# A Theoretical Study of the Magnetic Field Generated due to the Rotation of Coronae in Active Galactic Nuclei

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**Abstract**— Active Galactic Nuclei (AGN) are highly energetic centers of galaxies, powered by accretion of galactic matter onto a Supermassive Black Hole (SMBH). Due to the Conservation of Angular Momentum of the accreted galactic matter, a relatively cold axis-symmetrical accretion disk or alpha-disk is formed around the SMBH. Highly collimated relativistic jets are observed which are perpendicular to the accretion disk. This study proposes that the magnetic fields generated by a system of counter-rotating hemispherical shells separated by the accretion disk contributes to the formation of these jets.

**Index Terms**— Active Galactic Nuclei, Astrophysics, coronae, Supermassive Black Hole, Synchroton radiation.

## 1 Introduction

A galaxy is a gravitational system of stars, stellar remnants, dust, and dark matter. The three broad types within the galaxy morphological classification system, also called the Hubble Sequence are elliptical, spiral, and lenticular. It is now widely believed that the central mass of almost all galaxies are supermassive black holes (SMBHs), with a mass $m > 10^6 M_\circ$ . This assumption is due to an empirical relation called the M-σ relation. In a spiral galaxy, the system of stars proximal to the galactic center is called the galactic bulge. The M-σ relation expresses the stellar velocity dispersion (**σ**) as a function of a hypothetical central mass, which implies the presence of a SMBH. The M-sigma correlation [1] is:

$$\frac{M}{10^8 M_\circ} = 1.9 \left(\frac{\sigma}{200\ \mathrm{km\ s^{-1}}}\right)^{5.1} \quad (1)$$

Due to accretion of galactic matter onto this SMBH, an AGN is formed, and the host galaxy is classified as an active galaxy. The presence of an AGN is marked by a supernormal luminosity of the galactic center over some wavelengths of the electromagnetic spectrum. The primary distinction in emission spectra that distinguishes stars from AGN is the presence of emission lines of widths of the order of $10^3$ km $s^{-1}$ and in a quantity far greater than any type of matter [2]. Furthermore, the centers of the emission lines did not correspond to the rest wavelength of any element presently known in laboratories. This was resolved by the model that due to the high gravitational field formed by the SMBH in AGN, emission lines were dynamically broadened [2]. The distances travelled by observed photons were of the magnitude to have considerable redshift involved due to the cosmological evolution of the universe.

AGN

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typically emit over a broad range of wavelengths, from radio to gamma. In the optical wavelength, they include a UV excess, thus their emission spectra are bluer than stellar emission spectra. AGN demonstrate strong variability at all time periods, from hours to days, suggesting that the emission source has a small size. Emission spectra of AGN also have a radio continuum emission which is due to bipolar relativistic jets discussed later and is also a signature of synchrotron radiation. Synchrotron radiation is an electromagnetic radiation from an accelerated charged particle such that the acceleration is

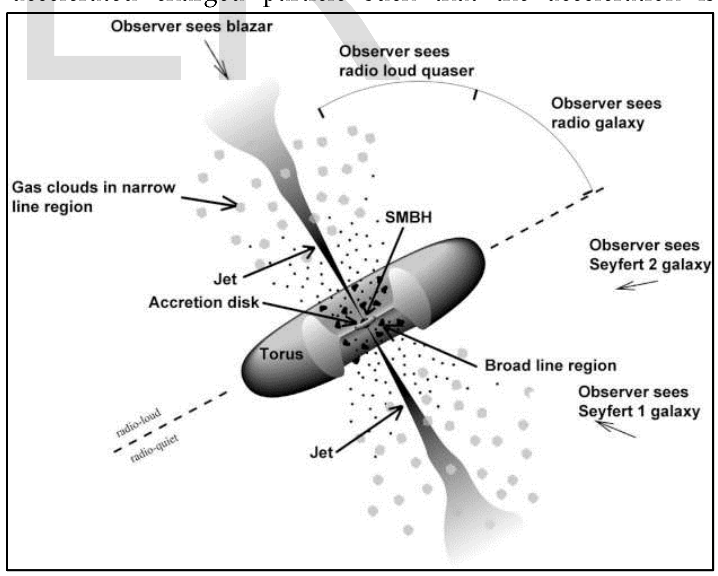


*Fig. 1: Unified model of AGN*

perpendicular to its velocity.

Fig. 1 [3] illustrates the various components of AGN and their classification based on observing angle relative to the plane of the accretion disk. Typical morphology of AGN involves a SMBH surrounded by an accretion disk of galactic matter. A relatively hot corona forms around the accretion disk which excites photons to X-ray energies due to Inverse Compton Scattering (ICS). ICS is the process of inelastic collision between a charged particle, usually an electron, and a photon. Highly collimated bipolar jets or outflows from the accretion disk are observed in some AGN, however, the mechanism or formation or the composition of these jets is not well-known due to low resolution of current astronomical instrumentation. A toroidal cloud of molecular gas and dust is formed around the AGN, usually obscuring the accreting processes.

AGN are typically classified into different systems. Firstly, on the basis of radio emission. Radio-loud AGN emit strongly in radio wavelengths, while radio quiet AGN still emit in radio wavelengths but at a much lower magnitude. Active galaxies with radio-quiet AGN are also called Seyfert galaxies. Secondly, on the presence of broad and narrow emission lines, which in turn, depends on observational angle. The gas relatively close to the SMBH moves at high velocities and is ionized due to the accreting process. This is the reason behind broad emission lines. The gas relatively far from the SMBH orbits at velocities comparable to that of stars in the galactic bulge. This gas is ionized by ultraviolet (UV) radiation, resulting in narrow emission lines. Thus, when observing from a relatively large acute angle relative to the plane of the accretion disk, a Type-I AGN is observed, the emission spectrum of which shows both narrow and broad emission lines. However, when observed from relatively small acute angles, the dusty torus obscures the broad emission region, resulting in a Type-II AGN with narrow emission lines. The focus of this study is the cause behind the formation of relativistic jets. A widely-accepted hypothesis is called the Blandford-Zjanek model [4], [5] which explains the collimation of jets by considering the magnetic field threaded through the accretion disk which is funneled by the SMBH perpendicular to the plane of the accretion disk or the alpha-disk. This is due to a toroidal current, which produces a poloidal magnetic field threading the SMBH and accretion disk. Thus, the magnetic field funneled by the SMBH restricts and therefore, collimates, the relativistic jets. However, this current model does not explain the cause of the formation of these jets and the system which powers it.

In Section 2, a model of uniformly charged hemispherical shells acting as the coronae in a counter-rotating system relative to each other and a solution of the magnetic field obtained due to this interaction is established. In Section 2.1, the origin of these coronae are discussed. In Section 3, the magnetic field for the AGN in Cygnus A is constrained and discussed. In Section 4, further potential in research is discussed.

## 2 Counter-rotating Coronae

Recently, a 'soft excess' in the X-ray continuum spectrum of AGN, which did not have any characteristic features has been observed [6]. Two models support this hypothesis. Both models give similar statistical fits and are vigorously debated. One of them is the two coronae model which suggests that the soft excess is due to ICS between an inner relatively hot corona and an outer relatively warm corona made of a cooler and denser plasma.

Further, it has been established that the magnetic field strength (B) increases while moving radially inwards from the innermost stable circular orbit ($r_{isco}$) to the event horizon of the SMBH ($r_{eh}$). The Blandford Zjanek model suggests a uniform poloidal magnetic field. Therefore, an additional factor of B exists. Using the two coronae model and the observational evidence of a non-uniform net B, it can be inferred that the source of the additional factor of B is a model of a relatively hot corona rotating above and below the accretion disk, and a relatively warm oblate spheroidal corona enveloping the AGN made of a thicker and cooler plasma [5].

Consider a hemispherical shell of radius R rotating with an angular velocity (**ω**) and a uniform surface charge distribution (**σ**). Due to the rotation of the shell, the charge on the surface moves in a circular path, inducing an electric field, and therefore a magnetic field. Thus, by integrating the magnetic fields generated by each of these circular currents, the magnetic field of the rotating hemispherical shell of charge can be found.

Consider a cross section of the shell in the xy plane. The result is an annulus, the outer edge of which makes an angle θ with the axis of rotation of the shell and a radius d. The thickness of annulus dA is $dA = 2\pi d \cdot d\theta$

(2)

Therefore,

$$dA = 2\pi R \cdot \sin\theta \cdot d\theta$$

Using Biot-Savart's Law:

$$dB = \frac{\mu_0}{2} \cdot dI \cdot \frac{d^2}{R^3} \tag{3}$$

Now, $dI = \frac{dQ}{dt}$ and (3) can be rewritten as:

$$dB = \frac{\mu_0}{2} \cdot \frac{\sigma \cdot dA}{T} \cdot \frac{R^2 \cdot \sin^2\theta}{R^3}$$

Now, $T = \frac{2\pi}{\omega}$, thus rewriting:

$$dB = \frac{\mu_0}{2} \cdot \frac{\sigma \cdot (2\pi R \cdot \sin\theta \, d\theta)}{\frac{2\pi}{\omega}} \cdot \frac{R^2 \cdot \sin^2\theta}{R^3}$$

Simplifying:

$$dB = \frac{\mu_0 \cdot \omega \cdot \sigma \cdot R}{2} \cdot \sin^3\theta \cdot d\theta \tag{4}$$

Integrating with respect to dθ:

$$B = \int_0^{\frac{\pi}{2}} dB \cdot d\theta \tag{5}$$

Therefore,

$$B = \frac{\mu_0 \cdot \sigma \cdot \omega \cdot R}{3} \tag{6}$$

Where B is the magnetic field strength at a point P at a

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distance r from the center of the shell such that $r \leq R$ and is in the direction of the angular velocity ω. This magnetic field is uniform for any point inside the hemispherical shell.

Thus, applying this model to AGN coronae in the form of hemispherical coronae results in a uniform magnetic field powering the relativistic jets. However, this is with the assumption of a uniform charge distribution.

### 2.1 Formation of Counter-rotating Hemispherical Coronae

As mentioned earlier, the model in consideration draws from the two coronae model and the increase of magnetic field while moving radially inwards along the accretion disk to the SMBH. In this section, rotating uniform hemispherical shells have been discussed, along with their related magnetic field strength. This subsection will discuss the origins of such a coronae structure.

The disk evaporation model [7] assumes a hot accreting corona and a relatively cold accretion disk. Due to the rotation of this hot accreting corona, one might assume the development of an ellipsoidal corona in the shape of an oblate spheroid. The corona is heated directly due to viscous dissipation. Energy radiation from the corona is inefficient, and is therefore propagated to the lower and cooler layers of the corona. If the corona has a density lower than a critical value, the conductive heat flux will be radiated efficiently via thermal bremsstrahlung. Otherwise, if the density is relatively high and bremsstrahlung is efficient, some part of the corona will be cooled to a relatively low temperature, resulting in condensation towards the accretion disk. Generally, it is assumed that the gas originating from the corona is cold and the corona itself is hot, as in the case of X-ray binary stars. However, it is possible in the case of AGN that the gas originating from the hot corona enters as a corona itself. Further, due to the rotation of the hot corona, considering the non-inertial frame of reference of the corona, Coriolis Effect is developed, leading to an inner layer of gas from the hot corona becoming a counter-rotating coronal layer itself. Further, this leads to a thicker cooler outer coronal layer which is in the shape of an oblate spheroid, fitting the two-corona model.

## 3 Approximation of Magnetic Field caused due to Counter-rotating Coronae [9]

As detailed by Larmor's Formula [8]

$$P = \frac{2}{3} \cdot \frac{q^2 v^2}{c^3} \tag{7}$$

any accelerated particle having a charge q and instantaneous velocity v radiates electromagnetic radiation of power P. However, Larmor's formula applies only for non-relativistic cases where $v \ll c$.

Acceleration produced by a magnetic field causes magneto bremsstrahlung, which is in the case of AGN. The character of magneto bremsstrahlung depends on the velocity of the charged particle. If the particle is mildly accelerated with kinetic energy comparable to $m_e \cdot c^2$ where $m_e$ is the rest mass of the electron, the radiation emitted is cyclotron radiation. However, when the kinetic energy of the particle is $\gg m_e \cdot c^2$ synchroton radiation is casused. Most of the radio emission of AGN is accounted for by synchrotron radiation.

For synchrotron radiation to be emitted, a relativistic case where electrons moving with velocity $v_e \sim c$ should be considered with an energy density of $U_e$ and a magnetic field accelerating the electrons with an energy density

$$U_B = \frac{B^2}{8\pi} \tag{8}$$

Hence, for a synchrotron source of radio luminosity

$$L = \int_{v_{min}}^{v_{max}} L_v \cdot dv \tag{9}$$

The minimum total energy required can be found by finding the proportionality between the energy of electrons E and the magnetic field B.

Now, the energy density of the relativistic electrons can be expressed as the integral of the product of the energy of electrons E and the number density of electrons n(E), which is essentially the total energy of electrons $U_e$

$$U_e = \int_{E_{min}}^{E_{max}} E \cdot n(E) \cdot dE \tag{10}$$

The majority of the radiation emitted by electrons is observed at a frequency

$$v \propto E^2 B \tag{11}$$

Thus,

$$E \propto B^{-\frac{1}{2}} \tag{12}$$

Thus the ratio of energy of electrons and radio luminosity can be expressed as

$$\frac{U_e}{L} \propto \frac{\int_{E_{min}}^{E_{max}} En(E)dE}{\int_{E_{min}}^{E_{max}} (-\frac{dE}{dt}) \cdot n(E)dE} \tag{13}$$

Where synchrotron power $P = -\frac{dE}{dt}$ for a power-law energy distribution of an electron the number density of electrons $n(E) \propto E^{-\delta}$. Solving further, it is obtained that

$$\frac{U_e}{L} \propto B^{-3/2} \tag{14}$$

Thus,

$$U_e \propto B^{-3/2}$$

$$U_B \propto B^2$$

Now, ions and photons contribute negligible synchrotron radiation, but contribute to the total energy. Thus, let η be the ion to electron ratio. Thus, the total energy can be expressed as

$$U = (1+\eta)U_e + U_B \tag{15}$$

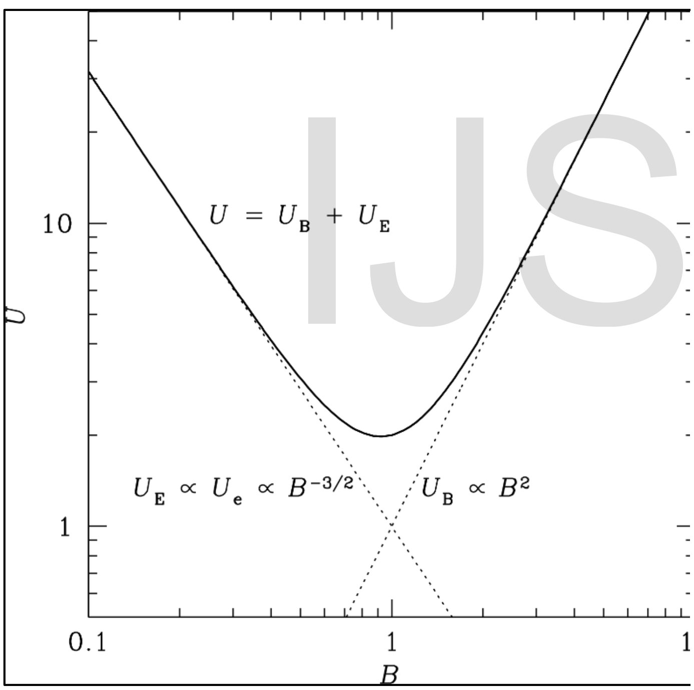


*Fig. 2 A sharp minimum observed near equipartition in the plot of U vs. B*

As illustrated in Figure 2, the minimum near equipartition exists when the slope of the graph is zero:

$$\frac{dU}{dB} = \frac{d[(1+\eta)U_e + U_B]}{dB} = 0$$

Further,

$$\frac{dU_e}{dB} \cdot {U_e}^{-1} = -\frac{3}{2} \cdot B^{-\frac{5}{2}} \cdot B^{\frac{3}{2}} = \frac{-3}{2B}$$

Similarly,

$$\frac{dU_B}{dB} \cdot {U_B}^{-1} = \frac{2B}{B^2} = \frac{2}{B}$$

Therefore,

$$\frac{-3(1+\eta)U_e}{2B} + \frac{2U_B}{B} = 0$$

Thus,

$$B_{min} = [4.5(1+\eta)kL]^{2/7} \cdot R^{-6/7} \tag{16}$$

Where k is a constant.

The synchrotron lifetime $\tau_s$ of a source is defined as the time period for which a source would emit synchrotron radiation, and can be expressed as the ratio of the total energy $E_E$ to the total energy lost $L_E$:

$$\tau_s = \frac{E_E}{L_E} \tag{17}$$

Further, synchrotron lifetime can be approximated as:

$$\tau_s = k{B_\perp}^{-3/2} \tag{18}$$

However, this considers that the dominant form of radiation, and therefore, loss of energy, is synchrotron radiation. However, if other forms of radiation are dominant, such as Compton Scattering (CS) and ICS, synchrotron lifetime is shorter. Figure 3 illustrates the various values of constant k as a function of negative spectral index.

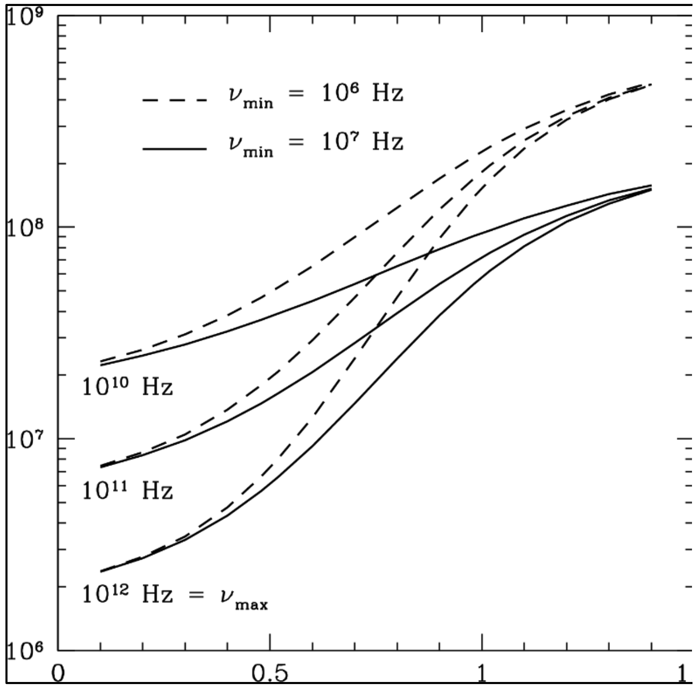


*Fig. 3 Plot of k as a function of negative spectral index*

Now, consider Cygnus A, a luminous radio galaxy. The minimum magnetic field strength of Cygnus A will now be calculated:

$$B_{min} = \left[\left(4.5 \times 3.9 \times 10^7 \times 1.33 \times \frac{10^{45}}{2}\right)^{\frac{2}{7}} (9 \times 10^{22})^{-\frac{6}{7}}\right]$$

$$\cdot (1+\eta)^{2/7}$$

Values of η in Cygnus A have not been obtained yet, however, cosmic rays can be assumed to be composed of electrons and positrons getting a value of $\eta \approx 1$. However,

$$\frac{m_p}{m_e} \approx 2 \times 10^3$$

And protons emit negligibly, thus increasing the value to

$$\eta \approx 2 \times 10^3$$

However,

$B_{min} = (1+\eta)^{2/7}$ is weakly dependent on η with $(1+\eta)^{2/7} \in [1,9]$

Therefore,

$$B_{min} \approx 10^{-4} \text{ gauss}$$

Setting this value in the final expression for B found in section 2, we obtain:

$$3 \times 10^{-4} \times \frac{1}{\mu_0} \times \frac{1}{2\pi} = \frac{\sigma R}{\mathrm{T}}$$

Furthermore:

$$\sigma = \frac{Q}{3\pi R^2} \tag{19}$$

Thus,

$$\frac{Q}{R\mathrm{T}} \approx 357.995 \text{ Fr cm}^{-1}\text{ s}^{-1} \tag{20}$$

## 4 Discussion of Further Research

This paper is a theoretical study proposing a possible magnetic field developed by the coronae of AGN. Due to the lack of observational data around the formation and powering of relativistic jets in AGN, it is difficult to constrain numerical solution to confirm a correlation between the model and the data. Numerical values for the charge distribution, radii, and time period of rotation of coronae can validate the model. Further research could clarify the details of the model and remove some of the assumptions that it entails, e.g., the surface charge distribution is considered to be uniform in this model. Further, hemispherical shells formed are assumed to be regular and uniform.

## 5 Acknowledgment

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