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Accretion on a wormhole with monopole magnetic field

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Abstract. The presence of even simple magnetized wormholes may have observable consequences. If the wormhole and its surrounding magnetic fields are static, symmetrical, and spherical, and gas in the vicinity falls radially into the wormhole, the resulting spectrum would feature bright cyclotron or synchrotron lines caused by interactions between charged plasma particles and the magnetic field. This radiation would be non-polarized due to the symmetry of the system. The emission of this exotic, non-thermal yet non-polarized type of radiation could serve as a signature for wormholes. Additionally, in this scenario, the formation of an accretion disk is still possible at some distance from the wormhole; however, a monopole magnetic field may complicate this process and lead to the emergence of asymmetrical and one-sided relativistic jets.

Keywords: accretion, accretion disks, magnetic fields, gravitation

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1 Introduction

The study of wormholes is of serious interest, as their properties and potential existence may influence our understanding of cosmology in the Universe. Kardashev et al. (2007) proposed the hypothesis that some galactic nuclei are in fact wormhole mouths.

Many authors have explored the distinct observational features of wormholes, specifically identifying characteristics that differentiate them from black holes. However, almost all of them have concluded that those features, even when present, are often challenging to observe with current astronomical equipment, and in some instances, it may not be possible at all. In our work, we utilize objects and physical mechanisms that are established in astrophysics, which enables us to achieve significant observational results.

Wormholes have unique properties that present a theoretical opportunity for generating a monopole magnetic field. And there are many works linking wormholes with a monopole field (Misner & Wheeler 1957; Bronnikov 1973; Ellis 1973).

Polarization, which is responsive to the anisotropy of matter distribution, is important in the examination of optically unresolved central regions of AGNs, including the accretion disk.

Previously (Piotrovich et al. 2020a,b) we have considered the possible accretion of matter into a wormhole. We examined the scenario where accretion into a traversable wormhole takes place from both sides, each positioned at the center of the active galactic nucleus. As a result, high-energy accretion flows collide inside the wormhole, which can lead to plasma heating to extremely high temperatures up to 10^{14}K. And plasma with such parameters will have a very specific spectrum, different from the spectrum of ordinary active galactic nuclei.

Now we will consider the accretion in the presence of a magnetic field, considering that the wormhole has a monopole magnetic field, which greatly distinguishes it from the much better studied Kerr black hole. In this work, we propose that the existence of even simplest magnetized wormholes may result in observable consequences that have not been previously discussed in the literature, to the best of our knowledge.

2 Our model and some calculations

The simplest compact radially magnetized object could be a wormhole based on the framework of Reissner–Nordström spacetime (actually, as long as the magnetic field outside the object is monopole, the structure of the former is irrelevant).

Select three positive parameters: $Q,\ m$, where $m > Q$, and r_0, of which the former two will describe, correspondingly, the magnetic charge and "mass" of the wormhole;

while r_0 will obey the inequality $r_0 > r_{\mathrm{Horizon}}, r_{\mathrm{Horizon}} \equiv m + \sqrt{m^2 - Q^2}$ and characterize "the size" of the wormhole. The auxiliary "half-wormhole", W_1, is defined as $W_1 : \mathrm{d}s^2 = -\nu(r)\,\mathrm{d}t^2 + \nu(r)^{-1}\mathrm{d}r^2 + r^2(\mathrm{d}\theta^2 + \cos^2\theta\,\mathrm{d}\phi)$, where $r > r_0, t \in \mathbb{R}$, $\nu \equiv 1 - \frac{2m}{r} + \frac{Q^2}{r^2}$.

W_1 is *almost* the sought-for spacetime: it is static, spherically symmetric and resolves the Maxwell–Einstein equations when a radial magnetic field $\boldsymbol{B} = \left(Q/r^2\right)\boldsymbol{e}_{\hat{r}}$ is applied. A characteristic of W_1 is that it has a single asymptotically flat end, which means W_1 is an extendable structure referred to as one of its extensions U_1, and it functions as a funnel rather than a wormhole. To address this aspect, we will define the wormhole, W, as a pair of equal funnels, U_1 and U_2, with their stems identified (the existence of a suitable isometry relating regions U_1 and U_2 is a non-trivial condition), see Fig. 1 from Morris et al. (1988).

This work focuses on spherical accretion; however, it but one can reasonably assume that a monopole field will impede the movement of plasma along Keplerian orbits near the wormhole and, in particular, will complicate the formation of an accretion disk. The formation of an accretion disk remains a possibility at a certain distance from the wormhole, where the low magnetic field and temperature (resulting in a low degree of ionization) of the accreting matter may limit the influence of the monopole field on the matter. It should be noted that accretion disks near wormholes without their own magnetic fields have been discussed in the literature (Harko et al. 2009; Lobo 2017; Piotrovich et al. 2020b).

A phenomenological study can be conducted on the formation of relativistic jets by the accretion disk at a wormhole with a monopole magnetic field. The disk wind may be influenced by the monopole field, indicating that jet formation is primarily facilitated through the Blandford–Znajek mechanism (Blandford & Znajek 1977). In this process, the surrounding interstellar matter, which does not originate from the disk, is collimated through the interaction between the disk's poloidal magnetic field and the rotating black hole or wormhole. Thus, if the wormhole rotates, then jets can, in principle, form. Moreover, if the monopole field of the wormhole is much stronger than the dipole field of the accretion disk, then the cyclotron radiation from them may be significantly stronger and at different frequencies compared to the case of a black hole. It is also possible that the jets themselves will be more powerful/faster, but this is not certain. If the wormhole monopole field strength is similar to the disk dipole field, there may be a decrease in field strength at one of the dipole field's poles due to the superposition of fields. This could lead to a reduction in cyclotron radiation from that side of the jet and possibly result in a jet that is less powerful, less collimated, or potentially not formed at all. However, the mechanism of jet formation is complex and not completely understood, so these outcomes are not definitive. Note that asymmetrical and one-sided jets have been observed near some active galactic nuclei (Cawthorne 1991), and explaining this phenomenon poses challenges for classical theories, while our wormhole model offers a simple explanation.

Let's analyse the movement of single charged particle near a gravitating object with a monopole magnetic field in a simplified fictional space $\mathbb{R}^3$ (which is the Newtonian approximation of our metric W) in which we use the Newton gravity approximation (here the "mass" and the charge of the wormhole are described by the parameters m and Q, and it is a point-like object at the origin). In this case, the trajectory of a particle moving far enough from a gravitating object (so that relativistic effects can be neglected as a first approximation) can be obtained relatively easily (in our model we use non-relativistic Maxwell equations). Let's take for example a proton near a point-like object with the mass of the Sun $M_\odot$. In order to define the magnetic field strength we set the value of the field B_{10} at the radius $R = 10$ km. To simplify the analysis, we disregard the loss of proton energy from cyclotron radiation, as the trajectory is considered over a time interval of only 0.01 seconds.

We have numerically calculated the proton trajectories for various values of parameters such as the magnetic field strength B_{10}, starting position $R_{\rm st}$ and velocity $V_{\rm st}$ of a proton using a rather simple method. The total force acting on the proton can be expressed as the sum of the Lorentz force and the gravitational force: $\mathbf{F} = \mathbf{F_L} + \mathbf{F_g} = q_p/c[\mathbf{V} \times \mathbf{B}] - GM_\odot m_p \mathbf{r}/r^3$, where q_p is the proton charge, c is the speed of light, $\mathbf{V}$ is the proton speed, G is the gravitational constant, m_p is the proton mass, $\mathbf{r}$ is the radius vector, $\mathbf{B} = \mu\mathbf{r}/r^3$ is the magnetic monopole field strength, μ is the magnetic permeability, which in our case is $\mu = B_{10}R^2$.

Thus, 10^9 iterations were made for the proton flight time of 0.01 seconds. If the proton flew closer to the central object than 10 km, then we considered that it will inevitably fall on the object and the calculation stopped. To minimize errors, we ensured that the total (kinetic plus potential) energy of the proton divided by the proton mass $E_p/m_p = (\dot{x}^2 + \dot{y}^2 + \dot{z}^2)/2.0 - GM_\odot/\sqrt{(x^2 + y^2 + z^2)}$ did not vary by more than 0.001.

Figure 1 shows some of these trajectories. We see that even a relatively weak ($B_g \sim 1$G) monopole magnetic field prevents, as we conjectured earlier, the emergence of classical Keplerian orbits around the object. Instead, the proton begins to form spiral trajectories around radial magnetic field lines. The form of this spiral and the direction of the proton movement strongly depend on the parameters. In particular, at ~ 67000 km/s the proton's trajectory becomes closed (see the bottom picture in Fig.1). This is a kind of the "first escape velocity" for this particular situation. (However, it's important to note that the presence of energy loss from cyclotron radiation prevents these circular orbits will from lasting long, causing them to become spiral orbits.) Consequently, at speeds below $\sim$ 67000 km/s, the proton is drawn towards the central object, whereas at speeds exceeding $\sim$ 67000 km/s, it moves away from the central object. As the magnetic field strength increases, the radius of the helix quickly decreases, resulting in motion of the proton that approaches a more radial path.

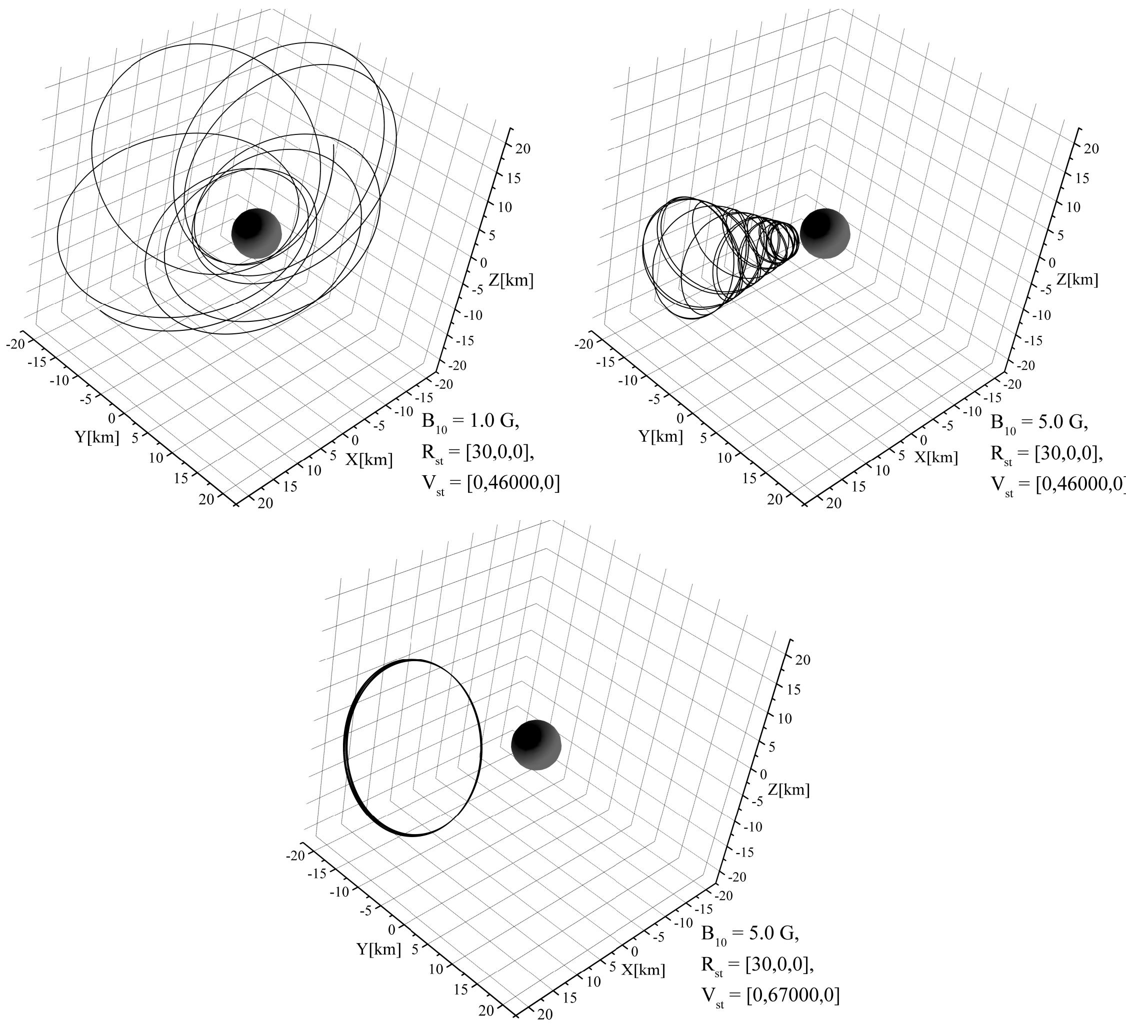

Fig. 1. Trajectories of a proton near a point-like gravitating object in the fictional space with the mass of the Sun and a monopole magnetic field for different starting parameter values. B_{10} is the magnetic field strength at $R = 10$km, $R_{\rm st}$ and $V_{\rm st}$ are starting position and speed of a particle in km and km/s respectively.

3 Conclusions

Current work has demonstrated that a wormhole with a monopole magnetic field can generate non-polarized cyclotron radiation, which is not commonly observed in known astrophysical objects. Possible candidates for such objects include both supermassive relativistic objects located in the centres of galaxies, as well as primordial wormholes of medium and small "mass" that may have formed in the early Universe. In particular, the latter may appear as star-like objects with an unusual non-polarized non-thermal spectrum consisting of cyclotron or synchrotron emission. Calculations based on a toy model suggest that even a relatively weak ($\sim$ 1G) monopole magnetic field may inhibit the formation of classical Keplerian orbits around the object. This result supports the idea that accretion is primarily radial at a close distance from the wormhole. However, the formation of an accretion disk is still quite possible at some distance from the wormhole. Also, if we consider the case of an accretion disk, a monopole magnetic field may impact its formation near the wormhole and result in the emergence of asymmetrical and one-sided relativistic jets.

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