Astrophysical Indirect Magnetic Monopole Searches and the Monopole Parameter Space

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Magnetic monopoles are particles that contain a single isolated north or south pole, as opposed to the dipole always found in nature, giving it the property of magnetic charge. Throughout the 20th century, direct detection searches in particle accelerator experiments and cosmic ray observatories that seek to provide bounds on the monopole parameter space have failed to yield proper candidates. Emerging technology in the detection of gravitational wave backgrounds and large-scale magnetic fields have made indirect detection methods a potentially feasible alternative to direct detection. It is found that such methods would be effective at setting stringent bounds on understudied parameter spaces for low-velocity, intermediate-mass, and milli-charged monopoles. Some indirect detection methods may also benefit existing monopole searches by providing guidance for future observations.

1 Introduction

Magnetic monopoles have been part of the scientific discussion surrounding electrodynamics for nearly a century. Magnets always appear in nature as dipoles, in which the north and south poles cannot appear independently of each other. Magnetic monopoles, on the other hand, would have a single isolated pole analogous to electric charge, which, by extension, posits that monopoles themselves are carriers of magnetic charge. In the late 1800s, James C. Maxwell published his equations of electrodynamics:

$$\begin{aligned} \nabla \cdot \vec{E} &= \frac{1}{\varepsilon_0}\rho_e & -\nabla \times \vec{E} &= \frac{\partial \vec{B}}{\partial t} \\ \nabla \cdot \vec{B} &= 0 & \nabla \times \vec{B} &= \mu_0 \vec{j}_e + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \end{aligned} \tag{1}$$

where $\vec{j}_e$ represents the electric current density and ρ_e is the electric charge density.

The equations are the best classical description of the behavior of electric and magnetic fields from the perspective of classical mechanics. Gauss' law for magnetism states that $\nabla \cdot \vec{B} = 0$ due to the description of the magnetic field as the curl of a gauge-invariant vector potential $\vec{B} = \nabla \times \vec{A}$. The lack of magnetic field divergence predicts that there must be no magnetic charges. However, the equations of electrodynamics take on an elegant symmetry when adjusted to accommodate them[1].

$$\begin{aligned} \nabla \cdot \vec{E} &= \frac{1}{\varepsilon_0}\rho_e & -\nabla \times \vec{E} &= \vec{j}_m + \frac{\partial \vec{B}}{\partial t} \\ \nabla \cdot \vec{B} &= \rho_m & \nabla \times \vec{B} &= \mu_0 \vec{j}_e + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \end{aligned} \tag{2}$$

Note how there are now terms for magnetic current density $\vec{j}_m$ and magnetic charge density ρ_m. Furthermore, the key equation $\nabla \cdot \vec{B} = 0$ is now non-zero.

Though Maxwell's equations provide a compelling classical formulation of the magnetic monopole, it is the quantum origins of magnetic monopoles that has driven developments in theoretical physics for decades. Paul Dirac later proved that by imagining a solenoid of infinite length and infinitesimal width (with no physical meaning outside of the mathematical realm) connecting two monopoles with a strength $\mu = \frac{1}{2}nhc/e$, quantum mechanics allows for a working magnetic monopole solution. From the concept of this "Dirac String" it is possible to derive the original equations

$$\frac{hc}{eg_D} = 2 \tag{3}$$

$$g_D = \frac{137}{2}, \tag{4}$$

where g_D is the quantum of a Dirac magnetic charge. The most notable finding was that the observation of quantized magnetic charge requires quantization of electric charge, where magnetic and electric charges are related by the Dirac Quantization Condition (DQC), now in natural units for simplicity:

$$\frac{qg}{2\pi} \in Z \tag{5}$$

Amazingly, quanta of electric charge have been observed for over a century. Thus, the convenient and aesthetically pleasing solution provided by the DQC has become a primary motivation in the search for monopoles[2,3].

Subsequent developments in quantum field theory have introduced further motivations. Gerard 't Hooft and Alexander Polyakov significantly altered the theoretical search for monopoles when they independently discovered that certain solutions to the Higgs and gauge field equations (namely the "hedgehog solution") allow for monopoles. The solution can be imagined as a vector field that radiates from an origin. At its origin, the field takes on a form resembling a dense packet of energy that, according to mass-energy conversion, is functionally a particle with measurable mass. That particle appears to take on the properties of a magnetic monopole, and such solutions appear in the vast majority of Grand Unified Theories (GUTs)[*]. These monopoles are stable and thus do not exhibit any form of decay because the hedgehog solution is impossible to smoothly turn into a uniform vacuum state[4,5].

In GUTs, 't Hooft-Polyakov monopoles appear as the universe cools (in what is known as a phase transition where the symmetry of GUTs break and separate the fundamental forces) following the Big Bang and would have a mass on the order of at least 10^{16} GeV. However, many theories predict a high rate of monopole formation that is not observed experimentally. The theory of inflation, originally created to solve the so-called "monopole problem", rectifies this disparity by stating that GUT monopoles were diluted to the levels observed today by the rapid growth of the early universe immediately after the formation of monopoles[†]. At such levels, GUT monopoles would be difficult to observe[6], and this theory has become a primary focus of modern monopole research.

The search for magnetic monopoles has been as eclectic as it has been inconclusive. Modern searches, though significantly more advanced than their predecessors, mostly follow the same methods. The properties of monopoles, apart from the fact that they carry magnetic charge, are relatively unknown and predicted values can differ significantly between models. As such, monopole research focuses on eliminating certain values of the properties that are least likely to correspond to experimental results. This "parameter space" spans multiple orders of magnitude for many different properties, and it is thought that providing increasingly stringent limits on monopole parameter spaces, bolstered by new theories beyond the Standard Model (SM), will play a role in the particle's eventual discovery or discredit[7].

One can imagine the monopole parameter space as a large, dark room containing a small box. An observer is placed in the room with a flashlight and is told to find the box. As the observer uses the flashlight to illuminate parts of the room, failure to find the box eliminates all visible areas as candidates for the box's location. Consider the position of the box as its parameters (the x coordinate could be an analog to mass, y to charge, etc), and the flashlight as an observation method (such as a particle accelerator search).

It is clear that the lack of candidates (though it is naive to describe such a situation as stagnation) may be attributable to shortcomings within the methods used today. Furthermore, new advancements in scientific instrumentation are beginning to provide novel opportunities for future research in astroparticle physics and cosmology, of which some may have potential applications for magnetic monopole research. Indeed, magnetic monopole research as a whole is likely to continue as its various potential applications would help to confirm some of the most comprehensive[‡] theories in modern physics.

This paper seeks to summarize the physics behind current direct and future indirect methods of magnetic monopole research to answer the question of how novel indirect searches for magnetic monopoles can compensate for the shortcomings of direct detection methods. The structure of this review is as follows: The research methods are elaborated along with discussions of the limitations of this paper. The theoretical motivation and findings of previous searches for magnetic monopoles are presented in Section 3. Several candidates for indirect detection methods are explained Section Section 4. Discussions and a comparison between direct and indirect methods, as well as the implications future research may have on the parameter space is mentioned in Section 5. Suggestions for future research and final comments are made in Section 6.

2 Methods

This review does not seek to provide its own bounds on monopole research, instead referencing data from other experiments. It intends to synthesize the information to compare indirect and direct monopole searches as a means to identify their strengths and weaknesses.

Such a compilation of various experimental searches for monopoles inherently contains results deriving from dissimilar datasets that are constantly evolving. With varying parts of the parameter space being covered, it is difficult to propose a direct comparison between these data sets as noted by A. Rajantie[8]. Findings that handle similar parts of the parameter space are therefore grouped, and preliminary results from recent experiments are noted but not elaborated upon due to the general

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[*] GUTs are believed to apply at high energies found immediately following the Big Bang where the electromagnetic, strong, and weak forces combine. It can be described as the gauge group $SU(5)$ (or others), which breaks apart during the GUT phase transition into the groups $SU(3) \times SU(2) \times U(1)$ once the local energy goes below a certain threshold, producing more familiar mechanics.

[†] It is important to note that inflation also solves both the horizon and flatness problems in cosmology, lending more credibility to the theory as a possible explanation for the experimental scarcity of GUT monopoles.

[‡] especially String theory, which is the only working theory of quantum gravity

lack of sufficient data necessary to make specific conclusions. Magnetic monopole-adjacent particles such as dyons (particles with electric and magnetic charge) and pseudo-monopoles are excluded as they lie beyond the scope of this review.

It is important to note that the recency of most of the information regarding indirect monopole searches entails that any claims about the future exploration into the monopole parameter space from indirect methods are purely hypothetical. The experiments referenced in this paper are assumed to have employed adequate controls to eliminate alternative explanations to the results found, and judgements regarding the validity of the data falls outside of the scope of this paper. Nonetheless, some sources may not have been peer-reviewed at the time of writing or are published exclusively on ArXiv. The lack of more recent data to be corroborated is therefore a limitation.

3 Previous Monopole Searches

Most searches for magnetic monopoles have come from efforts to either create or observe them directly. Magnetic monopoles would theoretically leave behind distinct signs that measurement devices can detect, and the theoretical feasibility of such direct detection methods makes them attractive to experimental physics[1]. The main methods in use today are monopole synthesis in particle accelerators, cosmic-ray searches, and the study of matter.

3.1 Particle Accelerators

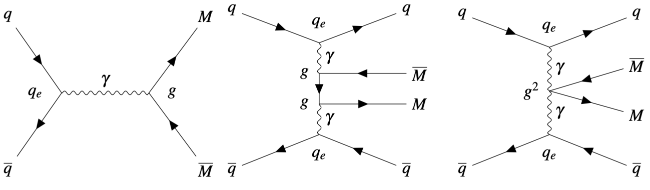
Particle accelerators are some of the most advanced instruments in modern science that can search for monopoles. They operate by pushing particles (frequently protons) through a vacuum to speeds approaching the speed of light. Superconducting magnets kept at extremely cool temperatures aid in guiding and accelerating the particles. The subsequent collisions between these high-energy particles give rise to new ones through energy-mass conversion, and the products of their decay can be measured[§]. The largest of these is the Large Hadron Collider (LHC), which can reach a center-of-mass energy of 14 TeV[9]. This energy is orders of magnitude below GUT scale energies. Still, monopole production at energies below 14 TeV has not been theoretically discounted, and measurements at particle accelerators can feasibly provide nontrivial limits for the monopole parameter space. Indeed, it may even be possible to detect electroweak pairs of monopoles and antimonopoles (sometimes called monopolium) heavier than 7 TeV at the LHC[10].

3.1.1 Monopole Production Channels in Particle Accelerators

Accelerator searches primarily look for monopoles produced through the Drell-Yan (or photon fusion) process. In this "tree-level" process, quark-antiquark pairs exist inside the colliding hadrons and annihilate into a photon that can decay into other particles. Although Drell-Yan production has described many SM particles[11], this process can be extended to the formation of magnetic monopoles in proton-proton collisions conducted at the LHC. This production is often grouped with the photon fusion channel, which also arises from proton-proton collisions (see Figure 1). The process works as the name suggests: two hadrons emit photons that fuse to create new particles, including magnetic monopoles. It was recently found that the photon fusion cross section is dominant over the Drell-Yan process[12].

The primary drawback to using the Drell-Yan and photon fusion processes as a production channel is that they rely on perturbation theory. Perturbation theory works by using a small deformation or "perturbation" in a problem to calculate approximations of systems that are either extremely difficult or impossible to solve exactly. Given that one of the most important conditions required by the DQC is that the magnetic charge must be very strong, calculations using perturbation theory are frequently impossible (especially if the coupling constant of the theory is $>> 1$). Furthermore, most magnetic monopole models ('t Hooft being chief among them) are solitonic or posit the existence of monopoles in a type of bound state, cases in which perturbation theory breaks down[1].

Mass bounds from cross sections using Drell-Yan therefore only provide estimates for the monopole parameter space, which may prove to be a fundamentally flawed method in determining a monopole's true properties[13]. However, this has not stopped efforts to detect monopoles through Drell-Yan and photon fusion, since there remains a chance that some magnetic monopole models will work under perturbative methods, in which case studies using such production channels would be necessary.



(a) DY monopole production. (b) Three-vertex PF process. (c) Four-vertex PF process.

Fig. 1 Feynman-like graphs depicting Drell-Yan and photon fusion monopole production[12].

The second prominent channel is the pair production of magnetic monopoles via the Schwinger mechanism. In his 1951 paper, Schwinger proved that the presence of an incredibly strong electric field could produce electrically charged particle pairs[14]. This idea can be extended to magnetic monopoles assuming that electromagnetic symmetry will give rise to the same phenomena

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[§] It is well-known that particle accelerators in the past have confirmed the existence of hypothetical particles. A famous example is the Higgs Boson, which was experimentally confirmed in 2012, completing the SM as we know it.

for magnetic monopoles (see Section 1). Should monopoles exist, a magnetic analog to the Schwinger mechanism is therefore likely.

Schwinger production has the counterintuitive advantage of being non-perturbative. Many magnetic monopole theories predict composite particles as opposed to point-like charges. The production cross sections are generally difficult to calculate since they are exponentially suppressed by the term $e^{-4/\alpha}$ where α is the electromagnetic fine structure constant, and magnetic monopoles tend to have strong coupling constants. Non-perturbative production channels like Schwinger production may not have this issue, and calculations for the production cross section may be done using semiclassical methods. So, non-perturbative methods can give more precise bounds for the mass of a magnetic monopole[15]. The mass M of a monopole produced by a field of strength $|\vec{B}|$ is given by the equation

$$M \gtrsim \sqrt{\frac{g^3|\vec{B}|}{4\pi}} \tag{6}$$

The major caveat to this theory is that the original model for Schwinger production has not been experimentally observed, requiring an electric field strength of 10^{18} V/m as given by the masses of known carriers of electric charge. This strength is beyond current technological capabilities, and as such it is not yet possible within modern technological constraints to induce the pair-production of electrons[13]. If it is found that the Schwinger mechanism does not exist, it would functionally invalidate any magnetic equivalent. Such a lack of evidence may call into question the viability of accounting for such production channels in the search for monopoles, even if magnetic Schwinger effects can occur at weaker field strengths. Nevertheless, as one of the few non-perturbative methods to date, one that is currently understudied, Schwinger pair-production is a promising avenue of monopole production and has been gaining attention as a candidate for future research endeavors.

3.1.2 MoEDAL

The Monopole and Exotics Detector at the LHC (MoEDAL) is an ongoing monopole search at CERN as the only instrument specifically built to detect magnetic monopoles and other Highly Ionizing Particles (HIPs). It is positioned near the LHCb detector and has provided some of the best bounds for monopole production at particle accelerators.

Its primary instruments used in magnetic monopole detection are the Nuclear Track Detector (NTD), which reads the distinctly ionizing tracks from magnetic monopoles in plastic sheets, and a magnetic trapping detector (MMT), which uses aluminum nuclei to trap magnetically charged particles using aluminum's unique magnetic moment. Both NTD and MMT are analyzed annually. A new subdetector called MAPP began operations in 2024 and uses scintillator bars to detect passing HIPs while being protected from cosmic rays. Due to the lack of sufficient data from the MAPP project, this review will not provide further descriptions of the experiment.

MoEDAL has searched for Drell-Yan/photon fusion and Schwinger monopoles within a pseudorapidity[¶] of $2 < \eta < 5$ with data from NTD and MMT[16]. MoEDAL did not find any monopoles but presented new bounds on monopole production for Drell-Yan/photon fusion with magnetic charges from $1g_D$ to $10g_D$ and a mass up to 3.9 TeV. For the Schwinger mechanism, it provided bounds for monopoles of charges between 2_{gD} and 45_{gD} and limited masses < 80 GeV[17]. The results are shown in Figure 2.

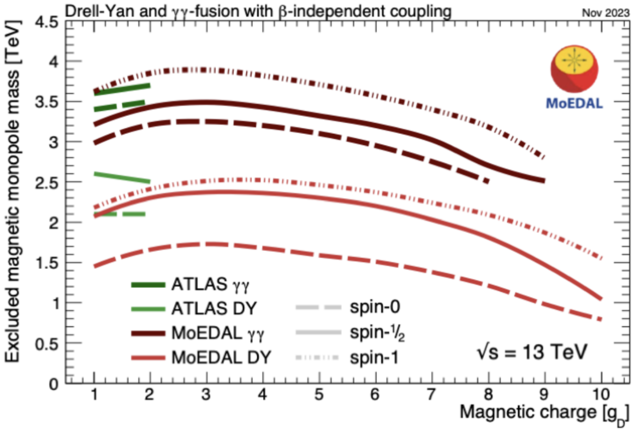

Fig. 2 Lower bounds from the first two runs of the MoEDAL experiment compared to results from ATLAS[17].

The data demonstrates the lower bounds for magnetic monopole masses according to Drell-Yan and photon fusion channels. The bounds often differ heavily between different hypothetical monopole properties. However, as it has already been established that the perturbative nature of Drell-Yan and photon fusion render these production methods ineffective, this data may not be entirely valid (see Section 3.1.1). Furthermore, the excluded monopole masses occur on the scale of TeV, which is around the order of 10^3 GeV. This represents only a small sliver of the monopole parameter space, limited by the amount of energy produced in the LHC. Without new instrumentation, it not currently possible to reach higher energy levels.

3.1.3 ATLAS

The ATLAS detector is a multipurpose detector at the LHC that uses an Argon or Xenon gas-based Transition Radiation Tracker. It also consists of an electromagnetic calorimeter, which uses layers of lead and liquid Argon-filled copper electrodes. ATLAS is more sensitive to magnetic charges of $1g_D$ to $2g_D$ and a pseudorapidity of $|\eta| < 1.375$ and has provided stronger bounds than MoEDAL for magnetic monopoles of these

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[¶] Pseudorapidity is a measure of angular coordinates used within the particle accelerator tube at LHC.

charges created by Drell-Yan and Schwinger mechanisms (reference Figure 2). The ATLAS group also provided a lower limit of 3.5×10^3 GeV on the mass of magnetic monopoles produced by Drell-Yan and photon fusion pair production and < 120 GeV for Schwinger-produced monopoles[18,19].

The results from ATLAS experience the same pitfalls as MoEDAL, however, being extremely limited in scope and held back by the technological constraints of the LHC. Though it creates stronger bounds for low-charges, especially for Schwinger-produced monopoles, it is less comprehensive than the MoEDAL study.

3.2 Cosmic Rays

Cosmic rays are particles that travel through space at relativistic speeds. Though they can be difficult to detect, they provide significant information regarding the conditions of the early universe and high-energy objects. Cosmic ray detectors searching for monopoles consider monopole masses on the order of around 10^{17} GeV or near the order of GUT monopoles. Monopoles would leave distinct tracks in detectors due to their high energy and ionizing effects, hypothetically arriving from all directions, with variations in their velocity providing clues about their origin[20]. Monopole searches in cosmic rays frequently seek to improve upon what is known as the Parker Bound, which operates on the principle that concentrations of magnetic monopoles above a certain threshold would lead to the extinction of large-scale magnetic fields (This will be elaborated upon in Section 4)[21].

It is important that extra emphasis is given to a crucial differentiating factor between accelerator and cosmic ray studies. Compared to accelerator studies, which mostly consider the mass and charge of magnetic monopoles, studies into cosmic rays can consider the abundance of monopoles in interstellar space evidenced by their flux.

3.2.1 MACRO

The Monopole Astrophysics and Cosmic Ray Observatory (MACRO) is an underground GUT monopole detector[‖] located in Gran Sasso, Italy. The rock above it limits the mass of particles that can make it through to at least 1.3 TeV, making it a good candidate to search for massive cosmic rays. It has several components. The first is a scintillator, which absorbs cosmic rays and re-emits their energy as detectable light. In MACRO, there are specific scintillator detectors sensitive to slow monopoles (those traveling at $10^{-4}c$ to $10^{-2}c$) and fast monopoles (traveling at $5 \times 10^{-3}c$ to $5 \times 10^{-2}c$). It also has a streamer tube system in which rapid catalysis of nucleon decay attributable to GUT monopoles can be observed.

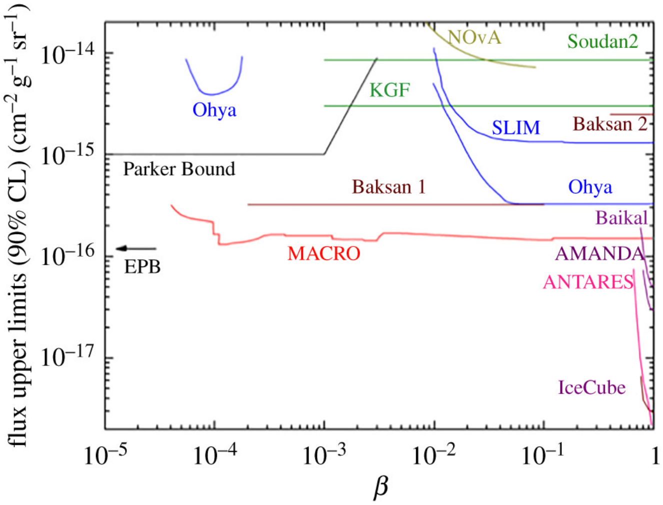

Fig. 3 Upper limits of the flux of GUT monopoles from MACRO compared with other cosmic ray searches[22].

Figure 3 shows the relationship between the flux and velocity range of magnetic monopoles. The experiment specifically determined the upper limits for the flux of GUT monopoles with a velocity range of $> 4 \times 10^{-5}c$ and charge between $1g_D$ and $3g_D$, with a general flux being at around $3 \times 10^{-16} cm^{-2} sr^{-1} s^{-1}$. This can be interpreted as the maximum number of magnetic monopoles that could feasibly exist in nature given observational constraints calculated from the lack of a significant monopole detection event[20]. Perhaps the most striking feature of Figure 3 is that MACRO appears to be the source of the strongest bounds on a vast swathe of the monopole parameter space despite being over two decades old. Currently, it is the most widely accepted upper bound for the monopole parameter space for velocity and flux, with stronger bounds only appearing at Cherenkov neutrino detectors specializing in ultra-relativistic particles such as IceCube and lower-mass cosmic rays from the SLIM experiment (see Section 3.2.2).

The only certainty provided by MACRO is that magnetic monopoles of the GUT variety are exceedingly rare, and such rarity appears to be common throughout much of the monopole parameter space. Nonetheless, newer experiments such as NOvA have already provided bounds for monopole mass ranges excluded by MACRO ($< 10^{10}$ GeV), albeit to a limited extent given their recency[23]. It will take some time before all of the data collected in this experiment is analyzed.

3.2.2 Improvements on MACRO Bounds

Of the most significant improvements on MACRO-derived bounds, the limits on relativistic monopoles from neutrino detectors have been the subset with the most recent progress. IceCube was originally built to detect neutrinos and is buried under the ice at the South Pole. Neutrinos interacting with the ice can produce muons that create Cherenkov light. Cherenkov light is radiation

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[‖] MACRO was also capable of detecting other cosmic particles, but its primary objective was to search for monopoles.

created as particles in cosmic rays travel in a medium faster than the speed of light in said medium. Relativistic monopoles, therefore, would also create Cherenkov light as they pass through the ice at incredibly high speeds, leaving behind a straight, extremely distinct path that would be easily recognizable. Other particles would exhibit some form of decay that would not be present in magnetic monopole signatures[24].

Much like the results from MACRO, IceCube placed bounds on the flux of the magnetic monopoles according to a recent study of the data collected at IceCube between 2011 and 2018. IceCube's results pertain to monopoles traveling at speeds of around .750*c* to .995*c*, putting its measurements into the relativistic monopole range. It considered monopole masses above 10^8 GeV (with higher sensitivity at higher masses) and determined an approximate flux of about $2 \times 10^{-19} cm^{-2} sr^{-1} s^{-1}$. The results are shown in Figure 4, which can be interpreted in context as a zoomed-in section of Figure 3[25].

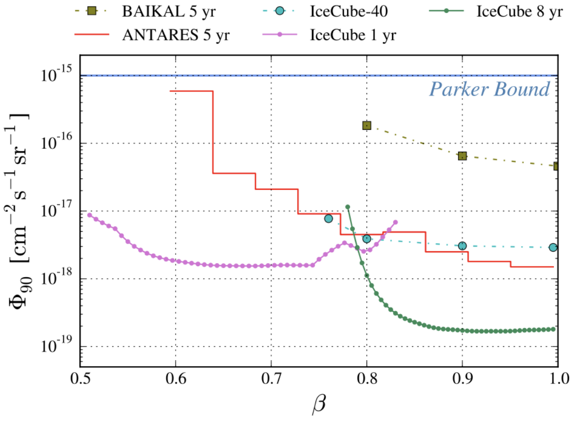

Fig. 4 Upper limits of the flux of GUT monopoles from IceCube compared with those from similar studies[25].

Though these bounds are incredibly stringent, IceCube and other relativistic monopole studies are often limited to extremely high velocities and are unable to consider slower monopoles.

Another improvement on the MACRO bound comes from the SLIM detector, which is unique among direct detection searches as the only experiment that is specifically sensitive to intermediate-mass magnetic monopoles. It primarily studied monopoles within the 10^5 to 10^{12} GeV range. The detector uses NTDs similar to those at MACRO except placed at the high-altitude Chacaltaya Laboratory in Bolivia instead of underground. The decreased number of particles between the NTDs and space allowed for lower-mass monopoles of charges between $1g_D$ and $3g_D$ traveling at $< .7c$ to penetrate to the location of the detectors.

SLIM set flux bounds at $1.3 \times 10^{-15} cm^{-2} sr^{-1} s^{-1}$, with its improvements to MACRO's results occurring below around 10^9 GeV masses[26]. Although these bounds are some of the strongest to date for intermediate masses, there is a distinct discrepancy between the strength of this bound and those for higher monopole masses. Intermediate mass monopoles continue to have some of the weakest parameter space limits today.

3.2.3 The Valentine's Day Monopole

Although it is widely regarded that there has been no evidence thus far to confirm the existence of monopoles, there is one case study that is worth mentioning.

On Valentine's Day, 1982, the superconducting ring[**] at Blas Cabrera's laboratory in Stanford University registered a quantized jump in the flux of its superconducting ring. The change in flux perfectly mirrored the amount predicted by a single Dirac charge assuming an uncertainty of ±5% and demonstrated quantization according to the DQC. Despite multiple efforts, the results of this experiment were never replicated even with newer, more advanced superconducting coil instruments. With a notable lack of potential causes for this measurement, it is not possible to discount the Valentine's Day Monopole as one of the best monopole candidates to date. However, the lack of replication means that the anomalous measurement is not proof of the existence of monopoles, nor is it confirmation that monopoles would have the specific flux observed in 1982. Still Cabrera's experiment provided bounds, for the flux of any moving particle with a charge greater than $.6g_D$[27].

3.3 Monopoles in Matter

The search for monopoles in matter is unique in that, while it has failed to reveal the existence of magnetic monopoles, it has simultaneously provided unique insights into the potential properties that monopoles may have.

3.3.1 Analysis of Matter

Early searches in this category often relied on the use of superconducting coils, not unlike the kind used in Section 3.2.3 connected to a SQUID. Magnetic monopoles of the GUT variety would be attracted to materials with magnetic dipoles, and passing such materials through a superconducting loop would generate a noticeable change in flux that could not otherwise be explained by the dipole moment. It is possible that the GUT monopoles trapped in matter would have accumulated during the formation of astrophysical bodies. Thus, trapped monopoles could be more feasibly detected by experiments than cosmic ray searches.

Nonetheless, no monopole has been found using this method. An influential study in 1995 tested a variety of magnetic materials, including meteorite fragments and hematite. It found

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[**] Superconducting rings have a detection loop carrying an electric charge. It is connected to a superconducting quantum interference device (SQUID) magnetometer that would detect a noticeable quantized change in the flux through the superconductor ring should a monopole of any origin pass through.

that the ratio of monopoles to nucleons of normal matter is 1.2×10^{-29} or less[28].

3.3.2 Psuedo-Monopoles

Further research into the analysis of matter is relatively slim as it has been overshadowed by new developments regarding the analysis of matter as a way to probe pseudo-monopoles. Pseudo-monopoles, while not being proper monopoles (monopoles as a new type of elementary particle), exhibit some of the characteristics of several monopoles predicted by quantum mechanics. Most notably, recent research into the emergent, Dirac string-like properties in Bose-Einstein condensates (namely, spin ice)[29] and materials science advancements for diamond quantum magnetometry experiments in hematite[30] have yielded technically monopole-like magnetic moments that do not have an independent component of mass or spin. Because these pseudo-monopoles do not contribute directly to the parameter space, this paper will not discuss their properties or methods of their creation further.

4 Novel Indirect Observation Efforts

All of the previous searches fall under the category of direct detection, in which the experiments and instruments attempted to explicitly measure the properties of a magnetic monopole. However, such searches have not identified any monopoles. Indirect observation methods have existed for years, but they may well be the future of monopole research as a result of significant developments in observational astrophysics and cosmology.

4.1 Parker Bounds and Large-Scale Magnetic Fields

One of the earliest and most prominent methods of indirect monopole observation is the observation of the survival of large-scale magnetic fields in the universe. The presence of a sufficient number of electric charges can neutralize electric fields. Thus, assuming symmetry, magnetic monopoles would do the same to magnetic fields. As they accelerate, monopoles convert the electromagnetic energy within the field into kinetic energy. Over time, the strength of the field would diminish by an observable amount[31]. There are two major types of magnetic fields used for Parker Bound measurements: galactic and intergalactic.

4.1.1 Galactic Fields and the Parker Bound

Galactic magnetic fields (GMFs) are magnetic fields that propagate within individual galaxies and often display a large level of organization relative to the galactic plane. The most studied field of this kind is, unsurprisingly, found in the Milky Way. There are several ways to measure such fields. Dust grains in interstellar space often align to magnetic fields, and powerful instrumentation can identify large-scale structures indicative of large-scale magnetic organization. Electrons spiraling around these fields will also release synchrotron emission in the radio frequency range, which displays a level of polarization that is easily observed. Further information comes from the Faraday rotation[††] of starlight (the most useful of which comes from pulsars). Certain light-emitting regions of the Milky Way also create the Zeeman splitting of spectral emission lines[32].

The most significant difficulty inherent to these methods is that the local magnetic fields of stellar objects frequently contribute to excessive foreground noise that must first be removed before the data becomes useful.

For example, the Faraday rotation of the plane of polarized light at angle ψ can be calculated using the equation

$$\psi - \psi_0 = \frac{e^3 \lambda^2}{2\pi m_e^2 c^4} \int_0^d n_e(l) B_{\parallel}(l) dl \tag{7}$$

where ψ_0 is the initial polarization angle, l is the light's position along the line of sight of the GMF, $n_e(l)$ is the thermal electron density, $B_{\parallel}(l)$ is the parallel component of the magnetic field at position l, and d is the distance from the radio source. This equation yields a way to quantify the amount of rotation as a function of wavelength

$$\psi = \psi_0 RM \lambda^2 \tag{8}$$

Where RM is the rotation measure variable[33].

Measurements of RM and similar metrics relies on two fundamental factors: that of the measurement of gas and dust that is part of the interstellar medium has sufficient levels of accuracy, and that software algorithms are able to properly apply this data. However, the current knowledge of the internal structure of the Milky Way at smaller resolution scales is poorly understood primarily due to our position within the edge of the galactic plane, which only provides a side-profile of the field. The complexity of the interactions between radiation, dust, and stellar objects is similarly difficult to calculate. Efforts to minismize such limitations have been underway for several decades through missions dedicated to reading the CMB, in which the GMF itself is the foreground noise[34].

Nonetheless, measurements of the strength, orientation, and overall decrease in strength (or lack) of these magnetic fields can provide non-trivial in determining magnetic monopole flux[32].

The indirect observation of magnetic monopoles through the Milky Way's magnetic field has remained one of the most feasible methods in modern science. Should monopoles exist in large amounts, one would expect the GMF to decrease over time. Furthermore, there is a likelihood that this effect would exist regardless of a monopole's mass, even if the strength of such an effect is mass-dependent. Understudied bounds in the intermediate-mass magnetic monopole can be accessed through measurements of GMFs as a result.

Bounds can also be derived from milli-magnetic monopoles (MMMs). They appear in certain dark-sector theories for which

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[††] Polarization of light passing through a magnetic field

the DQC must hold, with electromagnetic charges appearing in a dark $U(1)$ gauge symmetry. However, given that the DQC only holds for this model when the charges of both dark and normal sectors are summed, and because they should only weakly interact with baryonic matter, they must have a fractional magnetic charge and a mass on eV scales. Observations of field decay from MMM acceleration has the potential to provide incredibly strong bounds for incredibly low-mass monopoles[35].

Unlike more massive GUT monopoles and other solitonic solutions, the small mass of the MMM would make direct detection efforts almost impossible in conventional detectors in particle accelerators [‡‡]. It is highly likely that such detectors would not be optimized for MMMs as the primary purpose of a powerful accelerator is to create particles that are more massive, not less.

The most influential calculations of GMF bounds came from E. N. Parker, who predicted in his original paper that monopoles of a charge $g = 137e$ must be less abundant than one per 10^{26} to 10^{28} nucleons in interstellar space due to the lack of such diminishing fields. This can be written as a flux of approximately $F \lesssim 10^{-16} cm^{-2} sr^{-1} sec^{-1}$ and this category of measurement has come to be known collectively as the ”Parker Bound”[31,36].

It is this bound that most cosmic ray searches discussed in Section 3.2 and indirect astrophysical monopole searches seek to extend. It has undergone various changes as theoretical frameworks, data analysis methods, and instrumentation have improved over time [§§].

4.1.2 Parker Bounds from Intergalactic Fields

Intergalactic magnetic fields (IGMFs) propagate in the space between galaxies and contribute to a much more complicated picture of the Parker Bound. Due to their diffuse nature, IGMFs are difficult to study, and research into these fields is in its infancy as only the most sensitive instrumentation would be able to detect the subtle effects of IGMFs on the matter around them. They are currently highly theoretical since observations of them are relatively low-resolution. Similarly to GMFs, IGMFs induce Faraday rotation to the plane of polarized light, albeit to a lesser extent, so the presence of the fields can be inferred by reading this light. Over large distances, it is also possible to measure extremely bright events such as gamma-ray bursts and the resultant stream of cosmic rays. Magnetic fields affect the trajectories and propagation of these rays, creating a map of intergalactic field orientation and strength[32].

As with GMFs, IGMFs would accelerate monopoles, thus draining energy from the field. Measurements of the flux of monopoles from IGMFs are of particular importance since the galactic Parker Bound relies on the Milky Way as a detector, and the effect of a monopole on the galactic field is dependent on the monopole’s incident velocity to the galaxy[37]. Intergalactic estimates of the Parker Bound would be free of this constraint, depending more heavily on the strength of the surviving intergalactic field as demonstrated by Figure 5.

An intriguing possibility lies in research on the evolution of primordial magnetic fields into the IGMFs seen today, since their interactions with magnetic monopoles would determine the survival of such fields. In many models, they form during high-energy states of the early universe following the big bang either through the quantization of electromagnetic fields during inflation or as a result of symmetry-breaking at the electroweak energy scale. They are very likely to contribute to significant parts of IGMFs as they transfer energy into the intergalactic medium or by surviving inflation-related dilution[38].

Conveniently, the formation of primordial fields would mean that they form almost directly after the formation of magnetic monopoles. In a post-inflation universe with a relatively homogeneous, isotropic landscape, the decaying effects of monopoles would remove energy from this field as the monopoles are accelerated. Measurements of the strength of primordial fields [¶¶] would shed light on these effects. Primordial fields could have also been strong enough to Schwinger-produce monopole-antimonopole pairs that would affect the survival of such fields. Bounds from conditions consistent with current observations are stronger than the Parker Bound and direct searches at MACRO as seen in Figure 6[21]. Such interactions would necessarily give rise to better estimates.

The data from Figures 5 and 6 demonstrate a promising new avenue for calculating more stringent monopole flux bounds *that would otherwise be impossible to obtain through direct detection methods*. Similarly to cosmic ray experiments, the magnetic field readings would determine monopole flux for different charges assuming certain IGMF strengths, but at a far wider range of monopole masses. The information in Figure 5 is especially promising because it provides bounds in the monopole mass range between 10^3 and 10^6 GeV. Improved Parker Bounds will be crucial for validating the importance of future cosmic ray experiments and providing guidance for new projects searching for GUT monopoles.

The study of IGMFs is a relative newcomer into the field of astronomy, meaning that concrete data is rather limited in resolution and reach. Especially given that measurements of IGMFs are prone to the same pitfalls as GMFs, exacerbated by imprecise measurements, more research is needed on both the characteristics and origins of such fields. Further developments in the technology to detect their weak interactions with light and overcome low-resolution data will be the key to determining

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[‡‡] Since magnetic fields stronger than those in magnetars have been produced at the LHC, MoEDAL’s bounds technically exclude monopoles of this type[13].

[§§] The principles for the Milky Way’s magnetic field also apply to the magnetic fields of other galaxies, though observation is more difficult due to sheer distances that limit the amount of resolvable detail.

[¶¶] Which, while there is currently no successful observation, would be done through the observation of the CMB or through the Faraday rotation of polarized light in a manner similar to GMFs.

whether or not IGMFs will be able to truly have an impact on monopole bounds.

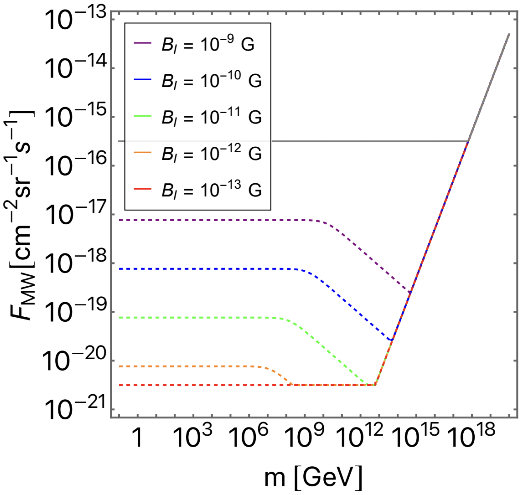

Fig. 5 Adjusted Parker Bounds for various intergalactic magnetic field strengths assuming a single Dirac monopole charge g_D. The grey line shows the original galactic Parker Bound[37].

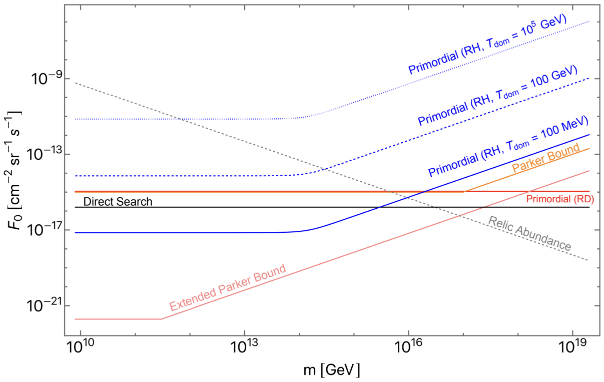

Fig. 6 Upper bounds for magnetic monopole flux for various primordial field reheating temperatures in comparison with other flux bounds. Direct search represents the MACRO experiment. Note that one primordial bound is stronger than the direct search results at lower masses[21].

4.2 Monopoles and the Gravitational Wave Background

Every monopole observation method mentioned so far has involved the use of light. Light itself is an electromagnetic wave, so it is sensible to believe that magnetic monopoles, a particle so fundamentally intertwined with the modern field of electrodynamics, would require observation through light. Even indirect detection methods through interstellar magnetic fields as seen in Section 4.1 invariably rest on measurements taken of light from objects affected by such a field. Yet gravitational waves suddenly become a feasible detection method if monopoles interact with extremely massive objects such as black holes and neutron stars. First predicted by Einstein's theory of general relativity, gravitational waves have been at the forefront of multi-messenger astronomy as the best alternative to electromagnetic radiation. They provide data on extremely high-energy events that warp spacetime[39], and the objects responsible for these events can not only interact with magnetic monopoles, but in these interactions give rise to measurable phenomena. There is a wide array of gravitational wave sources, but the interactions of neutron stars, supernovae, and black holes are the most promising.

4.2.1 Neutron Stars and Supernovae

One potentially useful tool in the search for monopoles comes from neutron stars. They form when stars collapse inward on themselves during a supernova and compact into an extremely dense body with uniquely strong magnetic fields. Similarly to GMF and IGMF measurements, reading the weakening of the magnetic fields in neutron stars from various monopole searches can provide bounds on the monopole parameter space. However, neutron stars (especially magnetars) have the advantage of briefly producing magnetic fields strong enough to Schwinger-produce monopoles. Not only would this have a stronger effect on the field itself, but it also provides one of the only known methods for the production of monopoles in an astrophysical source without GUTs. Most importantly, neutron stars would specifically be one of the only natural producers of MMMs[40].

While the incredibly small charge of MMMs makes conventional magnetic field measurements of neutron stars difficult, there is an emerging system that utilizes gravitational waves. As a result of their rapid rotation, especially immediately after formation, neutron stars experience surface deformations caused by strong magnetic fields, giving rise to continuous gravitational waves. Their oblate or prolate shapes can cause irregularities in the gravitational wave structures. This generates a distinct "pulse". Any monopole interaction with magnetars would weaken the effect of the magnetic field on the amplitude of the waves. The resulting change is theoretically distinguishable from monopole-free magnetars as seen in Figure 7. Since magnetic fields in this scenario would be much stronger at the beginning of a magnetar's life, they are a prime candidate for Schwinger-produced MMM bounds from gravitational waves[41].

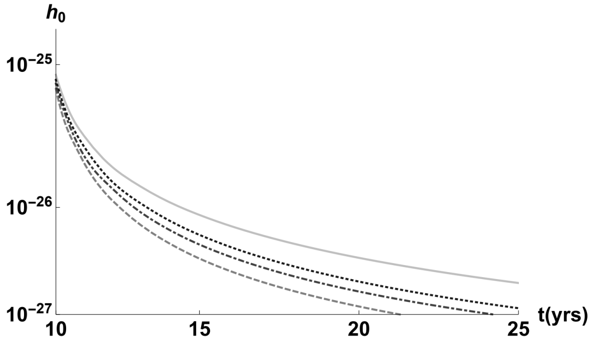

Fig. 7 Gravitational amplitude for waves created by a hypothetical millisecond magnetar. From top to bottom, the lines represent different MMM masses from no MMMs, 15meV, 20meV, and 25meV[41].

It is important to note that the existence of MMMs, like GUT monopoles, have yet to be confirmed. Although their potential usage in gravitational wave searches may be compelling, the theories surrounding them have little observational precedent that would separate them from other theories for magnetic monopole physics. Magnetic field decay in magnetars need not be the result of MMMs alone, and could feasibly occur as the result of more massive monopoles or from other phenomena unrelated to monopoles entirely. As of now, it is safe to assume that the overall weakening effect of monopoles on magnetar fields would occur regardless of whether monopoles were milli- or massive.

Gamma-ray bursts during core-collapse supernovae would also release gravitational waves, albeit from somewhat different mechanisms. Many GUT variety monopoles are expected to induce the decay of protons. Such effects should be present in a star that contains magnetic monopoles. Such processes would lead to the creation of neutrons. Measurements form the Super-Kamiokande experiment in 2012 provided proof that setting limits on monopole flux from measurements of neutrinos (as opposed to directly observing monopole Cherenkov light as was done in IceCube) would provide strong bounds [***] that can improve on existing bounds from cosmic ray observatories[42].

Monopole-related neutrino production may have strong implications for gravitational waves in supernovae. Traditionally, the majority of supernovae have been detected using electromagnetic radiation, but the detection of gravitational waves from the strongest ones may be feasible with third-generation gravitational wave observatories. During a supernova, neutrinos drive convection in the rapidly expanding plasma and create instability in the resulting proto-neutron star that has unique gravitational wave signatures[43]. Since monopoles affect the production of neutrinos, and by proxy the gravitational waves, such observations can provide monopole bounds by ”reverse-engineering” the monopole's impact in the star.

These gravitational wave measurements assume that stars will gravitationally attract monopoles through the accretion of matter during their formation. Certain measurements of unusually strong radial magnetic fields in various galactic cores (that cannot be explained by the accretion disk around the supermassive black hole) appear to match proposed models of supernovae catalyzed by monopole-related nucleon decay. Unfortunately, there are few investigations into this correlation, and further research is required before these proposed models can be validated.[44,45].

A significant limiting factor in this method is the convoluted system required for measuring the interactions between monopoles, neutrinos, plasma convection, and gravitational waves. This leaves many opportunities for outside factors to impact readings and create bounds that may not be accurate. Such interactions are only just now coming to light, so it is unlikely that monopoles will be the only contributing factor to gravitational wave anomalies in supernovae.

The superposition of gravitational waves from neutron stars and supernovae contribute to a Stochastic Gravitational Wave Background (SGWB).

4.2.2 Black Holes

Black holes may be capable of capturing magnetic monopoles, from which the strong magnetic charge would lead to pushing and pulling in the orbital resonance of binary systems[44]. Readings of this kind would be rather straightforward since gravitational waves from binary black holes were among the first kinds observed at LIGO, and it is no stretch to assume that a monopole's impacts on the orbital resonance would be distinct from non-monopole affected sources. These black holes would also contribute to the SGWB.

A much more difficult method would involve the study of primordial black holes. Magnetic monopoles formed in the early universe (likely of the GUT variety) would affect the matter around them and influence the formation rate and overall distribution of primordial black hole formation from the early accretion of large amounts of gas. These primordial black holes would release gravitational waves[46] forming a Cosmic Gravitational Wave Background (CGWB).

4.2.3 Detection of the Monopole-affected SGWB

SGWB observations appear to be more feasible than CGWBs because there are simply more of them to observe[†††]. Recent insights from LIGO and Virgo have brought the study of gravitational waves to the forefront of astrophysical research and a new opportunity to measure the early universe. Various sources

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[***] Though this method established incredibly strong bounds that would have significant effects on the parameter space, there is a concerning lack of follow-up research.

[†††] It is like the difference between observing a star and observing the CMB: stars are much easier to measure and often provide the foreground for the CMB.

of gravitational waves mentioned in this paper contribute to a local SGWB, which is the superposition of all these sources. The SGWB would appear to arrive from all directions and carry information about the objects that formed the constituent waves. Similarly to the cosmic microwave background (CMB), which is isotropic but displays subtle anisotropies, the gravitational analog would be anisotropic[47].

Until recently, the measurement of such backgrounds was not a feasible endeavor, but recent findings from the NANOGrav 15-year data set in its analysis of pulsar timings found evidence of a gravitational background with waves that have periods of years[48]. This research serves as a proof of concept that the observation of GWBs is possible with our current technology, albeit at prohibitively primitive levels.

GWB research may create opportunities for new magnetic monopole research as they provide a window to many events simultaneously and sections of space beyond the CMB. With the effects monopoles could have on existing sources of gravitational waves, future projects such as LISA[‡‡‡] and more comprehensive pulsar-timing studies will be invaluable tools in providing limits on large swathes of the monopole parameter space by means of the methods mentioned above.

As is the caveat with any indirect detection method, depending on the resolution of future GWB surveys, it will likely be nearly impossible to isolate magnetic monopoles as the sole cause of any detected anomalies. Gravitational waves are an emerging field, and significant improvements in the robustness of the data collected are necessary before it is possible to isolate monopole effects. Such shortcomings cannot be addressed until the technological gap is eliminated, which is unlikely to be tied to the construction of a single experiment or observatory.

5 Discussion

Direct and indirect searches, while both working toward the same goal, can consider fundamentally different parts of the monopole parameter space. This may not be obvious at first glance, as both methods use the same basic characteristics of monopoles such as flux, charge, and mass.

Let's return to the analogy of the parameter space as a dark room with a box from Section 1. While direct searches are like a flashlight that clearly illuminates a small section of the room, the search for magnetic monopoles from indirect astrophysical effects is akin to assuming the box has some previously determined effect on its surroundings. Consider the box makes a small but non-negligible amount of sound. Hearing the echoes of the sound bouncing off the walls may provide insights into the box's properties, but more importantly, such a measurement confirms the existence of the box in general. However, it is unknown what noise the box makes, nor how loud it will be.

Table 1 Qualitative Comparison of Direct and Indirect Detection Methods

Direct Detection Methods	Indirect Detection Methods
Strong technological precedent and robust research environment	Emerging field with little tangible data but with several planned experiments
Well-defined methodology for confirmation of monopole candidates	Incomplete methodology for confirmation of monopole candidates
Limited by energy scales producible and/or observable by instrumentation that are directly related to monopoles	Not limited by energy scales producible and/or observable by instrumentation but by monopole effects on astrophysical objects
Slower timescales for setting new bounds	Faster timescales for setting new bounds
High-resolution data	Low-resolution data

Each direct observation method in use today searches for monopoles by considering possible characteristics of the particle, more specifically by finding what the monopole cannot be. As shown in Table 1, such a method is thorough but incredibly slow, especially since monopoles may not even exist. Since the parameter space is quite large, spanning numerous orders of magnitude, there is no feasible method to find monopoles using direct observation within a short time frame. The intention of such methods is to ensure with certainty that a monopole has been found or to exclude that portion of the parameter space.

Table 2 General Bounds of Direct Detection Methods

Experiment/ Detection Method	Mass Bounds (GeV)	Flux Bounds ($cm^{-2}sr^{-1}s^{-1}$)	Charges Considered (g_D)	Velocities Considered (in terms of c)	Spins Considered
MoEDAL Accelerator	DY/PF: $< 3.9\times10^3$ Schwinger: < 80	Rarely considered	Drell-Yan: 1 - 10 Schwinger: 2 - 45	$< \frac{Z}{5}$	0, $\frac{1}{2}$, 1
ATLAS Accelerator	DY/PF: $< 3.5\times10^3$ Schwinger: < 120	Rarely considered	1 - 2	$> .999$ (Ultrarelativistic)	0, $\frac{1}{2}$
MACRO Cosmic Ray (Underground)	10^{10} - 10^{16}	3×10^{-16}	1 - 3	10^{-4} - 5×10^{-2}	Rarely considered
IceCube Cosmic Ray (Cherenkov)	10^8 - 10^{16}	2×10^{-19}	1	.750 - .995	Rarely considered
SLIM Cosmic Ray (High-Altitude)	10^5 - 10^{12}	1.3×10^{-15}	1 - 3	$< .7$	Rarely considered

Table 2 only includes information from the experiments featured in Section 3 for the sake of simplicity. It would be very

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[‡‡‡] The first space-based gravitational wave detector that can detect gravitational waves longer than those that can be found through terrestrial means[49].

difficult to compare every experiment and display it in a way that accurately reflects the complexity of the data. The mass bounds for MoEDAL and ATLAS are separated into Drell-Yan/Photon Fusion and Schwinger pair production for more specificity. All velocities are in terms of the speed of light, and the variable Z indicates a charge dependence when necessary. The category of analysis of matter is excluded because of the lack of recent findings.

As shown, current direct detection methods specialize in the extremes of monopole characteristics. Particle accelerators are capable of measuring low-energy, high-charge magnetic monopoles while considering spins, yet lack the power to probe high energies and rarely consider flux. Likewise, cosmic ray observatories excel in detecting high-energy, fast-moving particles that originate from extremely energetic events and provide insights into the early universe. However, due to the constraints of the environment on Earth, most detectors specialize in other particles, and those that have searched for monopoles are limited by the sensitivity of instruments and penetration ability of rays in the earth's atmosphere. This leaves a gap in the intermediate-mass, low-speed, milli-charged range within the parameter space.

Table 3 Indirect Analogs to Direct Detection Methods in the Parameter Space

Direct Detection Methods	Closest Indirect Analog
Particle Accelerator Searches	Magnetar/pulsar timing studies
MACRO-like Cosmic Ray Searches	GMF/IGMF measurements
IceCube-Like Cosmic Ray Searches	GMF/IGMF measurements, Studies of monopole-affected stars
SLIM-like Cosmic Ray Searches	GMF/IGMF measurements
Analysis of Matter	Studies of monopole-affected stars

Indirect observation methods may vary by method and consider completely different varieties of monopoles, but they are similar in that they may not be as dependent on the unique properties of specific parameter spaces. Most magnetic monopole models exhibit a strong magnetic charge and catalyze nucleon decay. These properties, regardless of their quantitative measurements, would fundamentally have the same overall type of effect on their surroundings exclusive to monopoles. Theoretically, nearly all masses, charges, and velocities are accessible to various indirect detection methods while each individual property remains independently testable. Findings would be defined primarily by the astrophysical source that is being observed, with different objects contributing to different parts of the parameter space as shown in Table 3.

Unfortunately, the benefits of indirect detection methods are greatly limited by the sheer lack of knowledge in the field. Many of the studies cited in this paper are based on theoretical models with no observational proof of existence. Until recently, technological constraints ensured it stayed that way. It is therefore exciting to consider new technological advancements in indirect astrophysical research as a way to rectify this situation. Ideally, by confirming the existence of magnetic monopoles through these signatures, indirect methods will guide the more targeted direct observation experiments to ascertain more specific properties.

6 Conclusion

Searches for magnetic monopoles through indirect detection methods provide a promising path forward from the precedent set by nearly a century of direct observation studies. While direct observation studies have contributed to stronger limits on the monopole parameter space, they have failed to confirm the existence of monopoles. With the large size of the monopole parameter space, it is inevitable that some sections may be overlooked or understudied. Indirect observation methods have been mostly unfeasible in the past, and with the proliferation of theories beyond the SM, theoretical progress will continue to require new experimental methods that can yield stronger bounds.

Measurements of the decay of galactic and intergalactic magnetic fields can help to probe for monopole candidates in the intermediate-mass, slow-moving sections of the parameter space. The wider-ranging scope of potential large-scale field studies has the potential to be an incredible guiding post for future direct detection studies. Similarly, gravitational waves can be used to measure the effects that monopoles have when concentrated into compact, high-energy objects. Future readings of the gravitational wave backgrounds that result from such monopole-affected objects will help search for milli-magnetic monopoles and aid flux estimates for GUT monopoles. In the case of significant monopole signatures, the work of indirect observation holds promise in revealing the general qualities of the monopole parameter space. It would be a surprise if monopoles, should they exist, do not have significant measurable effects on physical matter in the cosmos.

However, the study of intergalactic fields and gravitational waves is in its infancy, and it is only in the last decade that an experimental precedent for their detection has been established. There is no guarantee that any of the potential avenues for monopole research will be able to set stronger limits on the parameter space, and it would be counterproductive to discount existing direct detection methods in response. Further research is required in these fields before they can be used for magnetic monopole searches in astrophysical sources. It is my recommendation that future research regarding monopoles in the astrophysical realm be expanded and studied. Indeed, such searches, even if they fail to detect monopoles, will contribute significantly to the development of instrumentation crucial to the advancement of observational cosmology and astrophysics.

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