Signatures of Ultrarelativistic Magnetic Monopoles in Imaging Atmospheric Cherenkov Telescopes

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Abstract: Magnetic monopoles are predicted to exist in a wide class of theoretical extensions to the standard model of particle physics. Experimental searches for magnetic monopoles have been conducted without confirmed success since the famous Dirac 1931 paper explaining the experimental fact of electric charge quantisation with the existence of magnetic monopoles. A new strategy to search for ultrarelativistic ($\gamma > 10^3$) and massive ($Mc^2 > 1$ TeV) magnetic monopoles with imaging atmospheric Cherenkov telescopes is discussed. Sensitivity estimates for H.E.S.S. (High Energy Stereoscopic System) are given and compared to existing flux upper limits.

Keywords: Magnetic Monopoles, Cherenkov Telescopes

1 Introduction

Dirac [1] showed in the context of quantum mechanics that magnetic monopoles can exist and can explain the experimental fact of electric charge quantisation. Later [2] it was shown that magnetic monopoles arise naturally as classical solutions to the field equations of a wide class of Yang-Mills theories with topological non trivial vacuum configuration. Especially grand unifying theories (GUTs) that unify all known interactions as low energy manifestations of a single interaction allow the existence of magnetic monopoles if the GUT gauge group is compact, i.e. does not contain an explicit U(1) factor [3]. Predictions for masses of magnetic monopoles arising from GUTs are in the order of magnitude $\mathcal{O}(10^5) - \mathcal{O}(10^{15})$ GeV [3]. Up to now no confirmed detection of a magnetic monopole has been reported. Upper limits on the flux of cosmogenic magnetic monopoles on earth reach levels of $\mathcal{O}(10^{-16})$ cm^{-2}s^{-1}sr^{-1} to $\mathcal{O}(10^{-18})$ cm^{-2}s^{-1}sr^{-1} depending on the monopole velocity ([3],[8],[13]).
In [4] it is predicted that magnetic monopoles emit a factor of $n^2/(4\alpha^2)$ more Cherenkov photons than an electric charge in a medium with index of refraction n. For air ($n \approx 1$) and with the fine structure constant $\alpha = 1/137$ this means that a magnetic monopole is predicted to emit about 4700 times more Cherenkov photons than an electric charge when the monopole velocity is sufficiently high ($\beta > 1/n$). In this paper it is studied whether this predicted intensive Cherenkov emission of magnetic monopoles can be detected by imaging atmospheric Cherenkov telescopes (IACTs).

2 Magnetic Monopole Model and Sensitivity Constraints

As outlined in the introduction magnetic monopoles are predicted to emit a highly enhanced amount of Cherenkov photons compared to usual electric charges. In the following it will be studied whether this Cherenkov light directly emitted by a sufficiently fast magnetic monopole during its passage through the earth's atmosphere can be detected by ground based IACTs. Therefore the energy loss due to ionisation and the kinematical influence of the earth's magnetic field is assumed to be negligible for which constraints on the monopole mass and energy are derived. A magnetic monopole is not assumed to produce any secondary particles, e.g. due to nuclear photo effect. The following discussion holds primarily for H.E.S.S., a stereoscopic 4 telescope IACT array operating in the Khomas Highland (Namibia) since 2004 ([7]). The results can however easily be generalised to other IACTs.

2.1 Boost Factor and Mass Constraints

According to [4] a magnetic monopole with velocity $\beta > 1/n$ emits Cherenkov photons under an angle $\theta_C = \arccos(1/(\beta n))$ relative to the direction of the monopole propagation. The velocity of a magnetic monopole depends on the boost factor γ via

$$\beta = \sqrt{1 - \frac{1}{\gamma^2}} \approx 1 - \frac{1}{2\gamma^2} \ . \quad (1)$$

Expressing the index of refraction in terms of the correction to the index of refraction ($n = 1 + \epsilon$) leads to the condition

$\epsilon > 1/(2\gamma^2)$ for the emission of Cherenkov photons. If the boost factor is small, the monopole can emit Cherenkov photons only deep in the atmosphere where ϵ is large. This leads to a decrease in area illuminated by Cherenkov photons on the IACT observation level and therefore to a decrease in sensitivity of IACTs to magnetic monopoles. Simulations performed for an atmospheric model adequate to the H.E.S.S. site in Namibia show that the sensitivity to magnetic monopoles decreases rapidly for $\gamma < 10^3$. In the following it is assumed that the monopole boost factor exceeds this value in order to reach maximum sensitivity. A strong dependence on the atmospheric model, i.e. the site of an IACT searching for magnetic monopoles is not expected.

The IACT analysis to magnetic monopoles proposed in this paper is not sensitive to arbitrarily low magnetic monopole masses Mc^2. This constraint results in general from two points. First it is assumed that the ionisation loss ΔE_{Ion} as predicted in [5] is negligible. This leads to the condition

$$\Delta E_{\mathrm{Ion}} < \frac{dE}{dX}\lambda < 23 \text{ TeV} \ll \gamma Mc^2 \qquad (2)$$

where $\frac{dE}{dX}$ is calculated for the incident boost factor of the monopole entering the earth's atmosphere according to the model predicted in [5] and $\lambda < 1040$ gcm^{-2} is a conservative atmospheric thickness estimate for the H.E.S.S. site in Namibia.

A second constraint on the magnetic monopole mass results from the earth's magnetic field. At the H.E.S.S. site the dominant part of the magnetic field is parallel to the earth's surface leading to a deflection of an infalling magnetic monopole in direction of the magnetic field lines. In order to simplify the later discussed simulation of magnetic monopoles in the earth's atmosphere it is assumed that the influence of the earth's magnetic field on the kinematics of a magnetic monopole is negligible. An estimation of the deflection angle δ of a magnetic monopole due to the earth's magnetic field in Namibia is possible with the assumption that a magnetic monopole travels a distance $L_{\mathrm{max}} < 100$ km in the earth's atmosphere with a magnetic field $B_{\mathrm{max}} < 100\ \mu$T perpendicular to the direction of the monopole propagation, that is parallel to the earth's surface. With the electric charge e and the vacuum speed of light c it holds

$$\tan\delta < \frac{B_{\mathrm{max}} L_{\mathrm{max}} ce}{4\alpha\gamma Mc^2} < \frac{10^{12}}{\gamma Mc^2/\mathrm{eV}} \,. \qquad (3)$$

The deflection of a magnetic monopole due to the earth's magnetic field effectively changes the angle θ_C of Cherenkov emission to an angle $\theta_C \pm \delta$. If δ is much smaller than typical Cherenkov angles for an emission deep in the atmosphere, i.e. if $\delta \ll 1^\circ - 2^\circ$, the deflection is negligible. For $\delta < 0.1^\circ$ this leads to the monopole mass constraint $\gamma Mc^2 \gg 10^3$ TeV for the validity of the simulation approximations used in the suggested analysis.

Obviously the monopole energy constraint resulting from the demand for the negligibility of the monopole deflection due to a magnetic field $\gamma Mc^2 \gg 10^3$ TeV is more constraining than the energy constraint resulting from the negligibility of the ionisation energy loss $\gamma Mc^2 \gg 23$ TeV. Together with the constraint on the boost factor $\gamma > 10^3$ the monopole energy constraint leads to the monopole mass constraint $Mc^2 > 1$ TeV.

2.2 Monopole Simulation for H.E.S.S.

In the following, results obtained from the simulation of the response of the H.E.S.S. array to Cherenkov light emitted by a magnetic monopole propagating straight through the earth's atmosphere without significant energy loss or deflection are discussed. The simulation was realized with a modification of CORSIKA 6735 ([11]) to account for the enhanced predicted Cherenkov emission and the lack of other monopole interactions. The H.E.S.S. detector response simulation of the CORSIKA output was performed with SimTelArray ([10]) and standard H.E.S.S. Monte Carlo software.

3 Signatures of Magnetic Monopoles in IACTs

Figure 1 shows schematically a Cherenkov photon emitting magnetic monopole propagating straight through the earth's atmosphere. Most emitted Cherenkov photons cannot be detected in the camera of an IACT as they are missing the IACT for geometrical reasons. In general, Cherenkov photons that hit the mirror of a ground based IACT can be emitted at up to two different atmospheric height levels. If all Cherenkov photons that hit the mirror can be imaged to the IACT camera within the field of view, two different clusters of IACT camera pixel are triggered. Figure 2 shows the simulated response of one H.E.S.S. camera to a magnetic monopole event where two different clusters of pixels are triggered in the camera. For an IACT data analysis on magnetic monopoles, simulated monopole events have to be distinguished from background events. Events recorded by an IACT are mainly due to showers of primary protons, which constitute the dominant background for a monopole detection. Figure 3 shows the simulated response of one H.E.S.S. camera to an event due to the particle shower of a primary proton. It is clearly visible that the number of triggered pixel in the case of the proton event is much higher than for the shown magnetic monopole event. Additionally the intensity scale is $\mathcal{O}(10^3)$ in case of the monopole event and $\mathcal{O}(10^2)$ in for the proton event. The observation of the differences in the number of triggered pixel and overall intensity of the triggered pixel in the discussed example event displays offers a possibility of a separation of monopole events against background as outlined in the next section.

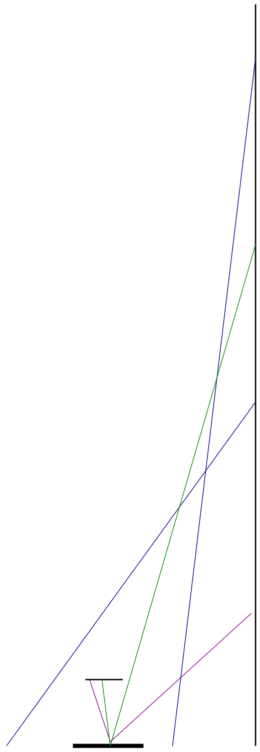

Figure 1: A magnetic monopole (vertical black line) emitting Cherenkov photons (coloured lines) in the earth's atmosphere. The Cherenkov emission angle between the monopole propagation direction and an emitted photon is increasing with increasing atmospheric depth. For geometric reasons most emitted Cherenkov photons miss the mirror of an IACT (thick horizontal black line). In general there are two different atmospheric levels where Cherenkov photons that hit the IACT mirror are emitted (magenta and green line). Given that it is possible to image the photons in both cases onto the IACT camera (thin horizontal black line) within the telescope field of view, it is expected that two different clusters in the IACT camera trigger.

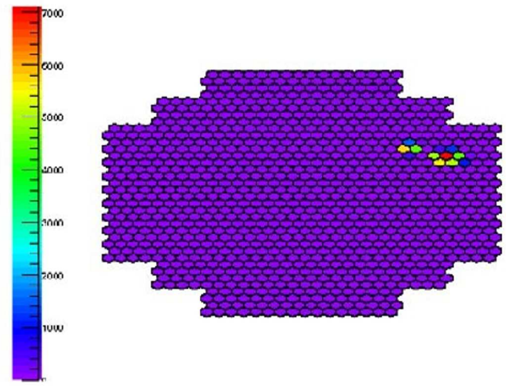

Figure 2: Simulated response of one H.E.S.S. camera triggered by a magnetic monopole event. Shown are two different clusters of pixel that are triggered by Cherenkov photons. Each pixel represents a camera photo multiplyer tube. The scale is the measured light intensity in units of photo electrons.

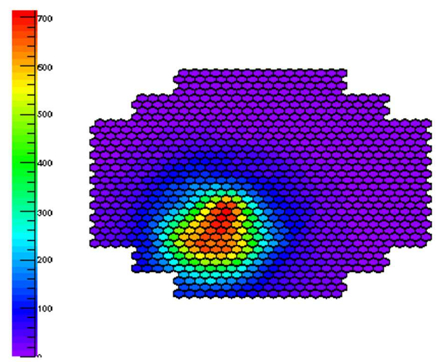

Figure 3: Simulated response of one H.E.S.S. camera triggered by a high energy proton shower. Each pixel represents a camera photo multiplyer tube. The scale is the measured light intensity in units of photo electrons.

4 Sensitivity Estimate for an IACT Analysis on Magnetic Monopoles

The example event displays Fig. 2 and 3 show obvious differences in the number of triggered pixel and the general intensity scale of triggered pixel in the cameras. For the quantitative separation of monopole events from background events it is useful to define a parameter space. The space is spanned by the number of triggered pixel in an event, i.e. the number of triggerd pixels in all 4 H.E.S.S. cameras and the number of saturated pixels in an event, i.e. the number of pixels in all 4 H.E.S.S. cameras with an intensity of more than 1500 photo electrons. Figure 4 shows the parameters space for simulated magnetic monopole events and for background events (high energy proton and photon showers). It is clearly visible that monopole events can be well separated from background events in this parameter space. Further studies show that a monopole selection efficiency of $> 90\%$ together with a background supression efficiency of $\gg 99\%$ is easily achievable. For the estimation of the sensitivity of the H.E.S.S. experiment to magnetic monopoles the effective areas A_{eff} have been calculated. At $20°$ zenith angle the obtained effective area is $(451 \pm 4_{\text{stat}})$ m^2sr at trigger level, i.e. without applied selection cuts. The stated monopole effective area for H.E.S.S. at trigger level is about 4.6 times bigger than the H.E.S.S. effective area for the detection of 1 TeV electrons [9]. The monopole trigger effective area is increasing with increasing zenith angle. At $60°$ the trigger effective area is a factor ≈ 4 bigger than at $20°$ zenith.
For the estimation of the sensitivity of the H.E.S.S. array to magnetic monopoles a livetime time of $\text{T} = 3000$ hours corresponding to the total livetime after about 5 years of

observation are assumed at zenith angle of $20°$. An estimation for the sensitivity is the upper limit on the magnetic monopole flux Φ that can be derived in case of a non detection via

$$\Phi < \frac{\mathrm{N}}{\mathrm{T}\epsilon_{\mathrm{cut}}\,\mathrm{A}_{\mathrm{eff}}} = \frac{\mathrm{N}}{\epsilon_{\mathrm{cut}}} \cdot 2 \cdot 10^{-14}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\,. \qquad (4)$$

Here ϵ_{cut} is the monopole selection efficiency and N is a statistical factor depending on the confidence level and the background suppression. Studies show that depending on the actual cut choice values of $\mathrm{N}/\epsilon_{\mathrm{cut}} = 2 - 4$ are achievable within the parameter space discussed above. Figure 5 compares the expected sensitivity of H.E.S.S. with a selection of upper limits on the magnetic monopole flux derived from different experiments ([6],[8]) and the Parker limit [6]. The sensitivity to a magnetic monopole flux expected from the analysis of a current generation IACT like H.E.S.S. is about 3 orders of magnitude worse than the upper limits derived from current generation neutrino telescopes. The main advantage of a neutrino telescope is the significantly bigger field of view. In the optimal case a neutrino telescope can cover the whole sky (4π). The magnetic monopole simulations performed for H.E.S.S. show that the field of view for H.E.S.S. is $\approx 4 \cdot 10^{-3}$ sr. Additionally the duty cycle of an IACT leads to a decrease in sensitivity to magnetic monopoles compared to the sensitivity of neutrino telescopes. Due to weather, moon and daylight limitations an IACT like H.E.S.S. is observing only $\mathcal{O}(4)$ h a day averaged over a year. A neutrino telescope can in the optimal case observe 24 h a day leading to a factor $\mathcal{O}(5)$ times more livetime of a neutrino telescope compared to a IACT in the same total time period. Additionally IACTs are only sensitive to magnetic monopoles with $\beta \approx 1$. Neutrino telescopes are in turn sensitive to magnetic monopoles with $\beta > 0.75$. However, IACTs offer a new and technically independent technique to search for magnetic monopoles.

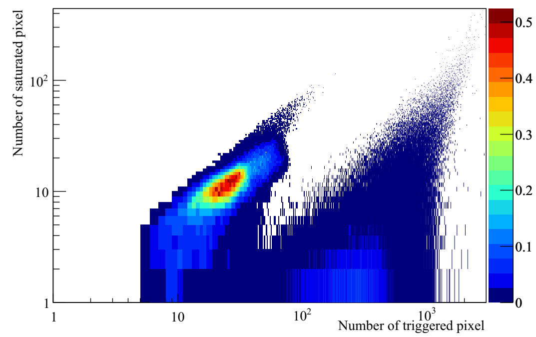

Figure 4: Parameter space for the suggested analysis as obtained from Monte Carlo simulations of magnetic monopole and background events. The space is spanned by the number of triggered pixel in an event (all four cameras) and the number of saturated pixel in an event. Magnetic monopole events are highly concentrated in the area $\approx 10 - 20$ number of triggered and saturated pixel. Simulated background (proton and VHE γ-shower) events are concentrated in the > 100 triggered pixel and < 3 saturated pixel area. The plot indicates the good separation power of the shown variables. The colour scale is the percentage of simulated events in a shown bin.

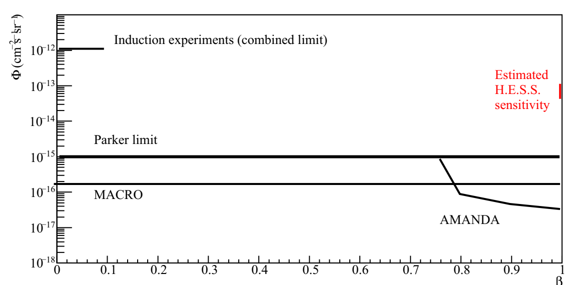

Figure 5: Upper limits on the magnetic monopole flux as function of the monopole velocity β as derived from selected experiments ([6],[8]) together with the Parker limit ([6]). The sensitivity of the H.E.S.S. experiment is shown in red. The sensitivity range indicates influences of cut choices.

5 Conclusion

The possibility of an analysis of IACT data for signatures of magnetic monopoles has been outlined. It was shown that IACTs offer good separation power of magnetic monopole events from background. Due to technical limitations concerning observation time and field of view the sensitivity of current generation IACTs like the H.E.S.S. array is however typically around 3 orders of magnitude worse than for modern neutrino telescopes. For planned IACT observatories as CTA [12] a sensitivity improvement of one order of magnitude can be assumed, leading to the possibility to reach a sensitivity comparable to the Parker limit.

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