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Ambient magnetic field interactions influencing jet propagation

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Abstract. Relativistic jets produced in vinicity of supermassive black holes are highly sensitive to the structure and strength of their surrounding magnetic fields. We argue that these magnetospheres are shaped not only by the magnetic fields generated internally (e.g., by the accretion disk, as typically theorized) but also by external fields. Encounters with ambient magnetic fields, whether from neighboring astrophysical objects or the host galaxy itself, can lead to significant changes in the jet's properties and morphology. In particular, the interaction between internal and ambient magnetic fields can reorient the jet, dissipate it, or even quench its propagation entirely. This study demonstrates that even the relatively weak magnetic field of the host galaxy can significantly impact jet dynamics at parsec scales, offering a potential explanation for the observed diversity in AGN jet activity, including the distinction between radio-loud and radio-quiet AGNs. We apply our model to two representative cases: Sgr A* and PKS 1717+177. For Sgr A*, which lacks an extended visible jet, we identify a characteristic distance from the core (0.7–2.2 mas) where the Galactic magnetic field can lead to jet dissipation or significant morphological changes, depending on its alignment with the jet. For PKS 1717+177, we demonstrate that the strong curvature of its prominent jet can be explained by a binary magnetospheric interaction scenario.

1. Introduction

Relativistic jets from active galactic nuclei (AGNs) are among the most powerful astrophysical phenomena, capable of extending over kiloparsec scales and influencing their host galaxies and the surrounding intergalactic medium. These jets are believed to originate near supermassive black holes (SMBHs) and are powered by the extraction of rotational energy from the black hole or the accretion disk (Blandford & Znajek 1977, Blandford & Payne 1982). The role of magnetic fields in jet formation and propagation is well-established, with internal fields generated by the accretion disk playing a central role in launching and collimating jets. This requires the large-scale vertical magnetic fields to be generated, which can arise e.g. from magnetorotational dynamo mechanisms, driving away the energy and angular momentum through plasma outflow (e.g. Jacquemin-Ide et al. 2024). However, AGNs reside in complex magnetic environments, where the SMBH magnetosphere can be influenced by external, ambient fields originating from the host galaxy or nearby astrophysical objects. The interaction between internal and ambient magnetic fields can significantly affect jet dynamics on different scales.

In this paper, we explore the effects of magnetospheric interactions on relativistic jets, focusing on how ambient magnetic fields, whether from the host galaxy or neighboring sources, can reorient, dissipate, or entirely suppress jet propagation. Using an analytical model that incorporates both internal and external magnetic field contributions, we demonstrate that even relatively weak ambient fields can disrupt the stability of the jet. These findings provide a potential explanation for the observed diversity in AGN jet activity, including the radio-loud and radio-quiet dichotomy.

In this study, we will also examine the case of Sgr A* with a potential jet, estimating the distance from the core of the jet at which the Galactic magnetic field can either cause the jet to dissipate entirely, under perfect antiparallel alignment, or significantly alter its orientation and morphology, depending on the relative angle between the magnetic field lines and the jet direction. Additionally, we apply the model to PKS 1717+177, a BL Lac object at redshift $z = 137$. This source is notable for its dynamic and evolving jet structure, which transitions from an initially straight configuration near the core to a strongly bent and meandering trajectory further downstream. We demonstrate that a supermassive binary scenario involving magnetospheric interactions can account for its unusual jet properties and morphology.

2. Modeling magnetospheric interaction

Magnetic fields near black holes vary widely in strength and origin, playing a critical role in shaping the behavior of surrounding matter and various astrophysical phenomena. Around SMBHs in AGNs with relativistic jets, the magnetic field strength is typically estimated to be around $B \sim 10^4$ G (e.g. Daly 2019). The SMBH at the center of our Galactic, Sgr A*, is untypically surrounded by a much weaker magnetic field, on the order of $10 - 100$ G (e.g. Eckart et al. 2017). In sharp contrast, the typical equipartition strength of galactic magnetic fields in many spiral galaxies, including the Milky Way, is approximately 10^{-5}G (e.g. Beck & Wielebinski 2013). However,

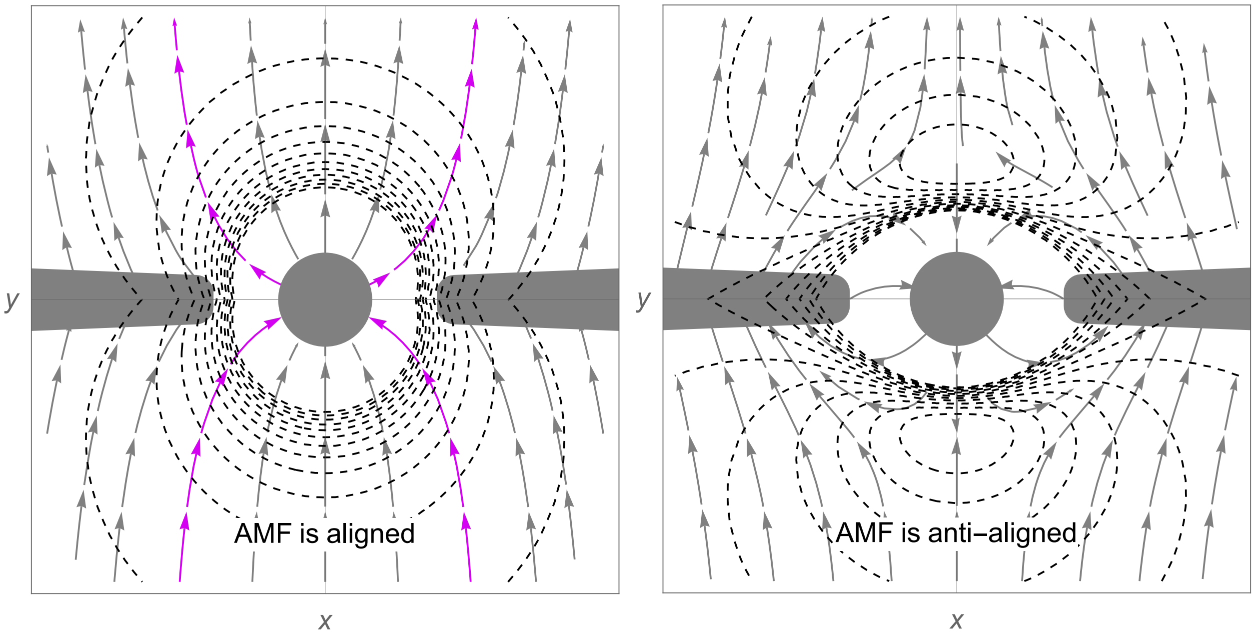

Fig. 1. Magnetic field configurations: aligned (left) and anti-aligned ambient magnetic field (AMF) scenarios for $|\beta| = 100$. The gray circle represents the black hole, with arrows indicating the magnetic field direction and dashed curves illustrating magnetic field intensity contours. The internal BZ field is sustained by electric currents within the disk, represented by gray polygons (not to scale). Magenta arrows in the paraboloidal configuration denote field lines connecting the black hole to infinity.

these galactic magnetic fields, often aligned with spiral arms, tend to be amplified toward the central regions of the galaxy (Beck & Wielebinski 2013, Lopez-Rodriguez et al. 2021).

Due to the relative weakness of galactic magnetic fields compared to those near the central engine of SMBH, their role in jet phenomena has often been overlooked in the literature. We will show below that even these weak fields can influence jets on larger scales, particularly through interactions between magnetic field components.

Magnetospheres of jetted SMBHs are often modeled by the paraboloidal configuration, which is also widely used in numerical simulations and supported by the radio-observations of jets (e.g. Nakamura et al. 2018, Kolos et al. 2023, and references therein). In this configuration the electromagnetic four-vector potential has the only non-zero spatial component, namely

$$A_\phi(r,\theta) = Br^k(1 - |\cos\theta|), \tag{1}$$

where B ranging from $(-\infty, \infty)$ is the field strength and k ranging from $[0, 1.25]$ is a declination of the paraboloidal field lines.

The disadvantage of this expression is that it is not obtained by solving the Maxwell equations, being heuristic in nature. It also does not explicitly include the black hole spin parameter in the potential. In contrast, we propose a new paraboloidal magnetic field solution, resulting from the combination of the Blandford-Znajek (BZ) split-monopole solution and the external vertical field (Wald 1974), when both field components are aligned. Such a combination is possible due to linearity of the Maxwell equations both in flat and curved spacetimes. The non-zero spatial component of the combined four-vector potential is then given by

$$A_\varphi = B_0 \left(g_{\varphi\varphi} + 2a g_{t\varphi} + \beta \frac{(r^2 + a^2)\,|\cos\theta|}{r^2 + a^2\cos^2\theta} \right), \tag{2}$$

where $\beta = B_{\rm BZ}/B_0$ is the ratio of the BZ-field intensity $B_{\rm BZ}$ and the ambient uniform magnetic field intensity B_0. The black hole spin parameter a is explicitly involved in the expression for the potential. The new solution represents the simplest extension of a generic magnetic field around a black hole using spherical harmonic decomposition, retaining only the zeroth (uniform) and first (split-monopole) components. Both field components, as well as their superposition, satisfy Maxwell's equations and adhere to Gauss's law for magnetism (Kenzhebayeva 2024).

The sign of β determines the relative alignment of the two magnetic field configurations, namely internal $B_{\rm BZ}$-field and the ambient B_0. When $\beta > 0$, the magnetic field components are aligned in the same direction, while for $\beta < 0$, they align in opposite directions. Near the black hole, the magnetosphere is dominated by the BZ split-monopole field, which weakens with distance, while at larger distances, it transitions to the homogeneous Wald solution 1974, driven by an ambient magnetic field.

3. Strong impact of a weak ambient field

3.1. Role of relative orientation of the fields

In Fig.1 we compare two magnetic field configurations differing in sign of the parameter β. The left panel represents the aligned case ($\beta > 0$), where the ambient magnetic field (AMF) and the internal BZ field are oriented in the same direction, resulting in a paraboloidal field configuration. The right panel depicts the anti-aligned scenario ($\beta < 0$), where the AMF and the internal BZ field are oriented in opposite directions.

In the aligned AMF scenario, the resulting configuration adopts a paraboloidal shape, with field lines extending from the black hole to infinity along a collimating cone. This geometry facilitates the extraction of energy and angular momentum from the black hole. The configuration is also strongly supported by GRMHD and GRPIC simulations, which consistently show the emergence of a paraboloidal magnetosphere around a black hole, regardless of the initial magnetic field structure or accretion dynamics (e.g. Tchekhovskoy et al. 2010, Kolos & Janiuk 2020, Parfrey et al. 2019).

The case with $\beta < 0$, where the AMF is pointing opposite to the BZ-field, forms a configuration with closed field lines connecting the black hole with an equatorial thin disk (see, Fig. 1, right). Such a connection between the event horizon and the accretion disk, if the black hole is rotating, enables energy and angular momentum transfer between the black hole and the disk while preventing any direct transfer of energy from the black hole to infinity. This resembles black hole-disk magnetic connection process by Blandford 1999, driven by currents at the disk's inner edge. Here we show that a similar effect arises from combining oppositely directed magnetic fields. In this configuration, relativistic jets, even if formed, cannot extend to large scales and are suppressed relatively close to the black hole.

3.2. Jet disruption distance and magnetic null-points

The anti-aligned configuration gives rise to magnetic null points, which play a crucial role as particle acceleration sites through magnetic reconnection, provided that plasma is properly injected (e.g. Karas et al. 2012). In a perfectly anti-aligned configuration, the jets are suppressed close to this point. This has also been demonstrated numerically by Kenzhebayeva et al. (2024). In cases of partial anti-alignment with a certain non-zero angle between the field components, the jets may reorient and propagate with altered trajectories, potentially leading to significant morphological changes. The numerical testing of this scenario will be done in future works.

In the anti-aligned AMF the magnetic null points emerge at the poles at a distance of

$$R_{\rm N} = \sqrt{-\frac{\beta}{2}} R_g, \qquad (3)$$

where $R_g = GM/c^2$. This expression is valid only for cases where $\beta < 0$. Furthermore, this distance serves as the characteristic scale for changes in the jet's morphology in scenarios involving partial anti-alignment.

In many cases, β is a relatively large dimensionless quantity. For typical AGNs, β defined as the ratio of the internal (disk) to ambient (galactic) magnetic field strengths typically ranges from 10^7 to 10^9. For a SMBH with $10^9 M_\odot$, the incident point is located within $0.2\text{pc} \leq R_{\rm N} \leq 2\text{pc}$. This implies that the jet, if launched, is unlikely to extend to large kiloparsec scales, or even beyond the confines of the host galaxy. Such suppression of jet propagation on parsec scales could offer a plausible explanation for the observed population of radio-quiet AGNs, where relativistic jets fail to develop into prominent large-scale structures.

3.3. The case of Sgr A*

A particularly interesting case is the well-known supermassive black hole Sgr A*, located at the center of our Galaxy. Unlike many AGNs, Sgr A* does not exhibit an extended, visible jet. This lack of a prominent jet could be attributed to several factors, including its relatively low accretion rate, the quiescent state of the accretion disk, or the inefficient collimation of outflows due to local conditions. On the other hand, some studies based on numerical simulations and observational data suggest that the jet should exist but remain undetected due to interstellar scattering, intrinsic variability, and instrumental limitations (Chavez et al. 2024). This raises the question of whether our proposed mechanism of magnetospheric interactions with the Galactic magnetic field could offer a plausible explanation for the apparent lack of large-scale jets.

Our study suggests in cases of anti-alignment or partial alignment of AMF, the interaction between internal and ambient fields may disrupt the jet-launching mechanism or lead to early jet dissipation. The anti-aligned AMF scenario for Sgr A* is both plausible and realistic given the structure of the Galactic magnetic fields. The Galactic magnetic fields are known to follow the spiral arms of the Galaxy, spiraling inward toward the Galactic center (e.g. Beck & Wielebinski 2013). At the same time, the internal magnetic field of Sgr A* is expected to align with the spin axis of the black hole. According to Event Horizon Telescope (EHT) (2022) results, the spin axis appears to be tilted toward us at a very small angle, lying in the plane of the Galaxy. Under such conditions, an anti-aligned configuration between the Galactic magnetic field and the internal field of Sgr A* is not only possible but likely.

Based on our model, we estimate the incident distance for jet dissipation in SgrA*, $R_{\rm N}$, to lie between $140 R_g*$ and $4.5 \times 10^3 R_g*$, where $R_g* = GM_*/c^2$, which corresponds to 0.7mas and 2.2mas of angular distance, respectively. This is the region where magnetic null points are likely to form

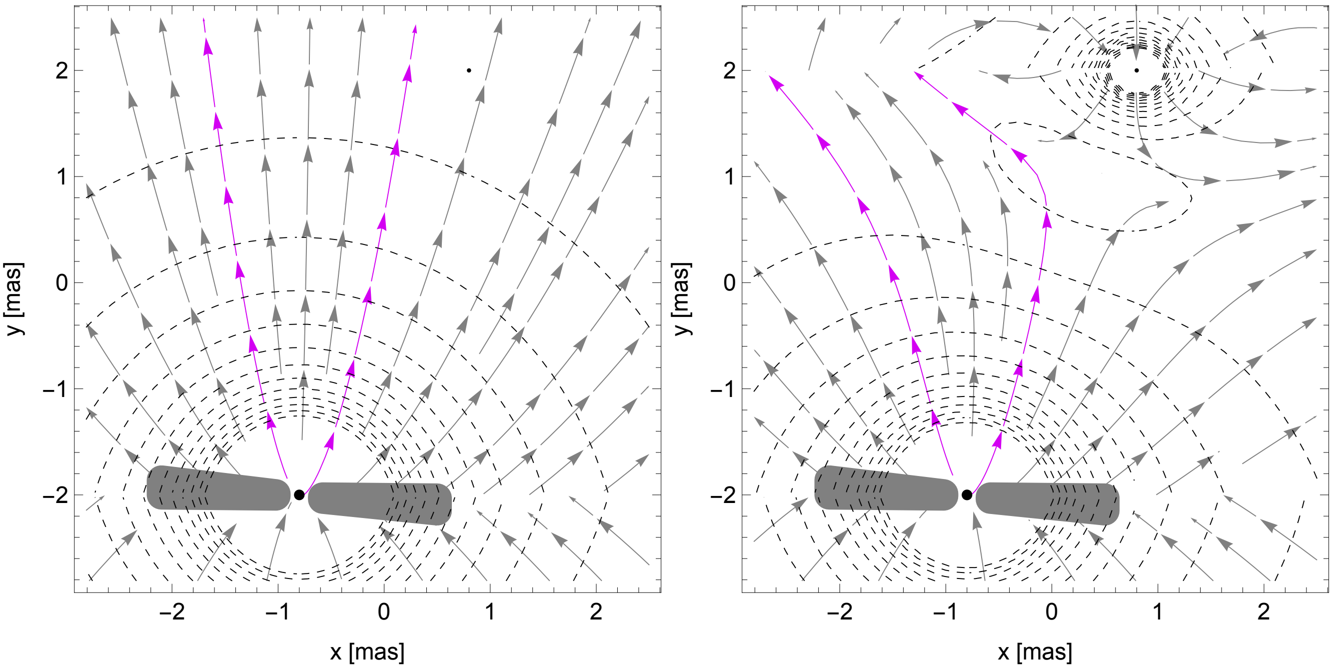

Fig. 2. Magnetospheric interaction model illustrating the magnetic field configuration in the absence (left) and presence (right) of a secondary, lighter black hole. Magnetic fields are in a paraboloidal configuration, with arrows indicating the direction and dashed curves representing the intensity contours. The magenta field lines correspond to those connected to the ergosphere of the primary black hole, defining the jet funnel region. The gray polygon depicts the accretion disk (not to scale). In the presence of the secondary black hole, the jet funnel region undergoes a sharp deflection. The right panel models the general jet behavior of PKS 1717+177, with the axes scaled in mas (see, details in Britzen et al. 2024).

with magnetic fields reversing direction, potentially halting the jet's propagation and preventing it from extending to large scales.

4. Jet bending by magnetospheric encounters

4.1. The model

Many jetted active galactic nuclei (AGNs) exhibit non-uniform motion and curved jet morphologies. These features are typically explained by interactions with the interstellar medium, gravitational influences from companion galaxies, or precession of the central engine due to binary black hole systems (e.g. Britzen et al. 2023). However, in certain cases, alterations in the jet trajectory may result from encounters with regions dominated by the magnetic fields of nearby astrophysical objects, such as companion galaxies, star-forming regions, or other active nuclei in dense environments. Such magnetic interactions can significantly redirect the jet, changing its path without the need for direct matter interaction with the secondary object. This mechanism offers a compelling additional explanation for the curved jet morphologies observed in some AGNs.

In Fig. 2 we plot a possible scenario of the turning of the BZ jet at the region, where the large-scale magnetic field of a primary black hole is connected with that of the second lighter black hole. This plot also presents the case of PKS 1717+177, discussed in the next subsection and by Britzen et al. (2024). The BZ jet funnel (magenta) is defined by the field lines connected to the black hole. Fig. 2 compares the field lines of a jetted black hole without (left) and with (right) a lighter companion black hole. The presence of a strong magnetic field source at large distances from the primary jet launching black hole will inevitably cause a change of the magnetic field topology along the directions towards the second black hole. The resulting field will be given by superposition of the corresponding components of the two magnetic field sources. Similarly, it will affect the jet propagation from the primary SMBH, causing it to turn, especially if the jet is initially launched towards the second black hole. Both field components are modelled with the same paraboloidal configuration differing in the strength, which scales inversely proportional to their masses (e.g. Tursunov et al. 2022).

For systems with larger mass ratios between the two black holes, the jet's turning point is expected to lie closer to the secondary (lighter) black hole. This behavior arises because the magnetic field of a black hole decreases with distance according to a power law, $\sim 1/r^k = R_g^k/R^k$, where r represents a dimensionless distance and R is the physical distance. In a paraboloidal magnetic field configuration, the parameter k is typically set to $3/4$. As a result, even though the magnetic field strength near the event horizon of the lighter black hole may exceed that of the primary black hole, it diminishes more rapidly with increasing distance. In cases of extreme mass ratios, the interaction cross-section of the magnetic fields may become too small to significantly influence the jet's trajectory. Thus, scenarios involving a lighter but still supermassive or intermediate-mass companion are more plausible than those involving stellar-mass objects.

4.2. The case of PKS 1717+177

To compare our findings with real observations, we apply our results to the source PKS 1717+177, a BL Lac object located at a redshift of $z = 0.137$. At this distance, the angular scale corresponds to 2.40 pc/mas. This source is notable for its intricate jet morphology and its potential as a neutrino-emitting AGN. Radio observations with the Very Long Baseline Array (VLBA) reveal a nuclear jet that initially appears straight but exhibits significant bending approximately 0.5 mas from the radio core. Over time, this bending evolves into a zig-zag or meandering structure. The temporal evolution of this jet, tracked over more than two decades, is among the unique characteristics of the source. A detailed description of multi-wavelength observations and modeling of PKS 1717+177 has been most recently provided by Britzen et al. (2024).

This source serves as an excellent candidate for studying magnetospheric interactions. Specifically, the observed bending and variability of the jet can be interpreted through a binary magnetospheric interaction scenario, where the jet's trajectory is influenced by the magnetic field of a nearby companion object, offering a plausible explanation for its dynamic behavior. Britzen et al. (2024) demonstrated that in this scenario, a jet launched toward the secondary black hole would always begin as a straight structure, consistent with observations. In the proposed model, the turning angle of the jet is highly sensitive to the pitch angle of the jet and the magnetic field direction of the secondary black hole. Given that the dynamical timescale of the secondary black hole is expected to be much shorter than that of the primary, it is highly likely that the jet's propagation beyond the turning point will vary across different epochs, as has indeed been observed.

As discussed in the previous section, the interaction between the magnetospheres can lead to the formation of magnetic null points also in the binary model of PKS 1717+177. Jets interacting with matter in this region are expected to produce high-energy emissions, including neutrinos and gamma rays, further linking the observed jet dynamics with potential multi-messenger signals.

5. Conclusions

In this study, we explored the role of magnetospheric interactions in shaping the relativistic jets from SMBHs. By modeling the interplay between internal and ambient magnetic fields, we demonstrated how magnetic field configurations influence jet propagation, reorientation, and suppression. Our results show that the alignment between the internal magnetic field of the accreting black hole and external fields, such as those of the host galaxy or nearby astrophysical objects, can play a crucial role in determining jet behavior.

We applied our model to two representative cases: Sgr A* and PKS 1717+177. For Sgr A*, which lacks an extended visible jet, we identified a characteristic region 0.7mas $\leq R_{\rm N} \leq$ 2.2mas, where interactions with the Galactic magnetic field likely cause jet dissipation or significant morphological changes. In the case of PKS 1717+177, we demonstrated that the pronounced curvature and temporal evolution of its jet can be explained by a binary magnetospheric interaction scenario, where the magnetic field of a secondary, lighter black hole alters the jet trajectory. This mechanism also suggests the formation of magnetic null points, providing a potential site for high-energy emissions, including neutrinos and gamma rays.

Our findings contribute to the broader understanding of AGN jet morphology by introducing magnetospheric interactions as a complementary explanation to the unified model of AGNs. While the unified model attributes the diversity of AGN appearances primarily to orientation and obscuration effects, our study highlights the critical role of magnetospheric interactions, particularly the alignment between internal and ambient magnetic fields. This novel mechanism provides a physical explanation for why some accreting supermassive black holes (SMBHs), classified as radio-quiet AGNs, fail to launch prominent large-scale jets, or why certain radio-loud AGNs exhibit curved jet trajectories. By incorporating magnetic field dynamics, we expand the framework of the unified model to account for additional environmental factors influencing AGN jet morphology and propagation. Future studies, especially those involving detailed numerical simulations and multi-wavelength observations, will be essential to further test and refine the proposed scenarios.

These findings emphasize the critical role of magnetic fields in regions of intense gravitational influence, where they drive a variety of high-energy phenomena across black hole systems of different mass scales. Beyond the generation and collimation of relativistic jets, magnetic fields play a key role in processes such as e.g. the occurrence of high-frequency quasiperiodic oscillations in microquasars and AGNs (e.g. Stuchlik et al. 2022), the acceleration of ultra-high-energy cosmic rays (e.g. Tursunov et al. 2019), among others (see, e.g. Stuchlik et al. 2020). Together, these results highlight the important role of magnetic fields in shaping the observable properties of black hole systems.

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