HAWC Contributions to IGMF Studies

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Abstract: The intergalactic magnetic field (IGMF), presumed to exist in the void regions between galaxy clusters, may play a role in galaxy formation, contain information about conditions in the early universe, or influence the trajectories of cosmic rays of extragalactic origin. Recent studies have attempted to measure the IGMF by searching for its influence on the pair cascades produced when very high energy gamma rays from blazars interact with the extragalactic background light (EBL). The analysis of simultaneous data from imaging atmospheric Cherenkov telescopes (IACTs) and the Fermi Gamma Ray Space Telescope (Fermi) suggests that the strength of the IGMF may be greater than $10^{-15}$ gauss. However, this conclusion relies on assumptions about the properties of the source that are difficult to verify with existing IACT observations. The High Altitude Water Cherenkov (HAWC) Observatory, currently under construction on the slopes of Sierra Negra in Mexico, is uniquely situated to contribute to measurements of the IGMF. With an instantaneous field of view of 2 sr, sensitivity to gamma rays with energies above 50 GeV, and a large duty cycle, HAWC will provide unbiased observations of the average fluxes from blazars and accurate measurements of the attenuation of gamma rays due to interactions with the EBL.

In this work, we present the capability of HAWC to contribute to measurements of the IGMF via observations of the delayed secondary flux following a bright blazar flare.

Keywords: HAWC, blazars, gamma rays, IGMF.

1 The Intergalactic Magnetic Field

Magnetic fields are known to exist ubiquitously within the galaxies, filaments, and clusters that comprise the large-scale structure of the universe. However, conclusive evidence for the existence of a magnetic field in the void regions that dominate the volume of the universe remains elusive. The voids can become magnetized during phase transitions in the early universe, after which components of the field with correlation lengths large enough to withstand magnetic diffusion over a Hubble time evolve in strength only due to the cosmic expansion \[1\]. Referred to as the intergalactic magnetic field (IGMF), the field in the voids may provide the seeds for magnetohydrodynamic processes that generate the fields presently observed in galaxies and clusters. Seed fields with present-day values as small as $B = 10^{-20}$ gauss could readily explain the observed galactic and cluster fields when adiabatic compression and dynamo generation are taken into account \[2\]. At present, however, Faraday rotation measurements of distant quasars constrain the IGMF strength to be smaller than $10^{-9}$ gauss \[3\], leaving a wide range of field strengths unexplored and the seed-field hypothesis largely untested.

In recent years, a new technique has been developed that employs gamma-ray observations of distant blazars to measure the intergalactic magnetic field (IGMF) in the unexplored range from $10^{-18}$ to $10^{-14}$ gauss \[4,5,6\]. Gamma rays with energies above a few hundred GeV interact with the extragalactic background light (EBL), producing electron-positron pairs whose trajectories are sensitive to the strength of the IGMF. The pairs scatter target photons, primarily from the cosmic microwave background (CMB), via the inverse Compton process, producing a secondary cascade of gamma rays. Owing to the deflection of the pairs, the influence of the IGMF manifests in the time profile \[7,8,9\] and angular extent \[10,11\] of the cascade emission.

Several recent studies \[12,13,14,15,16,17,18,19\] have used ground-based imaging atmospheric Cherenkov telescopes (IACTs) to measure the attenuated direct flux which gives rise to the cascade. These studies have found that, due to the absence of any observed cascade by the Fermi Gamma Ray Space Telescope (Fermi), the IGMF strength is likely larger than $10^{-15}$ gauss. However, the conclusions of these studies rest heavily on the assumption that the sparsely sampled measurements of the flux from a few sources are representative of the flux from those sources over a period of several years, and a change of 50% in the average flux could invalidate their conclusions \[20\]. Unbiased measurements of the average flux from the sources are therefore required to interpret the results of these non-observations of the cascade by Fermi.

2 The HAWC Detector

The High Altitude Water Cherenkov (HAWC) Observatory, currently under construction on the slopes of Sierra Negra in the Mexican state of Puebla, is uniquely situated to contribute to studies of the IGMF. The characteristics and general capabilities of HAWC are described in detail in \[21\]. Boasting a large field of view of 2 sr and a duty cycle above 90%, HAWC will observe all blazars with declinations between $-20^\circ$ and $60^\circ$ in an unbiased manner every day. Among many other science goals, HAWC will monitor the long-term properties of the gamma-ray flux from these blazars, and it also will search for strong flares. In this work, we focus on the capability of HAWC to detect the IGMF based on the timing information available from a bright blazar flare.
We assume a simple model in which the blazar emits a flare with
\[ S \]
where
\[ F \]
find pressed in flux units per
\[ \sigma \]
product of the secondary flux
\[ E \]
index, and
\[ \gamma \]
for background-limited observations, the significance
\[ S \]
as
\[ t \]
times
\[ EB \]
and
\[ CMB \]. If we observe this secondary flux between
\[ 3.1 \text{ Flare Model} \]
Blazars are known to be highly variable sources, often
\[ \gamma \]
will detect the Crab nebula at a significance of 5. Although equation 5 no longer applies because the flare and the time scale over which the cascade flux is observed is unlikely, it is worth noting that these simple calculations can select some reasonable values for the parameters of equation 5, so that a careful study of the internal structure of an intrinsic flare would show decay features on hour time scales in the HAWC energy range. Therefore, only a few extreme flares will have properties favorable for IGMF detection with HAWC. However, because of its wide field of view, HAWC will be able to catch many more flares than IACTs, boosting the chances of locating a hard flare with a high cutoff energy.

In the Fermi energy band, the picture is much different. Although equation 5 no longer applies because the flare and secondary emission occur in different energy bands, the cascade flux will be dominant, yielding a value of $f$ very close to 1. Thus, the interpretation of HAWC and Fermi data collected simultaneously during a flare may well yield information about the IGMF that would not be accessible to either instrument alone.

### 4.2 Time Scale

The time scale over which the cascade flux is observed should be long enough not to be confused with the intrinsic flare, but short enough that the significance as given by equation 5 is not reduced too much. We first consider the flare properties necessary for a detection of the IGMF using HAWC observations alone. When fully constructed, HAWC will detect the Crab nebula at a significance of 5σ in a single transit. It makes sense, then, to measure fluxes in Crab units and time in transits, or days. In this case, we can select some reasonable values for the parameters of equation 5: $S_0 \approx 5$, $f \approx 0.05$, and $I(t_1, t_2) \approx 0.9$. Plugging these values in, we arrive at

$$F_H \approx 20\sqrt{t_2 - t_1}. \hspace{1cm} (6)$$

In other words, for a cascade with a time scale of 100 days, if the flare lasted for 10 days, it would need to be about 20 Crab units. Although such an extreme event is rather unlikely, it is worth noting that these simple calculations demonstrate that the sensitivity of HAWC is good enough to make a marginal detection of the delayed flux following a flare. Moreover, equation 6 should be taken as an order-of-magnitude estimate rather than a firm limit, and it is likely that a more detailed analysis could reveal additional sensitivity.

Figure 4 displays the cumulative distribution of gamma rays in the cascade as a function of time. The intrinsic flare was injected at the redshift of Mrk421 with a spectral index of $\gamma = 1.5$ and a cutoff energy of 10 TeV. The curves are for field strengths ranging from 0 gauss to $10^{-16}$ gauss.

Figure 5 shows the cumulative distribution of cascade gamma rays for field strengths of 0 and $10^{-18}$ gauss, and for two different energy ranges to which Fermi is sensitive. Curves in the higher energy band are scaled by 0.4. The opening angles of the inverse Compton and pair production processes cause a delay time of a few seconds, while for $B = 10^{-16}$ gauss it takes about a year for the cascade to develop fully. If the intrinsic flare lasts for a week, then a field strength between $10^{-17}$ and $10^{-16}$ gauss will induce cascade delays on the order of a few months, much longer than the time scale of the flare, so HAWC should be sensitive to an IGMF with a strength in this range.

We next turn to the combination of HAWC and Fermi observations. For low field strengths, the cascade emission will be dominant in the Fermi energy band, and any time scale that is less than a year but longer than the intrinsic flare is likely to be detectable. Furthermore, it may be possible via a sophisticated analysis of the cascade structure to rule out a characteristic decay time scale in the Fermi data. In this case, we would be able to place a firm lower limit on the strength of the IGMF.

Figure 5 shows the cumulative distribution of cascade gamma rays for field strengths of 0 and $10^{-18}$ gauss, and for two different energy ranges to which Fermi is sensitive. Curves in the higher energy band are scaled by 0.5 for clarity. In the figure, it is clear that IGMF strengths around $10^{-18}$ gauss could be probed if the flare persists for no more than several days. Additionally, in the lowest energy band, the time scale in the $B = 0$ case is about an hour, suggesting that a careful study of the internal structure of an intrinsic flare would show decay features on hour time scales.
whereas the IGMF signal appears only in the cascade. Thus, would provide strong evidence for the existence of the within the flare, we may be able to identify the absence relative to the direct flux from the flare. Other mechanisms delay, however, will apply to all gamma rays in the flare, whereas the IGMF signal appears only in the cascade. Thus, a clear signature of the IGMF will be that only a fraction of the gamma rays would be energy dependent. An LIV-induced time delays are introduced into the gamma rays from a flare. Other mechanisms that introduce time delays can most likely be dismissed for the same reason.

In the future, HAWC will play a major role in any detection of the IGMF via blazar flares. Due to its ability to monitor the entire overhead sky, HAWC will catch flares as they happen, producing a large data set and identifying those flares most promising for a follow-up study using Fermi data. In the longer term, an instrument similar to HAWC but with significantly improved sensitivity could probe a broader range of IGMF strengths because it would be sensitive to delayed emission following weaker flares. HAWC can function as a pathfinder for such an experiment.

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