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Bounds on monopole abundance from acceleration in cosmic magnetic fields

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Magnetic monopoles are intriguing hypothetical particles and inevitable predictions of Theories of Grand Unification. They are produced during phase transitions in the early universe, but mechanisms like the Schwinger effect in strong magnetic fields could also contribute to the monopole number density. I will show how from the detection of intergalactic magnetic fields we can infer additional bounds on the magnetic monopole flux, and how even well-established limits, such as Parker bounds and limits from terrestrial experiments, strongly depend on the acceleration in cosmic magnetic fields. I will also discuss the implications of these bounds for minicharged monopoles and magnetic black holes as dark matter candidates. The discussion on this paper is based on [1–3] and some preliminary results.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

https://pos.sissa.it/

PoS(ICHEP2024)652

1. Models of magnetic monopoles

The possible existence of magnetic monopoles was first theorized by Dirac in 1948. His model was based on the interpretation of monopoles as semi-infinite string solenoids. The magnetic field at the exit of the string is that of a point source, $\vec{B} = g\left(\vec{r}/r^3\right)$. In Dirac's theory the monopole is interpreted as an elementary particle and the string associated with it is not considered physical. This implies that when one goes around the Dirac string, the quantum wave function of the electron in the static magnetic field of a monopole should remain single-valued. This is possible once imposed the charge quantization condition:

$$g = \frac{2\pi n}{e} = n g_{\rm D}, \tag{1}$$

where n is an integer and $g_{\rm D}$ is called Dirac charge, i.e. the fundamental magnetic charge. As a consequence of the charge quantization condition, the existence of monopoles provides a strong theoretical motivation for the quantization of the electric charge.

An interpretation of magnetic monopoles in terms of modern gauge theories has been proposed by 'T Hooft and Poliakov in 1974. They presented a model of magnetic monopoles as zero-dimensional topological defects of the vacuum manifold for gauge theories with spontaneous symmetry breaking (SSB). In particular, monopoles are interpreted as solitonic solutions of a vacuum manifold with non-trivial the second group of homotopy $\pi_2(G/H) \neq I$, where G is the symmetry group in the unbroken phase and H is the residual symmetry after the SSB, $G \to H$.

The simplest model that contains all the ingredients for the monopole solitonic solution is the $SU(2)$ Georgi-Glashow model,

$$\mathcal{L}(t,\vec{x}) = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \frac{1}{2}(D_\mu\phi^a)(D^\mu\phi^a) - \frac{1}{4}\lambda(\phi^a\phi^a - \eta^2)^2, \tag{2}$$

where $F^a_{\mu\nu}$ is the non-abelian field strength and ϕ^a is the vector triplet Higgs field responsible for the SSB. The monopole configuration is described by the so-called hedgehog solution for the Higgs field after the symmetry breaking:

$$\phi^a(\vec{x}) = \delta_{ia}\left(\frac{x^i}{r}\right)F(r), \tag{3}$$

where $F(r)$ is a shape function with $F(0) = 0$ and $F(r) \to \eta$ for $r \to \infty$. Within the monopole radius, the theory is still in the unbroken phase.

It can be shown that every time a simply connected gauge group is broken into a smaller group that contains a $U(1)$ the monopole solution exists and, consequently, monopoles are inevitable predictions of Grand Unified Theories.

2. New bounds from primordial magnetic fields

By noting that a population of monopoles would short out the magnectic fields inside galaxies, Parker obtained upper bounds on the flux of monopoles [4]. In [1] we presented a comprehensive study of the Parker-type bounds based on the survival of primordial magnetic fields during reheating and the subsequent epoch of radiation domination. We then extended the results to arbitrary charged

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monopoles and magnetic black holes in [2]. Our analysis can be applied to both elementary and solitonic monopoles.

Primordial magnetic fields accelerate the monopoles and the process of monopole acceleration extracts energy from the fields. The energy that the monopoles extract from the primordial magnetic field is consequently transferred to the primordial plasma through scattering processes with the relativistic charged particles of the plasma. With a monopole number density large enough, this can cause the disappearance of the field. The evolution of the magnetic field energy density can be derived by solving the equation:

$$\frac{\dot{\rho}_{\rm B}}{\rho_{\rm B}} = -\Pi_{\rm red} - \Pi_{\rm acc}, \tag{4}$$

where we define the dissipation rates due to redshifting and monopole acceleration as:

$$\Pi_{\rm red} = 4H, \quad \Pi_{\rm acc} = \frac{4gvn}{B}, \tag{5}$$

with v the monopole velocity and n the monopole number density. If $\Pi_{\rm acc}/\Pi_{\rm red} \gg 1$, the magnetic fields completely lose their energy and eventually disappear. If $\Pi_{\rm acc}/\Pi_{\rm red} \ll 1$, the back-reaction of the monopoles on the magnetic fields is negligible and the fields simply redshift as $B \propto a^{-2}$, where a is the scale factor.

In order to rewrite the condition for the survival of the primordial magnetic fields in terms of the monopole abundance today, we study the monopole equation of motion in the early universe and substitute the results for the monopole velocity in $\Pi_{\rm acc}$. The motion of a monopole with charge g and mass m that moves at velocity v in a Friedmann-Robertson-Walker metric from the end of magnetogenesis to the epoch of e^+e^- annihilation can be described by the equation:

$$m\frac{d}{dt}(\gamma v) = gB - \left(f_{\rm p} + mH\gamma\right) v, \tag{6}$$

where $-f_{\rm p}v$ is the frictional force due to the interactions of the monopoles with the particles of the primordial plasma, with:

$$f_{\rm p} \sim \frac{e^2 g^2 \mathcal{N}_c}{16\pi^2} T^2, \tag{7}$$

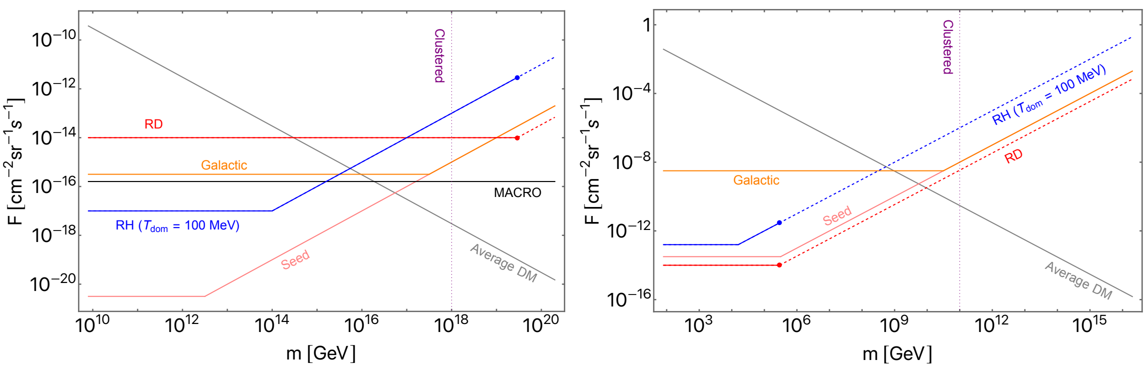
and $\mathcal{N}_c$ the number of charged relativistic degrees of freedom.

From the condition $\Pi_{\rm acc}/\Pi_{\rm red} \ll 1$, we obtain two different upper bounds on the average monopole number density in the present universe: one during radiation domination and one during reheating. During radiation domination, we obtain an expression that generalizes the result of [5] to arbitrary masses and charges:

$$n_0 \lesssim \max\left\{10^{-20}\ {\rm cm}^{-3},\ 10^{-20}\ {\rm cm}^{-3}\left(\frac{m}{10^{19}\ {\rm GeV}}\right)\left(\frac{g_{\rm D}}{g}\right)^2\right\}. \tag{8}$$

During reheating, we assume thermal equilibrium for the particles of the plasma, although stronger bounds can be obtained relaxing this assumption. For a process of magnetogenesis that ends sufficiently in the past, the bound is in this case:

$$\begin{aligned} n_0 \lesssim \max\Bigg\{ & 10^{-16}\ {\rm cm}^{-3}\left(\frac{B_0}{10^{-15}\ {\rm G}}\right)^{3/5}\left(\frac{T_{\rm dom}}{10^6\ {\rm GeV}}\right)\left(\frac{g_{\rm D}}{g}\right)^{3/5}, \\ & 10^{-13}\ {\rm cm}^{-3}\left(\frac{m}{10^{17}\ {\rm GeV}}\right)\left(\frac{T_{\rm dom}}{10^6\ {\rm GeV}}\right)\left(\frac{g_{\rm D}}{g}\right)^2\Bigg\}. \end{aligned} \tag{9}$$



(a) **(b)**

Figure 1: Upper bounds on the magnetic monopole flux today for (a) $g = g_D$ and (b) $g = 10^{-7} g_D$. Here we assume $B_0 = 10^{-15}$ G and for the monopole velocity today $v_0 = 10^{-3}$. Grey: cosmological abundance bound, red: bound in Eq. (8), blue: bound in Eq. (9) for a reheating temperature $T_{dom} = 100$ MeV, orange: Galactic Parker bound [4], pink: seed Galactic Parker bound [6], black: direct search limits from MACRO [7] (only for Dirac charge). The lower mass limit for clustering with the Milky Way is shown in dashed purple lines.

Here B_0 is the amplitude of the intergalactic magnetic field today. In this case, the bound depends on the reheating temperature, T_{dom}.

For this analysis we assume that the monopoles are able to transfer the energy gained by the magnetic fields to the primordial plasma, although this is not always the case. In particular, the interaction between monopoles and primordial plasma is strong enough to dissipate the gained magnetic energy only under the condition $m \lesssim 10^{19}$ GeV $(g/g_D)^2$. Strictly speaking, for larger masses a violation of the bounds does not lead to the disappearing of the primordial magnetic fields, but only to a different redshift evolution.

3. Minicharged monopoles and magnetic black holes

Dark Matter candidates have to meet two fundamental criteria in cosmological models: they should account for the required energy density, and they should cluster with observable galaxies. While magnetic monopoles have been considered as potential Dark Matter candidates, their efficient production remains a significant challenge. This is primarily due to the fact that traditional magnetic monopoles must have masses of order M_{Pl} to fulfill the two requirements. To address this challenge, we explored two distinct strategies. First, there is the option of reducing the monopole charge, leading to the concept of "minicharged monopoles". On the other hand, the second strategy involves enlarging the monopole mass, considering the existence of "magnetic black holes".

Considering minicharged monopoles relaxes the mass requirements and allows lighter monopoles to potentially serve as Dark Matter constituents. In Fig. 1 we show previous bounds on the monopole flux together with our new results for different values of the magnetic charge. The region of the primordial bounds where the condition is only on the redshift behaviour of the magnetic fields, and not on their disappearance, is shown in dashed lines. Notably, the primordial constraints on the monopole abundance are less dependent on the monopole charge and therefore become the strongest for small charges. Minicharged monopoles can cluster with the galaxies and be Dark Matter for masses much smaller than $M_{\rm Pl}$ and are less constrained by Parker-type bounds. As a result, minicharged monopoles are good candidates for Dark Matter.

Because of the no-hair theorem, outside the event horizon magnetically-charged black holes act as extremely heavy magnetic monopoles. Therefore, they can be candidates of magnetically-charged Dark Matter. Because of the charge, such black holes cannot evaporate by Hawking radiation and stop the evaporation when they become extremal. This allows us to consider magnetic black holes with masses much smaller than the lightest possible mass for uncharged evaporating primordial black holes. Then, here we consider quasi-extremal magnetic black holes, which present the fixed mass-to-charge ratio $g = m/(\sqrt{2}M_{\rm Pl})$. From the characteristics of the magnetic fields of M31, we exclude extremal magnetic black holes as Dark Matter both because of the galactic Parker bound and of the clustering condition.

4. Acceleration in late universe and modification of the bounds

Although in literature monopole velocity on Earth is usually assumed to be comparable to the MW peculiar velocity $\sim 10^{-3}c$, this is usually not the case because of monopole acceleration in cosmic magnetic fields. We study the acceleration in Galactic magnetic fields and in intergalactic magnetic fields in cosmic voids, modelizing the fields as cells of uniform magnetic field with size comparable to the coherence length of the fields. For the Galactic magnetic fields we consider an amplitude of $B_{\rm G} = 2 \times 10^{-6}$ G and a coherence length of $\lambda_{\rm G} = 1$ kpc. For the intergalactic magnetic fields we considered different values of the parameters within the intervals allowed by the constraints [8]. We obtain that the monopoles can be easily accelerated to relativistic velocities.

Cosmic acceleration of the monopoles affects the bounds on the monopole abundance. Galactic Parker bounds depend on the monopole incident velocity on the Milky Way and therefore on the acceleration in intergalactic magnetic fields. In particular, the bound based on the survival of the seed Galactic magnetic field [6] is relaxed by several order of magnitudes in the presence of strong intergalactic magnetic fields. Moreover, many cosmic ray experiments (as, for example, IceCube [9] and Auger [10]), provide bounds on the monopole flux in terms of the monopole velocity at the detector. Considering that the relevant parameter for fundamental physics is the monopole mass, the study of monopole acceleration is crucial to recast the bounds in terms of the monopole mass. Considering such mechanisms and studying the energy loss of the monopoles in the Earth, we translate the bounds into mass-dependent ones.

In Figure 2 we show the bounds on the monopole flux, after taking into account acceleration in intergalactic and Galactic magnetic fields. From the plot, one can observe how relaxing the seed Galactic Parker bounds for large intergalactic magnetic field amplitude $B_{\rm I}$ makes the direct bounds from cosmic ray detectors of IceCube and Auger the strongest for intermediate-to-low monopole masses.

5. Conclusion

The evolutions of magnetic monopoles and cosmic magnetic fields are strictly coupled throughout the universe's history. In this work, we presented two possible applications. First, we derived

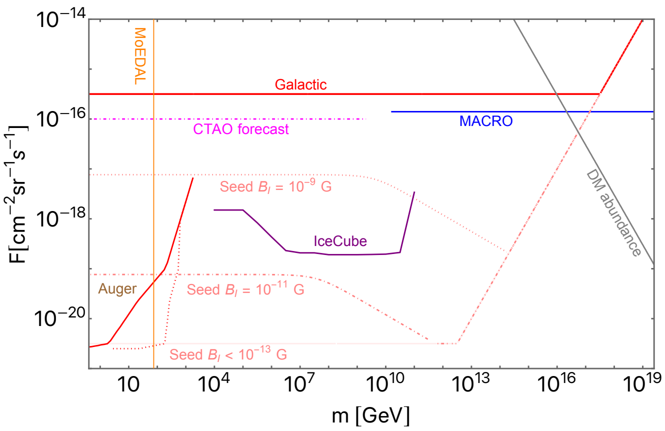


Figure 2: Bounds on the monopole flux. Gray: cosmological bound from comparison with the average dark matter density in the universe, red: Galactic Parker bound, pink: seed Galactic Parker bound (light: $B_{\rm I} < 10^{-13}$ G, dotdashed: $B_{\rm I} = 10^{-11}$ G, dotted: $B_{\rm I} = 10^{-9}$ G), blue: MACRO, purple: IceCube, brown: Auger (solid: Galactic acceleration only, dotted: intergalactic acceleration with $B_{\rm I} = 10^{-9}$ G and $\lambda_{\rm I} \gtrsim 1/H_0$), orange: lower limits on the monopole mass from MoEDAL [11], dotdashed magenta: expected sensibility for CTAO.

new bounds on the cosmic abundance of magnetic monopoles from the survival of primordial magnetic fields and generalized the results to arbitrary charged monopoles and extremal magnetic black holes. We then studied under which conditions monopoles can be considered as possible Dark Matter. Finally, we showed how the acceleration of monopoles in cosmic magnetic fields drastically affects the bounds on the monopole flux, in particular the seed Galactic Parker bound and direct search limits.

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