Revisiting Magnetic Monopoles bounds in light of new results of the Intergalactic Magnetic Field

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Abstract

Although significantly fainter than the Galactic Magnetic Field (GMF), the Intergalactic Magnetic Field (IGMF) is believed to pervade the vast Cosmic voids. The IGMF was lately constrained by novel upper and lower experimental limits which motivated us to investigate the scenario in which Magnetic Monopoles (MMs) are accelerated in the IGMF and GMF. We found that IGMF acceleration demands an update of the long-standing Parker bound. MMs are fascinating composite fields emerging naturally in several Beyond Standard Model physics. In this contribution we elaborate the acceleration scenario, and are therefore able to connect in a unique framework the MM mass, flux and speed at the Earth. This allows us to revisit the latest experimental limits solely expressed in terms of Lorentz factor. A dedicated attention will be made on the prospects for present and future Imaging Atmospheric Cherenkov Telescopes such as the Cherenkov Telescope Array in search of MMs.

Quick facts on Magnetic Monopoles

Magnetic Monopoles (MMs) are hypotetical particles that carry a quantized magnetic charge $g = n\, g_D = 2n\pi/e$, where the Dirac charge g_D is the unit magnetic charge, n is an integer. MMs were originally proposed by Dirac in 1931 [1] as an attempt to explain the quantization of the electric charge, which resulted in the exact symmetry of the Maxwell equations. In the '70s, 'T Hooft and Polyakov discovered that Grand Unification Theories (GUT) also predicted the existence of MM in the form of topological solitons, formed, as a result of symmetry breaking mechanisms [2, 3, 4, 5]. MMs would be stable over cosmological times and exist as cosmic relics in the present time, since the magnetic charge is conserved.

Magnetic Monopoles Acceleration

Once generated, MMs are accelerated by magnetic fields (MFs) present in the Universe. For this work, we limit to the two most contributing cosmic MFs: the **InterGalactic MFs (IGMFs)**, permeating the inter galactic space and cosmic voids, and the **Galactic MFs (GMFs)**, residing in our Galaxy. Further contributions should have smaller impact. IGMFs give significant contribution by virtue of the large coherence length of the fields, while GMFs because of their strength. IGMFs have not yet been detected, although we have now accumulated significant indirect evidence to support their existence. In particular, upper bounds are set by several measurements [6] (see Fig. 1). A recent conservative bound was set by the MAGIC collaboration [7] to $B > 1.8 \times 10^{-17}$ G and more stringent but less conservative bounds were set by *Fermi*-LAT [8].

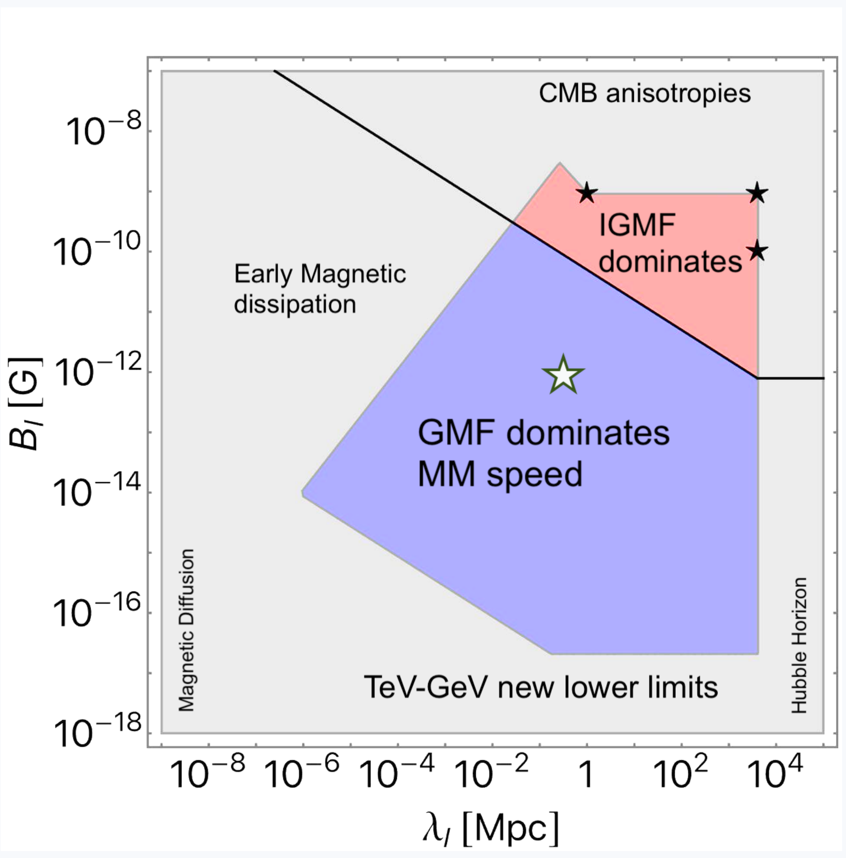

Figure 1: Current limits on IGMF (grey area). Red shared area is the region where the MM current speed is due to acceleration in the IGMF. Blue shaded are is where it is due to GMF.

Focus on IACTs

The only IACTs limits on MM were produced with H.E.S.S. data in [11]. In Fig. 3 we have upscaled the H.E.S.S. results of [11] considering the following factors: a) H.E.S.S. has a FOV of 6° (at least this was assumed in [12], while CTAO will host SSTs of 10°, thus entailing a factor 3 larger FOV, b) CTAO will display a factor of $10 \div 100$ larger effective area than H.E.S.S. [13], c) CTAO is planned to observe for 30 years, 6 times more than the H.E.S.S. data considered in [12].

Globally, **we may expect a factor** $3 \times 10 \times 6 \sim 200$ **of improvement**. Furthermore, [12] applies a speed threshold at $\gamma > 10^5$ to not account for the effect of the Earth magnetic field. We believe that by modeling this further effect, the speed threshold can be reduced to that required to generate Cherenkov photons close to the ground, that is $\gamma \gtrsim 100$.

As a result of this estimate, CTAO may be sensitive to intermediate MM mass up to $m = 10^9$ GeV. Such MMs would be accelerated to relativistic energies in the GMFs. Despite being generically less sensitive than PAO or IC, they could allow for independent measurement for MM, bridging PAO and IC results.

A global framework for acceleration of MMs

MMs are accelerated by MFs through the magnetic force As a consequence of the acceleration, in our ealier work [9] we demonstrated that, depending on the strength of the fields, the MM flux and the MM mass, cosmic MM background can reach relativistic velocities thanks to acceleration in IGMF. To compute the average current velocity of MM, we have taken into account the acceleration into IGMF and GMF in one Hubble time, the backreaction of the MM to the field energy and the MW peculiar velocity. As for the GMF, we model the Milky Way as $N \sim R/\lambda_G$ number of cells of uniform magnetic field B_G with size comparable to the coherence length of the field λ_G. Using $B_G = 10^{-6}$ G, $\lambda_G = 1$ kpc , and $R \sim 10$ kpc, we find a kinetic energy gain of $E_{k,G} = m(\gamma_G - 1) \sim g_D B_G \lambda_G \sqrt{N} \sim 10^{11}$ GeV.

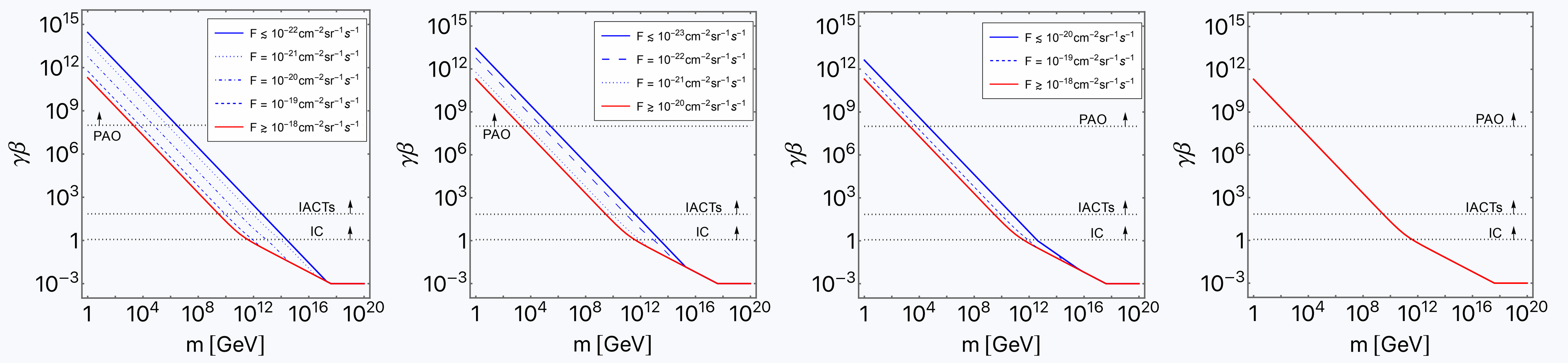

Figure 2: MM velocity on Earth as a function of the MM mass evaluated by taking into account the acceleration in IGMF and GMF. The results are shown for different MM fluxes, and the amplitude B_I and coherence length λ_I of IGMFs vary in each panel (From left to right: $B_\mathrm{I} = 10^{-9}\, G$, $\lambda_\mathrm{I} \gtrsim 1/H_0$; $B_\mathrm{I} = 10^{-10}\, G$, $\lambda_\mathrm{I} \gtrsim 1/H_0$; $B_\mathrm{I} = 10^{-9}\, G$, $\lambda_\mathrm{I} = 1$ Mpc; $B_\mathrm{I} \lesssim 10^{-11}\, G\, (1\,\mathrm{Mpc}/\min(\lambda_\mathrm{I}, R_\mathrm{H}))^{1/2}$.). The parameters for the Galactic magnetic field are fixed to $B_\mathrm{G} = 10^{-6}$ G, $\lambda_\mathrm{G} = 1$ kpc, and $R = 10$ kpc. The MM charge is fixed to $g = g_\mathrm{D}$. We show in black dotted lines the thresholds of the IceCube, IACT, Auger experiments for the detection of MMs.

The dominance of GMF versus IGMF acceleration depends on the characteristics of the considered IGMF and GMF and the effect of back-reaction on IGMFs as well as on the MM mass and flux. The relation of the speed with the MM mass is therefore non trivial. Examples are shown Fig. 2 for different choice of B fields and coherence lenghts and different values of the MM flux. We also add speed threshold level for detection in ground-based detectors.

Revisitation of the experimental bounds

With the acceleration framework above, we have build a mass-speed relation for MM and we can revisit the most stringent experimental limits in terms of the MM mass. We reformulate update results from MACRO, IceCube, the Pierre Auger Observatory and reports results from MoEDAL and order-of-magnitude predictions from future IACTs (Imaging Atmospheric ground-based Cherenkov Telescopes). Results are shown in Fig. 3.

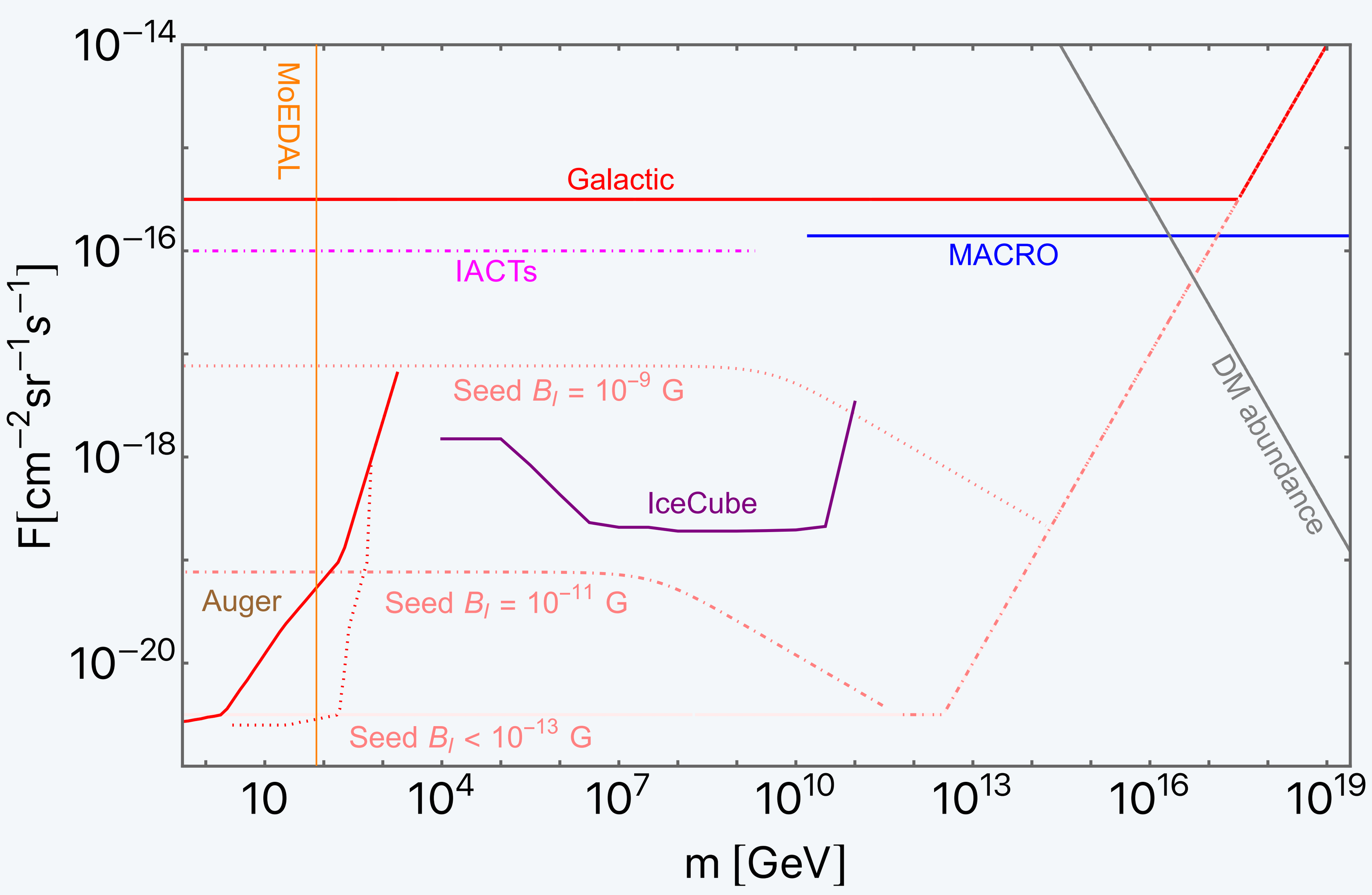

Figure 3: Fig 3. Bounds on the monopole flux. Gray: cosmological bound from comparison with the average dark matter density in the universe, red: Galactic Parker bound, pink: seed Galactic Parker bound (light: $B_\mathrm{I} < 10^{-13}$ G, dotdashed: $B_\mathrm{I} = 10^{-11}$ G, dotted: $B_\mathrm{I} = 10^{-9}$ G), blue: limits from the MACRO experiment, purple: limits from the IC experiment, brown: limits from the PAO collaboration (solid: Galactic acceleration only, dotted: intergalactic acceleration with $B_\mathrm{I} = 10^{-9}$ G and $\lambda_\mathrm{I} \gtrsim 1/H_0$), orange: lower limits on the MM mass from Schwinger production given by the MoEDAL experiment [10], dotdashed magenta: expected sensibility for the next generation of IACTs detectors.

The most constraining limits come from different experiments in different ranges according to the actual scenario. This should drive experiments to include the modeling of the MM acceleration in their limits. The **Galactic Parker bound (solid red curve)** appears to be the weakest of all bounds. The **seed Galactic Parker bound (pink curves)** would be the most constraining in several scenarios, especially at low IGMF amplitude or large MM masses (case $B_\mathrm{I} < 10^{-13}$ G or for $m \gtrsim 10^{12}$ GeV). We show also how strongly seed Galactic Parker bound is modified once taken into account MM acceleration from IGMFs [9].

The **MACRO limits (solid blue line)** are the strongest of those from direct searches for large MM masses. **IceCube limits (solid purple curve)** originally expressed in terms of speed, were recomputed using the MM energy loss in the Earth for all directions. They start to be competitive at small β, below the Cherenkov threshold in ice. For the fluxes tested by IC the acceleration mechanism is dominated by the GMFs. However, once the IC constraints will improve below $10^{-19}\ \mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$, they will become sensible to the acceleration for some values of IGMFs (red part of Fig. 1).

The bounds from **PAO (brown curves)** are the strongest at the very large Lorentz factors required to generate a sufficient signal in the atmosphere. Although the masses sensible to the PAO limits are currently almost completely excluded by the MoEDAL lower mass limit, increasing the sensibility of PAO to the MM fluorescence track would easily give access to larger MM masses. The current flux limits of PAO are sensitive to GMF only for an amplitude of $B_\mathrm{I} = 10^{-9}$ G (dotted curve for dominant IGMF acceleration, solid curve in the other cases). However, once the limit will improve with larger statistic, IGMF will be dominant.

Conclusions

In this work, soon to be submitted to journal, we re-evaluated the current strongest experimental limits on MM flux within a complete framework of MM acceleration. This framework includes acceleration in the IGMF, GMF, as well as mechanisms such back-reactions with depends on the actual MM flux. With this we have a complete mapping between MM mass and speed. Future updates on the cosmic magnetic fields could affect our results but our recipe will remain valid. We invite experiments to consider such framework for future limits and CTAO, ASTRI and Trinity to pursue MM searches.

References

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