Geomagnetic effects on atmospheric Čerenkov images

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Abstract.
Atmospheric Čerenkov telescopes are used to detect electromagnetic showers from primary gamma rays of energy $\sim 300$ GeV – $\sim 10$ TeV and to discriminate these from cascades due to hadrons using the Čerenkov images. The geomagnetic field affects the development of showers and is shown to diffuse and distort the images. When the component of the field normal to the shower axis is sufficiently large ($> 0.4$ G) the performance of gamma ray telescopes may be affected, although corrections should be possible.

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1. Introduction

It is now 45 years since Cocconi [1] drew attention to the broadening effects of the geomagnetic field on the lateral development of electron-photon cascades in the atmosphere. Allen [2] discussed the interaction of the geomagnetic field and the cascade electrons/positrons as the origin of the radio frequency emission produced by large cosmic ray showers. Earnshaw et al [3] suggested that the geomagnetic separation of muons could be used to estimate the height of origin of showers. Porter [4] and Browning and Turver [5] made calculations for the production of Čerenkov radiation by electron-photon cascades in the atmosphere, with allowance for the effects of the geomagnetic field.

Ground based gamma ray astronomy exploits the magnifying effects of the atmosphere to enable the detection of very low fluxes of gamma rays from a variety of sources [6]. The cascade of electrons initiated by a primary gamma ray produces, at an altitude of about 10 km, Čerenkov light which reaches the ground in a pool ~ 300 m in diameter. It is possible to detect gamma rays of energy > 300 GeV via this Čerenkov light produced in the atmosphere with an effective collection area, for our Mark 6 telescope, of $5 \times 10^4$ m$^2$.

Bowden et al [7] discussed the effect of the geomagnetic field on the performance of ground based gamma ray telescopes. The interaction of the field and the cascade electrons produces a broadening of the atmospheric Čerenkov light image resulting in a reduction in the density of light sampled by the telescope; so the energy threshold for the telescope increases. This is observed in the higher count rate for a telescope detecting showers propagating along the lines of the field (with no spreading) than when observing cascades developing perpendicular to the field lines (and being spread), all other factors being the same. Typical differences in measured count rate were about 20% in these extreme cases. The possibility was noted, on the basis of simulations, that an associated rotation of the direction of the Čerenkov light images may occur for cascades developing under high magnetic fields and in unfavourable directions. This could be of importance in ground-based gamma ray studies since the orientation of the image in gamma ray initiated cascades is the key to rejection of > 99% of the charged cosmic ray background [8].

Lang et al [9] showed that the measurements of TeV gamma rays from the Crab nebula using the imaging Čerenkov technique were not significantly affected when the magnetic field was < 0.35 G.

We report measurements made using a ground based gamma ray telescope of cascades developing under the influence of fields up to 0.55 G. Observations with the Mark 6 telescope operating in Narrabri, Australia which is discussed by Armstrong et al [10] are subject to such magnetic fields when observing objects to the south. The observational data demonstrate all the effects of the geomagnetic field on cascades which are predicted by simulations.
2. Geomagnetic effects on EM showers

2.1. Simple model

The lateral distribution of electrons and positrons near the maximum of an electromagnetic shower in air is approximately axially symmetric. The presence of a transverse component of magnetic field will cause the electrons and positrons to separate and the lateral distribution to become wider along the radial direction perpendicular to the transverse field component. The order of magnitude of this effect may be estimated.

A relativistic electron of energy $E$ (MeV) will follow a circular path in a transverse magnetic field of strength $H$ (G) with a radius of curvature $R$ (km) of $\sim E/(30H)$. The energy of the typical Čerenkov light-producing electron at shower maximum is $\sim 100$ MeV (the critical energy in air), which is at a height of $\sim 10$ km for a 250 GeV primary gamma ray. The radius of curvature of these electrons for a maximum transverse magnetic field of 0.56 G is $\sim 6$ km. The typical length of such an electron’s path in air at 10 km altitude is $\sim 1$ km, giving a lateral deflection of $\sim 80$ m. At a height of 10 km this corresponds to an angular deflection of $\sim 0.5^\circ$, the same order as the Coulomb scattering width. It should be possible to detect this as a broadening of the shower along one axis.

The effect of the broadening will depend on the orientation of the image with respect to the direction of the magnetic field. The direction of the shower axis in the atmosphere is within $\sim 1^\circ$ of the telescope-source line. The transverse magnetic field component therefore lies very close to the plane of the focal image of the shower. The parameters of an image which are used to discriminate between gamma rays and hadrons depend primarily on the second spatial moments. In a coordinate frame in which the x-axis is aligned with the projected field direction, these are $\sigma_x^2$, $\sigma_y^2$ and $\sigma_{xy}$. The orientation angle of the long axis of the image is $\tan^{-1}\left(\frac{\sigma_y^2 - \sigma_x^2 + \sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{2\sigma_{xy}}\right)$. Those shower images whose major axes are aligned with the projected direction of the magnetic field have $\sigma_{xy} = 0$. The moment $\sigma_y^2$ will be expected to be increased by the magnetic field and the images will be widened only. For images at other orientations, $\sigma_{xy} \neq 0$ and the result of an increase in $|\sigma_{xy}|$ will be to rotate their minor axes towards the projected field direction. The main parameter used to discriminate gamma rays is $\text{ALPHA}$, the angle contained within the long axis of the image and the radius vector from the source position to the centroid of the image. Any rotation of the image may affect $\text{ALPHA}$ and hence the sensitivity for gamma ray detection. This is discussed further in section 2.2.

2.2. Simulations

Monte Carlo simulations of gamma ray and hadron cascades have been made to investigate the strength of this geomagnetic effect. These simulations have been performed using a Monte Carlo code developed from that used in our earlier work [7] which incorporates the responses of the University of Durham telescopes. The results of
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Figure 1. The simulated effect of the geomagnetic field on the brightness of the observed image. We show the % reduction in event rate for hadrons as a function of primary energy for a field of 0.5 G relative to the zero-field case.

The simulations have been validated against established simulation codes e.g. MOCCA \cite{8}. Agreement has been found in all cases.

The consequence of an increase in the lateral and angular spread of the shower electrons is a decrease in the density of Čerenkov light on the ground. This leads to a decrease in counting rate for fixed threshold, which was reported by us from measurements, using a non-imaging telescope, of counting rate against azimuth at fixed zenith angle \cite{7}. Figure 1 shows the simulated reduction in the counting rate of a gamma ray telescope of the type used by us for hadron primaries, relative to the zero-field case, caused by a transverse magnetic field of 0.5 G. This is consistent with our earlier measurements — a reduction of up to \(\sim 20\%\) in count rate for gamma ray energies \(\geq 300\) GeV \cite{7} and, apparently, a greater reduction for \(< 300\) GeV cascades.

In our earlier work \cite{7} we suggested that the distribution of recorded photons in an imaging camera may be distorted. We show in figure 2 the pattern of photons in individual simulated 1 TeV gamma ray cascades developing under the effects of 0 and 0.56 G geomagnetic fields. We also show the predicted responses of our camera after allowing for optical distortion, pixellation of the camera, measurement noise and passing through our standard data analysis package. The simulations for the pairs of cascades developing under the influence of a field and no field have been initiated using the same random number seed; this ensures, as far as is possible, that the early development of the cascade (which dominates the resulting image and is nearly independent of field) is identical for the two simulations. The expected effects on the shape of the image (widening or lengthening and rotation, depending on the orientation of the image with respect to the magnetic field direction) was apparent, both in the distribution of photons hitting the detector and in the processed image.

The predicted width of a shower image was investigated as a function of magnetic field strength and angle for gamma rays of energy 500 GeV. Results are shown in
Figure 2. Simulations of a 1 TeV gamma ray cascade. The simulation has been performed with geomagnetic field values of (a) 0 and (b) 0.56 G. For each image, both a raw photon map (upper plot) and the results of fitting standard image parameters after allowance for mirror defects, pixelation and noise (lower plot) are shown.

Small transverse fields of 0.2 G have a limited effect on the image width. However, the effect on the pointing angle \( \alpha \) becomes noticeable and may vary both with the image's angle to the magnetic field and with its eccentricity (defined as the ratio \( \text{Width}/\text{Length} \)). For example, an image with very low eccentricity may be widened only by a small amount but rotated through a large angle. Histograms in \( \alpha \) are
Figure 3. The effect of the geomagnetic field on the width of simulated 500 GeV gamma ray shower images which are not subjected to any broadening effects of the mirror or camera. • is for a geomagnetic field of 0.0 G, ○ for 0.2 G and ▼ for 0.5 G.

Figure 4. The effect of the geomagnetic field on the distribution in pointing angle ALPBA for simulated 500 GeV gamma ray shower images. (a) is for a geomagnetic field of 0.0 G, (b) for 0.2 G and (c) for 0.5 G. Again, there is no allowance for the effects of mirror optics or camera pixellation.

shown in figure 4 for the simulated gamma rays, for which widths were shown in figure 3, under the influence of fields of 0.0, 0.2 and 0.5 G.

The effects of mirror quality and camera pixellation of a typical telescope may reduce this change in width but may not mask the change in orientation of the image.
2.3. Magnetic fields appropriate to Narrabri observations

We show in figure 5 the celestial sphere, as viewed from the site of the Mark 6 telescope in Narrabri, Australia, showing the loci of constant magnetic field strength. We indicate the tracks on the sky for the telescope during observations of a number of potential gamma ray sources which have been intensively studied. In fact, most of the sources studied at Narrabri are in the azimuth range $135^\circ - 225^\circ$ and in directions for which the magnetic field is $> 0.35$ G and in many cases $> 0.5$ G. The telescope sensitivity is therefore likely to be reduced by the broadening of the distribution of $ALPHA$ for many of our observations, unless corrections are applied.

3. The equipment

All data reported here have been obtained with the Mark 6 VHE gamma ray telescope which has been described in detail by Armstrong et al [10]. The telescope measures gamma rays in the energy range $300$ GeV – $10$ TeV, with a 50% trigger probability at an energy of $\sim 300$ GeV. It comprises an alt-azimuth mount with three 7m diameter f/1.0 aluminium mirrors with an rms spread for a point source of 0.18°. The pixel size for a 1" diameter photomultiplier is 0.25°. The focal plane of the central mirror contains a 109-pixel camera comprising a close-packed hexagonal array of 91 1-inch diameter photomultipliers surrounded by a ring of 18 2-inch diameter photomultipliers. The field of view of the imaging camera is 3° wide. The mirrors on the left and right of the mount each contain a triggering detector of 19 2-inch photomultipliers in a close-packed hexagonal array. Each photomultiplier is contained in a mumetal shell designed to give magnetic and electrostatic shielding. The effect of the geomagnetic field on the performance of the photomultipliers, with and without shielding, has been studied [11]. For the 1-inch Hamamatsu R1924 PMT the effect of a 0.5 G field on the gain was not measureable and less than 1%. For the 2-inch Phillips XP3422 PMT the measured
decrease in gain due to a 0.5 G field was 1%. Shielded photomultipliers of both types show no measurable effects due to the magnetic field.

The control of the attitude of the telescope is via DC servomotors driving onto gears mounted directly on the telescope structure. Angles are sensed by absolute digital 14-bit shaft encoders with a resolution of 0.022°. The calculated azimuth and zenith of a source is compared by a digital servomechanism (employing 12-bit resolution) with the shaft encoder outputs at 100 ms intervals. The error signals are passed via DACs to the DC motor amplifiers. These provide damping on acceleration and stabilise the movements of the telescope structure. Thus although the telescope pointing is known to a resolution of 0.022°, the source can be offset from the camera centre by up to 0.1° by this mechanism.

The attitude of the telescope is measured in two ways. The shaft encoder positions are recorded for each event to 14-bit accuracy. This gives a measurement of the pointing to ±0.022° within the telescope system. In addition, a coaxial optical CCD camera is mounted on the telescope. The output of this CCD camera is continuously monitored by microcomputer, which measures the position and brightness of a nominated guide star within the 2° × 2° field. This information is integrated into the data stream on an event-by-event basis. Guide stars of magnitude $m_v \leq 6$ can be employed, providing absolute position sensing for the telescope to better than 0.008°.

False source analysis has been shown to be a useful method of demonstrating that γ-ray like events originate from the source direction [12]. Conversely, such analyses may also be used to verify the steering performance of a telescope, if an established γ-ray emitter is observed. However, we have only one data set for a gamma ray source containing data which are not subject to the effects of a strong geomagnetic field — see section 5.1.

4. Experimental results

4.1. Data

Most of the data considered here were taken during routine observations of potential gamma ray sources during 1996 – 1998. A small amount of data was taken in dedicated measurements at fixed values of azimuth and zenith, corresponding to a range of values of the geomagnetic field. The only restriction imposed on data was that events should lie within 1° of the centre of the camera (to avoid edge effects) and were large enough (5 times the triggering threshold) to ensure that their shape was well measured.

4.2. Reduction in image brightness

The investigation of the sensitivity of the count rate to the magnetic field which established the effect with the Mark 3 and Mark 4 telescopes [7] has been repeated for the Mark 6 telescope. We find that the count rate observed with the Mark 6 telescope
for cascades developing under minimum and maximum values of the geomagnetic field at a constant zenith angle of 40° differs by about 15%, as expected.

4.3. Effects on the shape of Čerenkov images of hadron showers

The widths of images recorded by the Mark 6 telescope in directions parallel and perpendicular to the magnetic field have been investigated. For a large sample of cascades measured during observations of a range of sources the differences of the mean width in the parallel and perpendicular directions are shown in figure 6 for a range of values of distorting field. The widths of images in directions perpendicular to the field are significantly greater than those in parallel directions for fields $> 0.4$ G. Although the differences in widths are small, because of the effects of pixellation and noise which are common to all data, the measurements are free from systematic effects. This is because the orientation of images to the magnetic field depends on the orientation of the image in the camera. Measurements of the width of the images parallel and perpendicular to the magnetic field are derived from events distributed throughout the same observation.

We have attempted to measure the differences in widths of images in cascades measured at fixed zenith angles of 40° for values of fields less than and greater than 0.35 G. Such measurements are difficult and require large exposures ($\gtrsim 100$ hr) to give significant differences. For example, with exposures $\sim 1$ hr we find for $B < 0.35$ G, the mean width is $0.292° \pm 0.0035°$ (SD = $0.041°$) and for $B > 0.35$ G the mean width is $0.283° \pm 0.0036°$ (SD = $0.042°$). The small difference in means, significant at the $\sim 2\sigma$ level, demonstrates the difficulty in making such a small measurement for which the standard deviation is approximately similar for all $B$. 

**Figure 6.** The observed difference in the mean width ($D_{\text{width}}$) for images in hadronic cascades developing parallel and perpendicular to fields of varying strength for zenith angles in the range $35° - 40°$. The concentration of data at values of high magnetic field strength reflects the directions of observation of potential VHE sources from Narrabri.
4.4. Effects on the orientation of Čerenkov images of hadron showers

In the absence of any magnetic field and detector triggering biases, the distribution of the orientation of the images in the camera of a telescope will be isotropic. If we define a coordinate system where the angle $a_x$ is the angle of the long axis of an image to the horizontal in the camera frame, then the distribution of $a_x$ should be flat between $-90^\circ$ and $90^\circ$. Minor deviations from uniformity in angle might be expected near to threshold because of the increased effect of small changes in triggering probability and the six-fold symmetry of the hexagonal arrangement of close-packed detectors.

4.4.1. Distribution of projected shower angles

We show in figure 7(a) the distribution in the angle $a_x$ for background hadronic events which are subject to small values of the transverse magnetic field (0.15 G). We show in figure 7(b) the distribution in $a_x$ for images due to hadron-induced cascades recorded in special observations at fixed azimuth and zenith angles which gave a transverse geomagnetic field of 0.52 G. All of these events were recorded in dedicated observations with the telescope at a fixed zenith angle (40°). Data at different values of the transverse magnetic field were obtained by varying the azimuth angle. All data presented here were recorded within a period of one hour, so potential variations due to changes in camera performance, atmospheric clarity, etc. were minimised. The data were processed following our normal procedures (see e.g. [14]). The requirement that images have a minimum brightness and fall within the camera ensures that the data are free of effects of variations in night sky brightness. The data for $B = 0.15$ G show the expected distribution indicative of a near isotropic distribution of directions in the camera with a small peak. We note a strong anisotropy, with a peak containing twice the number of events resulting from the skewing or distortion of the image, for events subject to a 0.5 G field. The maximum of the distortion occurs at $a_x = 0$, which is appropriate for those observations which were made at magnetic south.

4.4.2. Correlation of amplitude of $a_x$ peak and geomagnetic field strength

The magnitude of the anisotropy displayed in figure 7(b) should depend on the strength of the magnetic field. In figure 8 we plot the amplitude of the peak of the distortion in the $a_x$ distribution as a function of the magnetic field strength. Each point corresponds to the result for a 15 minute segment of data.

Note that for values of transverse component of the geomagnetic field less than 0.35 G there is no great distortion of the $a_x$ distribution, as suggested by the work of Lang et al [9], but for values of field in excess of 0.4 G substantial distortion occurs.

4.4.3. Correlation of directions of $a_x$ peak and geomagnetic field

The position of the peak in the $a_x$ distribution depends on the angle between the projected magnetic field and the vertical direction in the camera — $H_{FOV}$. We show in figure 9 the correlation between $H_{FOV}$ and the position of the peak in $a_x$. The data demonstrate the expected
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4.5. Summary

We have evidence that the geomagnetic field should, and does, influence the lateral development of atmospheric cascades. The observed effects on the threshold of a telescope and on the shape of the image and the magnitude and phase of the distortion of the pointing of images produced by background cosmic ray protons are as expected.

Figure 7. Distribution of $a_x$ for cascades developing under (a) a small transverse geomagnetic field ($B = 0.15$ G) and (b) a large transverse geomagnetic field ($B = 0.52$ G).

Figure 8. The measured amplitude of $a_x$ anisotropy as a function of transverse geomagnetic field.

relation between these angles. Again, each point is based on a 15 min sample of data taken during routine observations of a range of potential gamma ray sources.
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5. The orientation of gamma ray images

A number of potential gamma ray sources has been observed using the Mark 6 telescope at Narrabri. In several cases there is evidence for gamma ray emission [13, 14, 15]. The evidence comes mainly from a comparison of the $\alpha$ distributions for data selected on the basis of image shape for the ON-source and OFF-source scans. The difference between the $\alpha$ distributions should show an excess of events — the gamma ray candidates — at low values of $\alpha$. If the data were taken in geomagnetically unfavourable directions, as is the case for most of our data, it might be expected that the $\alpha$ distribution of the excess events would be wider than that for data taken in more favourable geomagnetic directions. Consideration of data recorded from a gamma ray source which are subject to $B < 0.35$ G may provide the only true indication of the $\alpha$-distribution for our telescope.

5.1. Observations of PKS 2155–304

Observations of this object were made with the cascades recorded over a range of transverse geomagnetic field strengths between 0.25 and 0.5 G. The total data set contained 41 hrs of observation, as reported [15]. The $\alpha$ plot for the difference between the ON-source and OFF-source data taken at zenith angles $\theta < 45^\circ$ is shown in figure 10(a). The significance of the excess at $\alpha < 30^\circ$ is $5.7\sigma$ according to the maximum likelihood method [16].

We are able to select a subset of data for which the strength of the projected field to which the cascades were exposed was $< 0.35$ G and for which minimal distorting effect would be expected. The $\alpha$ plot for this subset is shown in figure 10(b). The excess events all have $\alpha < 15^\circ$ (significance $4.7\sigma$). The distribution is narrower.

Figure 9. The measured direction of $a_x$ anisotropy as a function of the direction of transverse geomagnetic field. $\blacktriangledown$ represents data from the directions of Cen X-3, $\blacktriangledown$ from SMC X-1, $\circ$ from PKS 2005–489 and $\bullet$ from PKS 2155–304 to cover a range of $H_{FOV}$. 
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Figure 10. The distribution in ALPHA of excess gamma ray events from PKS 2155–304. (a) is for all events, (b) those for transverse fields < 0.35 G, and (c) those for transverse fields > 0.35 G.

than that of the total dataset and is typical of that expected for a 0.25° pixel camera. (In the absence of any other data for gamma rays detected with our telescope and not subject to the effects of the magnetic field, we assume that this is reasonable.)

The ALPHA plot for the majority of the events for which the field is > 0.35 G is shown in figure (c). It is evident that the width of the peak is larger for these events recorded under the influence of higher transverse magnetic fields, with equal populations for values of ALPHA between 0° – 15° (3.6σ) and 15° – 30° (3.1σ). It should be noted that the peak at 60° – 70° is superimposed on an ALPHA-plot with increasing frequency for ALPHA approaching 90° — see [15]. The significance of this peak is therefore ~ 2σ (before allowing for the number of bins in the ALPHA-plots).

On the basis of our only measurement of a gamma ray source not subject to the effects of the geomagnetic field, we have evidence that the excess events with 15° < ALPHA < 30° are confined to those measurements made with fields > 0.35 G. This conclusion is significant at the 2.5% level, on the basis of a 2 × 2 contingency test of the populations of the 15° – 30° bins in figures (b) and (c).

6. Conclusions

We have demonstrated that, on the basis of simulations and measurement, the Čerenkov images from gamma rays and cosmic rays are broadened and rotated by the geomagnetic field. The broadening results in an increase in the telescope threshold and a reduction in counting rate. The rotation of the images away from the projected direction of the magnetic field in the image plane broadens the ALPHA distribution.

These results suggest that the geomagnetic field can have an important effect on the operation of atmospheric Čerenkov telescopes in some directions and that, for detected and candidate sources, our Narrabri site is particularly susceptible. These effects may be removed using appropriate correction techniques; unlike noise, geomagnetic effects...
do not reduce the information contained in the image.

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