SMU-HEP-22-08

Notes on the Magnetic Monopole and the Black Hole Jet

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1. Introduction

For almost 100 years the concepts of symmetry dominated the phenomenological description of experimental observations and the development of theoretical physics. More recently the concept became a base for development of the cosmological model of the universe. The most often quoted successful example is the symmetry of the electrical and magnetic interactions. Introduced by the Maxwell's equations. Much of the work in the following 100 years on the mathematical foundations of the theory lead to the development of the Standard Model that unifies the description of electromagnetic and weak interactions and includes elements of the strong interactions. Its successes can be partially ascribed to the importance of the Maxwell's legacy. Recent successes of the Standard Model of Particle Physics and the current lack of significant experimental disagreements with its predictions that can be tested with the current technology has been frustrating progress in our understanding of what happens at higher energies. In parallel to particle physics a revolutionary progress has been made in observational and theoretical astrophysics. Hubble discovery of the expanding universe provided a connection between the particle physics and cosmology within the concepts of thermodynamics. The present picture postulates that at high enough temperature all interactions fulfill a global symmetry, i.e., have equal strength. With the expansion of space and lowering of the energy density with corresponding lowering of the temperature the sequential phase transitions dilute strength and separate interacting forces. The phase transitions freeze local fluctuations leading to emergence of particles representing lowest energy states.

For the past 60 years many scholarly articles and lectures started by listing the major inconsistences: the cross section for longitudinally polarized weak vector bosons W scattering raising to infinity with raising energy and the mass difference between the massless photon and heavy neutral weak boson Z. The discovery of the scalar Higgs particle resolved some of the theoretical issues but the question of why the desired symmetry of interactions is not fully manifested remains unanswered. A common example is a lack of full symmetry between electrical and magnetic interactions expressed by the existence of the lowest energy electrical charge e associated with electron and a failure to observe the corresponding unit magnetic charge – a monopole.

Much of the following introduction is based on somewhat dated but still the most accessible, excellent article by John Preskill [1]. Preskill prefaced his article with the following statements:

"How is it possible to justify a lengthy review of the physics of magnetic monopole when nobody has ever seen one? In spite of the lack of experimental evidence, there are sound theoretical reasons for believing that magnetic monopole must exist."

The motivation for the renewed interest in the magnetic monopoles is due to the impressive progress in understanding of the astrophysical process that can and do generate large magnetic fields. In particular jets originating from the vicinity of supermassive rotating back holes have been associated with enormous magnetic fields extending over distances of many parsecs and powering the jet-like emission of matter from the holes′ vicinity.
It is thus interesting to explore if we could learn something about monopoles from astrophysics research.

2. Symmetry in electrodynamics

Historically, magnetic field has been known since prehistory. The magnetic properties of the naturally occurring lodestone have been mentioned in writing of Greek Thales of Miletus at ~600 BC and have been mentioned in ancient Chinese documents. The pieces of lodestone, have been used as part of navigation equipment since early middle ages. The basic modern understanding of the laws of electricity and magnetism have been only discovered in the 19th century and culminated in the writings of J.C Maxwell in 1865 who has given the first hint of a symmetry of the behavior of electric and magnetic fields.

Maxwell's Equations

Gauss Law for electricity	$\nabla \cdot E = \frac{\rho}{\varepsilon_0}$
Gauss Law for magnetism	$\nabla \cdot B = 0$

Faraday Law for magnetism $\nabla \times E = -\frac{\partial B}{\partial t}$

Ampere Law $\nabla \times B = \mu_0 \text{ J} + \frac{1}{c^2}\frac{\partial E}{\partial t}$

Lorentz force equation $F = q_e(E + v \times B)$

3. Charge quantization

Historically, the next step was incorporation of the Maxwell equations into a quantum theory. Quantization brings additional problem. Measured electric charges are always found to be integer multiples of the electron charge. This statement was usually inserted in the discussions of classical electrodynamics. In the 1931 paper Dirac [2] considered the problem why the charge appears to be quantized. He observed that the existence of the magnetic monopole would be consistent with the quantization of the electric charge.

In his derivation he used a concept of semi-infinitely long thin solenoid, so thin that its diameter can be neglected. The end of such solenoid looks like a magnetic charge (see fig. 1) and if no conceivable experiment could detect the solenoid then its end could be considered as a magnetic monopole. In quantum mechanics the description of such monopole would be consistent with vector potential even though it has a “string” singularity at -π along the imagined solenoid.
If one places the end such end of the “solenoid” at the origin and its semi-infinite length along the negative z axis then the quantum mechanics description of wave function of electron moving along any closed loop trajectory requires that the phase of the electron wave function must be the same after return to the same point in space, irrespectively of the trajectory and of the wave function. This is possible only under assumption that the detection of the existence of the thin solenoid string cannot be detected, i.e., the loop can cross the singularity of the string. This change of the phase, however, can differ by 2πn. This is, in fact, a statement of the gauge invariance. For a pole of strength g and electric charge equal to e, the condition is fulfilled only when

$$eg = \frac{1}{2}\text{n}\hbar c.$$

Thus, the existence of one (magnetic) pole of strength g would require all electric charges to be quantized in units of $\frac{1}{2}\,\hbar c/g$ and similarly the exitance of one charge would require all poles to be quantized.

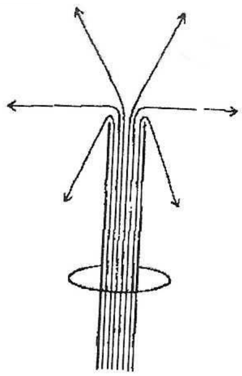


Fig.1 Dirac monopole approximation (from Ref. [1]).

In 1948 Dirac expanded [3] this simplified approach to a full-blown quantum filed theory

with a strengthened conclusion that "the quantization of the equations of motion of charged particles and particles with poles is possible only provided the charges and poles are integral multiples of a unit charge and a unit pole". From the equation

$$eg_m = 1/2n\hbar c$$

one can get the unit magnetic charge corresponding to n=1

$$g_m = \frac{1}{2}\frac{\hbar c}{e} \sim \frac{137}{2} e$$

There is no restriction on the strength of the magnetic pole or, for that matter, on the electric charge. The expectation is that for minimal (magnetic) pole and minimal electric charge (i.e., n=1) the numerical result is given by the fine structure constant $\alpha = \frac{1}{137}$.

Caution : many articles and textbook use variants of these definitions typically varying by a factor of 2 or 4π. In today's notation the "Dirac" magnetic charge of the monopole is $g_m = ½ e$ and the total magnetic flux emanating from the charge g_m is 4πg, while the electric charge emanating from the charge e is e.

The numerical value of the magnetic charge is

$$g_m = \frac{h}{\mu_0 e} = 3.29 \cdot 10^{-9}\ [A \cdot m\ \ or\ Jm^{-1}T^{-1}]$$

On a fundamental level Dirac has shown a consistency of the postulated existence of monopole with the quantization of charge. His approach does not exclude other possibilities of charge coming in multiples of a charge of electron. The Dirac magnetic monopole can be treated as a particle but there is no prediction for the classical Dirac monopole mass and the estimate of its production cross section cannot be derived. In all calculations the magnetic monopoles are treated as particles that come in two magnetic charges. The field theory allows particles to have both electric and magnetic charges. Such particles are called dyons. There is extensive literature discussing electrodynamics of such particles and except of complexity of calculations no special problems against their existence have ever been found.

4. Electrodynamics with magnetic monopoles

The postulate of magnetic monopole requires modification of the Maxwell equations and of the Lorentz force equation to produce full symmetry between electric and magnetic fields.

Maxwell's equations and Lorentz force equation with magnetic monopoles: Gaussian cgs units

Name	Without magnetic monopoles	With magnetic monopoles
Gauss's law	$\nabla \cdot \mathbf{E} = 4\pi\rho_e$	
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$	$\nabla \cdot \mathbf{B} = 4\pi\rho_m$
Faraday's law of induction	$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$	$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_m$
Ampère's law (with Maxwell's extension)	$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_e$	
Lorentz force law[23][24]	$\mathbf{F} = q_e\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right)$	$\mathbf{F} = q_e\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right) + q_m\left(\mathbf{B} - \frac{\mathbf{v}}{c} \times \mathbf{E}\right)$

Here the parameter ρ_m is the magnetic charge density and j_m is the magnetic current density. Note that in absence of electric charge and external electric field the Lorentz force [4,5,6] is

$$F = q_m B$$

For those accustomed to the SI units the table below includes all parameters.

Maxwell's equations and Lorentz force equation with magnetic monopoles: SI units

Name	Without magnetic monopoles	With magnetic monopoles	
		Weber convention	Ampere-meter convention
Gauss's law	$\nabla \cdot \mathbf{E} = \frac{\rho_e}{\varepsilon_0}$		
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$	$\nabla \cdot \mathbf{B} = \rho_m$	$\nabla \cdot \mathbf{B} = \mu_0 \rho_m$
Faraday's law of induction	$-\nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t}$	$-\nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t} + \mathbf{j}_m$	$-\nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t} + \mu_0 \mathbf{j}_m$
Ampère's law (with Maxwell's extension)	$\nabla \times \mathbf{B} = \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} + \mu_0 \mathbf{j}_e$		
Lorentz force equation	$\mathbf{F} = q_e\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$	$\mathbf{F} = q_e\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right) + \frac{q_m}{\mu_0}\left(\mathbf{B} - \mathbf{v} \times \frac{\mathbf{E}}{c^2}\right)$	$\mathbf{F} = q_e\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right) + q_m\left(\mathbf{B} - \mathbf{v} \times \frac{\mathbf{E}}{c^2}\right)$

The most important observation in the context of the popular expectation of grand unified theory is that the magnetic monopole is needed to restore full symmetry between electric and magnetic fields.

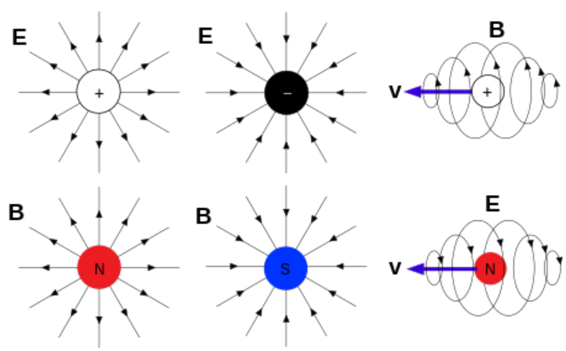


Fig.2 Illustration of field of forces. Credit Wikipedia. The first two figures on the left illustrate the field lines generated by individual electric or magnetic poles . The third figure illustrates the lines of induced field for a pole in motion.

Note that symmetry of electric and magnetic poles is not fully restored as their charges are significantly different and the classical approach of defining the magnetic fine structure constant $\alpha_m = \frac{g_m^2}{\hbar c} \approx 34.25$ is too large for application of perturbative theory.

5. GUT monopoles

There is a strong belief among theorists about the unification of gauge theories. The observed electroweak and strong interactions which have independent coupling constants will become unified at small distances (high energies) into a single interaction with its own gauge coupling. In 1974 `tHooft [6] and Polyakov [7] independently have shown that the unification necessitates the existence of magnetic monopole for all cases in which the global symmetry group spontaneously beaks down into subgroups that include among them the U(1) symmetry of the electromagnetic fields.

All grand unified theories are based on a large groups of exact gauge symmetries that mix strong and electroweak interactions and fulfill `tHooft`s criteria. These symmetries are broken at very small distances corresponding to the very large mass scales. The unification scale is determined by the scale of the spontaneous symmetry breakdown, which also defines the monopole mass and its size. The prediction does not depend on the actual mechanism of symmetry breaking, which can proceed via a number of different decompositions of the largest symmetry group. It also does not depend on gravity at the electroweak-strong unification scale. The unification mass scale depends on the choice of the grand unified model and the simplest expectations are derived from the assumption of no new physics between will appear between present energy and unification scale.

The field theoretical approach of `tHooft is independent of the choice of particular unification model. It is based on assumption that the electromagnetic group U(1) is a subgroup of a larger compact covering group like, e.g., SU(2) or SU(3). The expansion of the Dirac approach for field generated by superconducting string to the electromagnetic potential on a sphere provides unique solution for field equations which now require a 4π rotation to restore continuity.
The `tHooft's illustration is shown in Fig.3 below indicating that any circular flux line can be reduced to a constant by moving it around the surface of the sphere to the point opposite to the source.

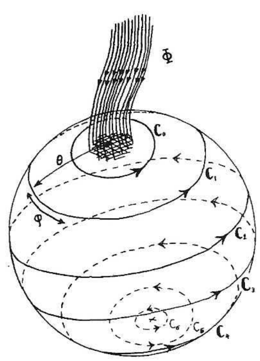


Fig. 3. Closed path on a surface of a sphere from Ref.[6].

The fundamental difference in the Dirac's and 'tHooft's results is that Dirac has shown a **consistency** of the electric charge quantization with the existence of the magnetic monopole. The grand unified theory result is potentially much stronger. The existence of the magnetic monopole with very large mass is now **required**. The approach also eliminates the need for the "string singularity" in the integration of the field equations as any of the loop trajectories can be topologically transformed into a single point on a sphere thus eliminating the defect created by a string.

The theoretical picture of a "grand unified" magnetic monopole is similar to that of a theoretical picture of electron that is very small while its effective radius is a result of it being screened by the cloud of virtual photons.
However, because monopole is formed at the unification scale, the GUT magnetic monopole is a particle that in addition to the magnetic charge can have mass, color and electric charge.
Aside:
The unification scale is usually associated with the Planck length, the minimum length where physics theories still apply. This comes from the observation by Planck that the combination of four fundamental constants of nature can be made to be consistent with unity:

$$\ell_P = \sqrt{\frac{\hbar G}{c^3}}$$

ℓ_P = Planck length

$\hbar$ = reduced Planck constant

G = gravitational constant

c = speed of light in a vacuum

Thus the smallest length appears to be 1.6 x 10^{-35} m.

It is expected to consist of a tiny core at the unification scale of ~10^{-28} cm where most of its mass is concentrated. It then exhibits at different distance scales from its core virtual boson interactions, color magnetic strong interactions and eventually the dominant screening of its magnetic charge by a virtual electron-positron cloud. Thus, the structure of the core of the monopole can be illustrated as shown in the following figure 4.

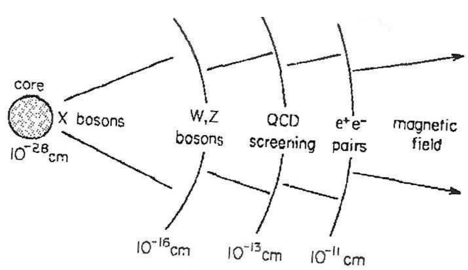


Fig.4 Structure of the magnetic monopole. Ref [1]

The unification scale depends on a particular model.
In the case of no new physics until the unification scale we have [8]

$$SU(5) \rightarrow SU(3) \times SU(2) \times SU(1) \rightarrow SU(3) \times U(1)$$

For theories with several stages of symmetry breaking due to complex structure of the initial scalar Higgs field there may exist monopoles with masses corresponding to different stages of spontaneously symmetry breaking, e.g.,

$$SO(10) \rightarrow SU(4) \times SU(2) \times SU(2) \rightarrow SU(3) \times SU(2) \times U(1)$$

In any of these approaches the mass of the monopole is proportional to the mass of the gauge boson breaking symmetry.

For the unification scale of about 10^{14} GeV the expected core size of the monopole is

$$R \approx M_x^{-1} \approx 10^{-28} \text{ cm}$$

and its corresponding mass

$$m \approx (4\pi/e^2)\, M_x \approx 10^{16} \text{ GeV}.$$

Thus, if such monopole exists, it has a mass comparable to a bacterium or a kinetic energy comparable to that of a fully loaded truck speeding on the Dallas freeway.

6. GUT Monopole in Cosmology

The very large mass of the GUT magnetic monopole precludes its production in any accelerator based experiment. It is also unlikely to be produced in any of the currently known astrophysical process. However, if the cosmological picture is considered, the energies of the processes in early universe shortly after the Big Bang were sufficiently large that copious production of the monopoles could take place. Presumably in analogy to all other particles, the production of monopoles and anti-monopoles was followed by their respective annihilations at short distances. The estimates of the abundance of the magnetic monopoles in the early universe led to too many of them. Their present-day number density would exceed the critical density of the Universe. The need to find a mechanism for the reduction of their number was one of the motivations of the seminal paper on inflation by Alan Guth [9].

Inflation sweeps away the monopoles and generates our entire universe from a tiny pre-inflation region of local quantum fluctuations. It may not contain even one monopole. So, the next step in an estimate of the monopole density depends on whether the phase transition happened before or after the inflation.

The general picture of monopole creation is tightly coupled to the understanding of the Big Bang cosmology. As the universe expanded and cooled, it is expected to have undergone phase transition at the unification mass/energy scale. The expansion of the Universe presumably maintained the number of monopoles per comoving volume established during the phase transition. Their density would depend on the type of the phase transition in which the scalar Higgs field was trapped in the local bubbles and created topological discontinuities with no causal contact [1].
In the so called "second order" transition the quenched large random fluctuations of the scalar field froze the "topological" defects of the scalar field as monopoles and anti-monopoles.
In the "first order" transition a supercooling occurs freezing out bubbles of thermodynamically unstable space with broken gauge symmetries. The resulting after coalescing monopole density is large, comparable to the density of the baryons and need further inflationary model-dependent reduction factors.

7. Experimental searches for the magnetic monopoles

In the following 80 years from the original paper a very large number of experiments and projects attempted to find the magnetic monopole. Most of the early searches concentrated on searching for a particle-like object with relatively low mass and excessive electromagnetic interactions due to the large value of its magnetic coupling. There are over 1000 papers published on this topic. Partial list of experimental searches can be found in Refs, [10-11].

The description of effects of magnetic monopole on an electric field is analogous to the motion of electron in the magnetic field but with distinct, striking characteristics, e.g., much stronger coupling effects of ionization or excitation of atoms or molecules with subsequent photon emission, non-helical path in uniform magnetic field, strong Cherenkov radiation effects and others. A Dirac magnetic monopole in motion is expected to induce detectable electric field resulting in photon emission and create a signal via induction. It would lose energy in interactions with matter that is several thousand times larger than that of electrically charged particle and the penetration of matter would depend of the charge structure of the material. There are many ways to apply these effects in design of the monopole detector. Some of the most commonly used are:

- Induction techniques: SQUID – Superconducting Quantum Interferometer Device

Monopole passing through a loop of a superconducting coil with inductance L will induce a persistent current change due to the long-range interaction between the magnetic charge and the quantum state of the superconducting ring $\Delta i = 4\pi g_m / L$. Theoretically, this is one of the cleanest ways to detect the monopole. The technical difficulties are related to the creation of a suitable superconducting ring and shielding of electromagnetic and particle background.
A device with 4 turn coil of 5 cm diameter superconductor was employed [12] by Cabrera in 1982 and observed one event in ~5 month of continuous operations.

Cabrera observation remains unreproduced. No additional events were ever found in this and any follow up experiments. The problems of size and technical difficulties related to maintenance make this technique useful only is searches for monopoles absorbed in matter and in several small, accelerator-based detectors. The searches for monopoles bound in matter, based on classical induction or SQUID techniques were performed by many different groups using various old minerals from the Earth surface and mantle, meteorites, see water and even Moon rocks. No signal was ever detected and the limits on the ratio of monopoles per nucleon of the order of ~10^{-29} have been published [13]. It is difficult to interpret such limits in the cosmological models.

- Energy loss in nuclear track detectors

Heavy ionizing particles can leave a latent track in insulating materials like polymers, kapton and nitrocellulose, in glasses and minerals like mica and obsidian. The visibility of these tracks under microscope can be enhanced by chemical etching. This technique was used in searches through old glass (mostly coming from renovations of old churches), in balloon-flown nuclear emulsions and in searches through material irradiated in accelerators and surrounding beam collision point in colliders.

- Light yield in scintillators and ionization effects in gaseous detectors

The light yield in liquid or plastic scintillators depends on the total electromagnetic energy deposited near the track by the passage of the monopole and thus on the monopole velocity, and the length of its trajectory. At low velocities the light yield increases with β and saturates due to quenching at about $\beta \approx 10^{-3}$. At higher velocities the liberated ionization electrons can escape the local track region as e.g., δ rays, and the light yield increases again due to molecular excitation. The amount of light depends on the material.

In gasses, the ionization can be employed to generate electronic signals in drift (Sudan) or streamer (MACRO) tubes. The large experiments used a combination of electronic signal with light detectors to improve efficiency and separation of signals from backgrounds.

- Velocity dependence

The monopoles originating in the Big Bang are expected to have very low kinetic energies independent of their masses. Often the viral velocities comparable to that of relative motions of galaxies are assumed. The external magnetic field of any origin can provide, however, significant acceleration. Low mass Dirac monopoles can easily attain relativistic energies, i.e., high velocities. On the other hand, the heavy GUT monopoles even those with high kinetic energies, are expected to be rather slow and could have been trapped in terrestrial matter unless a special accelerating mechanism is devised.

- Accelerator based searches

Accelerator based experiments have been employed at every accelerator ever built. The mass reach of such searches for Dirac monopoles is limited by the accelerator energy corresponding to the maximum monopole mass that can be produced. Non have ever been seen. Upper limits for monopole production cross section obtained at accelerators and colliders [13] are shown in Fig.5

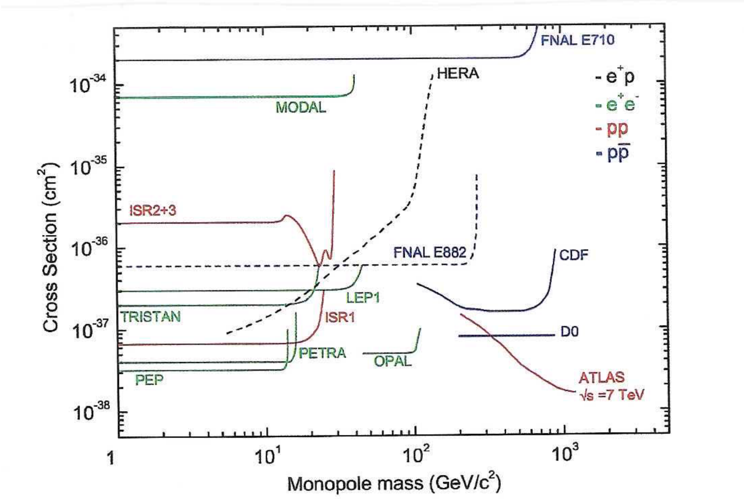


Fig. 5 Upper limits on monopole-pairs production cross section in various electromagnetic processes obtained at accelerators. (From Ref.13.)

Cosmic ray experiments are sensitive, in principle, to a much larger range of cosmic monopoles energies and masses. These are of greater interests in searches for GUT monopoles. The detection techniques utilize strong electromagnetic interaction resulting in large photon showers that can be employed over large surface areas thus increasing sensitivity of the measurements. They have been sensitive to Cerenkov light and radiative showers in underground, underwater and surface based large experiments. The lack of positively identified event candidates allows to estimate upper limits on the flux of monopoles reaching Earth under many assumptions like, uniformity, passage through the galactic and extra-galactic fields, etc.

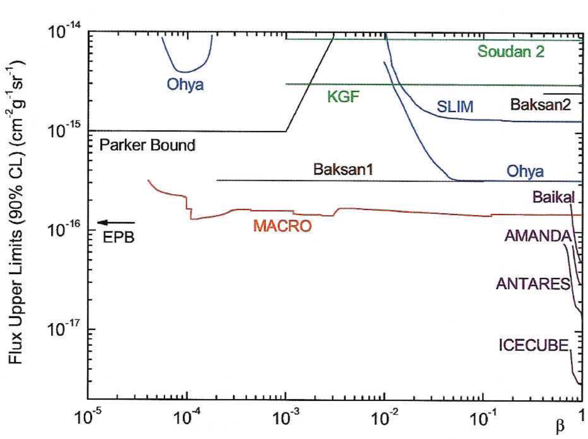


Fig.6 Upper limits for GUT monopoles as a function of their velocity. (From Ref. [13])

There are several additional active or planned experiments.
So far, all results have been negative with the exception of a single, not reproduced observation by Cabrera. The bottom line of any review available in the literature is a general impression is that if they exist their observation rate is negligible. Such negative result is a persistent problem for field theory.

8. Rotating black holes

Einstein's theory of relativity [14] developed in 1907-1915 described a geometric theory of gravitation as a geometric property of space and time. The curvature of spacetime is directly related to the energy and momentum of matter and radiation present in the space considered. The description if given by the set of field equations- second order partial differential equations.

Subsequently there have been many exact solutions of these equations for specific cases.
Karl Schwarzschild found [15] a solution that characterized an area from which no light can escape, commonly known today as a black hole. This was done for a static, spherical object at rest and for a long time it was considered a mathematical curiosity.

The static solution was expanded by application of the Kerr metrics of space-time [16] to rotating and charged holes.
The fast rotation of the black hole at the singularity point can create a process called frame dragging, where the rapid rotation will drag spacetime surrounding the singularity region.
Furthermore, in elegant papers Bardeen [17] and Thorne [18] and their collaborators have shown that the angular momentum conservation effects due to matter and radiation infalling onto the static black hole from the interstellar medium or neighboring star will from a large radius matter accretion disk and the matter infalling from the accretion disc into the black hole will spin it up.

The discovery of neutron star in 1967 and first observation of a massive invisible binary companion of Cygnus X-1 in 1971 provided impetus to more detailed studies of gravitational collapse and black holes as potentially real objects. Fascinating consequences were derived [19-21] by considering extensions of the simple picture of static black hole by discussing electrodynamics, rotation, charge, binaries and especially magnetic field.
Among those, the expectation of the existence of strong magnetic fields stimulated a broad push for astrophysical observations. This is a hot field and we're lucky to have a leading expert in these fields here.

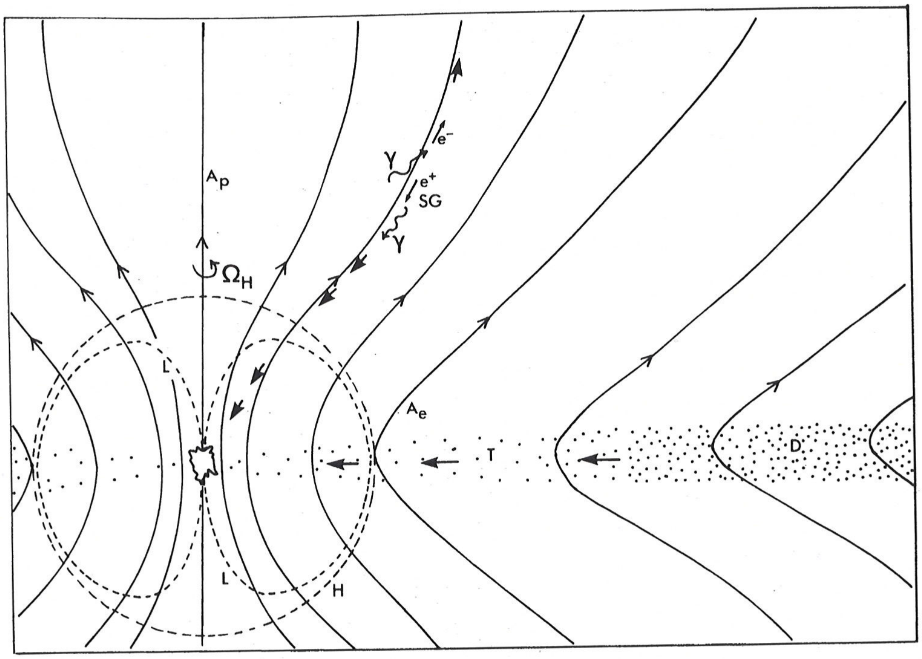


Figure 1. Schematic cross-section of black hole and magnetosphere, using r and θ coordinates in normal way. (Due to axial and time symmetry the diagram is independent of the azimuthal and time coordinates that are being held constant; these can be the Kerr coordinates v and $\tilde{\phi}$, or for $r > r_+$ the Boyer–Lindquist coordinates t and ϕ.) The poloidal field has been chosen so that $\mathbf{\Omega}_H \cdot \mathbf{B} > 0$. H is the event horizon $r = r_+$. The poloidal field surfaces (i.e. surfaces of constant A_ϕ) are shown as solid lines, with the polar and equatorial surfaces $A_\phi = A_p$ and $A_\phi = A_e$ specifically labelled. A current I is flowing from the magnetosphere into the hole, and back out of the hole into the disc D lying in the $\theta = \pi/2$ plane (denoted by heavy stippling). Particles can only cross the event horizon one way, into the hole. In the magnetosphere there are spark gaps like SG creating pairs of positrons e^+ and electrons e^-. Positrons are flowing into the hole along surfaces A_ϕ = const. at a faster rate than electrons, and there is a higher density of electrons (as the space charge has to be negative). Projections of typical particle velocities are shown by arrows. Particles can remain on the hypersurfaces of constant A_ϕ only as long as the normals to these surfaces are space-like. The locus where these surfaces become null is L. Between the disc and the hole there is a transition region T in which the matter is falling from the disc to the hole. This is shown by lighter stippling.

Fig. 7. Schematic cross-section of the black hole and its magnetosphere (From ref. [21])

<u>Aside: Nomenclature:</u>

Schwarzschield black hole - stationary, not charged, not rotating object

Event horizon - radius of no return

Kerr black hole - rotating black hole with reference frame described in Kerr metrics.

Accretion disk - region of matter rotating around black hole and “feeding’ it

In general relativity the fast rotation of the black hole at the singularity point can create a process called frame dragging, where the rapid rotation will drag spacetime surrounding the singularity region. In the plane perpendicular to the hole axis of rotation the speed of matter particle depends on the radial distance to the hole. It will increase the closer it is to the hole. A particle arriving from any other direction will move along a spiral path. In the region closest to the hole the speed of particle approaches the speed of light. A particle in that region the hole event horizon from which there is no return for a massive particle though a photon could in principle escale is called an ergosphere. See. Fig.8. Once the material from the disc enters the ergosphere it is doomed to fall beyond the event horizon.

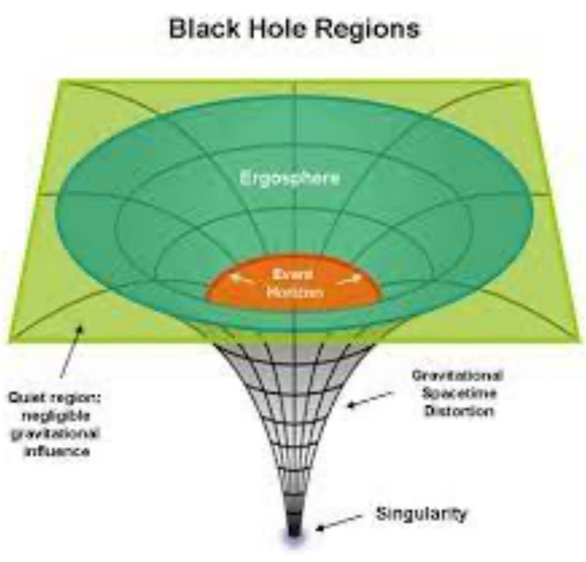


Fig. 8. Schematic geometry of the black hole. From Image © Ask The Van / UIUC Physics Department.

One of the consequences of the strong magnetic field is the acceleration of massive and charged particles out of the area of the black hole. See Fig.9.

Fig.9 . Black hole jets image. Hubble Space Telescope 2019.

The mechanism of such acceleration described in Ref. [22] is due to twisted lines of the magnetic field creating a jet perpendicular to the plane of hole rotation and aligned with the spin of the accretion disc and that of the black hole. The power of the jet is directly related to the accretion power $dM_{BH}/dt\ c^2$.

The studies of mechanism that generating the magnetic field in the vicinity of the hole is subject to numerous studies. Most of them use simulations based on the magnetohydrodynamics (MHD) approach. There also have been criticisms of the Blandford-Znajek (BZ) approach which proposed that the jets from the galactic nuclei are powered by the electromagnetic extraction of spin from the central black hole. The BZ mechanism applies to a rapidly rotating black hole located in a spin aligned magnetic field and is assumed to carry no electric charge. The accretion disk provides the current generating magnetic field. If the black hole is surrounded by a conducting medium the induced electric field will induce a current through the black hole that due to dissipation will tap the energy of the spinning hole, thus powering the jets.
Wald [23] argued that the surrounding plasma may consist of separated charges and that the black hole will selectively accrete charges that will concentrate on opposite poles of the hole, As a result, such charges will nullify the effect of the electric field. In the following analyses [24] the condition for powering the jet ends when the accumulated net charge reaches the value $Q = 2\ BJ$, where B is the magnetic field and J is approximately the total angular momentum. The criticism implies that therefore the BZ mechanism may not be the origin of the continuous astrophysical jets.

All of the papers that I have seen start with the magnetic field generated by the moving plasma. It is unclear at this time how the generated an effective strong field due to positively charged plasma is affected by the free electrons.

- Observations

All observations of a black hole are based on gravitational effects. The measurements of the trajectories of visible stars around an invisible central gravitational attractor provided first "pictures" of a black hole. Similar studies based on multifrequency observation determined the existence of a black hole at a center of our galaxy in the Sagittarius region in the sky.

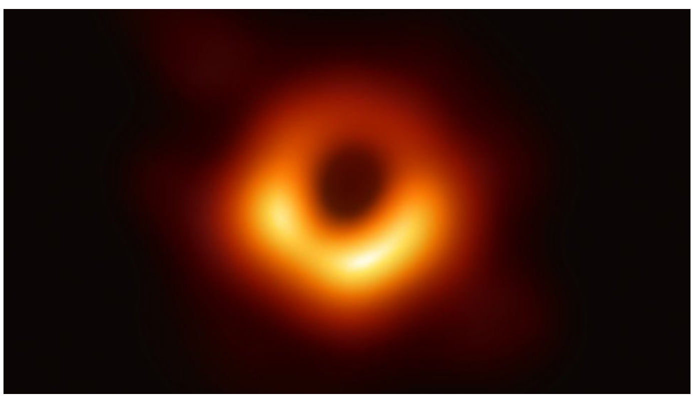


Fig. 10. Composite image of the Black hole observed by the Event Horizon Telescope. Ref [25]

Mergers of black holes have been detected by the LIGO-VIRGO collaborations with unfortunately insufficient directional capabilities to locate them in space. Major expansion of the gravitational detection capabilities is expected from new detector including e.g., LISA project.

A special characteristic observed for some of the black holes is a prominent jet of matter perpendicular to the torus of the accretion disk and assumed to be aligned with the spin of the hole.

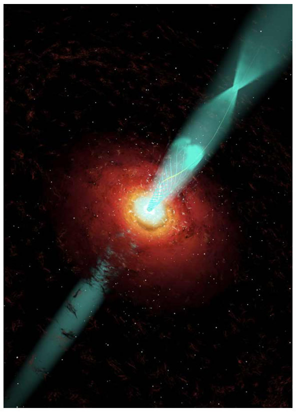


Fig. 11. *An artist impression of the innermost part of an active galaxy, in the immediate surroundings of the super-massive black hole. Credit: Boston University Blazar Group / Cosmovision.*

9. Experimental observation of the magnetic field of the black hole jets

Magnetic fields associated with a black hole became recently a hot topic of astrophysical observations and research. Since the developments of current large and expensive program in observational astronomy and astrophysics were often motivated by the field theory of particle physics. It may be interesting to see if particle physics may learn something back from the impressive new developments.

A recent paper [26] provided estimates of the rapidly varying magnetic field on the six parsec scale jets of active galactic nuclei.

The analysis of several frequencies of radiation detected by the Very Long Baseline Array correlated with the optical observations allowed for an estimate of the magnetic field strength responsible for 4.6 - 43 GHz range of emission. The observed jets are usually described by a conical jet model. [27]

The observation deduced from the several radiation wavelengths indicate that the magnetic field appears to decrease with radial distance from the black hole with a power-low dependence approximated as

$$B = B_l r^{-1} ,$$

where r is the distance to the black hole and B_l represents the vertex of the cone. The measurements of the eight frequencies dependences of the position of the cores and their overall spectral distribution as function of the radial distance from the blazar indicated the strength of the magnetic field in excess of 10^4 G near the black hole and still of the order of 1 to 10 G at the radius of the accretion disc.

The results are consistent with theoretical expectations of the models of the magnetic powered jets. The results are consistent with theoretical expectations of the models of the magnetic powered jets.

The model describing the origin of the jet is based on the assumption of the rapidly rotating charged black hole entangling the lines of the magnetic field that provides the accelerating mechanism for matter trapped in the jet cone.
The actual measurements for the black hole denoted 2200+420 as derived from different frequencies of electromagnetic wave spectrum is shown below.

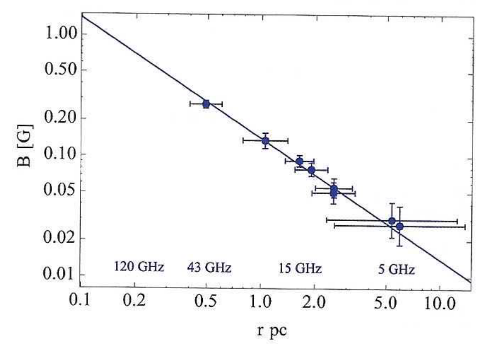


Figure 4. Plot of magnetic field strength (B) in units of Gauss versus distance along the jet (r) in units of parsecs for the core of 2200+420 at 4.6, 5.1, 7.9, 8.9, 12.9, 15.4, 22.2 and 43 GHz using $k_r = 1$. Also plotted is the best-fitting line $B = B_1 r^{-1}$ with $B_1 = 0.139$ G with a formal error of 0.006 G.

Fig. 12. Plot of the magnetic field of the core of 2200+430 black hole. From Ref.[26]

The authors were able to estimate the strength of magnetic field at the jet launching distance from the black hole.

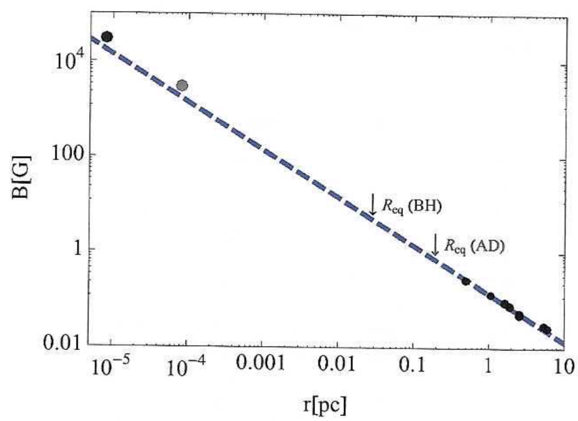


Figure 5. Extended plot of B versus r for 2200+420 to include the extrapolated magnetic field strength ($B \simeq 0.14r^{-1}$) at the accretion disc ($10r_g$) and black holes (r_g) distances. The estimated equipartition radii from K07 are indicated by the arrows with $R_{eq,AD} \sim 0.2$ pc and $R_{eq,BH} \sim 0.03$ pc. Also plotted are points at $10r_g$ (grey) and r_g (black) representing the theoretically expected magnetic field strengths for a magnetically powered jet.

Fig. 13. Extrapolation of the strength of the field to the vicinity of the hole. Ref. [26].

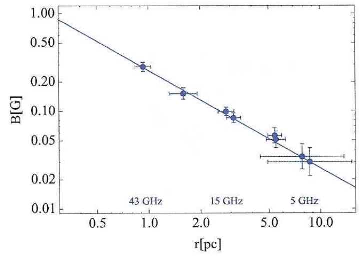


Figure 9. Plot of magnetic field strength (B) in units of Gauss versus distance along the jet (r) in units of parsecs for the core of 2007+777 at 4.6, 5.1, 7.9, 8.9, 12.9, 15.4, 22.2 and 43 GHz using $k_r = 1$. Also plotted is the best-fitting line $B = B_1 r^{-1}$ with $B_1 = 0.257$ G with a formal error of 0.007 G.

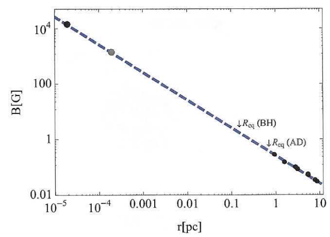


Figure 10. Extended plot of B versus r for 2007+777 to include the extrapolated magnetic field strength ($B \simeq 0.26r^{-1}$) at the accretion disc ($10r_g$) and black holes (r_g) distances. The estimated equipartition radii from the model K07 are indicated by the arrows with $R_{eq,AD} \sim 0.7$ pc and $R_{eq,BH} \sim 0.1$ pc. Also plotted are points at $10r_g$ (grey) and r_g (black) representing the theoretically expected magnetic field strengths for a magnetically powered jet

Fig. 14. Measured magnetic field and its extrapolation to the vicinity of the black hole for the galaxy 2007-777. Ref [26]

Note: 1 parsec is equal to $1p = 3.086 \times 10^{13}\ km$ so the distance of 10^{-5} p is about 1 AU or Sun-Earth distance.

10. Monopole acceleration in a varying magnetic field

In the following, one can consider what happens to the magnetic monopole trapped in the black hole jet.
Since the current estimates of the magnetic field in the jets arising from the black hole appear to have a power low behavior as a function of the distance from the source it is interesting to provide an estimate of the energy increase attained by a single charge magnetic monopole due to its acceleration by the field.

The Lorentz force acting on the monopole is given by the equation

$$\vec{F} = (\vec{E} + \vec{v} \times \vec{B}) + g_m(\vec{B} - \frac{\vec{v}}{c^2} \times \vec{E})$$

In a simplest approximation one can neglect the electric charge of the monopole and the effects of the electric field, i.e., q = 0, E = 0. Thus, the Lorentz force reduces to

$$\vec{F} = q_m \vec{B}$$

The relativistic momentum of the monopole is given by

$$\vec{p} = \gamma m \vec{v}$$

Where m is the monopole mass and $\vec{v}$ is its velocity vector. We assume the initial velocity vector aligned with the direction of the field.
The relativistic force acting on the monopole by the field is

$$\vec{F} = \frac{d\vec{p}}{dt} = \frac{d(\gamma m\vec{v})}{dt} = \gamma^3 m\vec{a}$$

where $\vec{a}$ is the acceleration along the field line.
In a simplest case one can assume straight line acceleration a=$|\vec{a}|$. More complicated fields will require full simulation.

Recent papers discussed in section 8 indicate the radial dependence of the strength of the field as

$$B = \frac{k}{r}$$

with r describing the distance from the black hole in parsecs and k is a strength coefficient fitted to the data. The Lorentz force in such case is

$$F = \gamma^3 m\frac{dv}{dt} = g_m\frac{k}{r}$$

Which allows to estimate the acceleration and the energy increase from the initial space point near the black hole r_1 to a more distant point r_2. The total monopole energy at r_2 is

$$E_2 = g_m\, k\, ln\left(\frac{r_2}{r_1}\right) + mc^2\gamma_1$$

The first term corresponds to the increase of the kinetic energy and the second term corresponds to the initial energy/mass of the monopole.
In order to obtain energy in unit of GeV a conversion factor is needed for the magnetic charge

$$g_m = 3.29 \times 10^{-9} \times 6.242 \times 10^9$$

11. Discussion

The above expression shows significant differences of final velocities depending on the mass of the monopole. For a monopole with mass comparable to particles that can be produced in the current accelerators, i.e., less than ~1 TeV, the first term of the above expression would dominate leading to particles with relativistic velocities. On the other hand, for the heavy, GUT type monopole the attained kinetic energy would remain small in comparison to the mass leading to low velocities, comparable to those at its capture by the black hole's jet.

An example of the energy of accelerated monopole is based on the projections extracted from the paper of Sullivan and Gabuzda [26] for black hole 2200+420 assuming that the monopole is captured in the jet at a distance r_1 with negligible velocity ,i.e., $\gamma = 1$ and that is accelerated while travelling to a distance r_2 = 10 parsecs.

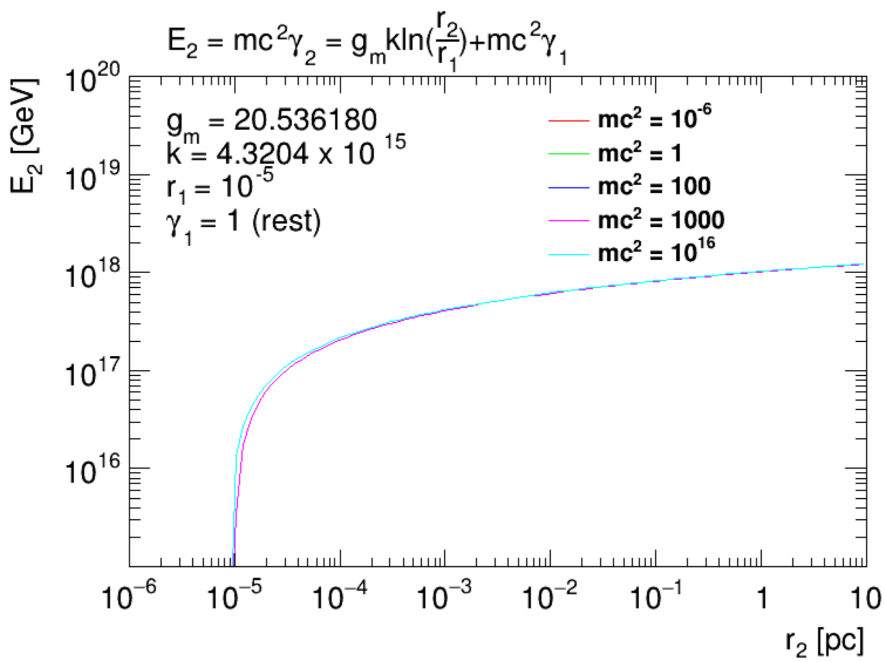


Fig. 15. Energy gain as a function of the distance to the black hole (credit Li-Yin Yang)

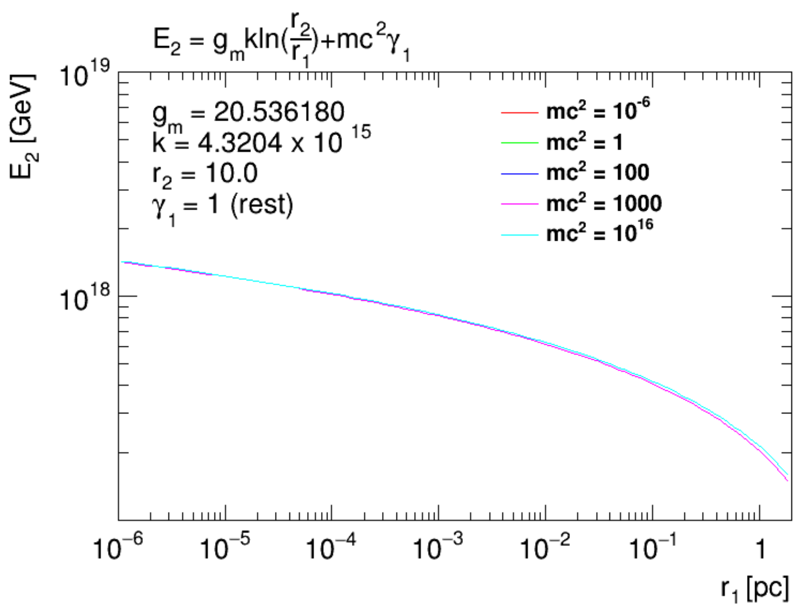
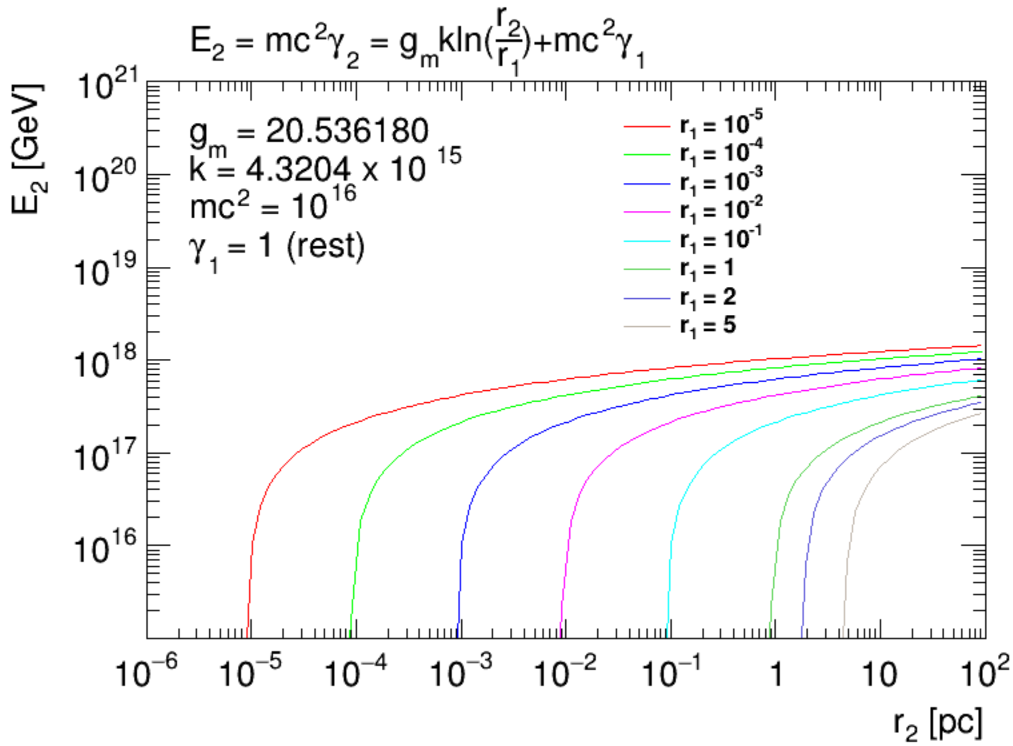
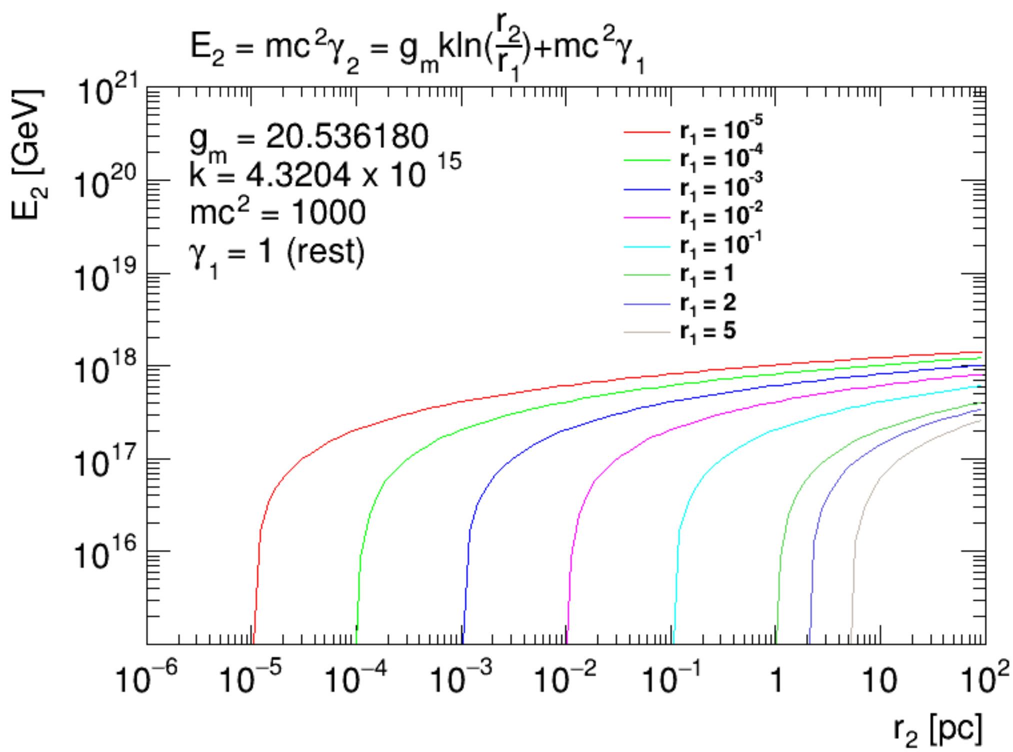


Fig. 16. Energy gain dependence on the initial distance from the black hole(credit Li-Yin Yang)



$E_2 = mc^2\gamma_2 = g_m k \ln(\frac{r_2}{r_1}) + mc^2\gamma_1$
$g_m = 20.536180$
$k = 4.3204 \times 10^{15}$
$mc^2 = 10^{16}$
$\gamma_1 = 1$ (rest)
$r_1 = 10^{-5}$
$r_1 = 10^{-4}$
$r_1 = 10^{-3}$
$r_1 = 10^{-2}$
$r_1 = 10^{-1}$
$r_1 = 1$
$r_1 = 2$
$r_1 = 5$
E_2 [GeV]
r_2 [pc]



$E_2 = mc^2\gamma_2 = g_m k \ln(\frac{r_2}{r_1}) + mc^2\gamma_1$
$g_m = 20.536180$
$k = 4.3204 \times 10^{15}$
$mc^2 = 1000$
$\gamma_1 = 1$ (rest)
$r_1 = 10^{-5}$
$r_1 = 10^{-4}$
$r_1 = 10^{-3}$
$r_1 = 10^{-2}$
$r_1 = 10^{-1}$
$r_1 = 1$
$r_1 = 2$
$r_1 = 5$
E_2 [GeV]
r_2 [pc]

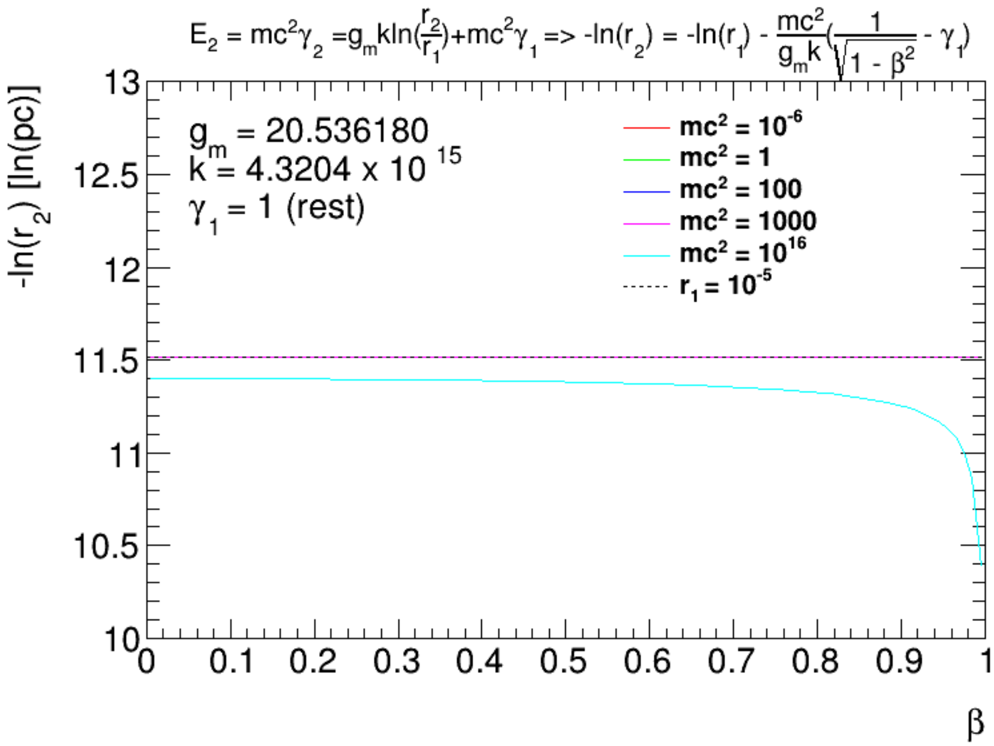


Fig. 17. Energy and velocity gains dependence on the capture distance to the black hole and departure from the accelerating magnetic field region.

12. Cosmic rays

The most likely environment of very high energy magnetic monopoles is in the study of high energy cosmic rays. Here the progress is continuous and scales with the scale of detectors. Recent measurements of the rate and energy cover 12 orders of magnitude in energy and over 10 orders of magnitude in rate. No clear explanation exists for the sources of changes of the spectrum and the origin of very high energy cosmic rays. Since GUT monopole is expected to be very heavy of particular interest is the structure of the spectrum in the region above 10^{17} eV.

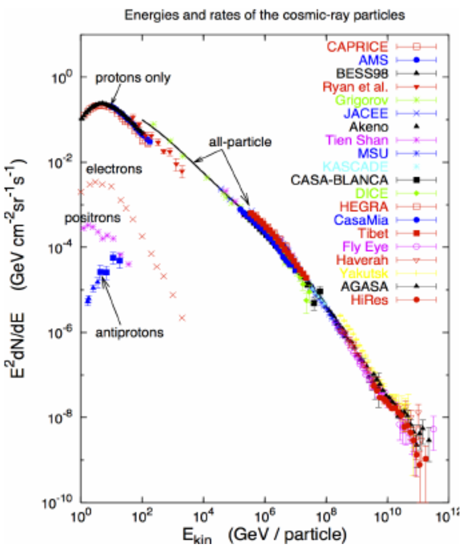


Fig.18 The composition of the spectrum was well measured by the AMS Collaboration [28] at energies up to about 10^4 GeV. It includes all "stable" elementary particles and nuclei produced in the stellar evolution.

The high energy region has been extensively studied by the Pier Auger Collaboration[29]. The high end of the spectrum is shown in Fig. [], but its composition is more difficult the discern.

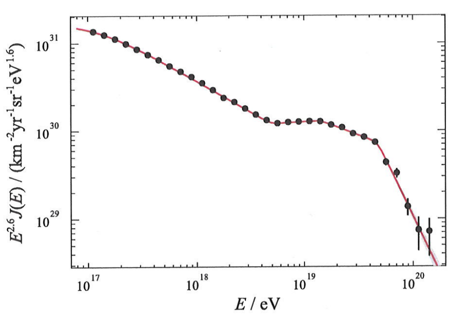


Fig. 17 SD energy spectrum after combining the individual measurements by the SD-750 and the SD-1500 scaled by $E^{2.6}$. The fit using the proposed function (Eq. (13)) is overlaid in red along with the one sigma error band in gray

The possibility of identifying monopoles by their expected copious Cherenkov radiationin the Earth atmosphere was proposed Tompkins in 1964. [30]. Recent simulations by Spengler and Schwanke [31] indicated that a pattern of detector signals in the HESS experiment in Namibia could provide a separation of monopoles from background.

Since the origin of the very high energy cosmic rays reaching energies of 10^{21} eV remains a mystery today, it may be interesting to consider if there are special characteristics that would distinguish effects of magnetic monopole detected in cosmic ray showers from those of the high energy protons.

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