THE EFFECT OF ACTIVE GALACTIC NUCLEI ON PARTICLE MOTION AND EVOLUTION OF HOST GALAXIES

By

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Abstract

Active Galactic Nuclei (AGNs) are amongst important astrophysical systems used in astrophysical studies that require diverse areas of physics entertaining from quantum field to gravitation. Its interaction with its environment involves relativistic effects and geometry that arises from spin, charge and strong gravity. Research in the field is very fresh and active. Thus, in this thesis we studied the interaction of AGNs on the motion of particles, accretion process and feedback effects of on their surrounding environment including the host galaxies and beyond. Methodologically, General relativity (GR) electromagnetic field equations have used with Kerr-Newman metric to include spin and charge of the underlying Super-massive Black Holes (SMBHs). From the field equations, we developed particle orbit equations using the Euler-Lagrange equations where the invariant geodesic line element has used for the exteriorization purpose. Then, constants of motion and important orbit determining quantities like the effective potential have derived. The potential has used in characterizing the orbits were the results have addressed with plots and analytically. In the case of accretion, process the Eddington luminosity limit has used to quantify the effect of AGNs in the energy conversion at their horizons. As the analytical result indicates, the main source of energy release from the AGNs is nuclear fusion of the accreted matter. However, we comment that the dissipation during radiative transfer in the host galaxy expected to decrease the theoretical value, where we have also addressed the effects in the radiative transfer. Finally, our results indicate that the AGNs have both geometrical and gravity effects that arise from gravity, spin and charge.

Key words: AGN, SMBH, GR, Accretion, Particle motion, Host galaxy, Kerr- Newman metric, Euler-Lagrange equations and AGN-feedback

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Chapter 1

Introduction

1.1 Background and Literature review

Active galactic nuclei(AGN) are compact cores of a special category of galaxies that are characterized by high luminosity of non-stellar origin. They are the most luminous persistent sources of the Universe, and as such can be used as means for discovery of distant objects [1][2]. The AGNs is so bright that it outshines its entire host galaxy, and differs from a normal stellar system in its emission properties. AGN hosting galaxies are called active galaxies. Their luminosity comes from the central region of a galaxy, and the most engine of the activity is the supermassive black hole in the center of the host galaxy. The radiation from AGN is believed to be the result of accretion of mass by a Super-Massive Black Hole (SMBH) having $10^6 - 10^{10} M\odot$, located at the centres of their host galaxies [3]. This energy is released into the surrounding medium in a number of different ways, ranging from collimated radio-plasma jets, UV to γ-ray emission [4]. The huge amounts of energy released by the active SMBH can have an impact on the life and evolution of their entire host galaxy [5].

The first recorded observational evidence for the existence of active galactic nuclei came from Edward A. Fath in 1908 who was obtaining spectra of star clusters and spiral nebulae at the Lick Observatory in 1909. Then, the systematic study of galaxies with nuclear emission lines began with the work of Seyfert [6]. As consequence, similar objects are now called Seyfert galaxies. However, even the systematic study by Seyfert (1943) was not enough to launch active galactic nuclei (AGN) as a major topic of astronomy.

Furthermore, the development of radio astronomy during 1950s was one of the key initiatives in understanding AGN including the detected active elliptical radio source galaxies such as Messier 87 and Centaurus Bolton [7]. These observations indicated that their radio luminosities were larger than those of normal galaxy by a few orders of magnitude [8]. Collectively powerful radio galaxies, quasars and Seyfert galaxies are now referred to as active galactic nuclei (AGN), due to the luminous emission produced at their nuclei. These discoveries demanded the attention of observers and theorists, and AGN have been a subject of intense effort ever since [9]. In general, the discovery of quasars in 1960s had given attention towards the subject that has lead to the common understanding; these objects are AGNs of galaxies [10].

The idea that most galaxies, especially those with dynamically relaxed bulges, contain dormant SMBHs in their centers took much longer to develop [11]. Lynden-Bell (1969) proposed that accretion of matter onto super-massive black holes could produce vast amounts of energy on small scales. However, in the late sixties, the existence of black hole was hypothetical, and the processes responsible for such enormous energy production remained speculative for decades [12]. This makes the study of AGN particularly important as they are the main place to study black holes on this scale. As AGN are bright, they are seen over a wide range of redshifts and so also provide a way of studying the evolution of super-massive black holes [13],[14]. However, acceptance of this idea came slowly, encouraged by the discovery of black hole X-ray sources in our galaxy and, more recently, SMBHs in the center of the Milky Way and other galaxies.

On the other hand, the energy (radiative and mechanical) deposited by the AGN on its environment is thought to fundamentally influence its host galaxy. However, details on the mechanisms allowing nuclear activity to play a significant role on the formation and evolution of its host galaxy, remain elusive [15]. The less studied feeding processes of SMBHs precede the feedback processes, and play a fundamental role not only on the SMBH evolution, but also in the evolution of its host galaxy [16]. Even though the global AGN picture seems rather understood, the details of AGN physics are still poorly constrained. In addition to this, observationally, the small size of the central engine (less than a parsec) makes it challenging to spatially resolve the innermost regions of an AGN and its host galaxy with current spatial-resolution capabilities [17].

The role of AGN activity in influencing the evolution of the global galaxy population is not yet clear. This issue has been investigated, and correlations searched for between average AGN and host properties, such as BH accretion rates or AGN luminosity on the one hand, and star formation rates (SFRs) [18]. The relationship of an AGN to its host galaxy is one crucial question in the study of galaxy evolution. On the other hand, one of the most important questions about AGN concerns the nature of their emitted energy source [19]. Furthermore, massive AGN-driven outflows are now suggested to affect the evolution of galaxies due to the large amounts of energy they feed back into the interstellar medium. It is increasingly clear that a role in galaxy evolution is played by active galactic nuclei, as suggested by the tight correlation between supermassive black hole mass and galaxy bulge properties [20][21][22]. However, for these, theoretical framework are yet not so fully developed. So, motivated by this scientific rationale, we are interested to study the effect AGN on particle motion and evolution of host galaxies using Kerr−Newmann metric.

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1.2 Statement of problem

The study of active galactic nuclei have lead to some of the most important discoveries in the last century [8]. AGN have become a major and important component in modern galaxy formation models and theories. It is believed that AGN are powerful energy sources, and their energy feedback may have important impact on the intergalactic medium as well as on the formation and evolution of galaxies [23]. Both theoretical models and observations suggests that black holes and their energy output play an important role in shaping modern day galaxies [12],[24] and [25]. However, our understanding of the fundamental processes operating in AGN is far from complete, but we are reasonably confident that in all cases, the ultimate source of power is accretion via some form of an accretion disk onto BHs. But many of these details are still an active field of research. In addition to this, although the global AGN picture seems rather understood, the details of AGN physics are still poorly constrained [8][17][18] [19]. Now, this exotic system is at least understood as the center of an active galaxy. Since, the consensus of this recent theory a lot of issues are currently open to research for the progress of the astrophysical science that include;how the hosting galaxy evolves with respect it, matter in host galaxies, how do matter and energy flow towards and outwards, feedback testing mechanism, the working hypothesis that they involve at their core a supermassive black hole producing energy by accretion of gas, geometry of the AGN etc are the serious problem today.

Research questions

- What are the geodesic equations of motion near the central black hole of AGNs?
- In what way does AGN affect the motion of nearby particles?

- How does AGN affect the evolution of its host galaxy?
- What is the source of high luminosity of AGNs?

1.3 Objectives

1.3.1 General objective

To study the effect of active galactic nuclei on particle motion and evolution of host galaxies.

1.3.2 Specific objectives

- To derive equation of motion of particles in the vicinity of AGN central BHs.
- To describe the effect AGNs on particle motion.
- To explain the effect of AGNs on the evolution of their host galaxies.
- To determine the source of luminosity of AGNs.

1.4 Methodology

The central engine of the AGN is considered with charged and spinning suppermassive black hole, so that the Kerr-Newman metric is used in Einstein general relativity field equations. The field equations are used to develop general relativistic Euler-Lagrange equations of motion of particles around the SMBHs.

The Euler-Lagrange equations are used to derive the effective potential to characterize orbit of particles in the vicinity of the BH.

Accretion by the AGNs at the BH horizons and the nuclear energy conversion to luminosity is determined by the Eddington luminosity limit.

Furthermore, relativistic radiative transfer equations for matter-energy transport phenomena from the horizon to and through the AGNs environment including their host galaxies will be derived and used to describe the effect of the AGN feedback.

For analysis of the results, Mathematica 11 software is used for plots. Latex is used for documentation process.

The scheme of thesis presented as following. In this introductory chapter we provide the detail background of the work including literature reviews/issues, objectives and methods. In chapter 2 the background physics, General Relativity theory (GR) is previewed. Chapter 3 is devoted to discuss active galactic nuclei and environment in general. In chapter 4 we develop the necessary equations. In chapter 5 discuss the results and discussion will follow. The final chapter, chapter 6 goes to summary and conclusion.

Chapter 2

An Overview of General Relativity

General Relativity (GR)or general relativity theory (GRT) has been the most successful gravitational theory of the last century, fully accepted as a theory that describes the macroscopic geometrical properties of spacetime. It is the theory of space, time and gravitation formulated by Einstein in 1915. The fundamental physical postulate of general relativity is that the presence of matter causes curvature in the spacetime in which it exists. This curvature is taken to be the gravitational field produced by the matter. Moreover, once this curvature is given, general relativity describes how other objects (such as planets and light beams) move in this gravitational field via the geodesic equation. General theory of relativity is a theory of gravitation where one recognises the power of geometry in describing the physics. Einstein field equation encompasses all we need to know about the energy and momentum of matter fields, which act as a source for gravity [26].

Under the normal conditions the general relativistic effects are very small and extremely difficult to detect. In the neighbourhood of an object of mass M and radius R general relativistic effects are of the order of $\frac{GM}{Rc^2}$, G being the Gravitational constant, c the speed of light. The ratio is equal to $\sim 10^{-6}$ in the case of sun, hence it is very difficult to detect these effects. For the massive and compact objects for which $\frac{GM}{Rc^2} \sim 1$ the general relativistic effects can be easily detected. Neutron star, white dwarf, black hole are very compact objects in which the relativistic effects come into existence and can not be ignored. The dominant role of gravitation and general relativity became very much evident with the discovery of pulsars and their identification as fast rotating neutron stars [27]. Throughout the Universe many powerful events are driven by strong gravitational effects that require general relativity to fully describe them. These include compact binary mergers, black hole accretion, and stellar collapse, where velocities can approach the speed of light and extreme gravitational fields mediate the interactions [28].

2.0.1 Exact solution of Einsteins field equations

Exact solutions of Einsteins field equations gives a unique survey of the known solutions of Einsteins field equations for vacuum, Einstein Maxwell, pure radiation and perfect fluid sources. It starts by introducing the foundations of differential geometry and Riemannian geometry and the methods used to characterize, find or construct solutions. The solutions are then considered, ordered by their symmetry group, their algebraic structure or other invariant properties such as special subspaces or tensor fields and embedding properties. Exact solutions of Einstein-Maxwell field equations are important in the modeling of relativistic astrophysical objects. Such models successfully explain the characteristics of massive objects like neutron stars, pulsars, quark stars, or other super-dense objects.

In general relativity, stationary axisymmetric solutions of Einsteins equations play a crucial role for the description of the gravitational field of astrophysical objects. In particular, the black hole solutions and their generalizations that include Maxwell fields are contained within this class. This type of exact solutions has been the subject of intensive research during the past few decades. In particular, the number of know exact solutions drastically increased after Ernst discovered an elegant representation of the field equations that made it possible to search for their symmetries. These studies lead finally to the development of solution generating techniques which allow us to find new solutions, starting from a given seed solution.

More than one hundred years ago, in 1915, Einstein presented what are now known as the Einstein field equations. The Einstein field equations in vacuum [29] are:-

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 0. \tag{2.0.1}$$

For non-vacuum space-time, it can be shown that EFEs take the forms of:-

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = -kT_{\mu\nu} \tag{2.0.2}$$

where λ is cosmological constant, $R_{\mu\nu}$ is Ricci tensor, R Curvature scalar, G Newton's constant, $T_{\mu\nu}$ energy-momentum tensor, $g_{\mu\nu}$ general metric tensor and $k = \frac{8\pi G}{c^4}$. The Einstein field equation for non zero cosmological constant can be written as

$$G_{\mu\nu} + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4}T_{\mu\nu} \tag{2.0.3}$$

where the Einstein tensor $G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu}$; with non-zero cosmological constant Λ to avoid a gravitational collapse of the whole universe. These equations specify how the geometry of space and time is influenced by whatever matter and radiation are present, and form the core of Einstein's general theory of gravity [27].

By the end of 1915, the astrophysicist Karl Shwarzschild found the first non$-$trivial exact solution to the Einstein field equations, that is Schwarzchild metric;

$$ds^2 = (1 - \frac{r_s}{r})c^2dt^2 - (1 - \frac{r_s}{r})^{-1}dr^2 - r^2(d\theta^2 + \sin^2\theta d\phi^2) \tag{2.0.4}$$

where $r_s = \frac{2MG}{c^2}$.

Shwarzschild found two exact solutions to Einsteins field equation; the exterior solution which is relevant outside the star and the interior solution which is an approximation to what goes an inside the star. The exterior Schwarzschild solution is not a degenerate case for over-simplified situations but physically most meaningful. It is this solution by means of which one can explain most general relativistic effects in the planetary system. The reason is that it describes the gravitational field outside of a spherically symmetric body like the planets and the sun.

In following years, generalizing Shwarzschild's solution to include electrical charge resulted in the Reissner−Nordstrom equation;

$$ds^2 = (1 - \frac{r_s}{r} + \frac{r_Q^2}{r^2})c^2dt^2 - (1 - \frac{r_s}{r} + \frac{r_Q^2}{r^2})^{-1}dr^2 - r^2d\Omega^2 \tag{2.0.5}$$

where

$$r_Q^2 = \frac{Q^2G}{4\pi\epsilon_0 c^4} \tag{2.0.6}$$

$$d\Omega^2 = d\theta^2 + \sin^2\theta d\phi^2 \tag{2.0.7}$$

The Kerr solution is exact solution describing a rotating, stationary, axially symmetric black hole. The Kerr metric in Boyer-Lindquist coordinates;

$$\begin{aligned} ds^2 = & -dt^2 + \rho^2(\frac{dr^2}{\Delta} + d\theta^2) + (r^2 + \alpha^2)\sin^2\theta d\phi^2 + \\ & \frac{2Mr}{\rho^2}(\alpha \sin^2\theta d\phi - dt)^2 \end{aligned} \tag{2.0.8}$$

where

$$\Delta = r^2 - 2Mr + \alpha^2 \tag{2.0.9}$$

$$\rho^2 = r^2 + \alpha^2\cos^2\theta \tag{2.0.10}$$

[30]. The one which generalize the all metrics in general relativity is the Kerr−Newman solution that describes the gravitational and electromagnetic fields of a rotating charged mass.

In 1965, Ezra Ted Newman found the axisymmetric solutions of Einstein's field equation for a black hole, which is both rotating and electrically charged. It is a generalization of the Kerr metric for an charged spinning point mass. The Kerr−Newman metric describes the geometry of space−time in vicinity of rotating mass M with charge Q. The formula for this metric depend upon what coordinates or coordinate conditions are selected. In spherical coordinates, (Boyer−Lindquist coordinates);

$$\begin{aligned} ds^2 &= -(\frac{dr^2}{\Delta} + d\theta^2)\rho^2 + (cdt - \alpha \sin^2\theta d\phi)^2 \frac{\Delta}{\rho^2} \\ &\quad -((r^2+\alpha^2)d\phi - \alpha c dt)^2 \frac{\sin^2\theta}{\rho^2} \end{aligned} \tag{2.0.11}$$

where the coordinates (r, θ, ϕ) are the standard spherical coordinate system, and the length−scale;

$$\alpha = \frac{J}{Mc} \tag{2.0.12}$$

$$\rho^2 = r^2 + \alpha^2 + r_{Q^2} \tag{2.0.13}$$

$$\Delta = r^2 - r_s r + \alpha^2 + r_{Q^2} \tag{2.0.14}$$

[31].

2.1 Kerr-Newman metric

According to the no-hair theorem of black hole, the only physical characteristics of the Einstein−Maxwell equations are three quantities: mass (M), electric charge(Q), and angular momentum [32]. The Kerr−Newman metric describes a special rotating charged mass and is the general solution for the asymptotically stable black-hole solution in the Einstein-Maxwell equations in general relativity. It is an exact solution of the Einstein-Maxwell equations that describes the exterior gravitational and electromagnetic field of a rotating charged source with mass M, and angular momentum α and electric charge Q. Therefore, it is obviously pertinent to the mathematical framework of general relativity[31].

For all physical quality detailed in this thesis, I have adopted $c = G = 1$. Einsteins equation of general relativity is as follows:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi T_{\mu\nu} \tag{2.1.1}$$

where $R_{\mu\nu}$ is the Ricci tensor, which can be obtained from the Riemann tensor:

$$R_{\mu\nu} = R^{k}_{\mu\kappa\nu} = \Gamma^{\rho}_{\nu\mu}, \rho - \Gamma^{\rho}_{\rho\mu}, \nu + \Gamma^{\rho}_{\rho\lambda}\Gamma^{\lambda}_{\nu\mu} - \Gamma^{\rho}_{\nu\lambda}\Gamma^{\lambda}_{\rho\mu} \tag{2.1.2}$$

and $T_{\mu\nu}$ is the energy-momentum tensor, which is given by;

$$T_{\mu\nu} = \frac{1}{4}g_{\mu\nu}F_{\alpha\beta}F^{\alpha\beta} - g_{\nu\beta}F_{\mu\alpha}F^{\beta\alpha} \tag{2.1.3}$$

where $F_{\alpha\beta}$ is the electromagnetic field strength tensor (note $T_{\mu\nu}$ the has a zero trace)

$$T \quad = \quad g^{\mu\nu}T_{\mu\nu} = \frac{1}{4}g_{\mu\nu}g^{\mu\nu}F_{\alpha\beta}F^{\alpha\beta} - g_{\nu\beta}g^{\nu\beta}F_{\mu\alpha}F^{\beta\alpha} \tag{2.1.4}$$

$$\tag{2.1.5}$$

$$g_{\mu\nu}g^{\mu\nu} \quad = \quad 4. \tag{2.1.6}$$

The Chrostoffel symbols $\Gamma's$ are the connection coefficients obtained through

$$\Gamma^{\alpha}_{\mu\nu} \quad = \quad \frac{1}{2}g^{\alpha\beta}(\partial_{\mu}g_{\nu\beta} + \partial_{\nu}g_{\mu\beta} - \partial_{\beta}g_{\mu\nu}). \tag{2.1.7}$$

According to the covariance principle of general relativity covariance, the gravity equation remains unchanged in the coordinate transformation. Now applying the transformation ,$x \to (r^2 + \alpha^2)^{\frac{1}{2}} \sin\theta \cos\phi,\ y \to (r^2 + \alpha^2)^{\frac{1}{2}} \sin\theta \sin\phi,\ z \to r\cos\theta$ and $t \to t$ ellipsoid to coordinate changes to Minkoswiki space time, we get the following metric;

$$ds^2 = dt^2 - \frac{\rho^2}{r^2 + \alpha^2}dr^2 - \rho^2 d\theta^2 - (r^2 + \alpha^2)\sin^2 d\phi^2 \tag{2.1.8}$$

where α being the coordinate transformation parameter. This equation represents an empty space-time of ellipsoid symmetry. If α approaches zero, it morphs into a polar coordinate with spherical symmetry. Then, by introducing the new coordinate system, $dT = dt - \alpha \sin^2\theta d\phi$ and $d\psi = d\phi - \frac{a}{r^2+\alpha^2}dt$. After the coordinate transformation, [33] eq. 2.1.8 is transformed into a simplified orthogonal metric, as presented in equation below;

$$ds^2 = \frac{r^2+\alpha^2}{\rho^2}dT^2 - \frac{\rho^2}{r^2+\alpha^2}dr^2 - \rho^2 d\theta^2 - \frac{(r^2+\alpha^2)^2}{\rho^2}\sin^2\theta d\psi^2 \tag{2.1.9}$$

To get the Kerr−Newman metric we have to introduce the following two terms i.e $e^{2\nu(\nu,T)}$ and $e^{2\lambda(\nu,T)}$

$$ds^2 = e^{2\nu(\nu,T)}dT^2 - e^{2\lambda(\nu,T)}dr^2 - \rho^2 d\theta^2 - \frac{h^2\sin^2\theta}{\rho^2}d\psi^2 \tag{2.1.10}$$

where $\rho^2 = r^2 + \alpha^2\cos^2\theta$, $h^2 = r^2 + \alpha^2$.

Using the eq 2.1.7 we will get total 14 non-zero Chrostoffel symbols. After such calculations, the Ricci tensor of all non-zero components can be obtained as follows:

$$\begin{aligned}
R_{00} &= [\partial_0^2\lambda + (\partial_0\lambda)^2 - \partial_0\lambda\partial_0\nu] + e^{2(\nu-\lambda)} \\
&\quad [-\partial_1\nu\partial_1\lambda + (\partial_1\nu)^2 + \partial_1\nu)^2 + \frac{2r}{h}\partial_1\nu] && (2.1.11) \\
R_{01} &= R_{10} = \frac{2}{r}\partial_0\nu && (2.1.12) \\
R_{11} &= e^{2(\lambda-\nu)}[\partial_0^2\lambda + (\partial_0\lambda)^2 - \partial_0\lambda\partial_0\nu] \\
&\quad +\partial_1\nu\partial_1\lambda - (\partial_1\nu)^2 + \partial_1\nu)^2 + \frac{2r}{h}\partial_1\lambda && (2.1.13) \\
R_{22} &= e^{-2\lambda}(r(\partial_1\lambda - \partial_1\nu) - 1 + \frac{2r^2}{\rho^2} - \frac{2r^2}{h}) + \frac{h^2}{\rho^4}(\frac{5r^2-4\rho^2}{h}) && (2.1.14) \\
R_{33} &= \sin^2\theta(\frac{2h}{\rho^2} - \frac{h^2}{\rho^4})[e^{-2\lambda}(r(\partial_1\lambda - \partial_1\nu)) \\
&\quad -\frac{r^2}{\rho^2}) + \frac{h^2}{\rho^4}(\frac{5r^2-4\rho^2}{h})(\frac{2h}{\rho^2} - \frac{h^2}{\rho^4})]. && (2.1.15)
\end{aligned}$$

Because of spherical symmetry, the only non-zero components of the electric and magnetic field are the radial components, which should be independent of ϕ and θ. Therefore, the radial component of the electric field has a form of

$$E_r = E_1 = F_{01} = \quad -F_{10} = f(r,T) \tag{2.1.16}$$

By substituting equation 2.1.16 into equation 2.1.3 we get the following after a few calculation and simplification.

$$T_{\mu\nu} \quad = \quad \frac{1}{2} g_{\mu\nu} F_{01} F^{01} - g_{\nu 1} F_{\mu 1} F^{01} \tag{2.1.17}$$

The components of the stress-energy tensor can now be easily obtained. We have

$$\begin{aligned}
T_{00} &= -\frac{1}{2} g_{00} F_{01} F^{01} = \frac{1}{2} \exp 2\nu(r,T) f(r,T)^2 && (2.1.18)\\
T_{11} &= -\frac{1}{2} g_{11} F_{01} F^{01} = -\frac{1}{2} \exp 2\lambda(r,T) f(r,T)^2 && (2.1.19)\\
T_{22} &= \frac{1}{2} g_{22} F_{01} F^{01} = \frac{1}{2} \rho^2 f(r,T)^2 && (2.1.20)\\
T_{33} &= \frac{1}{2} g_{33} F_{01} F^{01} = \frac{1}{2} \rho^2 (\frac{h^2}{\rho^4}) \sin^2\theta f(r,T)^2 && (2.1.21)\\
T_{00} &= 0. && (2.1.22)
\end{aligned}$$

Using these equation and after a little derivation we get $e^{2\nu(r,T)} = e^{-2\lambda(r,T)}$. Substituting this and after some mathematical process and assumption, t component become the following;

$$\partial(r^2 F^{10}) \quad = \quad \partial r(r^2 g^{11} g^{00} F_{10}) = \partial r(r^2 f). \tag{2.1.23}$$

Therefore $f(r) = \frac{cont}{r^2}$. The Gauss flux theorem gives $\frac{Q}{\sqrt{4\pi}}$, where Q is the total electric charge of a black hole. By considering the following $lim_{\alpha\to 0} R_{22} = lim_{\alpha\to 0} 8\pi R_{22}$ and

$lim_{\alpha\to 0}h = r^2$, $lim_{\alpha\to 0}\rho = r$ and

$$lim_{\alpha\to 0}R_{22} = e^{-2\lambda}(r(\partial_1\lambda - \partial_1\nu) - 1) + 1 \tag{2.1.24}$$

$$= e^{2\nu}(2r\partial_1\nu - 1) + 1 \tag{2.1.25}$$

$$lim_{\alpha\to 0}8\pi R_{22} = \frac{8\pi r^2}{2}(\frac{Q}{\sqrt{4\pi}r^2})^2 = \frac{Q}{r^2}. \tag{2.1.26}$$

and combining Eqs.2.1.26 and 2.1.26, it gives the following equation

$$\partial r(re^{2\nu}) = 1 - \frac{Q^2}{r^2}. \tag{2.1.27}$$

After integrating and solving Eq.2.1.27 and letting constant of integration $2M$, it yields

$$e^{2\nu} = \frac{r^2 - 2Mr + \alpha^2 + Q^2}{r^2 + \alpha^2\cos^2\theta} \tag{2.1.28}$$

$$e^{2\nu} = \frac{\Delta}{\rho^2} \tag{2.1.29}$$

$$e^{2\lambda} = e^{-2\nu} = \frac{\rho^2}{\Delta} \tag{2.1.30}$$

where $\rho^2 = r^2+\alpha^2\cos^2\theta$, $\Delta = r^2-2Mr+\alpha^2+Q^2$ is the delta function of the Kerr$-$Newman metric. Finally, we obtain the Kerr$-$Newman metric through

$$\begin{aligned} ds^2 &= -[\frac{\Delta - \alpha^2\sin^2\theta}{\rho^2}]dt^2 - \frac{2\alpha\sin^2\theta(r^2+\alpha^2-\Delta)}{\rho^2}dtd\phi \\ &\quad + \frac{[(r^2+\alpha^2)^2 - \Delta\alpha^2\sin^2\theta]}{\rho^2}\sin^2\theta d\phi^2 + \frac{\rho^2}{\Delta}dr^2 + \rho^2 d\theta^2 \end{aligned} \tag{2.1.31}$$

Chapter 3

Introduction of AGN

3.1 AGN and its classification

Active galactic nuclei represent an extreme stage in the life cycle of a galaxy. The term AGN encompasses a variety of energetic phenomena in galactic centers, triggered by matter spiralling into a SMBH at a relatively high rate. For a relatively short period of time a region less than a parsec across at the center of a galaxy produces tremendous amounts of energy, often outshining the rest of the galaxy by orders of magnitude. The most luminous of these objects are the most powerful, continuously emitting sources in the universe. The evidence that supports the current paradigm, under which the central source powering AGN is a supermassive black hole [34]. The basic structure, illustrated in fig.3.1, is seen in both radio−loud and radio−quiet objects and features a supermassive black hole at the center, accreting material, possibly through a disk.

Accretion is an elegant way to generate enormous luminosities within the small volumes required by the observed variability as it offers the potential of converting up to half of the gravitational potential energy from accreting matter into light and heat in the process. Surrounding the accretion disk are various layers of warm gas, which would explain the broad and narrow emission line features. Accretion disks were hyphothesised to form when gas endowed with angular momentum is accreted onto a central gravitating object. Disks are envisaged to play many roles in AGN. They are identified with the channels through which matter moves radially inward and with the source of the continuum emission, which we observe directly and which maintains the ionization in emission line clouds and the surrounding intergalactic medium [35],[36].

According to the standard unified model, AGN can be broadly classified into two categories. They are depending on whether the central black hole and its associated continuum and broad emission-line region is viewed directly or is obscured by a dusty circum-nuclear medium. Since this obscuring medium does not fully cover the central source, some of the radiation escapes and photoionizes surrounding gas, leading to strong narrow permitted and forbidden emission lines from the Narrow Line Region (NLR).

In type 1 AGN the optical continuum is dominated by non-thermal emission, making it a challenge to study the host galaxy and its stellar population. This is especially true of QSOs, where the continuum radiation from the central source outshines the stellar light from the host galaxy. Broad Line Region (BLR) is the region where the broad lines of active galactic nuclei are produced. It is most likely a relatively high density region (particle density in the range $10^9 - 10^{13}$ ions per cubic centimeter. It is believed to be very close to the central source of radiating energy of the active galactic nucleus. Narrow Line Region (NLR)is a region of active galaxies, where narrow permitted and forbidden emission lines are produced. The term narrow is used to distinguish lines whose width is typically $\geq 300 kms^{-1}$, hence already unusually broad for non-active galaxies, and lines whose full width at half maximum is several thousands kms^{-1}, emitted in a region of active nuclei (the Broad Line Region) distinct from the NLR. While in type 2 AGN, the central black hole and its associated continuum and broad emission-line region is obscured by a dusty circum−nuclear medium [4],[37][10].

Obscured AGN are systems where the emission from the accretion disk is not directly detected because of the presence of material between the accretion disk and the observer. In a general sense, obscuration is defined as anything that absorbs emission and scatters a large fraction away from the line of sight of the observer. In astrophysical sources, the obscuring medium is typically composed of dust and gas. Dust is the common term used to describe solid-state structures, which are typically carbonaceous grains and amorphous silicate grains. Gas is the term used to describe a broad range of gaseous states, from fully ionized gas, including electrons and protons, to neutral gas and molecular compounds. However, the obscuration can also come from the host galaxy (e.g., from dust-obscured star-forming regions or from dust lanes) and is likely to be more significant for inclined and edge-on galaxies and for galaxies in gas-rich mergers since, on average, the typical optical depth along a given line of sight will be higher than for face-on normal galaxies [38][39].

The basic AGN paradigm developed thus far consists of a central supermassive black hole, surrounded by an accretion disk, or more generally optically thick plasma, glowing brightly at ultraviolet (UV) and perhaps soft X-ray wavelengths. In the innermost region, hot optically thin plasma surrounding and mixed with the optically thick plasma gives rise to the medium and hard X-ray emission. Clouds of line-emitting gas move at high velocity around this complex core and are in turn surrounded by an obscuring torus or warped disk of gas and dust, with a sea of electrons permeating the volume within and above the torus. In some systems, highly relativistic outflows of energetic particles along the poles of the rotating black hole, accretion disk, or torus form collimated radio-emitting jets that lead to extended radio sources. These AGN are called radio loud because their radio emission is comparatively strong; AGN without collimated jets, which therefore have weaker (but

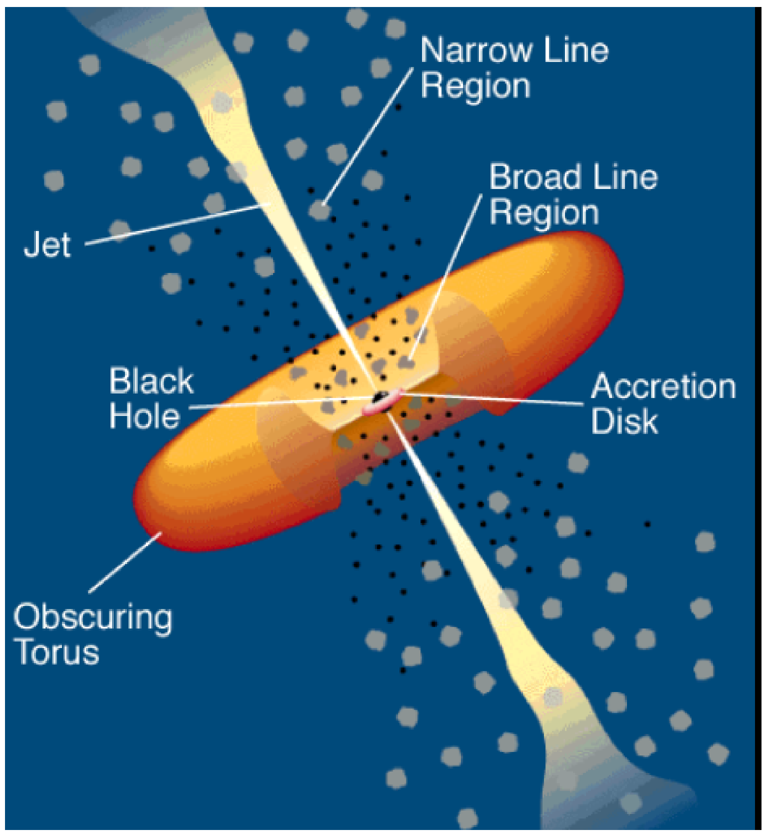

Figure 3.1: A schematic diagram of the currently most accepted model of the structure of AGN(credit to Planck collaboration;2016)

detectable) radio emission, are called radio quiet [40].

3.1.1 AGN Unified model and its effect on the evolution of host galaxy

Unified model is explain the main properties of the large zoo of active galactic nuclei with a single physical object. Much of the work on unified models is morphological in nature, i.e.,based on searches for correlations among observed parameters, which are motivated by some broad ideas about what kinds of physical effects might be operating. Even though diverse types of AGN are observed with different properties, it is generally believed that their fueling mechanisms are essentially similar. The current AGN model unification scheme between this different types of AGN were developed by Antonucci (1993) and Urry and Padovani (1995). Antonucci (1993) defined a preliminary simple model of two basic types of AGN: radio quiet and radio loud. Seyfert galaxies and radio-quiet quasars belong to the radio-quiet group, while radio galaxies, radio-loud quasars, and BL Lac objects make the radio-loud group. The radio-loud AGN have variability characteristics that are distinct from their radio-quiet counterparts. Variability in these objects is widely believed to be dominated by emission from a relativistic jet. They were further divided the radio-loud subclass into two intrinsically different types based on their radio luminosity: the high-luminosity sources, such as radio-loud quasars and FR II radio galaxies, and the low-luminosity sources, such as BL Lac objects and FR I radio galaxies [41]. With this division, all AGNs belong in one of three physically different types. Differences between AGN in each of these types are caused by different viewing angles from which we observe them.

In the unification by orientation scheme of Antonucci (1993) and Urry and Padovani (1995), it is assumed that galaxies host SMBH in their center. Furthermore, the torus is co-aligned with the accretion disk and partly obscures the emission from the accretion disk. This leads

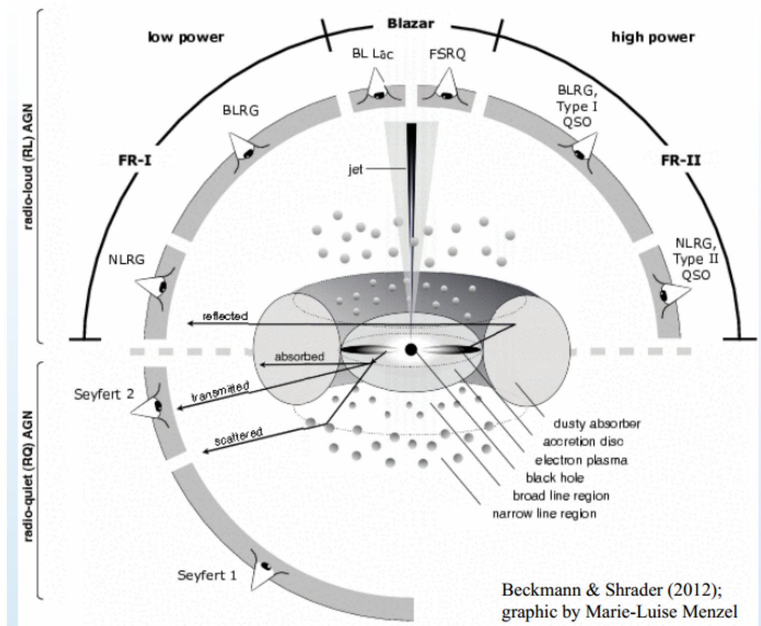

Figure 3.2: Beckmann and Shrader (2012); graphic by Marie-Luise Menzel

to the fact that the appearance of the central AGN region depends on the inclination of the AGN towards the line of sight of the observer. The unification paradigm of AGN implies the existence of a geometrically thick belt of matter which wraps and hides the inner, most luminous region of AGN from viewing close to the equatorial plane [42]. The AGN class includes different types of objects like Seyferts, LINERs, BL Lac objects, Optically Violent Variable objects (OVV), Blazars and broad-line radio galaxies, all of them sharing the basic above defined characteristics.

Seyferts are classified into two: Type 1 and Type 2 subclasses, with the Type 1 showing broad and narrow emission lines while the Type 2 produce narrow emission lines only. Radio galaxies are radio-loud AGN in general associated with massive, gas-poor elliptical galaxies. Most powerful radio galaxies are known to produce emission lines, whose luminosity correlates with the radio power. The radio emission is powered by relativistic jets through synchrotron radiation. Radio galaxies are further classified into two subclasses (Fanaroff and Riley 1974): the FRIs have low radio luminosities and are edge darkened, while FRIIs are the more powerful edge brightened ones. The high luminosity concentrated in a small region from the center of the AGN, can not be produced by stars, the idea of a very compact engine, namely a black hole, hosted in the center of the galaxy. Black hole (specially SMBH) attracts matter that from the surrounding galaxy which is accumulated in an accretion disc. In terms of energetics, an AGN is extraordinary in that it emits a large amount of energy from a very small region. The small size of the emission region and the large amount of energy output suggest that the central engine must be compact and have relatively large mass [8].

AGN zoology appearances strongly depends on the orientation of the AGN with respect to the observer. Optical images of luminous type-I AGNs show clear signatures of point like central sources with excess emission over the surrounding stellar background of their host galaxy. The non-stellar origin of these sources is determined by their SED shape and by the absence of strong stellar absorption lines. Type-II AGNs do not show such excess. The luminosity of the nuclear, non-stellar source relative to the host galaxy luminosity can vary by several orders of magnitude. In particular, many AGNs in the local universe are much fainter than their hosts, and the stellar emission can dominate their total light. For example, the V-band luminosity of a high stellar-mass AGN host can approach $10^{44} ergs^{-1}$, a luminosity that far exceeds the luminosity of many local type-I AGNs. This must be taken into account when evaluating AGN spectra obtained with large-entrance-aperture instruments. The relative AGN luminosity increases with decreasing wavelength, and contamination by stellar light is not a major problem at UV wavelengths[10].

The two largest subclasses of AGNs are Seyfert galaxies and quasars, and the distinction between them is to some degree a matter of semantics. The fundamental difference between these two subclasses is in the amount of radiation emitted by the compact central source; in the case of a typical Seyfert galaxy, the total energy emitted by the nuclear source at visible wavelengths is comparable to the energy emitted by all of the stars in the galaxy, but in a typical quasar the nuclear source is brighter than the stars by a factor of 100 or more. Historically, the early failure to realize that Seyferts and quasars are probably related has to do with the different methods by which these two types of objects were first isolated, which left a large gap in luminosity between them [43].

The mutual interactions between super-massive black holes and host galaxies are a key ingredient to understand the evolution of both source populations. When discussing the connection of the AGN with its host, it is useful to have a look at the morphologies of galaxies in general and what is believed to be their evolutionary path. The evolution of AGN and their observational appearance is connected to the evolution of the host galaxy. The ratio of obscured to unobscured AGN (R) increases with redshift, implying a change to the traditional unification model. Since the obscuring medium is changing with redshift, it must be influenced, e.g., by the cosmic star formation rate, which peaks at a very similar redshift as R. As star formation increases in a galaxy, also the absorbing gas and dust increase, acting as an obscuring medium.

Let us analysis the relation between host galaxy mass M_* and black hole mass M_{BH}. The ratio M_*/M_{BH} depends on M_{BH} at all redshifts. Studying systems at redshift$z \simeq 2$, found that for the lower black hole masses of $M_{BH} \simeq 10^8$ this ratio is higher ($M_*/M_{BH} \sim 280$) than for the highmass systems with $M_{BH} = 10^9 M_\odot$, where this ratio is about 40. This means that although high-mass AGN reside in larger host galaxies, there is no constant ratio between the host mass and the black hole mass. In the local Universe M_*/M_{BH} grows by a factor of$\sim 4-8$, which seems to indicate that the host galaxies grow faster than the black hole cores. Thus, there seems to be a rather large scatter in the ratio between the black hole mass and the total mass of the galaxy. The two masses, that of the host M_* and that of the central engine M_{BH}, seem to be correlated. In addition, correlations between the mass of these central black holes and host galaxy properties suggest that the evolution of galaxies must be intimately related to the growth of their central black holes.

In general, active galactic nucleus and galaxies have very different evolutionary properties. Active galactic nucleus evolve much faster: they are much rarer than galaxies at low redshifts and become much more numerous at redshifts of greater or equal to two [44].

3.1.2 Galaxy

A galaxy is a massive, gravitationally bound system consisting of stars, an interstellar medium of gas and dust, and dark matter. Galaxies are the places where gas turns into luminous stars, powered by nuclear reactions that also produce most of the chemical elements. But the gas and stars are only the tip of an iceberg; a galaxy consists mostly of dark matter, which we know only by the pull of its gravity. Most of the visible matter in the universe is concentrated in galaxies, which are the basic astronomical ecosystems in which stars are born, evolve, and die. The gross structural properties of galaxies and their distribution in space are determined primarily by the processes of galaxy formation, while other properties such as the stellar and gas content of galaxies and their evolution with time depend mainly on the processes of star formation and stellar evolution. However, it can be difficult to separate the processes of galaxy formation from those of galactic evolution, and both must be considered in any effort to understand the origin of the observed properties of galaxies and the correlations among them that are embodied in the Hubble classification sequence [45].

Beyond the Milky Way are billions of other galaxies. Some galaxies are spiral like the Milky Way while others are egg-shaped or completely irregular in appearance. Besides shape, galaxies vary greatly in the star, gas, and dust content and some are more active than others. Galaxies tend to cluster together and these clusters appear to be separating from each other, caught up in a Universe that is expanding. A galaxy is an immense and relatively isolated cloud of hundreds of millions to hundreds of billions of stars, and vast clouds of interstellar gas. Each star moves in its own orbit guided by the gravity generated by other stars in the galaxy [46].

In fact, the universe is now believed to be dominated by dark matter of an unknown nature everywhere except in the inner parts of bright galaxies, and the visible galaxies are thought to be just concentrations of ordinary matter located at the centers of much more massive and extended dark halos . We are interested here in the formation and evolution of these visible systems of stars and gas, but clearly their properties are controlled at least in part by the distribution and dynamics of the dark matter in the universe. A small fraction of all galaxies have a spectral energy distribution that is much broader than what is expected from a collection of stars, gas and dust. They typically emit over the full wavelength range from the radio to the X-ray, suggesting that the radiation is non-thermal. In addition, the optical/UV parts of their spectra often reveal numerous strong and very broad emission lines. These galaxies are referred to as active galaxies. For examples Seyfert galaxies, radio galaxies, and quasars. The non-thermal emission of active galaxies in general emanates from a very small central region, often less than a few parsec across, which is called the active galactic nucleus. The amazing aspect of an AGN is that, despite its extremely small size, the non-thermal luminosity can exceed that of the host galaxy, sometimes by as much as a factor of a thousand [4][47].

It is generally believed that galaxies were formed by the gravitational condensation or aggregation of matter that was initially much more uniformly distributed in the universe. Most of the efforts that have been made in recent years to model the growth of structure in the universe have been based on the hypothesis that the observed structure originated from initial density fluctuations having a wide range of length scales. Usually the power spectrum of these initial density fluctuations has been assumed to be approximately scale-free, and such that the density fluctuations have larger amplitudes on smaller scales. A galaxy is a complex system bound by gravity. In our current paradigm, the gravitational potential is dominated by dark matter, whose distribution is much more extended than the visible part, and forms a spheroidal halo. The ordinary matter loosely called baryonic matter is made up mostly of hydrogen and helium, in the form of stars, diffuse and clumpy gas, dust, planets, etc [4][48].

3.1.3 Galaxy formation and evolution

Understanding the properties and formation of active galaxies is an important part of galaxy formation. First of all, active galaxies form an important population of galaxies, and so any theory of galaxy formation should also address the formation of AGN. Secondly, it is believed that AGN are powered by matter accreting onto a supermassive black hole. The observed correlation between the masses of SMBHs and the masses of their host galaxies, strongly suggests that the formation of SMBHs is closely connected to galaxy formation. Furthermore, the fact that virtually all spheroids are found to harbor a SMBH suggests that many, if not all, normal galaxies may have experienced an active phase in their past. Finally, AGN are powerful energy sources, and their energy feedback may have important impact on the intergalactic medium as well as on the formation and evolution of galaxies.

The effects of such feedback must be taken into account in any theory of galaxy formation and evolution.

Galaxy formation requires an understanding of the most fundamental physical processes: gravitation, statistical mechanics, gas hydrodynamics, radiative transfer, atomic physics, etc. The fundamental issue related to galaxy formation is that AGN activity can affect the flow and heating of the gas that fuels star formation in galaxies. Therefore, although AGNs are confined to a minuscule volume within the galaxy (a $10^9 M_{\odot}$SMBH has a radius$r_g = \frac{2GM}{c^2} \simeq 20AU$ and they can control galaxy formation (i.e., over scales $\geq 50kpc$). It is believed that AGN activity provides a feedback mechanism that contributes to the quenching of star formation in massive galaxies. A strong correlation is found between galaxy properties and the mass of the central black hole [49].

Galaxy evolution is influenced by environment. The properties in terms of morphology, color, gas content, and star formation of galaxies residing in the field, groups, or clusters are markedly different. Environmental effects include gravitational interactions with other galaxies or the cluster potential and hydrodynamical effects as ram pressure stripping. One can distinguish two different classes of interactions based on gravitation or gas physics. The first class includes galaxygalaxy and galaxycluster tidal interactions. The second class involves the hot intracluster medium through which the galaxy is moving at a high speed. Whereas gravitational interactions act in the same way on all components of a galaxy (dark matter, stars, and gas), hydrodynamic interactions only affect the galaxys interstellar matter [34][4].

3.2 AGN and Enviroment

Active galactic nuclei are not isolated in space. In fact, they interact extensively with surrounding matter, first through accretion of nearby matter onto the supermassive black hole, but additionally through radiation and particles emanating from the AGN and propagating into the surrounding medium [50]. AGN can exert either negative or positive feedback on their surroundings. The former describes cases where the AGN inhibits star formation by heating and dispersing the gas in the galaxy, while the latter describes the possibility that an AGN may trigger star formation. Both these feedback modes are then capable to release energy directly in the environment from which the SMBH grows: the cooling, star-forming gas in the central region of the galaxy. This energy transfer not only reduces the rate at which the gas cools and form stars, but it also reduce the rate of accretion onto the SMBH. AGN feedback can operate in quasar-mode from radiation at high accretion rates, or radio-mode from AGN jets at predominantly low accretion rates. Active galactic nuclei release large amounts of energy to their environments, in several forms.

In luminous AGNs such as Seyfert nuclei and quasars, the most obvious output is radiative; indeed, radiation can affect the environment through both radiation pressure and radiative heating. Although jets and winds are usually associated with radio galaxies, recent theoretical and observational developments suggest that the kinetic energy output may be as important as (or more important than) the radiative output for most accreting black holes. There are various forms of energy injection. These are; radiation pressure, radiative heating ,energetic particles and kinetic energy.

In addition to charged relativistic particles that can diffuse through the surrounding medium, AGNs may also emit exotic particle outflows, consisting, for example, of relativistic neutrons and neutrinos. This form of energy injection could drive powerful, fast winds that start far from the central engine. In addition to the obvious example of radio galaxies, which often release the bulk of their power in the form of jets, most if not all accreting black holes could produce substantial outflows. Numerical simulations suggest that accretion disks, which transfer angular momentum and dissipate binding energy via magneto-rotational instability, may inevitably produce magnetically active coronae. These likely generate outflows that are further boosted by centrifugal force. AGN feedback due to kinetic energy injection is perhaps most evident in clusters of galaxies [51][52].

3.2.1 AGN Evolution

Today is widely accepted that the high energy phenomena involved in the AGN activity have their origins in the accretion of matter onto a supermassive black hole at the centre of the hosting galaxy [52]. Besides being among the brightest objects in the universe, AGN are further characterised by being strong emitters at any range of the electromagnetic spectrum. The power of these sources is based on the availability of material in their immediate surroundings, host galaxy, and circumgalactic medium. Different processes cause the fall of matter onto the center, eventually fueling the black hole through an accretion disk. Furthermore, the presence of dust and gas, and the influence of host galaxy emission shape the SED in a different way for each individual AGN. The luminosity of the disk radiation emitted during active accretion phases has an effect on the properties of the surrounding galaxy. Current studies suggest that feedback processes, which are driven by the energy release of the AGN, have a major impact on the interstellar matter and gas in the host galaxy. Feedback requires a minimum power and thus a minimum mass because, for a given black hole mass, there is a maximum AGN luminosity, called the Eddington limit, above which the radiation-pressure force outwards exceeds the gravitational force inwards, suppressing the gas flow onto the black hole [49].

As a characteristic tracer of AGN evolution, we introduce the luminosity function $\phi(L)$. Luminosity function $\phi(L)$ corresponds to the space density of sources of different intrinsic luminosities. The luminosity function of active galactic nuclei represents one of the crucial observational constraints on the growth of supermassive black holes over the history of the Universe. The number of sources per unit volume of luminosity between L and L + dL is calculated as

$$dN = \phi(L)dL \tag{3.2.1}$$

The shape of this function can be approximated by a broken double power law. The shape of the luminosity function reflects a combination of the underlying distribution of the SMBH masses and the distribution of their accretion rates or Eddington ratios [53]. At different redshifts, this shape gives interesting insights into the evolution of AGN activity: the break luminosity represents the typical black hole luminosity and the integrated luminosity can trace the epoch of rapid build-up of SMBH mass density.

A mechanism explaining the co-evolution of AGN and galaxies is assumed to be feedback. The general idea of feedback includes some form of energy release from the accreting black hole which either terminates the star formation in large regions of the bulge or blows away the gas supply in the nuclear scale. The energy release for the AGN is supposed to happen in different outflow modes, often referred to as the radiative mode and the kinetic mode. Churazov in (2005) proposed that the radiative mode shapes the overall galaxy and black hole at early times, and the kinetic mode has since maintained that situation where needed. The radiative mode is caused by the emitted AGN continuum from the accretion disk. The stronger interactions of the radiative mode might be due to line-driven winds generated close to the quasar and pushing the gas out while flowing through the galaxy. Furthermore, the radiation pressure acts on dust grains, which is typically charged in the energetic environment of the AGN and embedded in the interstellar partly-ionized gas [43][54].

A second outflow mode is the kinetic mode, which involves narrow-angle relativistic jets driven by the AGNs accretion flow. It is more likely to be observed than radiative outflows, because the surrounding gas is highly ionized and mostly optically thin. The kinetic mode typically operates when the galaxy has a hot halo or is at the centre of a group of galaxies and the accreting black hole has powerful jets [55].

3.2.2 Evolution of host galaxy

Host galaxy is a preferred kind of galaxy type in which a suppermassive black holes accreting matter. The Hubble type does not matter as much as the mass of the host galaxy, i.e., a more massive galaxy is more likely to harbor an AGN, but whether that is a spiral or an elliptical galaxy matters only as far as ellipticals are in general more massive than spirals. Even more controversial is the possible connection between black hole mass and the host galaxy. At present time one able to state the following: more massive black holes tend to sit in more massive galaxies. All AGN seem to be hosted in galaxies. Some claims have been raised of detection of naked AGN cores, which do not reside in a host galaxy. In some cases it is difficult to determine the type of host galaxy, for example in the case of blazars where the beamed emission greatly outshines its surroundings, but even for bright non beamed AGN at high redshift this can be observationally challenging. Nevertheless, even in blazars we can see evidence of the surrounding matter through absorption lines which are produced when the radiation from the jet travels through the host before leaving the galaxy [51].

The host galaxy feels the presence of its nuclear SMBH through the gravitational effect of its mass through the ionizing and non−ionizing radiation field emitted by the AGN and by the particle flows in the jets and radiation pressure driven winds with any associated magnetic fields [56]. It is becoming increasingly clear that active galactic nuclei play an important role in the framework of galaxy formation. The energy produced by AGN during their short lifetimes can influence the evolution of both their host galaxies and their surrounding environment. These extreme sources of energy are expected to have a strong feedback effect on the galactic gas content and star formation. AGN feedback may also self−regulate the growth of the central SMBH and its inclusion in models of galaxy formation improves the match between the simulated and the observed galaxy luminosity function for massive galaxies. There are several observations that indicate a correlation between the mass of the central SMBH and largescale properties of the host galaxy, such as the stellar velocity dispersion, luminosity, or the bulge mass. These relations imply a possible co-evolution of the black hole and its host galaxy [57].

The SMBH energy release can potentially affect its surroundings in two main ways. By far the stronger one actually in principle is through direct radiation. This is particularly effective during heavily dust-obscured phases of AGN evolution. The second form of coupling the SMBH energy release to a host bulge is mechanical. The huge accretion luminosity of SMBHs may drive powerful gas flows into the host, impacting into its interstellar medium [58].

3.2.3 Magnetohydrodynamics

Magnetohydrodynamics (MHD) is concerned with the flow of electrically conducting fluids in the presence of magnetic fields, either externally applied or generated within the fluid by inductive action [59]. The interaction of moving conducting fluids with electric and magnetic fields provides for a rich variety of phenomena associated with electro-fluid-mechanical energy conversion. In nature as in industrial processes, we can observe magnetic fields influencing the behaviour of fluids and flows. Sunspots and solar flares are generated by the solar magnetic field and the galactic magnetic field which influences the formation of stars from interstellar gas clouds. We use the word Magnetohydrodynamics for all of these phenomena, where the magnetic field B and the velocity field $\mathbf{u}$ are coupled, given there is an electrically conducting and non-magnetic fluid, e.g. liquid metals, hot ionised gases (plasmas) or strong electrolytes. The theory of Magnetohydrodynamics describes the fluid mechanics of plasmas and the behaviour of their magnetic fields. The magnetic field can induce currents into such a moving fluid and this creates forces acting on the fluid and altering the magnetic field itself.

The MHD approximation that makes this possible involves some assumptions : 1. The fluid approximation : Local thermodynamic quantities can be meaningfully defined in the plasma, and variations in these quantities are slow compared with the time scale of the microscopic processes in the plasma. This is the essential approximation. 2. In the plasma there is a local, instantaneous relation between electric field and current density (an Ohms law). 3. The plasma is electrically neutral:This statement of the approximation is somewhat imprecise. The first of the assumptions involves the same approximation as used in deriving the equations of fluid mechanics and thermodynamics from statistical physics. It is assumed that a sufficiently large number of particles is present so that local fluid properties, such as pressure, density and velocity can be defined. It is sufficient that particle distribution functions can be defined properly on the length and time scales of interest [60].

3.3 Black hole

A black hole is defined as a region of space time that cannot communicate with external universe. The boundary of this region is called the surface of the black hole or the event horizon. Black hole is cosmic body of extremely intense gravity from which nothing, not even light, can escape. It can be formed by the death of a massive star. Black holes are extreme cases of curved space-time and are described by general relativity or alternative gravitational theories. According to the current theory, mass, charge, and angular momentum are the only properties black holes can possess. This has become known as the no hair theorem of BHs [37].

Supermassive black holes are found at the centre of massive galaxies. These black holes, with masses ranging from millions to billions of times that of our Sun ($10^6 - 10^{10} M_\odot$), primarily grow through periods of radiatively−efficient accretion of gas when they consequently become visible as AGN. During the growth of these black holes they light up to become visible as active galactic nuclei and release extraordinary amounts of energy across the electromagnetic spectrum. This energy is widely believed to regulate the rate of star formation in the black holes host galaxies via so-called AGN feedback. We observe two separate classes of accreting black holes, the difference being in their masses. The first one is stellar-mass black holes in binary systems (Black Hole Binaries), i.e. those with masses of the order of $10 M_\odot$ and accreting matter from their stellar companions. The other class encompasses supermassive black holes, with masses of the order of $10^6 - 10^{10} M_\odot$, residing in centres of galaxies (AGNs). There are also exist black holes of intermediate masses, of the order of $100 M \odot$ [61].

The most basic characteristic defining a black hole is the presence of an event horizon ; a boundary in through which matter and light can fall inward towards the black hole, but can never re−emerge. Mathematically stated, the gravitational escape velocity equals the speed of light at the event horizon surface which occurs at a radius

$$R_s = \frac{2GM_{BH}}{c^2} \quad (3.3.1)$$

Any information resulting from an event occurring within the boundary defined by that radius cannot be communicated to an outside observer, thus the origin of the terminology [62].

It is convenient to describe the basic properties of a BH of mass M using the gravitational radius r_g defined as

$$r_g = \frac{GM}{c^2} \quad (3.3.2)$$

To a good approximation,

$$r_g \simeq 1.5 \times 10^{13} M_8 cm \quad (3.3.3)$$

where M_8 is the BH mass in units of $10^8 M\odot$. Here we neglect electrically charged BHs and consider only stationary and rotating (Kerr) BHs. All properties of stationary (Schwarzschild) BHs can be described by using r_g. Regarding rotating or spinning BHs, it is customary to define two other quantities, the angular momentum of the BH,

$$s \sim I\Omega \simeq M r_g^2 (\frac{v}{r}) \simeq M r_g c \quad (3.3.4)$$

where Ω is the angular velocity at the horizon, and the specific angular momentum of the BH (angular momentum per unit mass),s/M. A related quantity is the specific angular diameter parameter,α, defined such that

$$s/M = \alpha c \quad (3.3.5)$$

It is convenient to define yet another parameter, a, such that $\alpha = ar_g$ or $s/M = ar_g c$. This recovers the more familiar form of the specific angular momentum and shows that a can take all values between -1 and 1, where the plus and minus signs refer to the direction of rotation. Several important properties of AGN black holes depend on their spin since this determines the maximum energy that can be extracted from the hole during accretion [10][39].

3.3.1 Horizons

The horizon is the boundary between the black hole and the outside, asymptotically flat region. The event horizon is the surface at which gravity becomes so strong that light itself cannot escape its wretched pull. It is the boundary of a black hole beyond which it is impossible to get information of an object that make its way to the black hole. An event horizon is thus the region in space that clearly separates the black hole from the rest of the universe. The region outside the event horizon are affected by the gravitational pull of the black hole but are considered to be the part of the universe but the region inside the event horizon is not describable by the laws of causality and effects and the meaning of space and time are no more valid the same way inside this region as they are outside the event horizon. Besides the ring-like curvature singularity, there is additional singular behavior for the metric components in the various coordinate systems. These additional singularities can be removed by coordinate transformations, so they do not represent actual physical curvature singularities in space-time. Nevertheless, such coordinate singularities often underlie important structures which are of physical interest and have geometric descriptions independent of the choice of coordinates [63].

3.3.2 Environment of horizons

An event horizon is the region in space that clearly separates the black hole from the rest of the universe. As a body approaches a black hole the gravitational pull of the black hole gets stronger and a force acts on the body which is directly proportional to the size and mass of the body that it acts to elongate or stretch the body and also sideway suppress the body as it nears the black hole. This force is known as the tidal force of the black hole and it is the major cause of threat for the destruction of any body as it approaches the black hole. Before the body arrives at the event horizon it will be disrupted by these forces causing it to become like a noodle and finally disintegrating into individual atoms and absorbed by the event horizon. As a black hole rotates about its axis the region outside the event horizon is also dragged because of this rotation of the black hole and this dragging of space outside a rotating black hole is termed as frame dragging as any inertial frame considered in this region will move along with the rotating space of the black hole. The frame dragging is an intuitive concept as even the space is expected to be dragged along with the strong gravitational effects in the vicinity of a black hole. The non vanishing metric coefficient $g_{t\phi}$ implies that the angular coordinate ϕ is coupled with the time coordinate t and thus a non zero angular velocity ω is inherent to the spacetime of a rotating black hole [64].

The event horizon surrounding the object ensures that no communications can be carried out across the event horizon; therefore, a person outside the event horizon cannot observe the singularity point The region beyond which it is impossible for any observer to be static with respect to the asymptotic Lorentz frame is known as the static limit of the rotating black hole. This region is mathematically defined by the vanishing of the metric coefficient g_{tt} in the Kerr metric description of the rotating black hole. It vanishes at the r value of equation 5.1.6. An observer with fixed (r, θ) with respect to the rotating frame of reference in the vicinity of the black hole will appear to be stationary in this frame of reference of the black hole however locally stationary observer will be rotating with respect to the asymptotic Lorentz frame [63].

3.4 Relativistic Jets

Jets are collimated outflows associated with supermassive black holes in the nuclei of some types of active galactic nuclei. The jets are powered by these black holes and possibly by their associated accretion disks, and the jets themselves transport energy, momentum, and angular momentum over vast distances, from the tiny black hole of radius $r = 10^{-4} M_{BH}/10^9 M_\odot$ pc to radio hot spots, hot spot complexes and lobes which may be up to a megaparsec or more away. In another way, the jets transport energy and momentum from the central engine to remote locations. They are relativistic, at velocities approaching the speed of light in some objects. In some sources, energy and momentum are dissipated in hot spots hundreds of kiloparsec away from the galactic nucleus and in radio lobes which surround the jets and the hot spot complexes. Black holes are not only passive sinks of matter at the centers of galaxies and galaxy clusters. Their radiation and their jets have an impact on their host through heating and stirring of the interstellar and intracluster gas [65].

The nuclei of most normal galaxies contain supermassive black holes, which can accrete gas through a disk and become active. These active galactic nuclei, can form jets which are observed on scales from AU to Mpc and from meter wavelengths to TeV gamma energies. AGN jets are formed when the black hole spins and the accretion disk is strongly magnetized, perhaps on account of gas accreting at high latitude beyond the black hole sphere of influence. They are collimated close to the black hole by magnetic stress associated with a disk wind. Jets can have a major influence on their environments, stimulating and limiting the growth of galaxies. Synchrotron emission plays a key role in AGN jets, their accretion disk seems to emit thermal radiation, and the highest photon energies are reached through inverse Compton processes, for example in the jet or in a plasma close to the accretion disk [66].

Relativistic jets are almost certainly present in all radio-loud AGN though with a range of intrinsic kinetic powers. The weaker jets decelerate relatively close to the central engine, often within the galaxy, while more powerful jets plow through the interstellar medium and into the intergalactic medium before forming large-scale radio lobes [67]. Relativistic jets are ionized and produce non-thermal radiation from radio to gamma-rays in some cases [68]. Thus, these highly ionised flows are originated in the inner regions of the AGN outflows, and are likely driven by wide-angle winds launched from the accretion disks, accelerated by radiation pressure. General relativistic modelling of magnetized jets from accreting BH showed, that provided the central spin is high enough, a pair of relativistic jets is launched from the immediate vicinity of the BH, composed mostly by electrons and positrons (in light jets), or electrons and protons (in heavy jets). These jets could be powered either by the rotational energy of the central SMBH, or by the magnetized accretion disk wind accelerated by magneto-centrifugal forces [69].

3.4.1 Emission of jets and particles from AGN

There are two apparent manifestations of matter outflows from active galactic nuclei: relativistic jets observed mostly in radio-bands, and gas outflows visible in absorption in the UV and X-ray bands. Astrophysical jets are highly collimated streams of magnetized plasma produced by compact accreting objects. It can be observed in a variety of astronomical sources; among them young stellar objects(YSO), micro-quasars, or active galactic nuclei. In AGN, relativistic plasma jets are thought to be formed as the result of accretion onto super-massive black-holes in the presence of rotating accretion disks and co-rotating magnetic fields. Relativistic jets transport tremendous amounts of power away from the central region, necessitating them to be coupled with processes involving a SMBH. Therefore potential energy and rotation of the central SMBH are the main power sources for these jets.

In order to understand the emission of jet from AGN, three general categories of jet models are considered. The first is a thermal pressure model of the jet. Such models assume two antiparallel channels that propagate adiabatically from the vicinity of the SMBH. The second involves the strong AGN radiation that can overcome gravity along certain directions and produce radiative pressure-driven jets. The third class are hydromagnetic jet models that use hydromagnetic stresses exerted by magnetized accretion disks. Such flows are centrifugally driven and magnetically confined. Finally, magnetic lines thread the hole, which forces them to spin and push plasma outwards. The jets are presumably formed in the innermost regions of the source and then they emanate outwards along the rotation axis of the central object. It is possible to show that under very general conditions, MHD winds will always be collimated asymptotically, even in relativistic flows [39].

Once launched, the jet can carry away a major fraction of the kinetic power and angular momentum that was within the disk. A jet of high power thus will remain collimated for very long distance, flowing through the galaxy and out beyond it into the surrounding cluster as is indeed seen in virtually all sources. As the jet propagates, [34] the magnetic field is carried along with it, and once the jet has reached its terminal velocity, the magnetic field lines will be essentially along the jet direction. As the jet propagates, it carries with it an enormous amount of kinetic flux (up to 10^{61} ergs), and even though the flow is usually lower density than the surrounding medium, because of its high speed, it will deposit large amounts of energy into the surrounding regions. A number of effects can be stimulated, including star formation as well as hydrodynamic shockwaves that result in heating of the galactic and cluster medium.

Jets can affect the matter in the galaxy in two ways. The jet can shock heat matter as it propagates outwards. This will lead, similarly to radiative heating effects, to an expansion of the enshrouding gas. In addition, ram pressure of jets can drive out mass directly. Since jets are by definition confined to a certain direction, which therefore limits their effectiveness. In addition we observe many jets which reach far beyond the edges of the galaxies they start in. Thus, the transfer of momentum from the jet to the gas in the galaxy must be low in these cases. The effect of the jet on the surrounding medium will not set in immediately after the formation of the jet. As De Young (2010) points out, the heating will start only after the jet becomes fully turbulent sonic or subsonic due to the deceleration in the cold gas [51].

Since the major process observed at the center of an AGN is the accretion of disk matter onto the BH; the disk matter is heated and the excessive radiation energy is emitted, due to the viscosity of the accretion disk. Close to the BH, the accretion disk can convert the rest mass-energy of the in-falling matter onto the BH into output energy of either radiation or jets. There is overwhelming observational evidence that their emission originates from accretion onto supermassive black holes. As a general consensus AGN jets are powered by the accretion disk, the BH rotation, or both of them. Magnetic fields are a promising agent for jet reduction because they are abundant in astrophysical plasmas and because the properties of magnetically-powered jets scale trivially with BH mass [70].

The interest in AGN jet is also relevant due to their role in shaping their host galaxy. During a compact source injects collimated relativistic jets into its cold environment, it is expected that some fraction of the injected power will be dissipated by shocks in the circumstellar gas and dust. AGN jets heat their galactic surroundings, efficiently in the case of FR-I sources and rather inefficiently in the case of the more powerful FR-II sources, which, instead, produce hot cocoons that help protect jets from destructive instability. After the jet switches off or declines in power, these cocoons may separate to form giant bubbles that rise buoyantly away from the galaxy. They are ultimately assimilated by the circumgalactic medium, which they heat. This is most important when the host galaxies reside in a rich galaxy cluster [34].

3.4.2 Particle trajectory around AGN in Kerr−Newman metric background

Cosmic matter mainly exists in the form of plasma. It serves as the main ingredient of stars, interstellar nebulae,solar wind, jets, and AGN. Therefore, it is reasonable to assume that the matter accreted by a massive central object is some form of plasma. The particle cloud is assumed to form a plasma (if charged) and to be sufficiently dilute, such that particle collisions can be neglected, and the electromagnetic field of the particle cloud is negligible compared to the field of the BH. This leads to a ballistic accretion flow and a collisionless plasma. Since the accreting gas is highly ionized, we can expect the ambient magnetic field to be frozen in the plasma. It can be then amplified in the flow as a result of magnetorotational instability [71]. Furthermore, we assume that the electromagnetic and gravitational field formed by the plasma can be neglected compared to the field of the central BH. In this case the trajectory of each individual particle in the cloud, charged or uncharged, follows a path of test particles in the given spacetime as described by the equations of motion.

If the black hole rotates, then near it an electric field is also induced. An electric field also arises as a result of rotation of the accreting plasma. Under these conditions, the black hole behaves like a unipolar inductor, and through it an electric current can flow. For brevity, we shall say that such a black hole is magnetized. It is hoped that models of accretion onto magnetized black holes will explain the giant jets of relativistic particles and electromagnetic radiation from quasars, the nuclei of active galaxies, and x-ray and gamma sources. To elucidate the possibility of pair photoproduction, it is important for us to know the behavior of the electromagnetic field near the horizon of the hole. Near the event horizon of a rapidly rotating, almost extremal black hole through which an electric current flows, soft photons with trajectories close to spherical orbits can create e^+e^- pairs. The rotating black hole can approach the extremal state by the inductive accumulation of electric charge when plasma is accreted in the presence of a regular magnetic field. Accreting supermassive black holes can be near the extremal state [72].

Chapter 4

AGN interaction with its environment

4.1 Relativistic equation of motion of particles in Kerr- Newman geometry

Here, to derive the equation of motion we follow the standard variational principle to extremize the invariant geodesic element of the particle, i.e.,

$$\delta \int ds \quad = \quad 0, \tag{4.1.1}$$

where, the geodesic element is given as

$$ds \quad = \quad (-g_{\mu\nu} d\dot{x}^{\mu} d\dot{x}^{\nu})^{\frac{1}{2}} d\lambda \tag{4.1.2}$$

where

$$\dot{x}^{\mu} \quad = \quad \frac{dx^{\mu}}{d\lambda}, \tag{4.1.3}$$

where λ is the affine parameter along the worldline.

Using the polar spherical coordinates, upon expansion 4.1.1 yields

$$\delta \int \frac{1}{2}(g_{tt}\dot{t}^2 + 2g_{t\phi}\dot{t}\dot{\phi} + g_{rr}\dot{r}^2 + g_{\phi\phi}\dot{\phi}^2) d\lambda \quad = \quad 0, \tag{4.1.4}$$

where the Kerr-Newman metric is used.

With the notion of classical Lagrangian formalism, the integrand of eq. 4.1.4 is viewed as the relativistic Lagrangian of the system per unit mass given by

$$L = \frac{1}{2}(g_{tt}\dot{t}^2 + 2g_{t\phi}\dot{t}\dot{\phi} + g_{rr}\dot{r}^2 + g_{\phi\phi}\dot{\phi}^2). \quad (4.1.5)$$

Note that, the Lagrangian is used in the Euler-Lagrange equations of motion to derive important observable quantities of motion. In the Lagrangian mechanics approach, the Euler-Lagrange equations of motion is given as

$$\frac{d}{d\lambda}(\frac{\partial L}{\partial \dot{x}^\mu}) - \frac{\partial L}{\partial x^\mu} = 0. \quad (4.1.6)$$

The conjugate momentum p_μ to the coordinate x_μ is given by

$$P_\mu = \frac{\partial L}{\partial \dot{x}^\mu}. \quad (4.1.7)$$

In terms of this conjugate momenta, the Euler-Lagrange equations can be recast as

$$\frac{d}{d\lambda}P_\mu = \frac{\partial L}{\partial x^\mu}. \quad (4.1.8)$$

For the axisymmetrically static metric, $g_{\mu\nu}$ is independent of the t and the ϕ coordinates. Then,

$$\frac{\partial L}{\partial x^0} = 0 \quad (4.1.9)$$

$$\frac{\partial L}{\partial x^3} = 0 \quad (4.1.10)$$

where $x^0 = t$ and $x^3 = \phi$.

Notice that, if the metric does not depend on a given coordinate x^μ, the corresponding conjugate momentum is a constant of motion. Moreover, if the metric is independent by a coordinate, there is a Killing vector ξ^μ corresponding to this symmetry. Thus, $\xi_\mu \dot{x}^\mu$ is a constant of motion in the case of t and ϕ for the Kerr$-$Newmann metric.

In order to use the Kerr-Newman metric in the Euler-Lagrange equations, we recast its Boyer - Lindquist form 2.1.31 as

$$\begin{aligned} ds^2 &= -[\frac{\Delta-\alpha^2\sin^2\theta}{\rho^2}]dt^2 - \frac{2\alpha\sin^2\theta(r^2+\alpha^2-\Delta)}{\rho^2}dtd\phi \\ &+\frac{[(r^2+\alpha^2)^2-\Delta\alpha^2\sin^2\theta]}{\rho^2}\sin^2\theta d\phi^2+\frac{\rho^2}{\Delta}dr^2+\rho^2d\theta^2 \end{aligned} \tag{4.1.11}$$

where $\Delta = r^2 - 2Mr + \alpha^2 + Q^2$, $\rho^2 = r^2 + \alpha^2\cos^2\theta$, α is the angular momentum per unit mass and Q is the total charge of the hole.

Aiming to see the effects of rotation on geodesics, we consider motion of charged particles in an equatorial plane, where the zenith angle is $\theta = \frac{\pi}{2}$, the metric given by eq. 4.1.11, is recast as

$$\begin{aligned} ds^2 &= -[\frac{\Delta-\alpha^2}{r^2}]dt^2 - \frac{2\alpha(r^2+\alpha^2-\Delta)}{r^2}dtd\phi \\ &+\frac{[(r^2+\alpha^2)^2-\Delta\alpha^2]}{r^2}d\phi^2+\frac{r^2}{\Delta}dr^2. \end{aligned} \tag{4.1.12}$$

The components of the metric given by eq. 4.1.12 are given by

$$g_{tt} = -\frac{\Delta-\alpha^2}{r^2} \tag{4.1.13}$$

$$g_{rr} = \frac{r^2}{\Delta} \tag{4.1.14}$$

$$g_{\phi\phi} = \frac{(r^2+\alpha^2)^2-\Delta\alpha^2}{r^2} \tag{4.1.15}$$

$$g_{t\phi} = g_{\phi t} = -2\alpha(r^2+\alpha^2-\Delta) \tag{4.1.16}$$

Using these metrics, the Lagrangian of the system, eq. 4.1.5 is given by

$$\begin{aligned} 2L &= -[\frac{\Delta-\alpha^2}{r^2}]\dot{t}^2 - \frac{2\alpha(r^2+\alpha^2-\Delta)}{r^2}\dot{t}\dot{\phi} \\ &+\frac{[(r^2+\alpha^2)^2-\Delta\alpha^2]}{r^2}\dot{\phi}^2+\frac{r^2}{\Delta}\dot{r}^2 \end{aligned} \tag{4.1.17}$$

Then, the Euler−Lagrange equations of motion along t, r and ϕ are respectively given as

$$\frac{d}{d\lambda}\left(\frac{\Delta-\alpha^2}{r^2})\dot{t}+\frac{2\alpha(r^2+\alpha^2-\Delta)}{r^2}\dot{\phi}\right) = 0 \tag{4.1.18}$$

$$\begin{aligned}\frac{d}{d\lambda}\left(\frac{r^2}{\Delta}\dot{r}\right) &= \frac{(-2r^2+2mr+2\Delta)\dot{t}^2+(4mr\alpha-4Q^2\alpha)\dot{t}\dot{\phi}+(2r^4-2mr\alpha^2+2Q^2\alpha^2)\dot{\phi}^2}{r^3}\\ &+\frac{(2r\Delta-2r^3+2mr^2)}{\Delta^2}\dot{r}^2\end{aligned} \tag{4.1.19}$$

$$\frac{d}{d\lambda}\left(\frac{[(r^2+\alpha^2)^2-\Delta\alpha^2]}{r^2}\dot{\phi}-\frac{\alpha(r^2+\alpha^2-\Delta)}{r^2}\dot{t}\right) = 0. \tag{4.1.20}$$

Since the space time of the Kerr-Newmann family is stationary and axially symmetric, the momenta P_t and P_ϕ are conserved along the geodesics. So we obtain two constants of motion: one is corresponding to the conservation of energy (E) and the other is the angular momentum (J) about the symmetry axis, respectively given as

$$\frac{\partial L}{\partial \dot{x}^0} = -E, \tag{4.1.21}$$

$$\frac{\partial L}{\partial \dot{x}^3} = J, \tag{4.1.22}$$

where

$$E = (\frac{\Delta-\alpha^2}{r^2})\dot{t}+\frac{\alpha(r^2+\alpha^2-\Delta)}{r^2}\dot{\phi} \tag{4.1.23}$$

$$J = \frac{[(r^2+\alpha^2)^2-\Delta\alpha^2]}{r^2}\dot{\phi}-\frac{\alpha(r^2+\alpha^2-\Delta)}{r^2}\dot{t}. \tag{4.1.24}$$

Using eqs. 4.1.23 and 4.1.24 the velocities along t and ϕ are respectively given as

$$\begin{aligned}\dot{t} &= \frac{-Er^2}{[\Delta-\alpha^2][(r^2+\alpha^2)^2-\Delta\alpha^2][2\alpha(r^2+\alpha^2-\Delta)]}\\ &\times\frac{[(r^2+\alpha^2)^2-\Delta\alpha^2]}{[Jr^2+\alpha(r^2+\alpha^2-\Delta)]}\end{aligned} \tag{4.1.25}$$

$$\begin{aligned}\dot{\phi} &= \frac{[Lr^2+\alpha(r^2+\alpha^2-\Delta)]}{[(r^2+\alpha^2)^2-\Delta\alpha^2][\Delta-\alpha^2]}\times\\ &\frac{-Er^2[(r^2+\alpha^2)^2-\Delta\alpha^2]}{[(r^2+\alpha^2)^2-\Delta\alpha^2][2\alpha(r^2+\alpha^2-\Delta)][Jr^2+\alpha(r^2+\alpha^2-\Delta)]}.\end{aligned} \tag{4.1.26}$$

4.2 Accretion and energy conversion by AGN

Accretion is a process in which matter falls down the gravitational field of an object, and due to dissipation and nuclear fusion converts a part of its gravitational binding energy into heat and radiation. It provides radiant energy in a variety of astrophysical sources: stellar binaries, active galactic nuclei, proto-planetary disks, and in some types of gamma ray bursts. The consequences of accretion are vast. It is a result of matter in the host galaxy falling towards SMBH due to loss of angular momentum. As the gas falls inwards, the gravitational energy is converted into heat and light. Consequently, we observe objects with wide range of luminosities and variability. Mergers and accretion are both likely to be important in black hole mass growth, but accretion may dominate [73].

Since the nucleus of active galaxy contains a supermassive black hole, the level of nucleus activity depends on the amount of matter inflowing onto the black hole which varies over time. As the matter inflows, it loses angular momentum and energy, and the emission of matter from close vicinity of black hole provides us with information about this spatially unresolved region [73].

The AGN are powered by accretion onto massive black holes at the dynamical centers of their host galaxies. Accretion onto massive objects and the associated release of the binding gravitational energy are important sources of radiation in astrophysics. The process is geometry dependent and can proceed in various different routes. In particular, spherical and non−spherical systems can behave in a very different way. Gas that accretes onto the black hole should form an accretion disk. Despite this, there have been extensive analyses of spherical or quasi−spherical accretion flows onto black holes. Two fundamental quantities that are related to such processes are the Eddington luminosity and the Eddington accretion rate. The detailed structure of the accretion disk depends on a variety of parameters, such as the magnetic field strength and the accretion rate and the presence or absence of a disk corona or jets [41]. The luminosity of the source is defined by the rate at which mass is accreted and converted to energy.

The standard physical model of an AGN that starts with a central BH and is growing via mass accretion luminosity is given by

$$L_{acc} = \eta \dot{M} c^2, \tag{4.2.1}$$

where η is the mass−energy efficiency conversion (typically estimated to be ≈ 0.1, but is dependent on the spin of the BH with an expected range of $\eta = 0.05 - 0.42$, and $\dot{M}$ is the mass accretion rate.

The mass-energy conversion efficiency depends on the spin of the black hole, whereby high spin leads to higher efficiencies. A theoretical upper limit on L_{acc} can be calculated assuming accretion of fully ionized hydrogen onto a BH of mass M_{BH}, when the force of gravity is equal to the radiation pressure from the accretion luminosity. This upper-limit is called the Eddington luminosity and has the value

$$L_{Edd} = \frac{4\pi G M_{BH} m_p c}{\sigma_T} \tag{4.2.2}$$

$$L \approx 1.3 \times 10^{38} (\frac{M_{BH}}{M_{\odot}}) ergs^{-1} \tag{4.2.3}$$

where m_p is the proton mass, c is the speed of light, G is the gravitational constant and σ_T is the Thomson cross-section for an electron. It is the maximum luminosity allowed for objects that are by steady state accretion. The ratio of the observed accretion luminosity to the Eddington luminosity (called the Eddington ratio; λ_{Edd})is a useful measure for comparing BH accretion rates over a wide range of BH masses

$$\lambda_{Edd} = \frac{L_{acc}}{L_{Edd}} \tag{4.2.4}$$

The term high-accretion rate AGN is often used to refer to sources with high values of λ_{Edd}(i.e., $\lambda_{Edd} \geq 0.1$). The value of L_{acc} used in Equation 4.2.4 is assumed to be the radiative bolometric output of the AGN [74].

4.3 Radiative transfer equation

Radiative transfer is the physical phenomenon of energy transfer in the form of electromagnetic radiation. It is the study of how radiation propagates through a medium. The propagation of radiation through a medium is affected by absorption, emission, and scattering processes. Radiation transfer is a major way of energy transfer between the atmosphere and the underlying surface and between different layers of the atmosphere. The classical equation of radiative transfer describes the balance of radiative energy transport in absorbing, emitting and scattering media with uniform refractive index distribution. The specific intensity of radiation is the energy flux per unit time, unit frequency, unit solid angle and unit area normal to the direction of propagation [75].

The radiative transfer equation states that the specific intensity of radiation I_ν during its propagation in a medium is subject to losses due to extinction and to gains due to emission:

$$\frac{dI_\nu}{ds} = -\alpha_\nu.I_\nu + j_\nu \tag{4.3.1}$$

where ds is the differential path length, α_ν and j_ν are, the absorption and emission coefficients of the plasma at a frequency ν respectively [10]. The optical depth of the medium is

$$\tau_\nu(s) = \int_{s_0}^{s} \alpha_\nu(s^{'})ds^{'}. \tag{4.3.2}$$

The optical depth defined above is measured along the path of a traveling ray; occasionally, τ_ν is measured backward along the ray. By equating Eqs. 4.3.1 and 4.3.2

$$\frac{dI_\nu}{\tau_\nu} = -I_\nu + s_\nu \tag{4.3.3}$$

where the source function s_ν, is defined as the ratio of the emission coefficient to the absorption coefficient:

$$s_\nu = \frac{j_\nu}{\alpha_\nu}. \tag{4.3.4}$$

The equation of radiative transfer cab be solved by regarding all quantities as functions of the optical depth τ_ν, instead of s. Multiply the equation by the integrating factor e^{τ_ν} and define the quantities $\wp = I_\nu e^{\tau_\nu}$ $\Re = s_\nu e^{\tau_\nu}$. Then the equation becomes

$$\frac{d\wp}{d\tau_\nu} = \Re \tag{4.3.5}$$

with the solution

$$\wp(\tau_\nu) = \wp(0) + \int_{s_0}^{\tau_\nu} \Re(\tau_\nu^{'})d\tau_\nu^{'}. \tag{4.3.6}$$

Rewriting the solution in terms of I_ν, and s_ν, we have the formal solution of the transfer equation : so,

$$I(\tau_\nu) = I_\nu(0)e^{-\tau_\nu} + \int_{s_0}^{\tau_\nu} e^{-(\tau_\nu - \tau_\nu^{'})} s(\tau_\nu^{'})d\tau_\nu^{'} \tag{4.3.7}$$

where the constant $I_\nu(0)$ is the initial value of the specific intensity. Here $I_\nu(0)$ is the intensity of the background radiation, coming through the medium (e.g. an inter- stellar cloud) and decaying exponentially in the medium. The second term gives the emission in the medium. The classical radiative transfer we have developed so far is in general not covariant. Since τ_ν, is just the dimensionless e-folding factor for absorption, the above equation is easily interpreted as the sum of two terms: the initial intensity diminished by absorption plus the integrated source diminished by absorption [76]. The classical radiative transfer equations that have been developed is not covariant.

The general covariant radiative transfer equation can be derived from the basic principles based on the conservation of particles in phase space. The particle number density in the phase volume element

$$f(x,p) = \frac{dN}{dV} \tag{4.3.8}$$

is an invariant quantity along the affine parameter λ; where dN is the number of particles and dV is volume phase space which is given by:

$$dV = d^3x d^3p. \tag{4.3.9}$$

Liouville's theorem ensures that the phase space volume, which is unchanged along the affine parameter λ i.e.

$$\frac{dV}{d\lambda} = 0. \tag{4.3.10}$$

For relativistic particles, $|p| = E$, and $d^3p = E^2 dE d\Omega$ and the volume element of a bundle of relativistic particles is given by $d^3x = dAdt$. From this the phase space density of a bundle of relativistic particles of Eq.4.3.8 is written as

$$f(x,p) = \frac{dN}{E^2 dAdtdEd\Omega} \tag{4.3.11}$$

where dA is the area element of the bundle, Ω is the spherical solid angle [77] [78].

4.3.1 General relativistic radiative transfer

Recall that the number of photons flowing through an area dA in a time dt is

$$f = \frac{dN}{E^2 dAdtdEd\Omega} \tag{4.3.12}$$

and the specific intensity of the photon is

$$I_\nu = \frac{EdN}{dAdtdEd\Omega}. \tag{4.3.13}$$

By inspection of equations 4.3.12 and 4.3.13

$$f = \frac{I_\nu}{E^3} = \frac{I_\nu}{\nu^3} \tag{4.3.14}$$

where $\nu(= E)$ is the frequency of the photon. The Lorentz invariant intensity $f = I$ will be used to formulate the general relativistic radiative transfer formulation. So, the invariant Lorentz quantity is given by:

$$I = \frac{I_{\nu photon}}{\nu^3}. \tag{4.3.15}$$

Then, the corresponding Lorentz-invariant absorption and the Lorentz-invariant emission coefficients are the following respectively.

$$\chi = \nu\alpha_\nu \tag{4.3.16}$$

$$\eta = \frac{j_\nu}{\nu^3} \tag{4.3.17}$$

These two coefficients, Eqs. 4.3.51 and 4.3.51 as seen by the observer, are related to their counterparts in the local rest frame of the medium via

$$\nu\alpha_\nu = \nu_0\alpha_0\nu \tag{4.3.18}$$

$$\frac{j_\nu}{\nu^3} = \frac{j_0\nu}{\nu_0^3} \tag{4.3.19}$$

respectively, where the subscript "0" denotes variables measured in the local rest frame. Now the coefficient χ and η both by local rest frame and the frame at far point are invariant and thus

$$\chi = \chi_0 \Rightarrow \nu\alpha_\nu = \nu_0\alpha_0\nu \tag{4.3.20}$$

$$\eta = \eta_0 \Rightarrow \frac{j_\nu}{\nu^3} = \frac{j_0\nu}{\nu_0^3} \tag{4.3.21}$$

$$\alpha_\nu = (\frac{\nu_0}{\nu})\alpha_0\nu \tag{4.3.22}$$

$$j_\nu = (\frac{\nu_0}{\nu})^3 j_0\nu. \tag{4.3.23}$$

For photons (a massless relativistic particle)

$$k_\alpha k^\alpha = 0 \tag{4.3.24}$$

where k_α is the (covariant) 4-momentum. The photon's velocity in the co-moving frame of fluid, v^β, can be obtained by projecting the photon's 4-momentum into the fluid frame by considering a photon propagating in a fluid with 4-velocity u^β, i.e

$$v^\beta = p^{\alpha\beta}k_\alpha \tag{4.3.25}$$

$$= k^\beta + (k_\alpha u^\alpha)u^\beta \tag{4.3.26}$$

where

$$p^{\alpha\beta} = g^{\alpha\beta} + u^\alpha u^\beta \tag{4.3.27}$$

is the projection tensor and $g^{\alpha\beta}$ the space$-$time metric tensor. Then the relative energy shift in a moving medium with respect to an observer at infinity for photons

$$\frac{E_0}{E} = \frac{\nu_0}{\nu} = \frac{k_\alpha u^\alpha|_{\lambda obs}}{k_\beta u^\beta|_\infty}. \tag{4.3.28}$$

The variation in the path length s with respect to the affine parameter λ is then

$$\frac{ds}{d\lambda} = -||v^{\beta}|| \tag{4.3.29}$$

$$= -\sqrt{g_{\alpha\beta}(k^{\alpha} + (k_{\beta}u^{\beta})u^{\alpha})(k^{\beta} + (k_{\alpha}u^{\alpha})u^{\beta})}|_{\lambda obs} \tag{4.3.30}$$

$$= -k_{\alpha}u^{\alpha}|_{\lambda obs}. \tag{4.3.31}$$

For a stationary observer located at infinity

$$p_{\beta}u^{\beta} = -E_{obs}. \tag{4.3.32}$$

From Eqs.4.3.28 and 4.3.32, the relative energy shift of the photon between the observer's frame and the comoving frame is therefore

$$\frac{\nu_0}{\nu} = -\frac{k_{\alpha}u^{\alpha}}{E_{obs}} = -\frac{k_{\alpha}u^{\alpha}\mid_{\lambda}}{k_{\beta}u^{\beta}\mid_{\lambda obs}}. \tag{4.3.33}$$

Making use of the Lorentz-invariant properties of the variables I, χ and η, and of the optical depth τ_{ν}, we may rewrite the radiative transfer equation in the following form

$$\frac{dI}{d\tau_{\nu}} = -I + \frac{\eta}{\chi} = -I + S \tag{4.3.34}$$

where

$$S = \frac{\eta}{\chi} \tag{4.3.35}$$

is the Lorentz-invariant source function [79]. All quantities in Eq. 4.3.34 are Lorentz invariant, and hence the equation is covariant. For $d\tau_{\nu} = \alpha_{\nu}ds$ then

$$\frac{dI}{ds} = -\alpha_{\nu}I + \frac{j_{\nu}}{\nu^3} \tag{4.3.36}$$

and now using Eqs. 4.3.34, 4.3.31 and 4.3.36

$$\frac{dI}{d\lambda} = -k_{\alpha}u^{\alpha}\mid_{\lambda}(-\alpha_{0,\nu}\, I) + \frac{j_{0,\nu}}{\nu^3} \tag{4.3.37}$$

where $\alpha_{0,\nu} = \alpha_0(x^\beta, \nu)$ and $j_{0,\nu} = j_0(x^\beta, \nu)$, where, as before, "0" denotes variables that are evaluated in the local rest frame, for a given ν. Eqs. 4.3.36 and 4.3.37 are radiative transfer equations for massless particles.

On other hand, for particles with a non-zero mass m such as neutrinos or relativistic electrons;

$$p_\alpha p^\alpha \quad = \quad -m^2 \tag{4.3.38}$$

and the presence of the this mass modifies the particle's equations of motion, changing the geodesics from null to time-like. Then, the variation in the path length with respect to the affine parameter is

$$\frac{ds}{d\lambda} \quad = \quad -\sqrt{g_{\alpha\beta}(p^\alpha + (p_\beta u^\beta)u^\alpha)(p^\beta + (p_\alpha u^\alpha)u^\beta)} \mid_{\lambda obs} . \tag{4.3.39}$$

Now by using Eq. 4.3.38 into Eq. 4.3.39

$$\frac{ds}{d\lambda} \quad = \quad -\sqrt{p_\beta p^\beta + (p_\alpha u^\alpha)^2} \mid_{\lambda obs} \tag{4.3.40}$$

$$\quad = \quad -\sqrt{(p_\alpha u^\alpha)^2 - m^2} \mid_{\lambda obs} \tag{4.3.41}$$

and finally by inserting Eq. 4.3.41 into Eq. 4.3.34 and after some algebra, the general covariant transfer equation for relativistic particles is

$$\frac{dI}{d\lambda} \quad = \quad -\sqrt{1 - (\frac{m}{p_\beta u^\beta}) \mid^2_{\lambda obs}} p_\alpha u^\alpha \mid_\lambda (-\alpha_{0,\nu} I + \frac{j_{0,\nu}}{\nu^3}). \tag{4.3.42}$$

For a stationary observer located at infinity,

$$P_\beta u^\beta \quad = \quad -E. \tag{4.3.43}$$

Note that Eq. 4.3.42 differs from Eq. 4.3.37 by an aberration factor $\sqrt{1 - (\frac{m}{E})^2}$. This factor reduces the intensity gradient along the ray. In limiting case of $m \to 0$, the radiative transfer equation 4.3.37 is the radiative transfer equation Eq. 4.3.42. Equation 4.3.42 reveals, the essential components of the covariant radiative transfer formulation are the emission coefficient, the absorption coefficient, the relative energy shift of the particles with respect to the medium and the aberration factor. These are all evaluated along the particle geodesics [80].

4.3.2 Radiation pressure of AGN

Radiation pressure can exert a force on the gas via electron scattering, scattering and absorption on dust, photoionization, or scattering in atomic resonance lines. If the radiation flux from the nucleus does not greatly exceed the Eddington limit of the central black hole, the radiation force exerted through electron scattering will have a relatively minor dynamical effect on the gas in the host galaxy, compared to gravitational and thermal pressure forces [81]. Quasars are extremely luminous objects and if they are close to their Eddington limits, [61] then the pressure of radiation acting on electron-proton pairs may be sufficient to overcome gravity along certain directions. This could happen in the funnels formed by a radiation-pressure supported torus orbiting a black hole.

Accretion tori play a fundamental role in the evolution of their environment by converting gravitational potential energy into heat and radiation. On the other hand tori are subjected to the gravitational field of the central compact object. The presence of gas pressure and radiation pressure will modify the aspect ratio of the tori. The torus is the most likely source of gas for the inner accretion disk and the fueling of the black hole. This raises the important question of the nature of the mechanism that provides angular momentum redistribution. This includes the mechanism which operates on scales larger than the torus, and brings gas into the torus, and also the mechanisms operating within the torus [82][83].

The tori are considered to be stationary and axisymmetric. They consist of a perfect fluid, and the stress-energy-momentum tensor of the flow is given by

$$T^{\alpha\beta} \quad = \quad (\rho + P + \epsilon)u^{\alpha}u^{\beta} + Pg^{\alpha\beta} \tag{4.3.44}$$

where P is the pressure, ρ is the density, and ϵ is the fluid internal energy. Since $T^{\alpha\beta}_{;\beta} = 0$, the following continuity equation is obtained

$$(\rho + P + \epsilon)_{,\beta}u^{\alpha}u^{\beta} + (\rho + P + \epsilon)(u^{\alpha}_{,\beta}u^{\beta} + u^{\alpha}u^{\beta}_{,\beta}) + P_{,\beta}g^{\alpha\beta} \quad = \quad 0. \tag{4.3.45}$$

Projecting onto the 3-surface orthogonal to the fluid velocity u^{α} with the projection tensor

$$P_{\alpha\beta} \quad = \quad u^{\alpha}u^{\beta} + g^{\alpha\beta} \tag{4.3.46}$$

yields the momentum equation

$$(\rho + P + \epsilon)u^{\alpha}_{,\beta}u^{\beta} + P_{,\beta}g^{\alpha\beta} \quad = \quad 0. \tag{4.3.47}$$

Because the torus is stationary and axisymmetric, it has negligible poloidal flow components, hence

$$u_{\alpha;\beta}u^{\beta} \quad = \quad -\Gamma^{\sigma}_{\alpha\beta}u_{\alpha}u^{\beta} = -\frac{1}{2}u^{\sigma}u^{\beta}g_{\sigma\beta,\alpha}. \tag{4.3.48}$$

Since $u_{\alpha}u^{\alpha} = -1$ and differentiating with respect to δ

$$(u^{\alpha}u_{\alpha})_{,\delta} = g_{\alpha\beta,\delta}u^{\alpha}u_{\alpha} + 2u^{\alpha}u_{\alpha}\delta \quad = \quad 0 \tag{4.3.49}$$

This gives

$$u^{\alpha}u_{\alpha},\delta \quad = \quad -\frac{1}{2}g_{\alpha\beta,\delta}u^{\alpha}u_{\alpha}. \tag{4.3.50}$$

Then, it follows that

$$u^{\beta} u_{\beta,\alpha} = u^{t} \partial_{\alpha} u_{t} + u^{\phi} \partial_{\alpha} u_{\phi} \tag{4.3.51}$$

where ∂_α is the gradient in the x^α direction. For a purely circular motion ($u^\alpha = u^t(1,0,0,\Omega)$, then $\Omega = \frac{u^\phi}{u^t}$ is the angular velocity with respect to a distant observer and $l = -\frac{u_\phi}{u_t}$ is specific angular momentum. Therefore, it follows that

$$u^{\phi} u_{t} = \Omega(u^{t} u_{t}) = -\frac{\Omega}{1 - l\Omega} \tag{4.3.52}$$

and the gradiant of l is

$$\partial_{\alpha} = \frac{u_{\phi}}{u_t^2} \partial_{\alpha} u_{t} - \frac{1}{u_t} \partial_{\alpha} u_{\phi}. \tag{4.3.53}$$

then, it follows that

$$\frac{\Omega}{1 - l\Omega} \partial_{\alpha} l = \frac{1}{u_t} \partial_{\alpha} u_{t} + u^{t} \partial_{\alpha} u_{t} + u^{\phi} \partial_{\alpha} u_{\phi}. \tag{4.3.54}$$

Now Eq 4.3.52 can now be expressed as

$$u_{\alpha;\beta} u^{\beta} = \frac{\Omega}{1 - l\Omega} \partial_{\alpha} l - \frac{1}{u_t} \partial_{\alpha} u_{t}. \tag{4.3.55}$$

So that

$$\frac{\partial_{\alpha} P}{\rho + P + \epsilon} = \partial_{\alpha} \ln(u_t) - \frac{\Omega}{1 - l\Omega} \partial_{\alpha} l \tag{4.3.56}$$

In this equation, the gas within the torus is assumed to be barotropic. Barotropic equation of state $p = p(\rho)$ is assumed, and the matter is in orbital motion only $u^\theta = 0$ and $u^r = 0$. In the special case of l = constant, corresponding to a marginally stable torus, there is an analytic solution

$$\int_0^P \frac{dP'}{\rho + P' + \epsilon} = \ln(u_t) - \ln(u_t)\text{inner} \tag{4.3.57}$$

where $\ln(u_t)$inner is evaluated at the inner edge of the torus. The total pressure within the torus is the sum of the gas pressure and the radiation pressure, i.e.

$$P = P_{gas} + P_{rad} \tag{4.3.58}$$

where

$$P_{gas} = \frac{\rho k_B T}{\mu m_H} = \beta P \tag{4.3.59}$$

$$P_{rad} = \frac{4\sigma}{3c} T^4 = (1-\beta) P \tag{4.3.60}$$

where μ the mean molecular weight, m_H the mass of a hydrogen atom and β is the ratio of gas pressure to total pressure. After doing some arrangements and eliminating $k_B T$ in the eqs. 4.3.59and 4.3.60 yields

$$P = (\frac{45(1-\beta)}{\pi^2(\mu m_H \beta)^4})^{1/3} \rho^{4/3}. \tag{4.3.61}$$

For a polytropic equation of state

$$P = k\rho^{\Gamma} \tag{4.3.62}$$

and the internal energy is related to the pressure by

$$\epsilon = \frac{P}{\Gamma} - 1 \tag{4.3.63}$$

where Γ is the adiabatic index of the polytrope. So, from eq.4.3.61 we have

$$\Gamma = 4/3 \tag{4.3.64}$$

$$P = (\frac{45(1-\beta)}{\pi^2(\mu m_H \beta)^4})^{1/3}. \tag{4.3.65}$$

Combining the momentum equation eq.4.3.47 for a perfect fluid with the polytropic equation of state eq.4.3.62 gives

$$(\rho + \frac{\Gamma}{\Gamma - 1} P) a^{\alpha} \quad = \quad -P_{,\beta} g^{\alpha\beta} \tag{4.3.66}$$

where a^{α} is the 4- acceleration of the flow which is derived from 4-velocity. Now, differentiating the polytropic equation of state eq.4.3.62 yields

$$\partial_{\alpha} P \quad = \quad k\Gamma \rho^{\Gamma-1} (\partial_{\alpha}\rho). \tag{4.3.67}$$

The density structure of the torus is [83] then given by

$$\partial_{\alpha}\rho \quad = \quad -a_{\alpha}(\frac{\rho^{2-\Gamma}}{k\Gamma} + \frac{\rho}{\Gamma - 1}). \tag{4.3.68}$$

Finally, using eqs.4.3.59,4.3.60 and 4.3.61, the temperature within the torus may also be derived as a function of ρ, yielding

$$k_{\beta} T \quad = \quad (\frac{45(1-\beta)}{\pi^2 \mu m_H \beta})^{1/3} \rho^{1/3}. \tag{4.3.69}$$

Chapter 5

Result and Discussion

5.1 Boundaries, horizons and singularities

Depending on the geometry of the spacetime the metric solution of Einstein field equations are characterized by special boundaries determined by their peculiar characteristics generally classified as true singularities or coordinate dependent (pseudo) singularities called horizons. In the case of Kerr-Newman spacetime whose metric is given by eq. 2.1.31, the geometrical boundaries are:

i) True singularity; the ring singularity

Peculiar to the unremovable singularity of the metric given by

$$\rho^2 = 0$$

It is obtained at (r, θ) $= (0, \pi/2)$.

ii) Event horizons

It is Coordinate dependent singularities. Determined by the pseudo coordinate singularities given by

$$\Delta(r) = 0$$

whose horizon solution of

$$r_{\pm} \quad = \quad M \pm \sqrt{M^2 - \alpha^2 - Q^2}. \tag{5.1.1}$$

These surfaces are referred to as the outer (r_+) and inner (r_-) horizons; the former is called the event horizon, and the region $r < r_+$ is referred to as the interior of the black hole. From eq. 5.1.1, we can see that the black hole parameters cannot be arbitrary. Electric charge and angular momentum cannot exceed values corresponding to the disappearance of the event horizon. The following constraint must be satisfied: $\alpha^2 + Q^2 \leq M^2$. When the condition is violated, the event horizon disappears and the solution describes a naked singularity instead of a black hole. The structure of the Kerr$-$Newmann solution changes deeply when $\alpha^2 + Q^2 \geq M^2$. Due to the absence of an horizon, it does not represent a black hole, but a circular naked singularity in spacetime.

iii) The static limit of Kerr-Newman geometry

It is located at $g_{tt} = 0$ whose horizons solutions are given as

$$r = r^E_{\pm}(\theta) \quad = \quad M \pm \sqrt{M^2 - \alpha^2 \cos^2\theta - Q^2}. \tag{5.1.2}$$

The surface eq. 5.1.6 is often referred to as the stationary limit surface or ergosurface, and the region between the ergosurface and event horizon $r_+ < r < r^E_+(\theta)$ as the ergosphere. If we compare this with the horizons of the rotating black hole, eq. 5.1.3, we see that $r^E_+ \geq r_+ \geq r_- \geq r^E_- \geq 0$.

The Kerr$-$Newmann metric depends on three parameters: M, α and Q. Consider the following limiting cases to see the horizon solution.

Case 1: In the limit $Q \to 0$ (with α and $M \neq 0$), the metric eq.2.1.31 reduces to the Kerr metric 2.0.8.

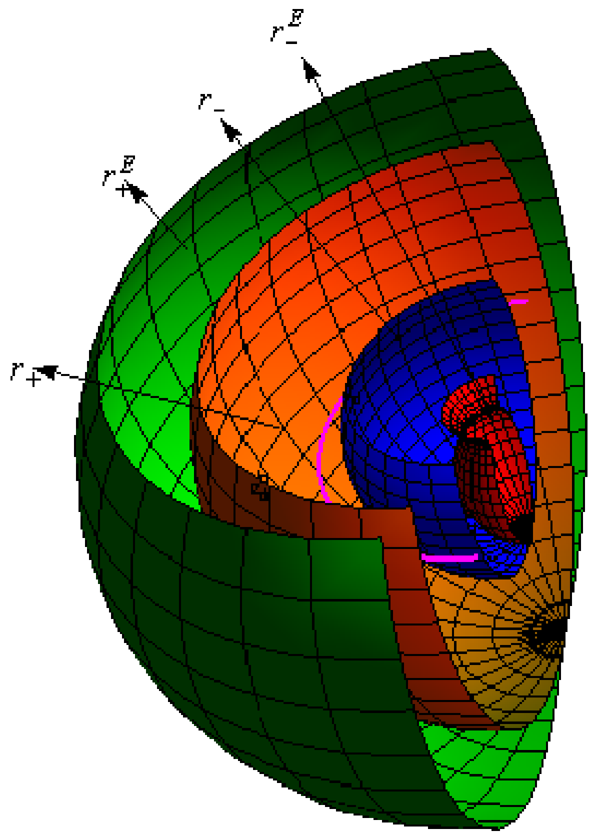

Figure 5.1: The plot of horizon solutions of Kerr−Newmann metric by making $r_\pm$ and $r_\pm^E$ dimensionless.

i) True singularity; the ring singularity

Peculiar to the unremovable singularity of the metric given by

$$\rho^2 = 0$$

It is obtained at (r, θ) = (0,$\pi/2$). In the limit $\alpha = 0$ this singularity degenerate to schwarzschild peacetime

ii) Event horizons

Determined by the pseudo coordinate singularities given by

$$\Delta(r) = 0$$

whose horizon solution of

$$r_{\pm} \quad = \quad M \pm \sqrt{M^2 - \alpha^2}. \tag{5.1.3}$$

where r_+ represents the black hole event horizon, while r_- represents the Cauchy event horizon. when $\alpha = 0$,r_+ readily reduced to the Schwarzschild radius, $r_+ = r_{sch}$ $= 2Gm/c^2$, while the r_- is degenerated to the zero true singularity of Schwarzschild black hole. Matters or events that happen in the cauchy horizon will not affect physics outside of it, i.e in the rest of the Universe. Since, particles in the region $r < r_-$ may never enter the region $r > r_+$ [33].

iii) The static limit of Kerr geometry

Also another important Kerr geometry is the boundary regions where ds^2 changes sign. It is located at $g_{tt} = 0$ whose horizons solutions are given as

$$r = r^E_{\pm}(\theta) \quad = \quad M \pm \sqrt{M^2 - \alpha^2 \cos^2 \theta}. \tag{5.1.4}$$

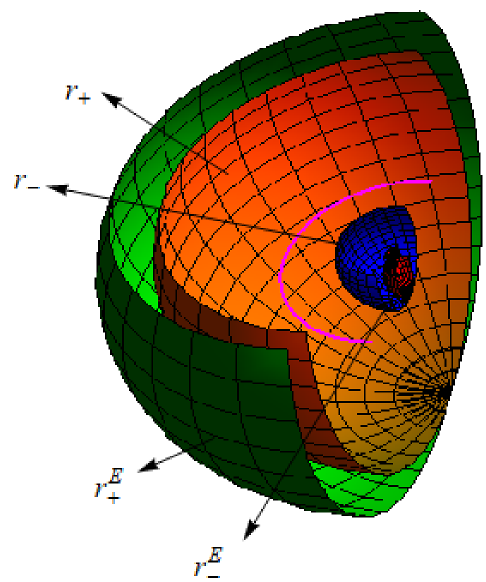

Figure 5.2: The plot of horizon solutions of Kerr metric by making $r_\pm$ and $r_\pm^E$ dimensionless.

Case 2: In the limit $r \to 0$ (with α is finite,$M \neq 0$ and $Q = 0$), the metric eq.2.1.31 reduces to 2.0.7.

i) True singularity; the ring singularity

The unremovable singularity of the Reissner$-$Nordstrom metric given by

$$r = 0$$

ii) Event horizons

Determined by the pseudo coordinate singularities given by

$$\Delta(r) = 0$$

whose horizon solution of

$$r_{\pm} = M \pm \sqrt{M^2 - Q^2}. \tag{5.1.5}$$

iii) The static limit of Reissner$-$Nordstrom geometry

It is located at $g_{tt} = 0$ whose horizons solutions are given as

$$r = r_{\pm}^{E}(\theta) = M \pm \sqrt{M^2 - Q^2}. \tag{5.1.6}$$

Case 4: In the limit $\alpha \to 0$ (with $M \neq 0$ and $Q = 0$, non-rotating black hole), the metric eq.2.0.7 reduces to the Schwarzschild metric 2.0.4: $\Delta \to r(r - 2M)$, $\rho^2 \to r^2$ then

$$ds^2 \to (1 - \frac{2GM}{rc^2})c^2dt^2 - \frac{1}{1 - \frac{2GM}{c^2 r}}dr^2 - r^2(d\theta^2 + \sin^2\theta d\phi^2). \tag{5.1.7}$$

This metric describe the spacetime manifold around a point mass. This equation shows that there are singular points when $r = 0$ and when $r = \frac{2GM}{c^2}$; the first is the center of the

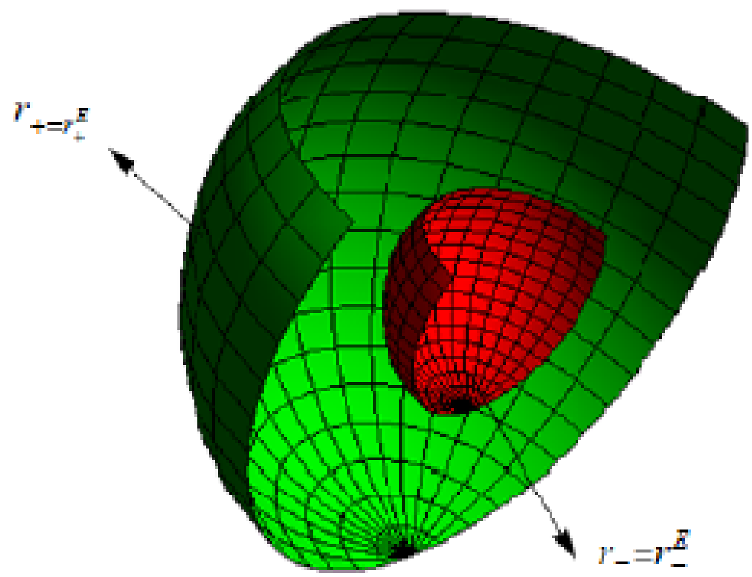

Figure 5.3: The plot of horizon solutions of Reissner−Nordstrom spacetime by making $r_{\pm}$ and $r_{\pm}^{E}$ dimensionless.

black hole; no particle can be in exactly the same place as another. The second singular point represents the event horizon of a black hole, and the Schwarzschild radius; the radius at which a ball of mass M collapses into a black hole. This metric also shows that the black hole consists of two connected sets of definition, that within the black hole, and the area outside. The singularity at $r = \frac{2GM}{c^2}$ can be removed using a different coordinatization (Kruskal-Szekeres coordinates), which gives the maximally extended solution and shows that space inside and outside the black hole are not completely different regions [84].

5.2 Orbital motion in the Kerr−Newmann metric

Employing Euler−Lagrange equations to the extremum of the metric, we obtained the constants of motion; energy, angular momentum and the carter constant. While the orbit equations are expressed in terms of these constants. Assuming motion of particles in the equatorial plane where $\theta = \pi/2$ and $\dot{\theta} = 0$. We impose the constrain that the carter constant vanishes to simply further the equations of motion. The Kerr−Newman metric has no explicit dependence on t and ϕ; they are cyclic coordinates in the Lagrangian. That tells us the conservation of energy and angular momentum respectively. Eqs.4.1.25 and 4.1.26 can be written as following;

$$u^t = \dot{t} = \frac{dt}{d\lambda} = E - \frac{(Q^2 - 2Mr)[(r^2 + \alpha^2)E - \alpha J]}{\Delta\rho^2} \tag{5.2.1}$$

$$u^\phi = \dot{\phi} = \frac{d\phi}{d\lambda} = \frac{1}{\rho \sin^2\theta} - \alpha\frac{[(Q^2 - 2Mr)E - \alpha J]}{\Delta\rho^2} \tag{5.2.2}$$

where $E = \partial L/\partial\dot{t}$ is the conserved energy of the particle and $J = \partial L/\partial\dot{\phi}$ is the conserved projection of the particle's angular momentum on the axis of the black hole's rotation (dots denote differentiation with respect to λ) and

$$\rho^2\dot{r}^2 = [(r^2 + \alpha^2)E - \alpha J]^2 - \Delta(r^2 + (J - \alpha E)^2). \tag{5.2.3}$$

The equation of the motion along the radial direction in thus becomes

$$\rho^2\dot{r}^2 \;=\; 2rE[(r^2+\alpha^2)E-\alpha J]-r\Delta-(r-M)[r^2+(J-\alpha E)^2]. \tag{5.2.4}$$

5.2.1 Circular orbit

Considering a particle of mass $m \ll M$ exhibit circular orbit within the conditions used in the equatorial plane, $\theta=\pi/2$, $\dot{r}=\ddot{r}=0$. That means $u^r=\dot{r}=0$, $u^\theta=\dot{\theta}=0$. Now using eqs.5.2.2 to 5.2.4 after some simplifications we get

$$u^t=\dot{t} \;=\; \frac{1+\frac{\alpha}{R}\sqrt{\frac{M}{R}-\frac{Q^2}{R^2}}}{\sqrt{1-\frac{3M}{R}+2\frac{Q^2}{R^2}+\frac{2\alpha}{R}\sqrt{\frac{M}{R}-\frac{Q^2}{R^2}}}} \tag{5.2.5}$$

$$u^\phi=\dot{\phi}=\omega_0 \;=\; \frac{\sqrt{\frac{M}{R}-\frac{Q^2}{R^2}}}{\sqrt{1-\frac{3M}{R}+2\frac{Q^2}{R^2}+\frac{2\alpha}{R}\sqrt{\frac{M}{R}-\frac{Q^2}{R^2}}}}. \tag{5.2.6}$$

In other way if $\xi=\sqrt{\frac{M}{R}-\frac{Q^2}{R^2}}$ then,

$$u^t=\dot{t} \;=\; \frac{1+\frac{\alpha}{R}\xi}{\sqrt{1-\frac{3M}{R}+2\frac{Q^2}{R^2}+\frac{2\alpha}{R}\xi}} \tag{5.2.7}$$

$$u^\phi=\omega_0 \;=\; \frac{\xi}{\sqrt{1-\frac{3M}{R}+2\frac{Q^2}{R^2}+\frac{2\alpha}{R}\xi}}. \tag{5.2.8}$$

As we observe from eq. 5.2.8 as Q and α increase, the natural frequency of the orbital frequency ω_0 of the orbit decreases. This implies that the orbit of the particles differ from the classical Schwarzschild geometry. As we see from Fig.5.4 in general, the unperturbed frequency ω_0 decreases with both increasing charge and spin parameter of the Kerr$-$Newmann black hole.

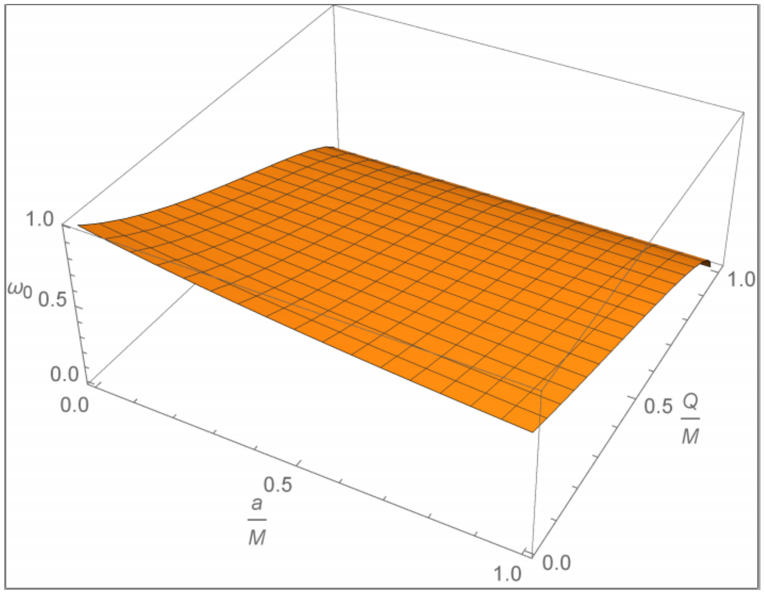

Figure 5.4: The plot of angular frequency of circular orbits in Kerr-Newman geometry with respect to the specific spin and charge parameters (a/M and Q/M).

5.2.2 General characterstics of the potential

Following the effective potential derivation of the well known Schwarzschild geometry, eq. 5.2.4 helps us to construct the equation of effective potential in the presence of charge of the form

$$\frac{1}{2}\dot{r}^2 + V_{eff}(r, M, \alpha, E, J) \quad = \quad \frac{\varepsilon - 1}{2}. \tag{5.2.9}$$

That means

$$V_{eff} \quad = \quad -\frac{M}{r} + \frac{l^2 + (1-\varepsilon^2)\alpha^2 + Q^2}{2r^2} - \frac{M(l-\alpha\varepsilon)^2}{r^3} + \frac{Q^2(l-\alpha\varepsilon)^2}{r^4} \tag{5.2.10}$$

where $l = \frac{J}{m}$ and $\varepsilon = \frac{E}{m}$ which is the energy parameter per unit mass, zero for massless particles otherwise 1.

The shape of an orbit depends on the energy E and the angular momentum L of the test

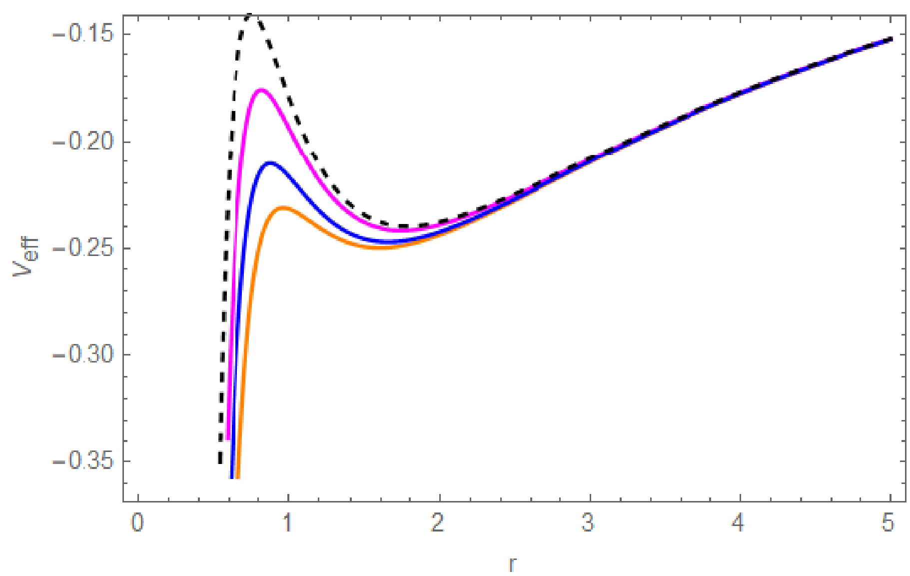

Figure 5.5: The plot of general effective potential for the Kerr-Newman geometry. In the plot Orange represents the Schwarzschild potential, Blue corresponds to Reissner-Nordstrom potential, Magenta represents the Kerr potential while the Dashed black represents the general Kerr-Newman potential where all effect have been included here.

particle. The stable and unstable orbits correspond to the local minima and maxima of the potential which we obtain from the radial geodesic equations. The potential depends upon the following parameters, the charge of the black hole (Q), spin parameter α. In the limits of Q $=0$ and Q $=0$, $\alpha=0$, the effective potential reduces to the ones for the Kerr and Schwarzschild black holes respectively. It is found that the presence of the charge of the black hole leads to the effective potential of the particle with stronger repulsive effects as compared with the Kerr black hole. The non-zero charge of the black hole seems to give repulsive effects to the particle as seen from its contributions to the centrifugal potential of the $1/r^2$ term as well as the relativistic correction of the $1/r^4$ term. These repulsive effects will shift the radius of the stable circular motion toward the black hole. The plots of the potential fig.5.5 indicates that the unstable circular orbit is dragged towards the black hole with decreasing radius while the stable circular orbit is drifted away with increasing radius and hence the orbital frequency decreases for bound orbits due to the Kerr-Newman space time geometry.

Case1: Massless particles: In the pure Schwarzschild spacetime the potential is always an attractor to the photons as we see from fig. 5.6. However, in the Kerr$-$Newmann spacetime geometry, depending on the parameters of the underlying black hole. The particles are kicked of to execute either a bounded stable orbits or being ejected to infinity. Thus, in the case of kickback to the greater distances will result in the emission of jets from the black hole.

Case2: Massive particles: For non-accreted particles the potential of will execute either a bound or unbound orbit. For bound orbit, in circular orbit, the radius relatively increase with respect to that of the Schwarzschild. In the case of the elliptical orbit the foci of the orbit will be kicked away. In other way, the feedback from the AGN, in the form of

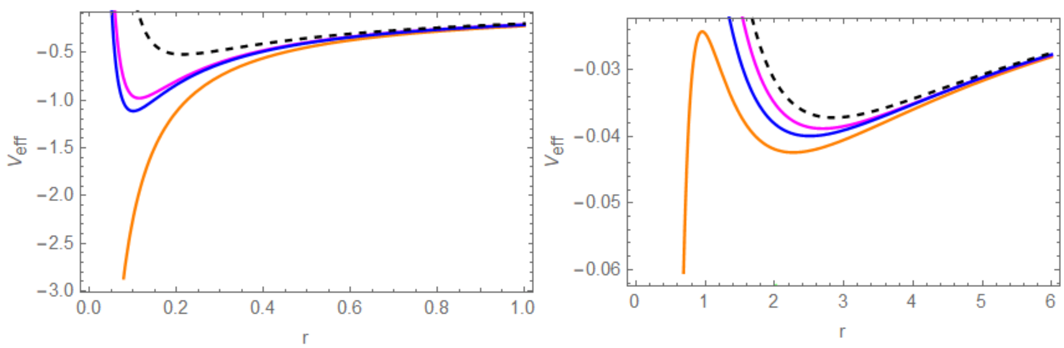

Figure 5.6: The plot of effective potential for massless(left panel) and massive (right panel) particles orbit. In the plots Orange represents the Schwarzschild, Blue corresponds to Reissner-Nordstrom, Magenta represents the Kerr while the Dashed black represents the general Kerr-Newman where all effect have been included here.

radiation, jets (kicked away) and accretion disk winds may indeed heat and remove gas from the nuclear region of the host galaxy, suppressing star formation and regulating the growth of the galaxy, impacting also in the surrounding intergalactic medium. The kickback or ejection from the AGN initiates turbulence in star−forming dark molecular clouds. Also, some particles that will be accreted in the Schwarzschild potential will execute bound orbit. Therefore, Active galactic nuclei interact tightly with their host galaxies, as reflected also by the observed strong correlations between SMBH mass and properties of the host galaxy, such as bulge luminosity, mass and velocity dispersion and by the need for an energetic (feedback) process able to remove or heat gas in massive galaxies to prevent further star formation.

5.3 The effect of kerr-newmann geometry on geodesy

Considerations on rotation are important in general relativity and frame dragging is one of its examples. Frame-dragging is an effect on spacetime, predicted by Einstein's general theory of relativity, that is due to non-static stationary distributions of mass−energy. It is a general relativistic feature of all solutions to the Einstein field equations associated with the rotating masses.

From the lagrangian we derived for the equations of motion particles, corresponding momentum in the coordinates of t, r, θ, and ϕ are given by

$$P_t = -E = g_{tt}\dot{t} + g_{t\phi}\dot{\phi} \tag{5.3.1}$$

$$P_r = g_{rr}\dot{r} \tag{5.3.2}$$

$$P_\theta = g_{\theta\theta}\dot{\theta} \tag{5.3.3}$$

$$P_\phi = J = g_{t\phi}\dot{t} + g_{\phi\phi}\dot{\phi}. \tag{5.3.4}$$

Using eqs. 5.3.1 and 5.3.4 we can write:

$$\dot{t} = \frac{g_{\phi\phi}E + g_{t\phi}J}{g_{t\phi}^2 - g_{tt}g_{\phi\phi}} \tag{5.3.5}$$

and

$$\dot{\phi} = \frac{-g_{t\phi}E + g_{tt}J}{g_{t\phi}^2 - g_{tt}g_{\phi\phi}}. \tag{5.3.6}$$

Using eqs.5.3.5 and 5.3.6, the angular velocity of frame-dragging $(d\phi/dt)$ becomes

$$\frac{\dot{\phi}}{\dot{t}} = \frac{u^\phi}{u^t} = \frac{d\phi}{dt} = \frac{-g_{t\phi}E + g_{tt}J}{g_{\phi\phi}E + g_{t\phi}J}. \tag{5.3.7}$$

Now, substituting eqs.4.1.23 and 4.1.24 into eq.5.3.7, the angular velocity of frame-dragging $(d\phi/dt)$ becomes

$$\frac{d\phi}{dt} = \frac{-g_{t\phi}[(\Delta-\alpha^2)\dot{t} + \alpha(r^2+\alpha^2-\Delta)\dot{\phi})] + g_{tt}[[(r^2+\alpha^2)^2 - \Delta\alpha^2]\dot{\phi} - \alpha(r^2+\alpha^2-\Delta)\dot{t}]}{g_{\phi\phi}[(\Delta-\alpha^2)\dot{t} + \alpha(r^2+\alpha^2-\Delta)\dot{\phi})] + g_{t\phi}[[(r^2+\alpha^2)^2 - \Delta\alpha^2]\dot{\phi} - \alpha(r^2+\alpha^2-\Delta)\dot{t}]}.$$

This equation is the angular velocity of frame-dragging of Kerr−Newmann spacetime for the equatorial plane.

From 5.3.7,making J=0, angular velocity of frame-dragging of a zero angular momentum test particle is obtained as:

$$\frac{d\phi}{dt} = \frac{-g_{t\phi}E}{g_{\phi\phi}E}. \tag{5.3.8}$$

Then, the general expression for angular velocity of frame-dragging $\frac{d\phi}{dt}(\phi,\theta)$ KN for a charged rotating body with radius R (emitted radially outward from the surface of a compact object) in Kerr-Newman Geometry is

$$\frac{d\phi}{dt}(\phi,\theta) = \frac{\frac{R\sin\phi\sin\theta}{\sin^2\theta}(1-(\frac{2Mr-Q^2}{r^2+\alpha^2\cos^2\theta}))+\frac{2Mr\alpha-\alpha Q^2}{r^2\alpha^2\cos^2\theta}}{-\frac{2Mr\alpha-\alpha Q^2}{r^2\alpha^2\cos^2\theta}(R\sin\phi\sin\theta)+(r^2+\alpha^2+\frac{2Mr-Q^2}{r^2\alpha^2\cos^2\theta})\alpha^2\sin^2\theta}. \tag{5.3.9}$$

In the above expression of frame-dragging given by eq.5.3.9:

- If $\alpha = 0$, then eq.5.3.9 gives the corresponding expression of frame dragging in Reissner-Nordstrom Geometry.
- If Q=0, then eq.5.3.9 gives the corresponding expression of frame-dragging in Kerr Geometry.
- If Q=0 and $\alpha = 0$, then eq.5.3.9 gives the corresponding expression of frame dragging in Schwarzschild Geometry, which can be considered as geodetic effect.

By substituting $\theta = \frac{\pi}{2}$ (equator) in eq.5.3.9, the expression of frame dragging for the equatorial plane in the Kerr-Newman Geometry can be written as:

$$\frac{d\phi}{dt}(\phi,\theta=\frac{\pi}{2}) = \frac{R\sin\phi(1-(\frac{2Mr-Q^2}{r^2}))+\frac{2Mr\alpha-\alpha Q^2}{r^2}}{-\frac{2Mr\alpha-\alpha Q^2}{r^2}(R\sin\phi)+(r^2+\alpha^2+\frac{2Mr-Q^2}{r^2})\alpha^2} \tag{5.3.10}$$

If $\theta = \frac{\pi}{2}$ (equator) and charge Q=0 eq.5.3.9 gives an expression of frame-dragging for the equatorial plane in the Kerr Geometry. Which is written as;

$$\frac{d\phi}{dt}(\phi, \theta = \frac{\pi}{2}) \quad = \quad \frac{R\sin\phi(1 - \frac{2Mr}{r^2}) + \frac{2Mr\alpha}{r^2}}{-\frac{2Mr\alpha}{r^2}(R\sin\phi) + (r^2 + \alpha^2 + \frac{2Mr}{r^2})\alpha^2} \tag{5.3.11}$$

5.4 Accretion as the main source of energy release from astrophysical objects

5.4.1 Accretion and radiation as luminosity

A matter falling onto the black hole heats up and emits radiation. According to the virial theorem, half of the gravitational energy acquired from gravitational contraction becomes gas thermal energy, while the other half is radiated away. One of the powerful technique in the observation is the extracting of the data in the form of energy spectra in the form of EM. Gravitational energy is the energy released from exotic astrophysical system like accreting compact objects (neutron stars, white dwarf, Black hole) and AGN in significantly in EM form. The source of energy release are stellar evolution which is significantly dominated by nuclear reaction and exotic objects like black hole, white dwarf ,neutron star, and AGN in which both nuclear energy and gravitational energy are due to accretion.

Let us see the contribution from nuclear reaction. If any of system accretes say dM then, the amount of energy converted to nuclear energy is by mass-energy conversion is given by;

$$dE_n \quad = \quad \eta dM_{acc}c^2$$

where η is the mass to radiation conversion efficiency which is conversion factor. When hydrogen in the core has been transformed into helium, the nuclear reactions stop and the core starts contracting again under the pull of gravity; hydrostatic equilibrium of the system requires the large hydrogen envelope that surrounds the core to expand and thence cool; the process is again halted by the ignition of nuclear reactions, which burn He into C and O. The larger temperatures and densities necessary to fuse heavier nuclei with larger electric charges are thus obtained by gravitational contraction of the stellar core. In fact the predominant conversion comes from hydrogen. So, if we suppose

$$\eta = \eta H + \eta He + \eta C + \eta O \tag{5.4.1}$$

$$\eta \approx \eta H \approx 0.007 \tag{5.4.2}$$

and now using eqs.5.4.1 and 5.4.2 we get

$$dE_n = 0.007 dM_{acc} c^2. \tag{5.4.3}$$

The second one is a contribution from gravity. It is in the form gravitational potential energy. So assuming accreting system is mass M, then we have

$$dE_g = \frac{GMdM_{acc}}{R}. \tag{5.4.4}$$

The total radiated energy from both contribution is

$$dE_{total} = dE_n + dE_g. \tag{5.4.5}$$

Then, the energy radiated per unit area per unit time is

$$\frac{dE_{total}}{A} = \frac{1}{A}(\frac{dE_n}{dt} + \frac{dE_g}{dt}) \tag{5.4.6}$$

$$= \frac{1}{A}(0.007\frac{dM_{acc}c^2}{dt} + \frac{GM}{R}\frac{dM_{acc}}{dt}) \tag{5.4.7}$$

$$= \frac{1}{A}(0.007c^2 + \frac{GM}{R})\frac{dM_{acc}}{dt} \tag{5.4.8}$$

$$= \frac{1}{A}(0.007c^2 + \frac{GM}{R})d\dot{M}_{acc} \tag{5.4.9}$$

where $d\dot{M}_{acc} = \frac{dM_{acc}}{dt}$. Hence accretion of material is the most efficient astrophysical energy source. In general, for the gravitating system the source of the energy released from their surface is dominated by gravity due to accretion and nuclear reaction.

5.4.2 Radiative transfer and energy dissipation

The energy released from the accretion-nuclear process and other energies released from the horizons due to geometry and thermodynamic effects has considered as AGN feedback. The interaction includes interstitial dusts and others including the host galaxy. From observational perspective the effects be determined from the received spectral energy distribution (SED) in the form of multi-wave radiation. In this thesis we covered only the maximum energy released from nuclear conversion in the form of luminosity using Eddington luminosity limit. However, the rest were covered in different subtopics without detailed mechanisms, which this thesis cannot cover.

On the other hand, it is important to note that the SED received at the observation is expected to be less than the the value expected theoretically. This is due to the interaction of the feedback with surrounding to dissipate in the form of absorption and scatter. Thus in our work we did derive the details of this covered in chapter 4, sec. 4.3.1.

Chapter 6

Summary and conclusion

Generally, AGNs are amongst important astrophysical systems used in astrophysical studies that require diverse areas of physics. They cover all electromagnetic spectral energy distributions and as well entertain strong gravity regime. AGN interaction with its environment involves general relativistic effects both on fluid and particle systems. In our study, we covered the geometrical effect of the AGN that arises from gravity, spin and charge. Our analytical study covers derivation and analysis of equation of motions, particle orbit characterization with the aid of the central effective potential of the AGN determined by the underlying SMBH. We have also studied accretion and nuclear energy conversion process. The AGN feedback effects, both from geometry and accretion process have covered in our study. We have also addressed the feedback testing mechanism, for the accretion process case in the form of Luminosity. Nevertheless, issues related to dissipation need further investigation because the dispassion is expected to reduce the theoretical value.

Thus, it is our belief that our work will help the scientific community for further progress in the study of AGN and its effects on its environments, especially in the mechanisms how energy particles will flow into and out of the AGN where geometry, gravity and charge effects will being considered.

Finally, in conclusion, the astrophysical nature of AGN and its effects on nearby environments, its host galaxy and distant objects is still fresh and active that needs further research.

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