Detection of Primordial Magnetic Fields in TeV gamma-ray data

A.Wingler[1]**, R. Plaga**[1]**, and F.Krennrich**[2]
[1] *Max-Planck-Institut für Physik, 80805 München, Germany*
[2] *Iowa State University, Ames, IA 50011, USA*

Abstract

The analysis of the time-variable flux of γ-ray photons from extragalactic sources is currently the only proposed way to directly determine the magnetic field strengths in intergalactic space - far away from galaxies and clusters (in the cosmological "voids") - in the range below about 10^{-10} Gauss (Plaga 1995). Remnant magnetic fields with field strengths much below this, which may well have formed in early cosmological times, could exist in these voids. Due to their interaction with infrared photons TeV gamma-rays induce pair production in intergalactic space. The electrons and positrons are deflected by ambient magnetic fields and produce γ-rays via inverse Compton scattering that are delayed with respect to the original photons in an energy-dependent, characteristic manner. A standard method to identify these delayed events in a data sample of a source with a variable VHE γ-ray flux (as available from several Cherenkov telescope experiments for the high-emission phase of the AGN Mrk 501 in 1997) is described. Monte-Carlo simulations of existing data sets (taking into backgrounds and instrumental limitations) are used to explore how sensitive data sets similar to the existing ones are to primordial magnetic fields. We find that about 22000 (15000) events from a source with characteristics similar to Mrk 501 are needed to detect a primordial B field of 3 (10) atto Gauss (10^{-18} G) with a 3 σ significance.

1 Introduction

The possible existence of primordial magnetic fields, i.e. fields which formed by processes in the early universe and lasted up to present times is a question of great interest to cosmology (11 papers on the this subject in the year before submission of this paper on the astro-ph server alone). In most scenarios the fields are very weak today because the field strength decreases with the cosmological scale factor squared after their creation at very early times (typically much below 10^{-10} Gauss today) A detection of such a field would offer a qualitatively new window to the very early universe and thus justifies great efforts.
It was shown by one of us (Plaga 1995) that the delay time induced by the process sketched in the abstract has the following behaviour to good approximation:

$$\Delta t = 9.6(d/\mathrm{Gpc})(E/\mathrm{TeV})^{-2}(B/\mathrm{aG})^2\mathrm{days} \tag{1}$$

This is the "maximal delay time", i.e. nearly all events have smaller delay times than the value calculated by eq.1. The formula ceases to be valid below about 0.4 aG because the effects of the finite tranverse momentum in pair production begin to play a larger role than the magnetic deflection. The basic idea is to search for this characteristic time-energy behaviour after an outburst from an astrophysical source of TeV γ-rays.
The active galaxy Mrk 501 showed a period of high activity in 1997 which was observed by several Čerenkov telescopes at energies from 200 GeV to above 10 TeV (Protheroe et al. 1997) and a large world data set on this object exists. Moreover the exponential cutoff in its energy spectrum around 20 TeV observed by the HEGRA system of Čerenkov telescopes (Aharonian et al. 1999) is probably due to the interaction with the cosmological infrared background. In this case the source spectrum is harder then the observed spectrum and the spectral index of its differential energy spectrum will not much smaller than -2 (Stecker & de Jager 1998). Its spectrum above a TeV then contains a considerable fraction of cascaded events *if* the magnetic fields in the cosmological void between us and Mrk 501 are lower than about 10^{-15} G.
VHE γ-ray data from Mrk 501 are thus well suited to search for the subtle effects of primordial magnetic fields, but in this source emits no δ peak of radiation in time with a background free tail of delayed events

which could be analysed in a straight forward way. Below we present a standard method to analyse data with a finite - and a priori unknown - temporal width of several source bursts in the presence of backgrounds. This method is then tried out on a simulated set of data similar to ones from Mrk 501.

2 Monte Carlo simulation of VHE γ-ray data sets

We assumed 7 Gaussian peaks irregularly spaced in time over a period of 120 days. They are numbered upwards in time; # 2/3 and # 4/5 are overlapping being close in time. The source spectrum was assumed to follow a power law with an index of -2 from 500 GeV to 200 TeV. The propagation of these events was then followed with a MC generator assuming the "low" infrared background in Stecker & de Jager (1998) and B_{prim}=3,10 aG (higher values are under study). A hadronic background with an differential index of -2.7 was added with a rate of 6.6 events/hour. Finally we applied a Gaussian energy resolution of 30 % to all events and assumed that the source was measured for 3 hours each night. Fig. 1 illustrates our generated data set for B_{prim}= 3aG. Shown is: upper left panel: the assumed time distribution of events emitted by the source over an observation period of 120 days; upper right panel: the distribution of cascade events that were delayed by a primordial field of 3 aG; lower left panel: remaining fluctuations of hadronic background, after g/h separation and subtraction; lower right panel: all three contributions summed ("time distribution as determined in an experiment"). This last panel looks qualitatively similar to data of Mrk 501 during the first half of 1997 (Protheroe et al. 1997). It is striking that it is absolutely impossible to see the effect of the delayed events from the time distribution "by eye" in spite of the fact that 32 % of all events are delayed cascade events. This is partly due to the effect of high energy with delays smaller than the total temporal width of the peaks.

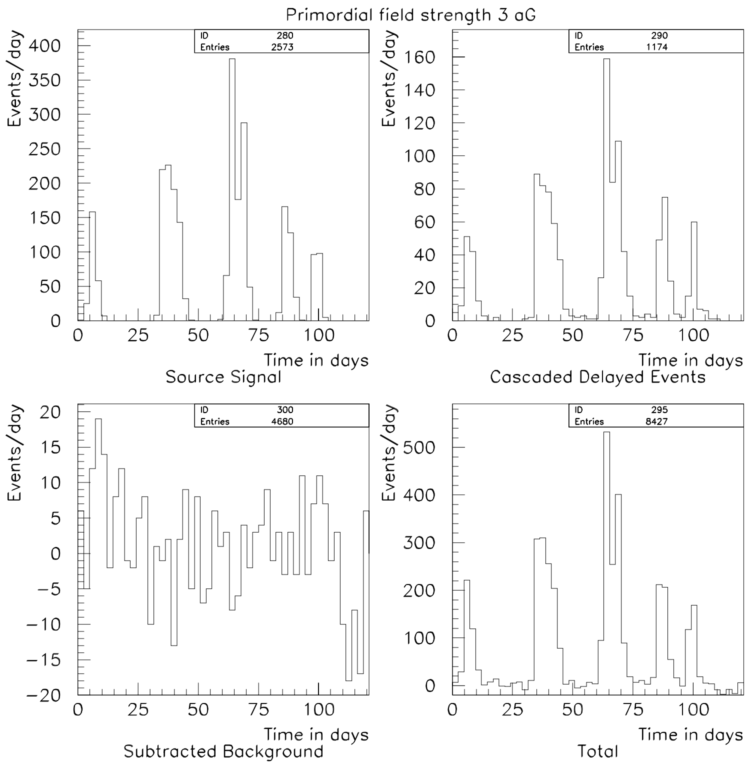

Figure 1: A simulated data set of a TeV γ-ray source with characteristics as the AGN Mrk 501.

3 The Method to detect γ-photons delayed by primordial fields

Given is a sample of N γ-ray events labelled 1...i...N with event times $t_e(i)$ and determined energies $E_e(i)$ which we call "ORI" in this paper. In simulations with hadronic background the background subtraction is performed before the later analysis. Those events which lie closest in energy and time (the "distance" is measured as $\Delta\text{energy}^2+\Delta\text{time}^2$ in optimised units, here TeV and 10 seconds) to a second set of hadronic events are removed. This subtraction method is biased but was used here for the sake of simplicity.

We also construct a large number N_p of "PERM" sets as reference where the energies of all events are randomly permutated. The PERM sets have identical energies and times as the ORI sets, but have lost all time - energy correlations. The analysis proceeds in five steps.

1. for each event determine the "delay times t_d" with $t_d=t_e(j) - t_e(i)$ of all later events within a time

Table 1: Significances sig_B of B field detection (100 repetitions, see text) of magnetic field signature for peak 5,6,7 with n kilo-events each. The significances stated after subtraction of the residual significances.

Peak	width in days	$t_{analysis}$	n, 3 aG	S_B, 3 aG	n, 10 aG	S_B, 10 aG
5	0.97	13	0.90k	9.8	0.95k	8.4
6	1.64	12	0.69k	5.3	0.71k	5.7
7	0.98	15	0.60k	3.9	0.63k	6.9

period from $t_e(i)+t_{standoff}$ up to $t_{analysis}$. $t_{standoff}$ and $t_{analysis}$ ("stand off" and "analysis time") are parameters of the method which have to be optimised. Each event is treated as a start-event which "sees" the later events (stop-events).

2. the pairs (t_d - energy of delayed event j) are inserted into a two-dimensional (delay time versus energy) histogram, both for the ORI and all PERM sets. The difference of an PERM from a ORI histogram (ORI-PERM) is shown in Fig.2. For data without any time-energy correlation all bin contents in this diagram randomly fluctuate around zero. We have to quantitatively identify the excess of events visible below the "maximal-delay limit".

3. to this end we construct one dimensional "diagonal" histograms in which the number of events between two "maximal delay lines" (see Fig.2) with different y-axis intercepts are counted in one bin. In other words the "maximal delay line" is shifted up and down in the (delay time versus energy) histogram. The amount of shift defines the one dimensional bin and the number of events lying along the line is the bin content.

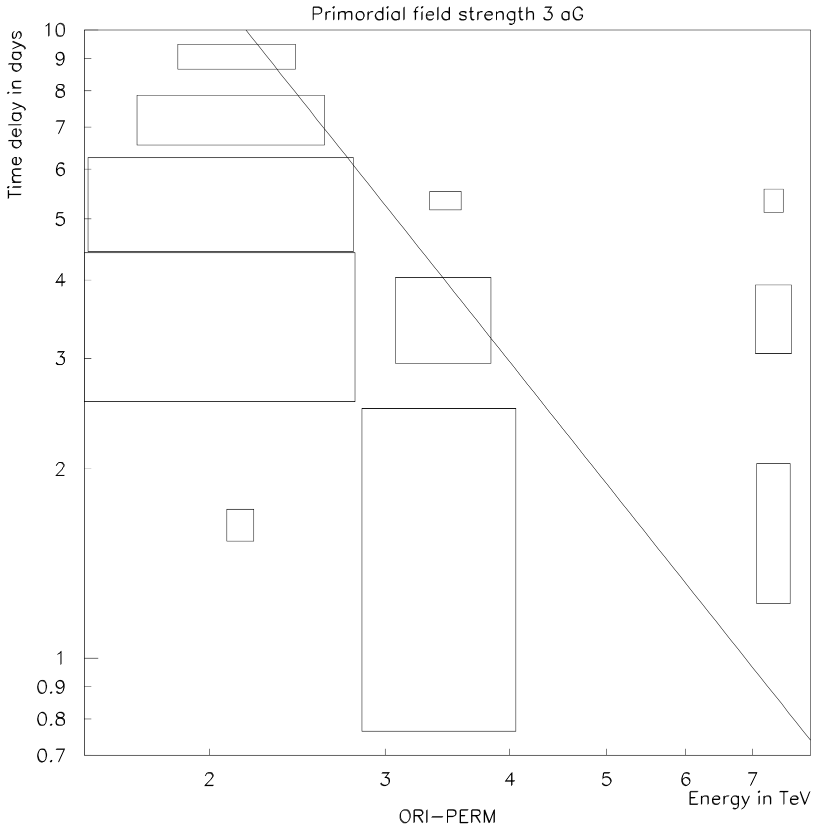

Figure 2: Subtracted delay time versus energy plot (ORI-PERM) for one combined analysis of peak # 5-7. Only positive entries are shown, the area of the boxes representing bins is proportional to the number of entries. The full line is parallel to the maximal delay line according to eq 1. shifted upwards by a factor 4.1 because of finite resolution effects.

4. N_p (here 100) diagonal plots for repeated permutations are averaged resulting in the "final diagonal" histogram. The searched for effect reveals itself now as an excess of events for small, and depletion for large y-intercepts. As a control, the mean of many PERMs is subtracted from a PERM diagram should result in histogram fluctuating around zero. This fluctuation is the statistical noise of our method. A plot resulting from this procedure is shown in Fig.3.

5. The complete procedure is repeated N_r times (here always 100 times). For each repetition the parameter

S_B is calculated from the final diagonal histogram with:

$$S_B = \sum h_i \times s_i \qquad (2)$$

where h_i are the bin actual contents and s_i the mean normalised bin content determined for the searched for magnetic field strength. $\mathrm{sig}_B(\mathrm{S}_B > 0)$ = $\left(\sum_{i=1}^{N_r} \mathrm{S_B}(\overline{\mathrm{ORI}-\mathrm{PERM}})_\mathrm{i}\right)/\ \sigma(\mathrm{S}_B(\overline{\mathrm{ORI}-\mathrm{PERM}}))$ is the significance a B-field detection in standard deviations. The bar symbolises the mean of many permutations as discussed in point 4. It was found that sig_B varies with the square root of N_r to very good approximation in the parameter range studied here.

4 Results

Fig. 2 and fig. 3 show the "delay time versus energy" the "final diagonal" histograms for the combined peaks 5,6 and 7. These peaks were chosen to be sure that the effect of earlier non-analysed peaks (which always exist in practice) are properly taken into account. The expected characteristic excess for bins corresponding to the region below the maximal delay line is clearly observed in both figures. The obtained significances in 100 independent repetitions of the numerical experiment are stated in table 1 for two field strengths.

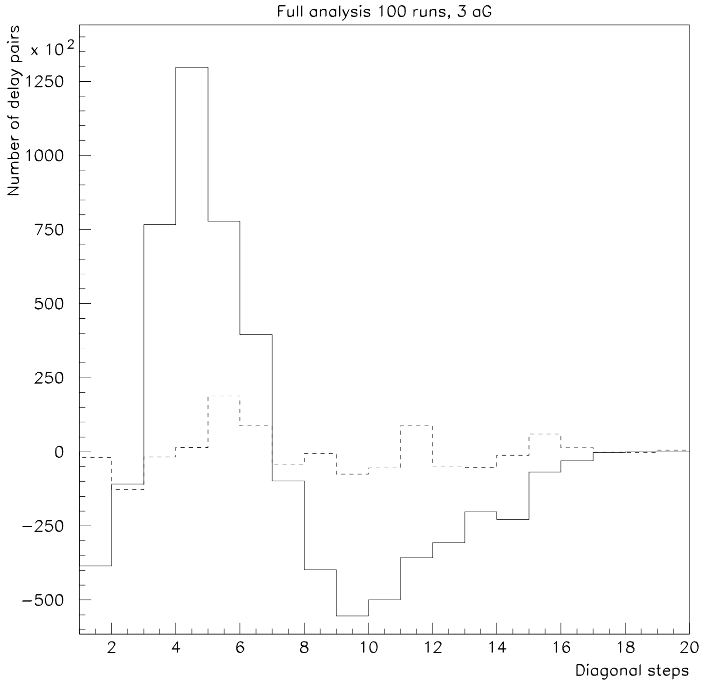

Figure 3: Final diagonal histogram. The dashed line is the control for permutated events.Bin 0 and 20 correspond to a y-axis intercept of 0.5 and $2.2 \cdot 10^4$ days (at 1.5 TeV).

For our conditions about 22000 (15000) events with characteristics similar to the peak 5-7 and a signal/noise typical for a state-of-the-art single Čerenkov telescope are needed for a 3 σ detection of a 3 (10) aG primordial field. When the signal and the hadronic background are analysed without delayed events, a finite signal with a "residual" sig_B (about a factor 2-3 smaller than the signal) still appears. This effect vanishes with the complete removal of the hadronic background. It is due to residual, non properly subtracted, background which leads to a softening of the spectrum after the after the maximum, qualitatively similar to the cascaded delayed events which are also softer than the source events. This is the major systematic background of the described method and could be reduced by using more refined, unbiased background subtraction methods. Recent determinations of the infrared background (de Jager & Dwek 1998) gave higher values than assumed in this study, the effect of cascaded events might therefore be stronger. An analysis of the combined existing world data set of Mrk 501,which contains roughly of the order of 50000 events along the lines described here therefore seems warranted.

References

Aharonian, F. et al. 1999, A & A to be published
Protheroe, R.J et al. 1998, Proc 25th ICRC Durban 1997, Vol.8 p317
Stecker, F.W. & de Jager, O. 1998, astro-ph/9804196, A & A to be published
de Jager, O. & Dwek,E. 1999, submitted to Astropart.Phys.
Plaga, R. 1995, Nat 374, 453