzati 1999; Sari 1999; Granot & Königl 2003; Salmonson 2003; Rossi et al. 2004). Most of these papers, and in particular the more recent ones based on numerical computations rather than on analytical approximations, agree qualitatively on the resulting polarization curve: it has two peaks, separated by a moment of null polarization roughly coincident with the break time of the total light curve. In this moment the position angle of the polarization rotates by  $90^\circ$ . The second peak is always stronger than the first, their ratio depending on the dynamics of the jet sideways expansion (SE): the faster the expansion, the smaller the second peak (the first peak is obviously only marginally affected by sideways expansion; see Rossi et al. 2004). In this paper we adopt the polarization curves computed by Rossi et al. (2004). After the jet break time we consider either no lateral expansion or a jet expanding at the speed of sound in the shocked fluid comoving frame (Eq. (8) of Rossi et al. 2004). These two assumptions are chosen in order to encompass the numerical results of Kumar & Granot (2003), who find a sub-sonic expansion until the expansion velocity becomes trans-relativistic. Extremely high sideways expanding efficiency were instead assumed by Sari (1999). In this case a different behaviour of the

post-break polarization is obtained, where the polarization can have either no change in position angle or a double change (see also Barth et al. 2003). The energy density within the jet opening angle is assumed to be uniform before and after the break time.

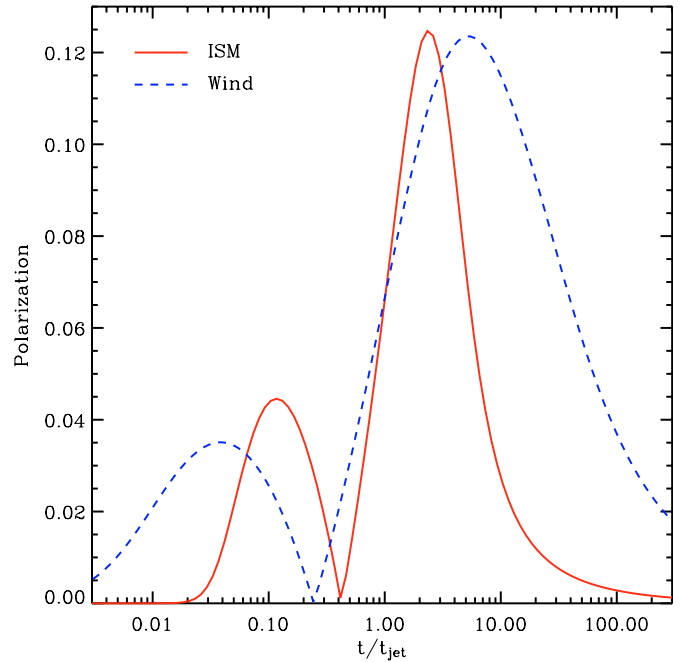
In addition to the calculations presented in the above mentioned papers, we show here the effect of a wind environment on the polarization curve. In Fig. 1 a polarization curve for a HHJ expanding in an ISM environment (solid line) is compared to that of the very same jet that propagates in a wind (where  $n(r) \propto r^{-2}$ ; dashed line). The qualitative result is identical, with the polarization curve characterised by two peaks with position angle shifted by  $90^\circ$ . The only difference is that in the wind case the evolution is slower, as already noted by Kumar & Panaitescu (2000) for the break of the total light curve. Before the non-relativistic transition ( $t \ll t_{\text{NR}}$ ) it is possible to obtain the wind polarization curve with good approximation from the ISM one rescaling the times according to  $t_{\text{wind}} = t_{\text{ISM}}^{3/2}$ . This, for a non sideways expanding jet, comes from the fact that the polarization behaviour mainly depends on the Lorentz factor  $\Gamma$  which scales as  $t^{-3/8}$  for the ISM case and as  $t^{-1/4}$  in the wind environment.

## 2.2. Hydrodynamic Structured Jet

A ‘‘Hydrodynamic Structured Jet’’ (HSJ) is similar to a HHJ from the micro-physical point of view, but has a distribution of energy per unit solid angle which is larger in the centre and smaller in the wings (Rossi et al. 2002). In order to preserve the standard jet energy (Frail et al. 2001), this distribution must have the form of a power-law with the energy scaling as  $\theta^{-2}$ . Polarization curves for this jet have been computed by Rossi et al. (2002, 2004). They are single peaked, with the time of the maximum coincident with the break time of the total light curve. The position angle does not vary throughout the evolution, and the maximum observed polarization grows with the angle that the line of sight makes with the jet axis. For this case we did not consider sideways expansion since it affects only marginally the behaviour of the polarization curve, to a level much smaller than the accuracy of the data we are dealing with. A discussion of theoretical light curves can be found in Rossi et al. (2004).

## 2.3. Magnetised Homogeneous Jet

We call here ‘‘Magnetised Homogeneous Jet’’ (MHJ) a jet in which the magnetic field has a toroidal structure, with the polar axis coincident with the jet axis. The energy is uniform within the jet opening angle, analogously to a HHJ. Such a magnetic configuration can be realized, e.g., if the energy is carried in rough equipartition by the baryons and an electromagnetic component (e.g., Proga et al. 2003). Such a scenario is naturally envisaged in the original GRB jet, where a sizable magnetic field component can be advected from the central engine. Whether this field can be propagated to the external shock is less certain, but such a possibility should be considered (Lyutikov et al. 2003; Lyutikov & Blandford 2004), given the



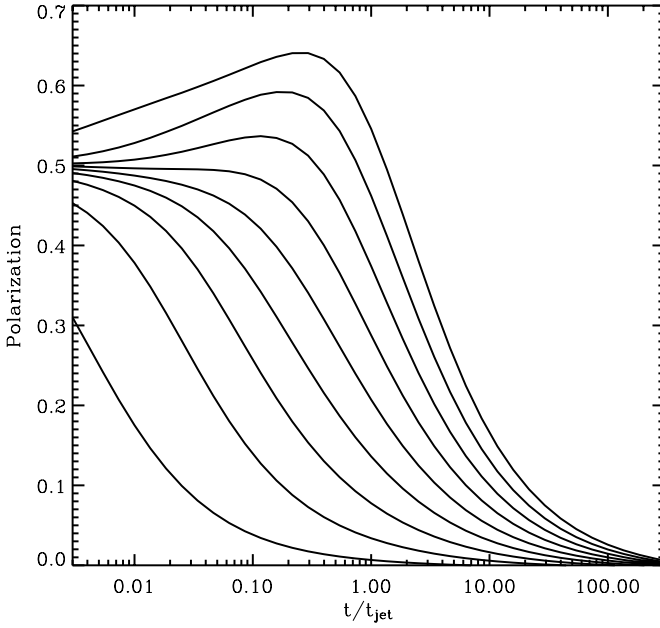
**Fig. 1.** Polarization curves from a homogeneous non sideways expanding jet with shock generated magnetic field in a standard ISM and wind environment. Both curves are computed for observers located at  $\theta_{\text{obs}} = 0.67\theta_{\text{jet}}$ . The break time  $t_{\text{jet}}$  has been measured independently for the two light curves. The polarization position angle rotates by  $90^\circ$  in the moment of null polarization.

fact that contact discontinuities are known to be maximally unstable (Landau & Lifshitz 1989) due to the lack of any restoring force. Here we assume that all the synchrotron emission is produced by the toroidal magnetic field, ignoring a possible (even likely, given the low measured levels of polarization) random component of the field (see below). We also consider uniform jets, i.e. jets with a well-defined cone angle within which the jet is uniform. Structured magnetised jets will be discussed in the next section. Polarization curves are shown in Figs. 2 and 3.

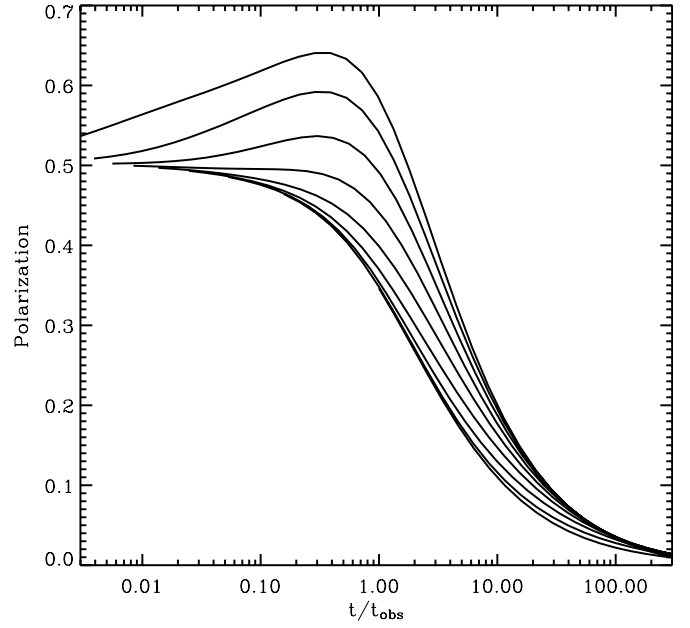
There are clearly major differences with respect to the hydrodynamic jets (either homogeneous or not). The first is that the polarization does not disappear for very small observer times. This is due to the fact that in the hydrodynamic jets the polarization is cancelled by symmetry unless the edge of the jet (for the HHJ) or the brighter core (HSJ) are visible.

In the MHJ case, the observed afterglow polarization is not due to a lack of cancellation, but rather to the presence of a genuinely ordered magnetic field. The higher the Lorentz factor of the fireball (and therefore the smaller the observer time) the less curved is the observed field on the plane of the sky and therefore the higher the polarization (see e.g., Lyutikov et al. 2003). For  $\theta_{\text{obs}}/\theta_{\text{jet}} < 0.6$  the polarization curve is monotonically decreasing, while for  $\theta_{\text{obs}}/\theta_{\text{jet}} > 0.6$  there is a maximum in the polarization curve at  $t \sim t_{\text{obs}}$ , where  $t_{\text{obs}}$  is defined through  $\Gamma(t_{\text{obs}}) = 1/\theta_{\text{obs}}$ . The position angle is constant throughout the whole evolution.

Another important difference between hydrodynamic polarization curves and MHJ ones is that in the case of hydrodynamic light and polarization-curves there is only one relevant



**Fig. 2.** Polarization curves for an MHJ jet with toroidal magnetic field. From left to right different curves refer to  $\theta_{\text{obs}}/\theta_{\text{jet}} = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8$  and  $0.9$ . The position angle of the polarization is constant throughout the entire evolution.



**Fig. 3.** Same as Fig. 2 but with the time shown in units of  $t_{\text{obs}}$  (defined through  $\Gamma(t_{\text{obs}}) = \theta_{\text{obs}}^{-1}$ ) rather than  $t_{\text{jet}}$  (defined through  $\Gamma(t_{\text{jet}}) = \theta_{\text{jet}}^{-1}$ ).

time-scale, while MHJ curves have two time-scales. As can be seen by comparing Fig. 2 with Fig. 3, the break in the polarization curve takes place approximately at  $t = t_{\text{obs}}$ , while the break in the total light curve happens at  $t = t_{\text{jet}}$ . In the case of hydrodynamic jets, the relevant change of behaviour in the polarization curve (the change of angle in HHJs or the peak in HSJs) takes place in coincidence with the change of slope in the total light curve, i.e. the break time  $t_{\text{jet}}$ . As a consequence, in an MHJ jet the simultaneous observation of light and polarization-curves can completely solve the jet and the observed geometry, something that is impossible in a hydrodynamic jet.

Before discussing the last configuration, that of a force-free magnetic bubble, it is worth stressing that the curves shown in Figs. 2 and 3 heavily rely on the assumption that the magnetic field contained in the ejecta is toroidal. Such a field should be transported out to the shocked ISM producing the afterglow radiation. In our computations it is assumed that all the magnetic field present in the shocked ISM comes from the GRB ejecta. It is more likely that a turbulent magnetic field is generated at the shock and mixed with the ordered magnetic field of the ejecta. This is also required by the fact that the typical afterglow polarization is at the level of few per cent, much smaller than the values predicted in Figs. 2 and 3. The simplest assumption that can be made is that the ratio between the turbulent and ordered components of the field stays constant throughout the evolution. In this case the resulting polarization curve may be obtained by rescaling those in the figures. However, the ratio between the two fields may change with time and in that case, even if it is likely that the general monotonic behaviour would be maintained, the actual shape of the curves may change. Given the quality of the dataset and the

theoretical difficulties in the propagation of the field, we adopt a completely ordered field or a mix with constant ratio.

#### 2.4. Magnetised Structured Jet

It has been proposed recently that many astrophysical jets may be dominated by electromagnetic forms of energy rather than by baryonic matter (Lyutikov & Blandford 2004; Lyutikov et al. 2003). If the plasma is sufficiently tenuous, the flow can be followed under the Force-Free approximation, a set of equations in which the inertia of the matter is neglected. We here consider the late phase of the evolution, when the external shock has developed and its dynamics does not differ any more from that of an hydrodynamic jet. Analogously to the MHJ jet, we assume that the magnetic field in the shocked ISM is transported from the magnetic bubble. We call this configuration a “Magnetised Structured Jet” (MSJ), i.e. a jet in which the energy distribution is inhomogeneous as described for the HSJ, and the magnetic field is toroidal as in the case of a MHJ. The difference with respect to the MHJ jet is therefore that the jet is not uniform within its opening angle but structured, with an energy per unit solid angle distribution  $E_{\Omega} \propto 1/\sin^2 \theta \sim \theta^{-2}$ , analogously to the HSJ. The polarization curve has been computed from Eqs. (2), (6) and (7) of Lyutikov et al. (2003) and is shown in Fig. 4. The polarization curve for this class of jets is unique, independent of the observer line of sight  $\theta_{\text{obs}}$ , if plotted against the observer time in units of the jet break time  $t_{\text{jet}}$ . The position angle is independent of time, since reflects the orientation of the magnetic field. As for the MHJ jet, a random magnetic field component is likely to be mixed in the toroidal field altering the detailed shape of the light curve, but not its general behaviour.

**Table 1.** Fit results.

Model <sup>(a)</sup>	$b^{(b)}$	$t_{\text{jet}}^{(c)}$	$\theta_{\text{obs}}/\theta_{\text{jet}}$	$\theta_{\text{OT}}^{(d)}$	$\chi^2/\text{d.o.f.}$
HHJ ISM	0.35	0.33	0.8	151.0	84.7/6
HHJ Wind	0.32	0.33	0.8	151.0	119.2/6
HHJ ISM SE	0.63	0.33	0.5		194.0/6
HHJ Wind SE	0.57	0.33	0.5	150.0	194.2/6
<b>HSJ ISM</b>	$0.475 \pm 0.02$	$0.29 \pm 0.07$	$2.0 \pm 0.1$	$152.0 \pm 1.2$	10.36/6
HSJ Wind	0.46	0.33	2.0		18.7/6
<b>MHJ ISM</b>	$<0.6^{(e)}$	$0.7^{(e)}$	$0.4^{(e)}$	$152.0 \pm 1.2$	8.9/6
<b>MHJ Wind</b>	$>0.5^{(e)}$	$0.38^{(e)}$	$0.13^{(e)}$	$152.0 \pm 1.2$	8.7/6
MSJ ISM	0.185	0.33		152.0	15.8/7
MSJ Wind	0.18	0.33		152.0	29.3/7

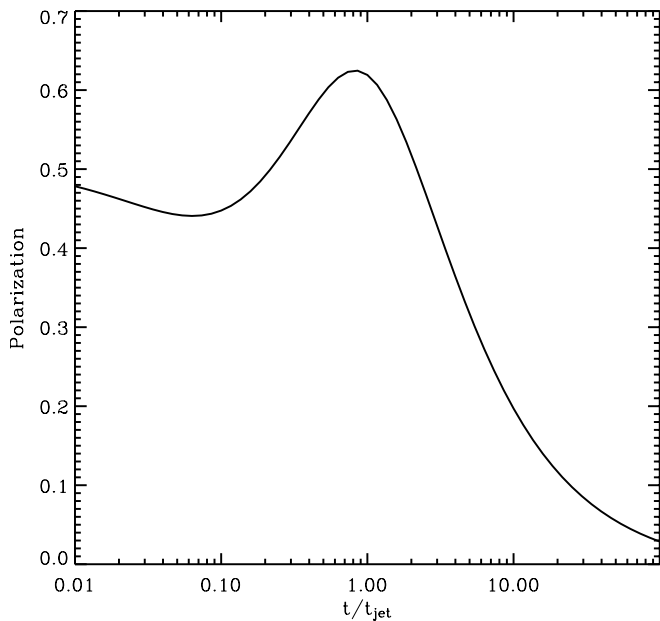
<sup>(a)</sup> Acronym of the considered model. Models yielding an acceptable fit have been highlighted in bold. Models with SE have sideways expansion included in the computation.

<sup>(b)</sup> Alignment of the magnetic field (see text).

<sup>(c)</sup> The jet break time (in days) is constrained to be consistent with what measured from the light-curve (Gorosabel et al. 2004). In most cases the break time is forced to be the smallest possible (0.33 days).

<sup>(d)</sup> Position angle of the intrinsic OT polarization before the propagation in the ISM.

<sup>(e)</sup> Despite the goodness of the fit it was impossible to derive meaningful error intervals for these parameters (see text).



**Fig. 4.** Polarization curve for a MSJ with purely toroidal magnetic field. The polarization curve is unique and independent of the observer line of sight as long as the time is plotted in unit of the light curve break time. The position angle of the polarization is constant throughout the entire evolution.

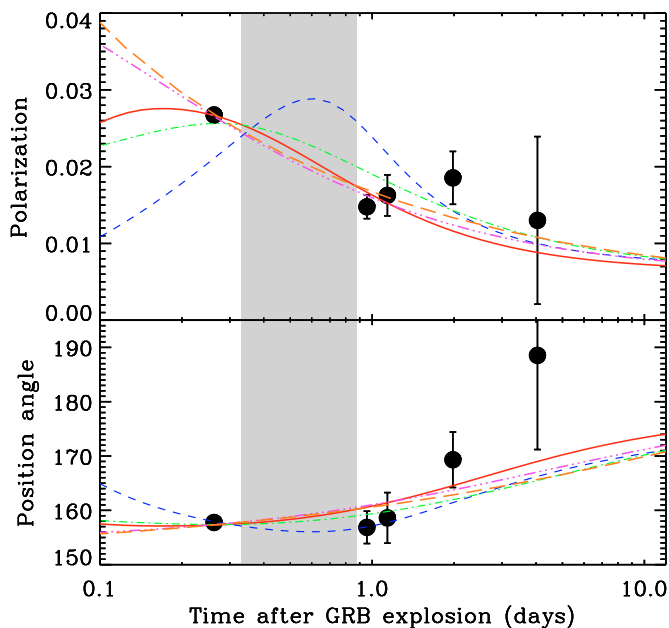
### 3. Comparison of the data with the models

The polarization dataset for GRB 020813 has been presented elsewhere (Gorosabel et al. 2004) and we here simply note two differences between their data and the data we adopt. First, we adopt the dataset uncorrected for polarization induced by the propagation into the Galactic ISM, as derived from the polarization properties of field stars. This choice is due to the fact that on the one hand the path of the OT light in the ISM is longer than that of field stars, and therefore the induced polarization may be different, and on the other hand

the host galaxy ISM may also contribute to the induced polarization. Since the total induced polarization can be dealt with using a single set of  $q$  and  $u$  Stokes parameters, we prefer to use here the uncorrected data (as previously done with GRB 021004, Lazzati et al. 2003), bearing in mind that the average Stokes parameters of field stars are  $q_{\text{ISM}} = 6.22 \times 10^{-3}$  and  $u_{\text{ISM}} = -3.95 \times 10^{-4}$  (Gorosabel et al. 2004). The second difference with respect to the dataset of Gorosabel et al. (2004) is that the observations have been binned in time in order to increase the signal-to-noise<sup>1</sup>. In particular, the first 4 data points (with 750 s exposure each) in Table 1 of Gorosabel et al. (2004) have been averaged into a single point, as well as the remaining 3 points of the first observing night (300 s exposure each). Our dataset is presented in Fig. 5. Even though we present polarization and position angle data, the fits were performed in the Stokes parameter space, where the uncertainties have a Gaussian distribution.

Fit results are reported in Table 1 for all the models described above. All the models have been fitted for evolution in a uniform ISM as well as for a wind environment. In the case of HHJ models, the possibility that the jet undergoes sideways expansion at the internal sound speed was considered as well. In addition to the jet parameters, the possible contribution of a polarizing ISM with free properties was considered. The resulting fit was always consistent with the  $q_{\text{ISM}}$  and  $u_{\text{ISM}}$  derived from the field stars. We have therefore frozen the induced polarization to the Galactic value in all the fits, in order to increase the number of degrees of freedom. This result is also consistent with the low upper-limit for reddening derived by Covino et al. (2003a) from *UBVRIJHK* quasi-simultaneous photometry and with the spectropolarimetry of Barth et al. (2003). In order to check also for the possible presence of an external ordered magnetic field (Granot & Königl 2003) we have allowed the ISM Stokes parameters to become comparable to the measured

<sup>1</sup> Polarization points that have been binned were consistent with each other.

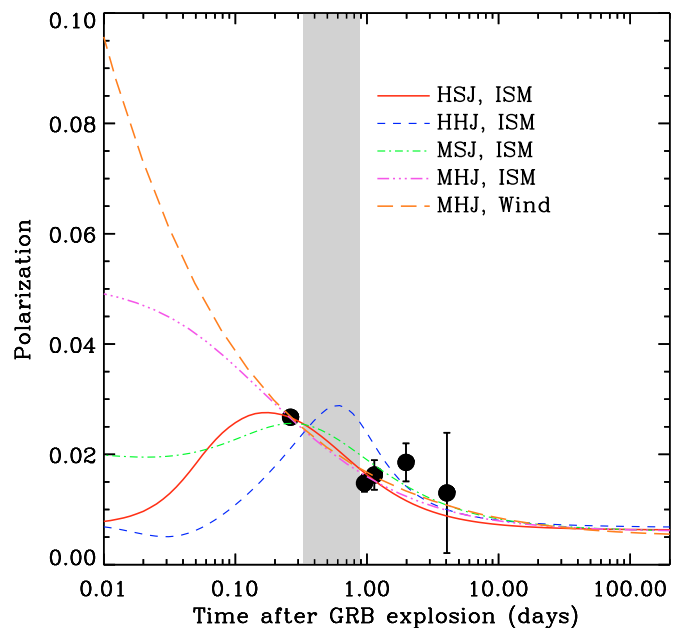


**Fig. 5.** Polarization (*upper panel*) and position angle (*lower panel*) data for GRB 020813 (Gorosabel et al. 2004). Different curves refer to different models, as indicated in Fig. 6. Models yielding an acceptable fit are plotted with a thick line, while non-acceptable models are shown with a thin line. The gray-shaded area shows the acceptable range for the jet break time.

polarization. This did not lead to a significant improvement of the fit.

Fits with a hydrodynamic homogeneous jet yield always non-acceptable  $\chi^2$  values. This is mainly due to the fact that a minimum of polarization in coincidence with the break time is not observed, nor a  $90^\circ$  rotation of the position angle between the data taken across the jet break time. A reasonable (even though still not formally acceptable) fit can be obtained only in two limiting cases, which are not likely. If the jet break time is allowed to become smaller than 0.33 d, which is not consistent with the break time detected in the light-curve (Gorosabel et al. 2004) or if the line of sight is allowed to be slightly outside the jet edge in a non sideways expanding beam, the measured polarization points lie in a time interval where the angle rotation is not expected. In this case reasonably good fits can be obtained (with reduced  $\chi^2$  values of  $\sim 2 \div 3$ ). The best HHJ fit is shown with a thin dashed line in Figs. 5 and 6.

The fit with a structured hydrodynamic jet gives better results. This is mainly due to the fact that in this case the position angle of polarization is constant, and the polarization curve has a maximum in coincidence with the break time. In this case a good fit is obtained ( $\chi^2/\text{d.o.f.} = 10.36/6$ ) for a jet expanding in a uniform medium observed very near to its core, consistent with the small measured opening angle from the light-curve break time (Covino et al. 2003a; Rossi et al. 2002). In this case the break time can be measured also from the polarization points, with a result that is consistent with the limits from the light-curve. A moderately ordered magnetic field is also required. A fit with the same model expanding in a wind environment does not yield an acceptable fit. The best fit is shown with a thick solid line in Figs. 5 and 6.



**Fig. 6.** Same as Fig. 5 but for the polarization only. The  $x$  and  $y$  axes have been expanded in order to show how the models differ at early times, where more data are needed in order to clearly understand the structure of the jet and of the magnetic field. The gray-shaded area shows the acceptable range for the jet break time (Gorosabel et al. 2004).

The best fit of the whole set is obtained for an MHJ jet, irrespective of the environment structure. The ISM and Wind fits are shown with a thick dash-dot-dot-dot and long-dashed lines, respectively, in Figs. 5 and 6. Even though the fit is good, it is not possible to independently constrain the parameters, since the covariances are strong and allow one to find always a minimum of the  $\chi^2$  within 1 from the absolute minimum.

Finally, the MSJ model yields a reasonable fit, even though not formally acceptable. The fit is shown with a thin dash-dot line in Figs. 5 and 6. Taking into account the oversimplification with which this model has been computed, we do not consider the lack of a formally adequate  $\chi^2$  value a condition strong enough to reject the model.

#### 4. Summary and discussion

We have presented a comprehensive modelling of the polarization curve of GRB 020813. This burst is particularly suited for polarization studies since it has an extremely smooth light curve (Gorosabel et al. 2004; Laursen & Stanek 2003). This is an important parameter, since any complexity in the light curve is likely associated with the breaking of the fireball symmetry, introducing a random fluctuation in polarization that cannot be predicted a priori by any model (Granot & Königl 2003; Lazzati et al. 2003). The polarization curve of GRB 020813 (Gorosabel et al. 2004) is one of the most extended published to date<sup>2</sup>, certainly the most complete associated to a smooth light curve, and is characterised by a constant position angle

<sup>2</sup> A more extensive polarization covering has been performed on GRB 030329 (Greiner et al. 2003). This burst, however, has a complex

and a smoothly decreasing degree of polarization. Importantly, the data encompass the break time of the light-curve, which is a critical time where different models make markedly different predictions (Rossi et al. 2004).

We first discuss the magnetic patch model (Gruzinov & Waxman 1999), in which polarization is due to the non-perfect cancellation of highly polarized radiation coming from a large number of ordered magnetic field domains independent from each other. This model predicts a strong flickering of the position angle which is not observed and can therefore be rejected based on our dataset (see also Barth et al. 2003 and, for the case of GRB 030329, Greiner et al. 2003).

We then model the polarization curve according to the predictions of several different models. We find that a homogeneous jet in which the magnetic field is shock generated (Ghisellini & Lazzati 1999; Sari 1999) cannot fit the data, since neither a minimum of polarization nor a rotation of the position angle are present in the data. On the other hand a structured model, in which the core of the jet is more energetic than its wings, can successfully reproduce the data, and predicts a jet break-time in agreement with what measured from the light-curve. We also compute models for a magnetised jet, in which the magnetic field has a non negligible toroidal component. We find that the best fit is obtained by a homogeneous magnetised jet, even though the dataset is not extensive enough to meaningfully constrain its parameters. We also consider a force-free magnetic bubble (Lyutikov et al. 2003), which is analogous to a structured jet but for the presence of a toroidal magnetic field. The fit in this case is not formally successful, but we cannot rule out the model since the details of how the toroidal magnetic component mixes with the shock generated one have not been deeply investigated.

All the considered fits require a non fully ordered magnetic field, even though the degree of order is always substantial (>40%). This is in disagreement with what is found in the prompt emission of GRB 021206 where a fully aligned magnetic field has to be considered in order to reproduce the observational constraints<sup>3</sup> (Coburn & Boggs 2003; Lyutikov et al. 2003; Granot 2003; but see also Nakar et al. 2003 and Lazzati et al. 2004). This indicates that the magnetic field geometry is different in the two epochs and seems to confirm the idea that the material responsible for the prompt emission is not the same one that produces afterglow photons. Our best fit model requires however a mixing of the two, or at least of their electromagnetic components.

Unfortunately the quality of the data is not good enough to allow us to constrain the models and/or the assumption on which they are based any further. Robustly and independently of the model assumptions we can conclude that: i) the magnetic field responsible for afterglow emission is not simply random since a net polarization signal is produced; ii) the difference between the magnetic field components parallel and

perpendicular to the shock front is small but non negligible, but it is not possible to understand which of the two dominates over the other; iii) a standard homogeneous jet with shock generated field can be ruled out, since no angle rotation is detected between observations before and after the jet break<sup>4</sup>. On the theoretical side, we show that the early time behaviour of polarization is crucial to understand the magnetic field configuration: a large scale field will produce large polarization at early time, while a small-scale field will produce polarization only within a couple of decades in time from  $t \sim t_{\text{jet}}$ .

We conclude by commenting on how future observations may help to gain a deeper insight on the structure of GRB jets and their magnetic field. As shown in Fig. 6, the various models differ substantially at early times. In particular, magnetised jets predict high polarization at early times, while unmagnetised models predict null polarization. Early polarization measurements of afterglows with smooth light curves will therefore be fundamental to pin down these important jet parameters.

We shall also conclude with a word of caution. Dense sampling of the polarization curve of GRB 030329 (Greiner et al. 2003) has revealed that the polarization curve associated to a complex light curve afterglow can be much more complex than what predicted by any of the models we discussed here, and that fluctuations in the light and polarization curves may not be strictly correlated. In the case of GRB 020813 the light and polarization curve sampling is not as dense, and therefore even if all data are consistent with a smooth evolution, short time-scale variability in both the light and polarization curve may have been missed<sup>5</sup>. We therefore strongly recommend an adequate sampling of GRB afterglow light curves in polarimetric mode in order to allow for a more robust comparison of the data with models.

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<sup>4</sup> A constant position angle does not imply necessarily an inhomogeneous jet with the structure adopted in this paper. Any jet with a brighter core and dimmer wings will produce qualitatively similar polarization curves.

<sup>5</sup> However Lazzati (2004) showed that a degree of fluctuation as large as that in GRB 030329 would have been easily detected in GRB 020813.

light curve which prevents the comparison of the polarization with models, as for the case of GRB 021004 (Lazzati et al. 2003).

<sup>3</sup> Note however that the result has been heavily criticised on data analysis grounds (Rutledge & Fox 2004) and any implication should therefore be taken with caution.

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