GALACTIC INTERSTELLAR DUST EXTINCTION EFFECT ON JETS EMITTED FROM GALACTIC NUCLEI

BY

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Acronym

ANG - Active GAlactic Nuclei

SMBH - Supper- Massive Black Hole

ISM - Interstellar Medium

SF - Star Formation

BLR - Broad Line Region

NLR - Narrow Line Region

FSRQs - Flat-Spectrum Radio Quasars

dE - dwarf elliptical

dSph - dwarf spheroidal

RTE - Radiative Transfer Equation

JWST - James Webb Space Telescope

Abstract

AGN jet research is essential to comprehending galaxy evolution and the interactions between supermassive black holes and their host environments. Interstellar dust in the host galaxy is frequently detected to obstruct the jets, which originate from the accretion disk encircling the central black hole. Misunderstandings of the jets' inherent qualities result from this dust extinction substantial influence on the jets' observed properties. By examining the influence of dust grain size and utilizing general relativistic hydrodynamic radiative transfer equations (RTE), This work explores the role of dust grain size and radiative transfer effects in galactic interstellar dust extinction and how they affect the jets that are released from AGN. We simulate the absorption and scattering of the jets using a radiative transfer model that takes into account a variety of dust grain sizes and compositions. Our findings indicate that dust extinction has a major impact on the jet properties that are observed.

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1

INTRODUCTION

1.1 Background

All matter pulled together by gravity, including dust, dark matter, interstellar gas, stars, and stellar remnants, is called a galaxy. Galaxies differed in form and in the energy they emitted from their cores, among other factors. Large galaxies with billions of stars, as well as tiny galaxies with only a few million [17]. Based on the galaxy's size and brightness, scientists can determine the variety of stars in the system. There exist galaxies that are primarily composed of neutral gases. Conversely, others are intricate systems composed of numerous discrete elements such as stars, dust, molecular clouds, dust, ionized and impartial fuel, magnetic fields, and cosmic rays. Galaxies can also form large clusters or smaller agencies in space. At the core of many galaxies is a compact nucleus that occasionally shines so brightly that it eclipses the galaxy's overall normal radiation.

The brightest normal galaxies may have a luminosity of 10^{12} solar luminosity, but the majority of them are much fainter; the smallest ones known to exist are approximately $10^5 L\odot$ [3]. Galaxies, the fundamental astronomical ecosystems where stars are born, grow, and eventually die, contain the majority of the visible matter in the universe and evolve slowly over time through a variety of stages and mechanisms. Its formed by the interactions of its constituent elements gas, dust, stars, and dark matter as well as by outside forces like galaxy mergers. It is thought by scientists that in the early universe, gas and dust collapsed to form galaxies. After trillions of years, most galaxies have reached a stage where they're defined in shape and form, such as the spiral arms of the Milky Way galaxy, while others may be elliptical or even irregular. One of the most fascinating aspects of galaxies is their evolution. Scientists believe that galaxies formed from the collapse of gas and dust in the early universe. Over billions of years, galaxies have continued to evolve and change through mergers with other galaxies, star formation, and the influence of dark matter. A galaxy is a vast cluster of stars and interstellar material that is separated from one another in space and held together by gravity. There are thought to be over 100 billion galaxies in the Universe, mainly residing in clusters and groups. The most famous galaxy is the spiral galaxy that we call home, the Milk Way.

Figure 1.1: The Milk Way Spiral "Artist impression - NASA Universe .

The brightest objects in the cosmos and a region of emission that is smaller than our solar system and is comparatively small in size; these are known as active galactic nuclei AGNs. which occur in the central regions or nuclei of some galaxies and are incredibly energetic phenomena [29]. The central area of a galaxy is the source of its luminosity, and the supermassive black hole at the center of the host galaxy is most likely the activity's main driver. Large amounts of matter are accreted from their surroundings by supermassive black holes, which power AGN. They can be used to find far-off objects because they are the universe's most luminous persistent sources [2],[21]. The emission properties of the AGN differ from those of a typical stellar system, and it outshine the galaxy in which it is located. In the 1920s,Edwin Hubble names"nebulae"the compact,bright cores he finds in certain galaxies. Early twentieth century these nebulae are later dubbed "Seyfert galaxies" after astronomer Carl Seyfert identifies them as a unique class of galaxies with active nuclei. Seyfert galaxies, blazars, and quasars are some of the sub-types that fall under these two broad categories. All of these categories have different physical characteristics and observational characteristics, but there are also sub-classes and variations within them. The BPT diagram is the name given to this classification scheme. Their brightness originates from the galactic center, with the supermassive black hole at the galaxy's center acting as the main source of activity. It is thought that AGN radiation arises from the mass accretion of a Super-Massive Black Hole (SMBH) with 10^6 - $10^{10} M\odot$, situated at the center of their host galaxies [27]. There are several methods by which this energy is released into the surrounding medium, such as $\gamma - ray$ emission,

UV radiation, and collimated radio-plasma jets [23]. The active supermassive black hole's enormous energy output can affect the host galaxy's entire evolution and way of life [25]. All kinds of galaxies, from massive ellipticals to tiny dwarf galaxies, contain AGNs. They are commonly observed in the centers of galaxies that are undergoing active star formation, where they are more prevalent. This implies a relationship between AGN activity and the formation and evolution environment of galaxies. An AGN's surroundings are extremely dynamic, complicated, and affected by the galaxy that hosts it. AGN environments are the areas around giant planets in the centers of galaxies that are responsible for large and powerful outflows and intense radiation. These environments are typified by high energy processes, like matter accreting onto the black hole and energy being released in the form of radiation, powerful magnetic fields, and powerful particle jets. Beginning in the early 20th century, study on AGN and their effects on the environment around them has long been conducted.

The strong radiation from these active nuclei, which can heat and ionize gas, affect star formation, drive outflows and jets, and affect the surrounding environment in a variety of ways, was discovered by Maarten Schmidt and other scientists towards the end of the 20th century. The black holes are located at the center of these galaxies.

These effects can be seen at different distances from the black hole itself, all the way out to the larger galaxy in which it is located [18]. High-energy radiation, such as X-rays and ultraviolet light, can be released from the accretion disk by heating and ionizing the gas and dust due to the intense radiation and magnetic fields present at the inner engine. The structure and dynamics of the inner regions, known as AGN winds or jets, which can extend thousands of light-years, can be strongly influenced by the powerful outflows of gas and particles that this radiation can also induce. The powerful radiation from the AGN can heat and ionize gas clouds in the broad line region, causing them to release strong emission lines at various wavelengths. It can also cause shocks and turbulence in the gas, changing its properties and possibly initiating star formation and it directly affects the ionized gas clouds in the narrow line region [23].

1.2 Statement of the problem

The study of galaxies and its dynamism is one of the active astrophysics research areas. In particular if the galaxy is active, its nuclei (Active Galactic Nuclei (AGN)) controls most of its activities. The AGN radiates all kinds of electromagnetic spectrum in various ways among which jets are more relevant to it than other astrophysical systems. Here, we focus on the extinction effect of the host galaxy interstellar medium on the jets.

Research Questions

1. What are astrophysical jets in astrophysical emission?
2. How does AGN emit jets?
3. What are the effects of dust extinction and emission on jets from AGN?

1.3 Objectives

1.3.1 General Objective

To study galactic interstellar dust extinction effect on jets emitted from galactic nuclei.

1.3.2 Specific Objectives

1. To explain astrophysical jets emitted Astrophysical objects.
2. To describe the way how jets emitted from AGN.
3. To determine the effect of galactic dust interstellar extinction on jets emitted from AGN.

1.4 Methodology

The general relativistic hydrodynamic radiative transfer equations are used to describe emissions and absorption of the jets propagated from AGN. Based on the model equation, the Eddington approximation is used to simplify the radiative transfer equation (RTE) with proper boundary conditions to quantify the effects. The amount of transfer effect in the interstellar medium of the host galaxy and the surface luminosity of the galaxy are used to generate some synthetic data to quantify the effect at the observation point. Moreover, the effect of dust on jets will be explained by general relativistic radiative transfer equations for energy flow from the AGN supermassive black hole through its environments. For analysis of the results, Python 3.11 software is used for plots, while Latex is used for documentation.

The thesis is organized as:
Chapter 1: Introduction - that provides the background information, literature reviews, goals, and methods as already discussed earlier and here. Chapter 2: Focuses on galaxies in general-providing a broad overview of their characteristics. Chapter 3: Explores Active Galactic Nuclei (AGN) and their features, including AGN jets and interactions with dust. Chapter 4: Develops the equations needed for the study, likely

including mathematical formulations for analysis. Chapter 5: Presents the study's results and discusses their significance. Chapter 6: Wraps up the thesis with a summary of key points, conclusions drawn, and potential future research directions.

2

Introduction to Galaxy

A galaxy is a self-gravitating system composed of an interstellar medium, stars, and dark matter. There are more than a billion billion stars in the largest galaxies. Moreover, fewer million galaxies could be found in smaller ones [16]. Galaxies and their nuclear Super Massive Black Holes $(SMBH)$ appear to be intimately related components of the same fundamental formation and evolutionary process [35]. A brightly shining AGN has a useful service by illuminating its host galaxy with an ionizing radiation field. The fluorescent emission that this produces can be studied to tell us about some rather fundamental galaxy properties such as , via emission line kinematics, the mass and, via line ratios and ionization modeling, the chemical composition of the interstellar medium (ISM).

With a luminosity that can far exceed that of its host, an AGN will not only illuminate its surroundings, it will push material around. Radiation pressure will affect dust clouds, ambient gas will be shocked in the presence of the particle jets, flows will be driven and the ISM will be generally mixed and redistributed. All these processes have to be recognized and understood if we are to generate a complete picture. Galaxies are thought to have begun from large irregular clouds of hydrogen and helium. This gas was created in the first few minutes of the universe. Certain sections of the clouds were probably slightly more dense than others. Because of this higher density, gravity caused them to collapse. As the large cloud collapsed, it cooled. On an even smaller scale, pieces of the collapsing cloud, also collapsed into even smaller pieces. These smaller denser regions created the first stars. When the first stars reached the end of their life cycle, they exploded, heating the surrounding gas and slowing the collapse of the galaxy cloud. These explosions also introduced heavier metals, such as carbon and nitrogen, into the galactic cloud. Eventually, this process of collapse, star formation, and slowing, balanced, giving us stable galaxies. How this process created elliptical and spiral galaxies, is yet another question. There are two main theories. The first theory is: as the cloud collapsed to form a galaxy, it's spin is what determined what type of galaxy it became. Some theorists believe that spiral galaxies were formed from clouds that had a significant spin. As the cloud collapsed the spin got even faster still, this is a feature of the principle of angular momentum. As this the spin increased, it flattened the material in the cloud along the spin axis, forming the characteristic disk of spiral galaxies. Elliptical galaxies were simply formed from clouds that did not have this spin. They therefore formed a more round structure, which has no particular axis of rotation. The second theory is that elliptical galaxies were formed from collisions of spiral galaxies.

This theory is supported by a couple of interesting facts. First, in the early universe galaxies were much closer together then they are now. Since they were closer together, especially in galaxy clusters, collisions were probably very common. So if collisions of spirals made ellipticals, the process of elliptical galaxy creation was definitely present. Second, large elliptical galaxies typically occur in rich galaxy clusters, where collisions most likely happen. Third, ellipticals don't have much interstellar gas, when compared to spirals. In the context of this theory, the collision of spirals would have ignited much of the gas, turning them into stars. This process can be seen today in galaxy collisions. Elliptical galaxies do show evidence of this "new" population of star formation, even though they currently have very low formation rates. Newer stars have a different metal composition than older stars, since they were created later in the galaxy's evolution (i.e. after several star life cycles).

In some elliptical galaxies, there are two distinct populations of globular clusters an "old" and a "new". The 'pressure effects' then density enhancements experience are due to the expanding Universe. The space itself between particles is expanding. So each particle is moving away from each other. Only if there is enough matter for the force of gravity to overcome the expansion do density enhancements collapse and grow. Structure could have formed in one of two sequences: either large structures the size of galaxy clusters formed first, then later fragmented into galaxies, or dwarf galaxies formed first, then merged to produce larger galaxies and galaxy clusters [19]. Dark matter, whose distribution is significantly wider than that of the visible part, dominates the gravitational potential and forms a spheroidal halo. The majority of ordinary matter, also referred to as "Byronic matter," is composed of hydrogen and helium and can be found in the form of stars, dust, planets, diffuse and clumpy gas, and other objects [12].

2.1 Morphology of Galaxies

Galaxies must be categorized using a system in order to be studied and their evolution in the cosmos. For a classification scheme to be successful, it usually needs to meet two requirements. In addition to serving as a quick way to identify the object, it should provide some context for understanding. Edwin Hubble's 1926 classification technique for categorizing galaxies is the one that is most commonly used. The way a galaxy appears visually on a photographic plate is the only factor used in his classification. Three primary classifications are listed in Hubble's system: elliptical galaxies, spiral galaxies, and irregular galaxies. There are two groups of spirals: normal and barred. There are other divisions among the elliptical galaxies, as well as regular and barred spiral galaxies, as seen in the figure2.1 and explained below.

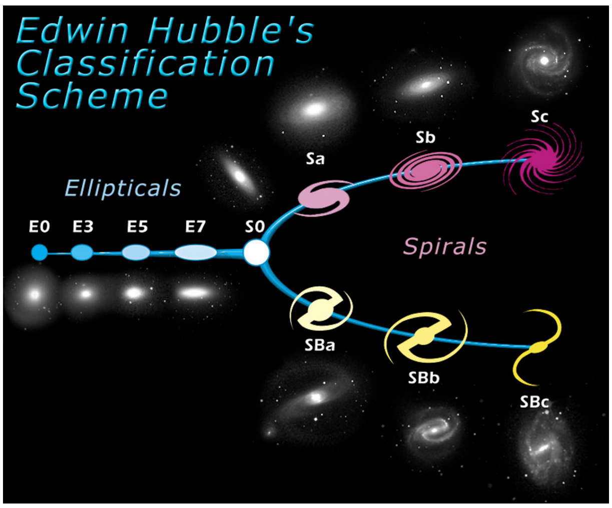


Figure 2.1: Edwin Hubble's: classification scheme (Source: The images of the galaxies were created from observations taken by the Sloan Digital Sky Survey).

The "Hubble Tuning Fork" is shown by this figure2.1.Based on how the galaxies appear visually, the Hubble tuning fork classifies them. Similar to how classifying stars a century earlier produced profound revelations, Hubble had originally believed that his categorization would also. According to one theory, this categorization system depicts an evolutionary pattern in which elliptical galaxies form at first, then as they get older, they rotate, flatten, and spread out. Three categories of galaxies are present: irregulars, spirals, and ellipticals. The Hubble sequence provides an even more detailed description of galaxy types according to appearance.

2.1.1 Elliptical Galaxies

Usually, elliptical galaxies exhibit a round and smooth shape, lacking any distinct features such as dust lanes or spiral arms. The scarcity of young blue stars in ellipticals can be attributed to their deficiency in cold gas. The size of elliptical galaxies can vary, with dwarf ellipticals being less than ten percent of the mass of the Milky Way. Elliptical galaxies are classified on a scale from E0 (nearly perfect circles) to E7 (elongated ellipses), depending on their level of elongation. The appearance of an elliptical galaxy when observed from Earth is influenced by its orientation, resulting in some appearing more elongated than others due to perspective. The largest ellipticals, known as cD galaxies, are typically found in galaxy clusters with high densities of galaxies. Ellipticals are the most common type of galaxy found in clusters. Normal or giant ellipticals, which can span tens of kilo parsecs in size, have luminosities several times greater than that of the Milky Way.

The stars in these luminous elliptical galaxies do not show much organized movement, like rotation; instead, their orbits around the galactic center are haphazard. Two distinct groups have emerged from the dimmest elliptical galaxies, which have a luminosity of less than about one-tenth of the Milky Way. One group consists of the unusual compact elliptical galaxies, such as the nearby system M32. The other group includes the even fainter dwarf spheroidal (dSph) galaxies and the dim diffuse dwarf elliptical (dE) galaxies. The dE and dSph galaxies exhibit very little rotational order. It is believed that elliptical galaxies are formed when spiral galaxies collide and merge. The less organized elliptical galaxies are created when the structure of spirals is disrupted by these collisions. The low rate of star formation in these galaxies may be due to the consumption of gas and dust by supermassive black holes at their centers, which are necessary for the birth of new stars.

2.1.2 Spiral Galaxies

The morphology of galaxies is mainly shaped by the interplay of gravity with various physical mechanisms such as star formation, gas dynamics, supernova feedback, and active galactic nuclei. Specifically, it is theorized that spiral galaxies emerged from a spinning disk composed of gas and stars, formed through the merging and accumulation of smaller, gas-rich galaxies. Spiral galaxies typically exhibit two separate disk structures: a thick disk housing older stars with a scale height of approximately 1kpc, and a thin disk containing young stars with a scale height of a few hundred parsecs and a relatively low velocity dispersion.

The central bulge found in these galaxies exhibits numerous similarities, such as density and kinematics, with elliptical galaxies (Ann et al., 2015). Bulges are typically composed of old stars that resemble thick disk stars in terms of metallicity and age. Spiral galaxies are classified based on the significance of their bulge: Sc galaxies possess small bulges and loosely wound spiral arms, while Sa galaxies have massive bulges and tightly wound arms. The absence of a bulge component in approximately 16 percent of spiral galaxies in the Local Universe poses a significant challenge to theories regarding galaxy formation. Additionally, around 50 percent of spiral galaxies feature a central bar that can extend up to half the radius of the disk.

2.1.3 Irregular galaxies

Irregular galaxies, unlike elliptical or spiral galaxies, lack a distinct regular shape. They do not possess a nuclear bulge or any indication of spiral arm structure, making them distinct from the regular classes of the Hubble sequence. Irregular galaxies often exhibit a chaotic appearance [6],[24]. Some irregular galaxies were initially spiral or elliptical galaxies but were distorted by an external gravitational force. Irregular galaxies can contain significant amounts of gas and dust [8]. However, this is not always the case for dwarf irregulars [39]. Despite their small sizes, they are susceptible to environmental effects such as collisions with massive galaxies and intergalactic clouds.

2.2 Formation and Evolution of Galaxies

Scientists have extensively examined and discussed the intricate mechanisms that contribute to the development and progression of galaxies. The exploration of galaxy formation and evolution encompasses the origins of the initial galaxies, their transformation throughout history, and the factors that have contributed to the wide array of structures observed in nearby galaxies. These processes have ultimately led to a universe that is diverse and varied, originating from a uniform starting point. Theories on the creation of structures propose that tiny quantum fluctuations following the Big Bang are accountable for the formation of galaxies.

The evolution of galaxies plays a crucial role in galaxy research. Understanding the formation of galaxies in the early universe provides valuable insights into cosmic structures. Galaxies develop and change over time due to various factors, such as their physical characteristics and interactions with dark matter. Processes like gas accretion, mergers, and interactions with neighboring galaxies all contribute to the continuous evolution of galaxies. These processes can lead to the creation of new stars, expansion of existing stars, and the emission of gas from the galaxy.

When the gas within merging galaxies undergoes compression, star formation can sometimes erupt due to the merger. The progression of star formation (SF) activity stands out as a key aspect of galaxy evolution. The initial stars in the cosmos originated from a cluster of primordial gas, and upon their demise, they dispersed the first heavy elements. This paved the way for subsequent generations of stars to form more effectively and kick started the phenomenon of stars forming in unison, leading to galaxy formation. Consequently, as stars came into being and perished, the chemical composition of the interstellar medium (ISM) within galaxies also evolved over time.

The concept of "galactic chemical evolution" is defined by this [36]. It is closely related to the production and development of dust, which plays a crucial role in the evolution of galaxies [31]. The evolution of galaxies is also heavily impacted by the accumulation of gas. Gas forms a disk of cold gas that can facilitate the formation of stars as it enters the gravitational potential well of the galaxy. Processes such as supernovae and stellar radiation can heat and expel gas from the galaxy, influencing the star formation process. Ultimately, this can lead to the cessation of star formation in certain galaxies and a reduction in the rate of new star formation.

Active galactic nuclei (AGN) are areas of intense activity surrounding supermassive black holes that have a significant impact on the evolution of galaxies. AGN can greatly influence their host galaxies by inhibiting star formation and ejecting gas and other materials from the galaxy. This process can lead to the formation of elliptical galaxies, which are characterized by their elliptical shape and absence of ongoing star formation.

3

Active Galactic Nuclei(AGN) and Galactic Interstellar Dust

3.1 Active Galactic Nuclei(AGN)

The active galactic nucleus (AGN) located in the central region of a galaxy emits a significant amount of energy across the electromagnetic spectrum. The luminosity of the AGN is distinct from that of stars, indicating a different source of energy. This energy is generated through accretion, as matter falls into the black hole and spirals inward within the accretion disk. As a result, various forms of energy, such as jets, visible light, X-rays, and radio waves, are released. AGNs, or active galactic nuclei, possess an immense amount of energy that can surpass the brightness of the entire galaxy they reside in. These cosmic entities are the most powerful sources of light in the universe, with quasars being the most energetic among them.

Quasars easily outshine the galaxies they inhabit, with many of them having luminosities exceeding $10^{12}L\odot$. This extraordinary brightness allows them to be observed throughout the observable Universe. The emission is believed to originate from the energy produced by gas falling into a supermassive black hole at the core, which may have a size no larger than that of the solar system. Supporting the current theory, it is suggested that these supermassive black holes power AGNs [26]. AGNs are classified into two categories, known as radio-quiet and radio-loud. Radio-quiet objects exhibit a simple jet-like structure similar to that of a radio-loud object. In the center of active galactic nuclei (AGN), supermassive black holes (SMBH) give rise to the formation of jets. These AGN jets traverse the galaxy, gradually making their way out of the host galaxy and into the intergalactic medium. Along their journey, these jets can have various impacts. They generate shock waves that propagate through the surrounding medium, leading to the heating and compression of gas. Additionally, they induce turbulence in the neighboring medium and strip electrons from atoms or molecules, resulting in the creation of positively charged ions through gas ionization. Furthermore, the jets must displace any gas obstructing their path. Due to the momentum lost to the interstellar gas, the tip of the jet cannot advance outward as swiftly as the material within the jet itself. Two shocks are subsequently created, with one expanding into the interstellar gas and the other reversing into the jet, causing it to decelerate. The high-energy particles within the AGN jets interact with the atoms and molecules in the ISM, resulting in ionization reactions. AGN jets exhibit high relativistic speeds, nearing the speed of light. Additionally, they possess immense energy, emitting luminosities that surpass those of their host galaxies by significant margins.

3.1.1 Unification Model of AGN

During the 1990s, the concept of the unified model for AGN emerged, with the purpose of elucidating the diverse nature of AGN by proposing that all AGN types are essentially different expressions of the same fundamental process. The unified model is primarily based on the notion that the appearance of an AGN is heavily influenced by orientation effects, which subsequently determine its classification into a specific sub-class. The primary factor contributing to the orientation effect is believed to be a thick and optically-thick dusty molecular torus situated in the accretion plane of the AGN.

In addition to obscuring the central source from direct view, this phenomenon has the ability to block the infrared photons generated by the heating of the dust within it. Another effect related to the orientation is observed in the radio-loud categories, which was initially proposed in the development of the unification concept [15]. AGN classes that are observed near the polar direction exhibit super-luminal motions, rapid variability, intense power-law continua, flat radio spectra, and high linear polarization. These characteristics are all attributed to the relativistic beaming effects associated with the jet. Based on the currently established AGN model unification, there are two fundamental types of AGN: radio-loud and radio-quiet [10]. Relativistic jets are present in the former, and it is believed that these jets are powered by the rotation of a supermassive black hole located at the center of the host galaxy. The radio-loud subclass can be divided into two types based on their radio luminosity: high-luminosity sources, including radio-loud quasars and FR II radio galaxies, and low luminosity sources, such as BL Lac objects and FR I radio galaxies [33]. The orientation of the dusty torus, which surrounds the central supermassive black hole in AGN, plays a crucial role in determining the observed properties of these objects.

The classification of AGN is primarily based on the orientation of the dusty torus. Type 1 AGN are characterized by a direct line of sight to the central supermassive black hole and its accretion disk, allowing for an unobstructed view. As a result, broad emission lines are observed in the AGN spectrum, indicating the presence of a broad-line region. Type 1 AGN are commonly associated with Seyfert galaxies and quasars, and their spectra typically display strong and broad emission lines. On the other hand, type 2 AGN are observed when the dusty torus obstructs the direct line of sight to the central black hole and accretion disk.

Consequently, the wide emission lines originating from the broad-line region become concealed, while only the narrow emission lines from the narrow-line region are visible in the spectrum. Type 2 AGN commonly display prominent narrow emission lines and are linked to Seyfert galaxies and other obscured AGN. The model depicted in Figure3.1 illustrates key components such as jets, a thick accretion flow or molecular torus, a hot corona, and various types of outflows. Depending on the observer's line of sight, this model can replicate the diverse characteristics of different AGN types. Blazers occur when the line of sight is within the jet, resulting in significant variability caused by jet processing and shocks, as well as high flux due to extreme beaming. Broad-line radio galaxies form when the line of sight passes through the non-uniform outflows in the evacuated funnel, excluding the jet, leading to broad absorption lines due to the rapid motion of clumps in the outflows. Narrow-line radio galaxies are observed when the line of sight directly intersects with the accretion flow.

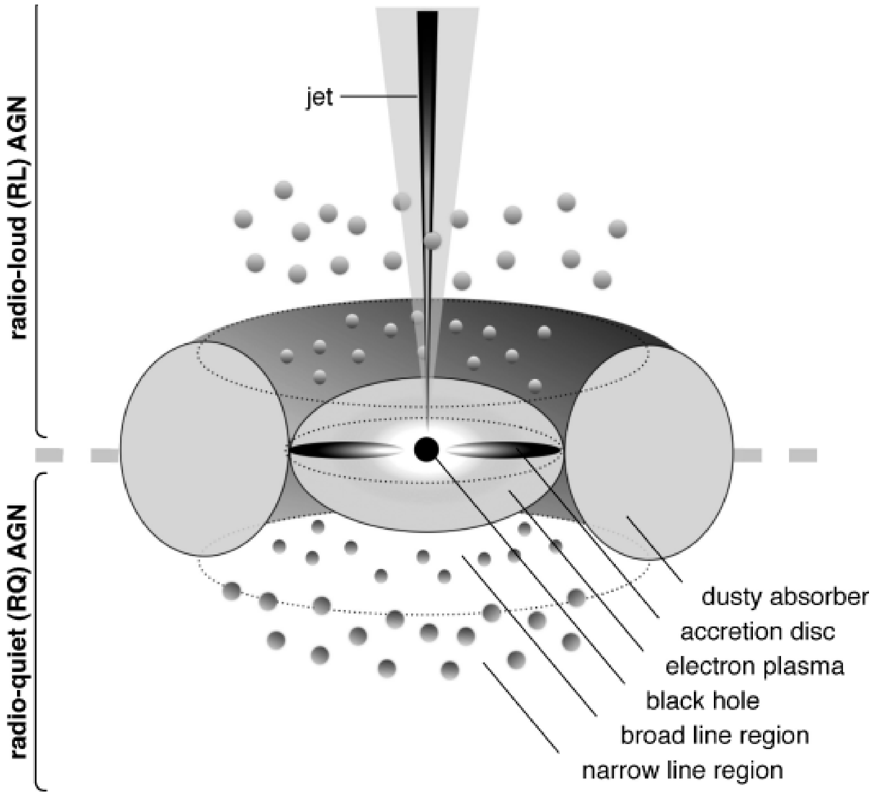


Figure 3.1: Beckman and Shredder (2012);graphic by Marie-Louise Menes

The intense X-ray radiation is generated through the process of comptonization of soft disk photons in a hot corona, likely heated by magnetic reconnection, while the remaining emission originates from the disk or outflows.

3.2 The Environment of Active Galactic Nuclei

From the early 1900s, when astronomers first discovered strange emission lines in the spectra of some galaxies, the study of the environment around active galactic nuclei (AGN) has a long and illustrious history. According to observational astronomers,the environment of active galactic nuclei (AGN) include the area around the supermassive black hole at a galaxy's center, where the AGN's strong winds and intense radiation interact with the surrounding gas and stars. 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. Through feedback mechanisms, AGN are also thought to be essential in controlling star formation and galaxy expansion [11],[1]. AGN can exert negative feedback on their surroundings,where the AGN inhibits star formation by heating and dispersing the gas in the galaxy, while the positive feedback describes the possibility that an AGN may trigger star formation. Both negative and positive feedback modes are then capable of releasing 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 forms stars, but it also reduces 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. 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 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 [41]. The creation and growth of active galactic nuclei are significantly influenced by their surrounding environment. The surrounding gas and dust are thought to control how much matter falls onto the supermassive black hole. Accretion disk is the structure created by gas and dust falling into the center supermassive black hole. Strong gravitational fields and high temperatures within the accretion disk cause massive amounts of radiation to become emitted throughout the electromagnetic spectrum. Strong charged particle jets that accelerate to relativistic speeds are a common feature of AGN. By interacting with the interstellar and intergalactic medium, these jets, which stretch over great distances from the central black hole, significantly influence the environment around them. The interstellar medium (ISM) and AGN jet interaction can have a major effect on the environment.

Jet-ISM interactions produce shock waves that can affect the evolution of the host galaxy by inducing star formation, influencing galactic dynamics, and releasing energy into the ISM. Furthermore, large-scale structures like jets and bubbles may arise as a result of interactions between the AGN and its surroundings, which may have an impact on the nearby galaxies and intergalactic medium. AGN is surrounded by a dynamic, complex environment that is made up of many different physical processes and interactions[40].

3.3 The Effects of Active Galactic Nuclei on its Environment

Active galactic nuclei (AGN) are extremely luminous sources of radiation that are powered by accretion onto supermassive black holes at the centers of galaxies. The intense gravitational forces of these black holes lead to the release of enormous amounts of energy, which can be observed as radiation across the electromagnetic spectrum. This energy can have a profound effect on the surrounding environment of the AGN and powerful radiation emitted by AGN can ionize the gas, stripping away electrons and creating a region of ionized gas known as a "bubble" or "radio galaxies". These bubbles can expand outward from the AGN, disrupting the gas distribution and potentially affecting the formation of new stars. This process can also heat the intergalactic medium, which affects the large-scale structure of the universe.

3.3.1 Host Galaxies of AGN and Interstellar Dust

Active Galactic Nuclei (AGN) are known to have a significant impact on the properties of their host galaxies. Host galaxy is a preferred kind of galaxy type in which a supermassive black hole accreting matter. 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 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 is 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 observational 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[1].

At the same time, the AGN can also prevent further mass accretion. If the black hole accretes close to the Eddington limit, the radiation pressure can drive the gas outwards and thus prevent further growth. This leads to an interesting self regulating mechanism: if gas is abundant in the vicinity of the AGN core, the enhanced emission that results will drive that gas out from its immediate surroundings. This will occur through winds and jets as well as radiation. In fact, photons can heat the gas by photo ionization, that is, by ejecting one or more electrons from atoms. Simulations show that the interstellar medium can be heated up to $10^6 K$ by the AGN activity through photo ionization and Compton heating [45].

Jets can also 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 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 a consequence of winds, the gas in-flow will slow down, leaving the central engine starving. This will in turn reduce the driving pressure of the AGN on its environment. As discussed in the previous subsection, the AGN might not only influence the accretion flow onto itself, it can also steer the growth of the bulge in which it resides. This type of feedback might thus cause the firm link between the black hole mass and the velocity dispersion in the bulge and be responsible for the MBH_{σ} relation [4].

3.3.2 Interstellar Dust

Galactic interstellar dust, consisting of minute solid particles, is a vital element of the universe. Despite its small scale, it serves a pivotal function in the creation of stars by offering platforms for atoms to merge and create dense clouds, which later implode to give rise to fresh stars. An intriguing occurrence in outer space or that has descended to our planet is known as interstellar dust, also commonly referred to as star dust, extraterrestrial dust, or space dust. It is composed of tiny solid particles typically measuring 0.1 mm (100μm) in diameter and varying in size from a few molecules [5],[13].

Various compositions of compounds, including oxygen, carbon, iron, silicon, and magnesium, can be found within it. These elements originate from dying stars that undergo either "burn out" or intense explosions towards the conclusion of their lifespan, resulting in the dispersion of dust particles into space.

Figure 3.2: Interstellar Dust [from U.S National science Foundation: March,9,2016]

Despite comprising only 1 percent of the interstellar medium, dust can significantly impact astronomical observations. Its ability to scatter and absorb visible light from distant celestial objects such as stars and galaxies has earned it a negative reputation. Consequently, optical telescopes face challenges or even impossibility in observing these objects. Dust's scattering effect, known as "reddening," causes it to scatter blue light from an object, resulting in a redder appearance. This phenomenon occurs because dust has a stronger impact on shorter wavelength light, such as blue. A similar effect is responsible for the red appearance of sunsets.

3.4 Jets from AGN and Interstellar Dust Interaction with the Jets

3.4.1 Jets from AGN

AGN jets are formed when the supermassive black hole rotates and the surrounding accretion disk becomes magnetized. This magnetization can occur when gas accumulates at high latitudes outside the black hole's sphere of influence [30]. Relativistic jets in AGN are narrow plasma outflows. About 10 percent of AGN are radio-loud and display powerful relativistic jets [38], which are concentrated streams of non-thermal plasma that often extend beyond the host galaxy. These jets are initially generated by strong magnetic fields that are amplified by the rotating black hole and the inner region of the accretion flows [14].

These jets consist of narrow beams of highly energetic particles that emerge at nearly the speed of light and are expelled outward in opposite directions from the disk. They serve as a means of transporting immense amounts of power away from the central region. As a result, the potential energy and rotational energy of the center of the supermassive black hole (SMBH) act as the primary power source for these jets. Subsequently, two shocks are formed: one moves outward into the interstellar gas, while the other moves backward into the jet, decelerating its speed. The high-energy particles within the active galactic nucleus (AGN) jets are extremely relativistic, as they travel at speeds approaching that of light. Moreover, they possess extraordinary levels of energy, with luminosities that can surpass those of their host galaxies by orders of magnitude.

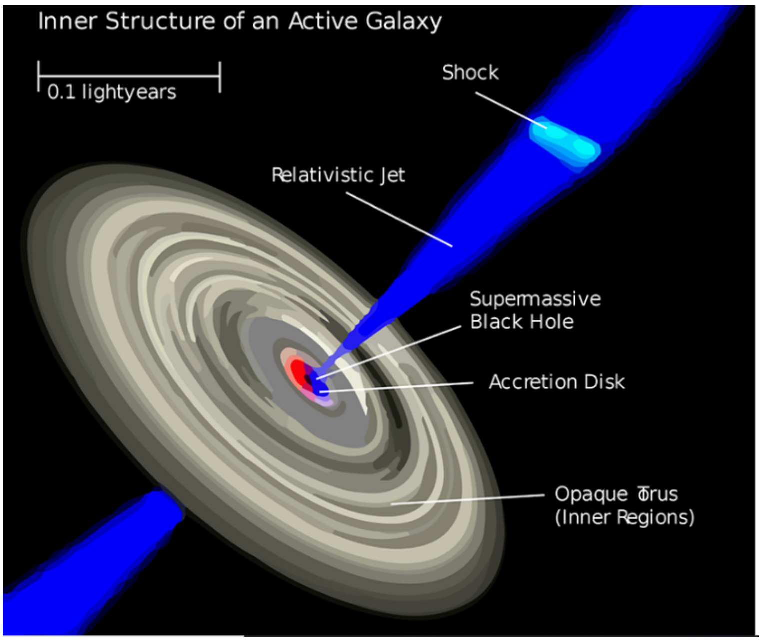


Figure 3.3: Jets from AGN [from Space and Astronomy News]

AGN jets have the ability to emit radio waves with great power. These jets can impact the interstellar medium (ISM) by compressing and shocking it, resulting in areas of increased density. These denser regions have the potential to trigger the formation of stars and play a crucial role in the evolution of galaxies. The interactions between AGN jets and the ISM affect gas dynamics, as well as heating and cooling processes. Through the regulation of star formation, AGN jets offer feedback that influences the structure and population of galaxies as a whole. It is important to note that jets do not travel through empty space, but rather through an ISM that is typically denser than the plasma within the jet. The first documented sighting of a jet was in 1918 in the elliptical galaxy M87.

Active Galactic Nuclei (AGN) jets interacting with interstellar dust present an intriguing field of research in astrophysics. These jets, composed of charged particles emitted by supermassive black holes at the cores of galaxies, can have a substantial impact on their surrounding environments. When these jets come into contact with the interstellar medium (ISM), which encompasses interstellar dust, they can trigger both positive and negative feedback mechanisms. These interactions may result in the inhibition or suppression of star formation in massive galaxies (negative feedback) or contribute to the relationship between the central black hole masses and the galactic spheroid mass or velocity dispersion (positive feedback) [9]. Furthermore, observations conducted by the James Webb Space Telescope (JWST) on NGC 7319 have unveiled how a low-power jet from an AGN can engage with the molecular material within the galaxy's disk. This interaction leads to the deceleration of the jet and introduces asymmetry in its length, as indicated by heightened emission from warm and hot molecular hydrogen (H2) at the point where the jet axis intersects with dust lanes in the disk [28]. AGN jets are influenced by interstellar dust. These jets, which are potent streams of charged particles emitted by supermassive black holes at the cores of galaxies, can interact with the interstellar medium (ISM), including dust, in various manners.

Collimation and Propagation: The jets may show signs of engaging with a clumpy ISM, particularly in early radio sources. This engagement could impact the focusing and spread of jets from the central sub-pc to hundreds of kpc distances. AGN feedback encompasses the impacts of jets, outflows, cosmic rays, and radiation on the parent galaxy and its ISM. The interaction with interstellar dust has the potential to either stimulate or inhibit star formation, contingent upon the prevailing physical circumstances.

Jet Recollimation: AGN jets, upon collision with the ISM, may undergo a process of recollimation. This phenomenon can lead to the formation of inner shocks, causing deceleration and enabling the blending of surrounding matter, such as dust particles

[37]. The confinement and shock of the surrounding environment, which includes interstellar dust, is made possible by the launch of extremely fast jets by AGN. This process plays a crucial role in controlling the formation of stars within the galaxy[9].

3.4.2 Amount of Jets Released from AGN

The origin of the energy released in jets from active galactic nuclei (AGNs) is thought to be the result of gas falling towards a supermassive black hole located at the center of the AGN. These jets are then channeled and constrained by powerful electromagnetic fields, forming focused beams [34]. They are propelled from magnetized accretion disks surrounding black holes. The relationship between the jet-disk connection in the universal model is proportional to the mass of the black hole. The total power radiated by the disk (including both sides) is given by:

$$E_{accr} = -\frac{1}{2}\frac{GM\dot{M}}{r_0} \tag{3.1}$$

Where (G) is gravitational constant, (M) is the mass of central object(AGN) $\dot{M}$ is the mass of an accretion disk rate and r is the radial distance from the central object. For jets radiative from AGN we use Eq.3.1 from total energy radiated accretion disk model [20].

4

Radiative Transfer

4.1 Classical Radiative Transfer

The scientific field that studies the transfer of energy in the form of electromagnetic radiation is referred to as radiation transfer or radiation transport. It focuses on the transmission of light through different substances. The way radiation propagates through a medium is influenced by processes such as absorption, emission, and scattering. One significant method of energy transfer between the layers of the atmosphere and the underlying surface is through radiation. The classical equation of radiative transfer describes the balance of energy transport in absorbing, emitting, and scattering media with a uniform distribution of refractive index [44].

4.1.1 Radiative Energy Density and RTE

To quantify the amount of energy being transferred in radiative transfer, one can consider the spectral radiance. Radiative energy transport in accretion disks can be understood through the Radiative Transfer Equation (RTE). The RTE describes how radiation propagates through a medium, accounting for absorption, emission, and scattering processes. In the context of accretion disks, the RTE helps elucidate how energy generated within the disk is transported outward through radiation. AGN Jets - it emit radiation like a black body; the black body radiation with surface it's temperature T is given by:

$$B_v(T) \approx \frac{2hv^3}{c^2}\frac{1}{e^{hv/k_BT}} \tag{4.1}$$

This is known as the **Planck function**. Spectral radiance is the quantity of energy emitted per unit solid angle $u_v(\Omega)$, which is equivalent to 4.2 with dV representing a volume element. In order to calculate this, it is helpful to initially examine the energy density per unit solid angle.

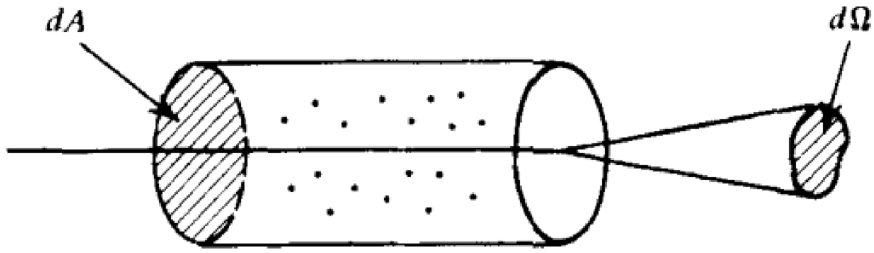


Figure 4.1: Ray passing through a medium of absorbers. [from [32],page 10]

$$dE = u_v(\Omega)dVd\Omega dv \tag{4.2}$$

By considering Spectral radiance is the quantity of energy emitted per unit solid angle $u_v(\Omega)$, which is equivalent to 4.2 with dV representing a volume element. In order to calculate this, it is helpful to initially examine the energy density per unit solid angle inside a cylinder about a ray of length denoted by 'ct', since the dV of the cylinder is $dAcdt$.

$$dE = u_v(\Omega)dAcdtd\Omega dv \tag{4.3}$$

This parameter helps describe how energy propagates through electromagnetic radiation in a given medium. Radiation travels at velocity c, so that in time dt all the radiation will pass out of it:

$$dE = I_v dAdtd\Omega dv \tag{4.4}$$

Equating the above eq.4.3 and 4.4 expressions yields

$$u_v\Omega = \frac{I_v}{c} \tag{4.5}$$

Integrating over all solid angles

$$u_v = \int u_v(\Omega) d\Omega$$
$$= \frac{1}{c} \int I_v d\Omega \quad (4.6)$$

or

$$u_v = \frac{4\pi}{c} J_v \quad (4.7)$$

where we have defined the mean intensity J_v:

$$J_v = \frac{1}{4\pi} \int I_v d\Omega \quad (4.8)$$

The total radiation density $(ergcm^{-3})$ is simply obtained by integrating u_v, over all frequencies

$$u = \int u_v dv$$
$$= \frac{4\pi}{c} \int J_v dv \quad (4.9)$$

A formal solution to the complete radiative transfer equation will be given shortly. Here, we can give solutions to two simple limiting cases:

Emission Only: The spontaneous emission coefficient j is defined as energy per unit time per unit solid angle and per unit volume

$$dE = jdVd\Omega dt \quad (4.10)$$

A monochromatic emission coefficient can be similarly defined so that

$$dE = j_v dVd\Omega dtdv \quad (4.11)$$

where j, has units of $ergcm^{-3}s^{-1}ster^{-1}Hz^{-1}$. In general, the emission coefficient depends on the direction into which emission takes place.

$$\frac{dI_v}{ds} = j_v \tag{4.12}$$

$$I_v(s) = I_v(s_0) + \int_{s_0}^{s} j_v(s\prime)ds\prime \tag{4.13}$$

The increase in brightness is equal to the emission coefficient integrated along the line of sight.

Absorption : We define the absorption coefficient, $\alpha(cm^{-1})$ by the following equation, representing the loss of intensity in a beam as it travels a distance ds (by convention, α, positive for energy taken out of beam):

$$\frac{dI_v}{ds} = -\alpha_v I_v \tag{4.14}$$

$$I_v(s) = -I_v(s_0)exp\left(-\int_{s_0}^{s} \alpha_v(s\prime)ds\prime\right) \tag{4.15}$$

This phenomenological law can be understood in terms of a microscopic model in which particles with density n (number per unit volume) each present an effective absorbing area, or cross section, of magnitude $\sigma(cm^2)$. These absorbents are assumed to be distributed at random. Let us consider the effect of these absorbents on radiation through dA within solid angle $d\Omega$ (see fig.**??**). The number of absorbents in the element equals ndA . The total absorbing area presented by absorbents equals $n\sigma$, dA ds. The energy absorbed out of the beam is

$$-dIdAd\Omega dtdv = -I_v(n\sigma_v dAds)d\Omega dtdv \tag{4.16}$$

thus

$$dI_v = -n\sigma_v I_v ds \tag{4.17}$$

$$\alpha_v = n\sigma_v = \rho\kappa_v \tag{4.18}$$

In the presence of emission and absorption, the radiative transfer equation can be expressed as

$$\frac{dI_v}{ds} = j_v - \alpha_v I_v \tag{4.19}$$

$$I_v(s) = I_v(s_0) + \int_{s_0}^{s} j_v(s\prime)ds\prime$$

$$-I_v(s_0)exp\left(-\int_{s_0}^{s} \alpha_v(s\prime)ds\prime\right) \tag{4.20}$$

4.2 Optical Depth and Source Function

The transfer equation takes a particularly simple form if, instead of s, we use another variable τ_v, called the optical depth, defined by

$$d\tau_v = \alpha_v(s)ds \tag{4.21}$$

$$\tau(s) = \int_{s_0}^{s} \alpha_v(s)ds \tag{4.22}$$

The optical depth defined above is measured along the path of a traveling ray; occasionally, τ_v is measured backward along the ray. A medium is said to be optically thick or opaque when τ_v, integrated along a typical path through the medium, satisfies $\tau_v > 1$. When $\tau_v < 1$, the medium is said to be optically thin or transparent. Essentially, an optically thin medium is one in which the typical photon of frequency v can traverse the medium without being absorbed, whereas an optically thick medium is one in which the average photon of frequency v cannot traverse the entire medium without being absorbed. By equating Eqs. 4.19 and 4.22

$$\frac{dI_v}{d\tau_v} = I_v + S_v \tag{4.23}$$

Where

$$S_v = \frac{j_v}{\alpha_v}$$

S_v is the source of function. By integrating eq.4.20 we obtain

$$I_v = I_v(s_0)e^{-s,0} + \int_{s_0}^{s} S_v(s\prime)e^{\tau(s,s\prime)}ds$$

$$= I_v(0)e^{-s,0} + \int_{s_0}^{s} S_v(s\prime)e^{\tau(s,s\prime)}ds \tag{4.24}$$

where the constant $I_v(s0)(= I_v(0))$ is the initial value of the specific intensity. While optical depth, which is a scalar quantity, is invariant under Lorentz transformations, the radiative transfer equations in the conventional form equation 4.19 and 4.22 $\tau(s, s\prime)$ optical thickness at the point of s and $s\prime$. Where is constant I_v is the initial value of the specific intensity and also the background radiation, coming through the medium and decaying exponentially in the medium. The second term gives the emission in the medium. The physical meaning of the solution eq.4.42 is clear; It expresses the fact that the intensity at any point and in a given direction results from the emission at all anterior points, $s\prime$, reduced by the factor $e^{\tau(s,s\prime)}$ to allow for absorption by the intervening matter.

In radiative transfer, we're concerned with how radiation (such as light or heat) interacts with a medium. The movement of photons isn't trivial because they can be absorbed or scattered by the medium. One key parameter is the **extinction coefficient** (also known as **opacity**), denoted by α_v , which quantifies the efficiency of a medium in absorbing radiation. Its unit is cm^{-1}.

Mean Free Path Interpreting the exponential in(39) (which equals e^{τ_v}) as the probability of traveling an optical depth τ_v, the mean optical depth traveled

$$< \tau_v >= \int_0^\infty \tau_v e^{-\tau_v} d\tau_v = 1 \tag{4.25}$$

The mean physical distance traveled in a homogeneous medium is defined as the mean free path I_v and determined by $< \tau_v >= \alpha_v I_v = 1$. The associated mean free path is:

$$I_v = \frac{1}{\alpha_v} = \frac{1}{n\sigma_v} \tag{4.26}$$

This quantity represents the average distance a photon travels before being absorbed or scattered. The denser the medium, the smaller the mean free path.

4.2.1 Thermal Radiation

To investigate thermal radiation, it is necessary to consider first of all black body radiation, radiation which is itself in thermal equilibrium. In equilibrium, the body emits and absorbs the same amount of radiation, at each frequency. Else, if the body were emitting radiation in some frequency more than it absorbed, the radiation would not in equilibrium and the state of the radiation field would be changing. Thermal radiation is described by second the law of thermodynamics. Because, energy cannot flow without violating the second law.

$$\implies u(T) = aT^4 \tag{4.27}$$

This may be related to the Planck function, since $I_v, = J_v$, for isotropic radiation Eq.4.7.

$$U_v = \frac{4\pi}{c} \int B_v(T) dv = \frac{4\pi}{c} B(T) \tag{4.28}$$

where the integrated Planck function is defined by

$$B(T) = \frac{4\pi}{c} \int B_v(T) dv = \frac{4\pi}{c} B(T) \tag{4.29}$$

We seen Planck function on eq.4.1

$$B_v(T) \approx \frac{2hv^3}{c^2}\frac{1}{e^{hv/k_BT}-1}$$

Based on Planck function two laws are important:

Jeans Light man: For low energy ($hv/K_BT \to 0$ and $e^{hv/k_BT}-1 \approx hv/k_BT$)

$$B_v(T) \approx \frac{2hv^3}{c^2}.k_BT$$

Wen's approximation: For high energy $hv >> K_BT$

$$B_v(T) \approx \frac{2hv^3}{c^2}e^{-hv/k_BT}$$

4.3 Scattering in radiative transfer

Our starting point is the transfer equation including emission and absorption that we derived on eq.**??** or **??** in the last class. Let

$$\frac{dI_v}{ds} = j_v - \alpha_v I_v + \int\int d\Omega' dv' \sigma(v,v')I_v(\Omega') \tag{4.30}$$

Scattering appears in the transfer equation in two forms:

$\Longrightarrow$ Just like the absorption term that represents the decrease in radiation intensity along a ray due to radiation being absorbed or scattered, and

$\Longrightarrow$ There is an extra source term that represents the extra radiation being added in a given direction due to scattering of radiation that was originally going in other directions. Formally, we can write the transfer equation with scattering as

$$\frac{dI_v}{ds} = j_v - [\alpha_v + \sigma_v]\, I_v + \sigma_v \int d\Omega' dv' \sigma(v,v')I_v(\Omega') \tag{4.31}$$

Given sufficient symmetry, the above equation can be reduced to a one-dimensional form. This occurs in the plane-parallel case, where the radiation field only depends on the z coordinate. It is common to calculate angular moments of the intensity in terms of $\mu = \cos\theta$, where θ is the angle between the ray and the z - direction. The Eddington approximation is most easily illustrated in the plane-parallel case. By assuming that the intensity may be written as a series of increasing powers in μ, the intensity may be expanded as

$$I_v(\mu, z) = \sum_{n=0}^{N} a_n(z)\mu^n \tag{4.32}$$

where a_n are coefficients in the expansion and N is the maximum order of the moment expansion. The i^{th} radiative moment (M_i) of the radiation field may now be written as

$$M_i = \frac{1}{2}\int_{-1}^{1} d\mu I_v(\mu, z)\mu^i \tag{4.33}$$

It follows that i.e. the Eddington approximation. In local thermodynamic equilibrium (LTE) the radiative transfer equation in an isotropic scattering medium reads

$$\mu\frac{dI_v}{dz} = -\alpha_v\left(I_v - B_v\right) + \sigma_v\left(J_v - I_v\right) \tag{4.34}$$

Where B_v is the black body emissivity, μ is the cosine of the angle between the direction of propagation of the radiation and the normal to the surface through wich the radiation is passing and also we have used the fact that$j_v = \alpha_v B_v(T)$ for a medium in thermal equilibrium. The first term represents emission and absorption, while the second represents scattering. If is convenient to rewrite this in terms of the source function.

$$S_v = \frac{\alpha_v B_v + \sigma_v J_v}{\alpha_v + \sigma_v} \tag{4.35}$$

So that the transfer equation become:

$$\mu\frac{dI_v}{dz} = \left(\alpha_v + \sigma_v\right)\left(S_v - I_v\right) \tag{4.36}$$

Where S_v contains a contribution from both thermal emission and scattering. The quantity $(\alpha_v + \sigma_v)$ is called the extinction coefficient, and its inverse is the photon mean free path. However, we have both scattering and absorption in this medium. We consider monochromatic radiation, for single scatter photon(beam):

$$\epsilon_v = \frac{\alpha_v}{\alpha_v + \sigma_v} \tag{4.37}$$

The quantity $1 - \epsilon_v$, the probability that the end of each step of the random walk is a scatter rather than an absorption, as the single scattering albedo. Written in terms of this quantity, the source function is

$$S_v = (I_v - \epsilon_v) + \epsilon_v B_v \tag{4.38}$$

For scattering we use **Rayleigh scattering:**

$$I_s = \left(1 + \left(1 + \frac{\cos^2\theta}{2R^2}\right)\right)\left(\frac{2\pi}{\lambda}\right)^4\left(\frac{n^2-1}{n+2}\right)^2 V \tag{4.39}$$

Where n is the refractive index, r is radius λ is wavelength and R is the distance to the particle and θ is the scattering angle.

4.3.1 Eddington approximation

The method used in radiative transfer to simplify the equation by assuming the radiation field is isotropic up to the second momentum. The mean intensity (J) is then related to the source function (S) by the following equation: By apply the Eddington approximation on the equation of radiative transfer, we gate:

$$\begin{aligned} \frac{1}{3}\frac{d^2 J_v}{d\tau_v^2} &= \frac{\partial H}{\partial \tau} \\ &= J - S \end{aligned} \tag{4.40}$$

For out ward radiation4.40

$$I^+ = J - \frac{1}{\sqrt{3}}\frac{\partial J}{\partial \tau} \tag{4.41}$$

4.4 General Relativistic Radiative Transfer

The absorption and emission properties of the medium from point to point must be known, and the whole method must be performed in a covariant manner, given that spacetime is curved. The developed classical radiative transfer equations are not covariant. The fundamental ideas based on particle conservation in phase space can be used to derive the general covariant radiative transfer equation. The particle number density in the phase volume element is given by the formula:

$$dN = f(\overrightarrow{x}, \overrightarrow{p})dxdyd_zdp_xdp_ydp_z \tag{4.42}$$

is an invariant quantity along the affine parameter λ; This equation defines the number of particles in a phase space volume equal to

$$dV = dxdydzdp_xdp_ydp_z \tag{4.43}$$

Louisville's theorem - ensures that the phase space volume remains constant along the trajectories of a system. This means that as a system evolves through phase space, the volume occupied by the system's points in that space does not change over time; this means the phase space volume is invariant along parameter λ, in order that:

$$\frac{dV}{d\lambda} = 0 \tag{4.44}$$

Where the sixth dimensional phase space volume element dV is given by eq.4.43[22]. For relativistic particles, E = | P | and $d^3 = E^2dEd\Omega$. The volume element of a bundle of relativistic particles is also given by $d^3\overrightarrow{x} = dAdt$ where dA is the area element of the bundle and Ω is the spherical solid angle[42],[32]. Thus, the phase space density of a bundle of relativistic particles may be expressed as

$$f(\overrightarrow{x}, \overrightarrow{p}) = \frac{dN}{E^2dAdtdEd\Omega} \tag{4.45}$$

The specific intensity of a ray (bundle and photons) is simple:

$$I_E = \frac{EdN}{dAdtdEd\Omega} \tag{4.46}$$

According to [7], it's follow

$$I = \frac{I_v}{v^3} = \frac{I_E}{E^3} \tag{4.47}$$

is a Lorentz invariant quantity. We denote I as the Lorentz invariant intensity, and it can also be regarded as the occupation number of particles in the phase space for a particle bundle. We may also obtain the corresponding Lorentz-invariant

$$x = v\alpha_v \tag{4.48}$$

$$\eta = j_v/V^2 \tag{4.49}$$

absorption coefficient and the Lorentz-invariant emission coefficient respectively. These two coefficients, as seen by the observer, are related to their counterparts in the local rest frame of the medium via

$$v\alpha_v = v_0\alpha_{0,v} \tag{4.50}$$

$$j_v/V^2 = j_{0,v}/V^2 \tag{4.51}$$

respectively, where the subscript "0" denotes variables measured in the local rest frame. For a mass-less relativistic particle(photons)

$$K_\alpha K^\alpha = 0 \tag{4.52}$$

WhereK_α is the (covariant) 4-momentum. Consider a photon propagating in a fluid with 4-velocity u^β. 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, i.e.

$$\begin{aligned} v^{\beta} &= P^{\alpha\beta} K_{\alpha} \\ &= K^{\alpha}(K_{\alpha} u^{\alpha}) u^{\beta} \end{aligned} \tag{4.53}$$

Where, $P^{\alpha\beta} = g^{\alpha\beta} + u^{\alpha}u^{\beta}$ 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.

$$\frac{E_0}{E} = \frac{v_0}{v} = \frac{K_{\alpha} u^{\alpha} \mid \lambda_{obs}}{K_{\beta} u^{\beta} \mid_{\infty}} \tag{4.54}$$

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

$$\begin{aligned} \frac{ds}{d\lambda} &= - \parallel v^{\beta} \parallel \lambda_{obs} \\ &= -\sqrt{g_{\alpha\beta}(K^{\alpha} + (K_{\beta}u^{\beta})u^{\alpha})(K^{\beta} + (K_{\alpha}u^{\alpha})u^{\beta})} \mid \lambda_{obs} \\ &= -\sqrt{K_{\beta}K^{\beta} + (K_{\alpha}u^{\alpha})^2 u_{\beta}u^{\beta} + 2(K_{\alpha}u^{\alpha})^2} \mid \lambda_{obs} \\ &= -K_{\alpha}u^{\alpha} | \lambda_{obs} \end{aligned} \tag{4.55}$$

where the minus sign arises from the metric signature adopted, and the fact that the convention that the photon energy must be positive is such that

$$\frac{ds}{d\lambda} = 1 \tag{4.56}$$

in the co- moving frame. For a stationary observer located at infinity

$$K_{\beta} u^{\beta} = -E\lambda_{obs} \tag{4.57}$$

The relative energy shift of the photon between the observer's frame and the co moving frame is therefore

$$\frac{v_0}{v} = \frac{K_{\alpha} u^{\alpha} \mid \lambda}{E_{obs}} = \frac{K_{\alpha} u^{\alpha} \mid \lambda}{K_{\beta} u^{\beta} \mid \lambda_{obs}} \tag{4.58}$$

Making use of the Lorenz invariant proprieties of the variable I, χ and η, and of the optical depth τ_v, the radiative transfer equation may be rewritten in the following form

$$\frac{dI}{d\tau_v} = -I + \frac{\eta}{\chi} = -I + S \tag{4.59}$$

Where $S = \frac{\eta}{\chi}$ is the Lorenz invariant source function. All quantities in eq.4.59 are Lorenz invariant and hence the equation is covariant. As 4.23, it follows that

$$\frac{dI}{dS} = -\alpha_v I + \frac{j_v}{v^3} \tag{4.60}$$

It follows that

$$\frac{dI}{d\lambda} = -\kappa_\alpha u^\alpha \mid_\lambda \left(-\alpha_v I + \frac{j_v}{v^3} \right) \tag{4.61}$$

where,$\alpha_{0,v} = \alpha_0(x^\beta, v)$ and $j_{0,v} = j_0(x^\beta, v)$, where, as before, "0" denotes variables that are evaluated in the local fluid rest frame, for a given v. Eq. 4.60 and 4.61 are radiative transfer equations for mass less particles. For particles with a non-zero mass m such as neutrinos or relativistic electrons;

$$P_\alpha P^\alpha = -m \tag{4.62}$$

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

$$\begin{aligned} \frac{dS}{d\lambda} &= -\sqrt{g_{\alpha\beta}(P^\alpha + (P_\beta u^\beta) u^\alpha (P_\alpha u^\alpha) u^\beta)}|_{\lambda_{obs}} \\ &= \sqrt{(P_\alpha u^\alpha)^2 - m^2}|_{\lambda_{obs}} \end{aligned} \tag{4.63}$$

and equation inserted into eq.4.59, which does not depend on the particle mass explicitly. After some algebra, the general covariant transfer equation for relativistic particles is obtained as

$$\frac{dI}{d\lambda} = -\sqrt{1 - \left(\frac{m}{P_\beta u^\beta}|_{\lambda_{obs}}\right)} P_\alpha u^\alpha \mid_\lambda \left(-\alpha_{(0,v)} I + \frac{j_{(0,v)}}{v^3}\right) \tag{4.64}$$

For a stationary observer located at infinity,

$$P_\beta u^\beta = -E$$

Eq.4.64 differs from eq.4.61 by an aberration factor $\sqrt{1 - (\frac{m}{E})^2}$.This factor reduces the intensity gradient along the ray. Because it approaches unity when $m \to 0$, the radiative transfer equation 4.61 is the radiative transfer equation 4.64 in the zero-mass limit.As equation 4.64 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 [43]. Interstellar dust can significantly affect the radiative transfer process in space. Dust particles can absorb and scatter radiation, leading to changes in its intensity and direction. The presence of dust alters both the extinction and emission coefficients in the radiative transfer equation.

5

Result and Discussion

In this chapter, we present the main results of our work on jets outflows from AGN and their mutual interactions with surrounding dusts. First, we provide the key model equations used in our work, particularly in the absorption, scattering, and emission processes. Then, we address our numerical results in the form of plots, where we used the latest Python 3 for the numerical data synthesis.

5.1 Jets from AGN and Its Interaction with Interstellar Dust

As addressed in chapter 3, section 3.4, the source of the jet emission is supermassive black hole at the center of an active galactic nucleus (AGN) that emanates from the accretion disk. It is related to the structure of the magnetic field, a dipole one, where jets are being streamed outwards along the poles. The total amount of energy radiated by the jets is derived from eq. 3.1 and is given as:

$$E_{accr} = -\frac{1}{2}\frac{G\dot{M}M_{AGN}}{r_0} \tag{5.1}$$

5.2 Effect of Dust on Jets Emitted from AGN

The presence of dust along the path of these jets can significantly affect their propagation and observational characteristics. Then, we address the extinction effect of dust on the AGN jet using the general relativistic radiative transfer equation (RTE) eq.5.1. Additionally, we compare general relativistic and classical radiative transfers.

$$\begin{aligned} \frac{dI}{d\tau} &= -I + \frac{j_i}{\alpha_v} \\ &= -I + \frac{\eta}{\chi} \\ &= -I + S \end{aligned} \tag{5.2}$$

Considering the equation (5.2), within the framework of the Eddington approximation for radiative transfer, we can express the boundary conditions that account for the absorption effect of interstellar dust. These conditions are essential for solving the second-order differential equation arising from the Eddington approximation. The overall form of the radiative transfer equation, denoted by (4.41), under the Eddington approximation is as follows:

$$\frac{d^2 J_v}{d\tau_v^2} = 3\epsilon_v \left(J_v - B_v\right) \tag{5.3}$$

The provided radiative transfer equation can be expressed in exponential form. To simplify, we introduce the symbol $x = J_v - B_v$. Consequently, the equation transforms as follows:

$$\frac{d^2 J_v}{d\tau_v^2} = 3\epsilon_v x \tag{5.4}$$

Given an assumption that the solution takes the form $x = e^{rt}$, we proceed to solve for (r), which represents a constant.

$$\frac{d^2 J_v}{d\tau_v^2} = r^2 e^{rt} \tag{5.5}$$

By equating eq.5.4and 5.5 we gate:

$$3\epsilon_v x = r^2 e^{rt} \tag{5.6}$$

$\implies r = \pm\sqrt{3\epsilon_v}$ (since,re^{rt} is never zero.) Hence, the general solution for (x) can be expressed as a linear combination of these two solutions.

$$\begin{aligned} x &= A_1 e^{\sqrt{3\epsilon_v}\tau_v} + A_2 e^{-\sqrt{3\epsilon_v}\tau_v} \\ &= J_v - B_v \end{aligned} \tag{5.7}$$

$$\begin{aligned} \frac{d^2 J_v}{d\tau_v^2} &= 3\epsilon_v x \\ &= 3\epsilon_v \left(A_1 e^{\sqrt{3\epsilon_v}\tau_v} + A_2 e^{-\sqrt{3\epsilon_v}\tau_v}\right) \end{aligned} \tag{5.8}$$

A_1 and A_2 are constants.

5.2.1 Radiative Transfer with Rayleigh scattering

We investigate the effects of dust absorption on jets emitted by Active Galactic Nuclei (AGN) using the radiative transfer equation, which incorporates Rayleigh scattering. Our analysis considers how the jets' radiation behavior changes as they traverse through the dust, accounting for relevant boundary conditions.We use eqs. 4.14, 4.13, and 4.39.

$$\frac{dI_v}{ds} = \alpha_v I_v + j_v - \left(1 + \left(1 + \frac{\cos^2\theta}{2R^2}\right)\right)\left(\frac{2\pi}{\lambda}\right)^4 \left(\frac{n^2-1}{n+2}\right)^2 V \tag{5.9}$$

or

$$\frac{dI_v}{ds} = \epsilon_v \left(A_1 e^{\sqrt{3\epsilon_v}\tau_v} + A_2 e^{-\sqrt{3\epsilon_v}\tau_v}\right) - \left(1 + \left(1 + \frac{\cos^2\theta}{2R^2}\right)\right)\left(\frac{2\pi}{\lambda}\right)^4 \left(\frac{n^2-1}{n+2}\right)^2 V \tag{5.10}$$

Boundary Condition:

Case 1, s = 0

Taking into account the initial radiation intensity and spectral distribution at the jet's base, where the AGN is the source,

$$\frac{dI_v}{ds} = I_0 \tag{5.11}$$

Where I_0 is the initial intensity, which we relate to the energy radiative from the accretion disk in the opposite direction at the center of the AGN. The equation for the radiation of jets at the origin comes to:

$$\frac{dI_v}{ds} = \frac{G\dot{M}M_{AGN}}{2r_0} \tag{5.12}$$

Case 2, $s \to \infty$

• When optical depth increases, the number of jets passing through dust decreases because of the absorption effect of interstellar dust.

• Then, radiation intensity should approach zero as it escapes into space and the influence of the medium decreases.

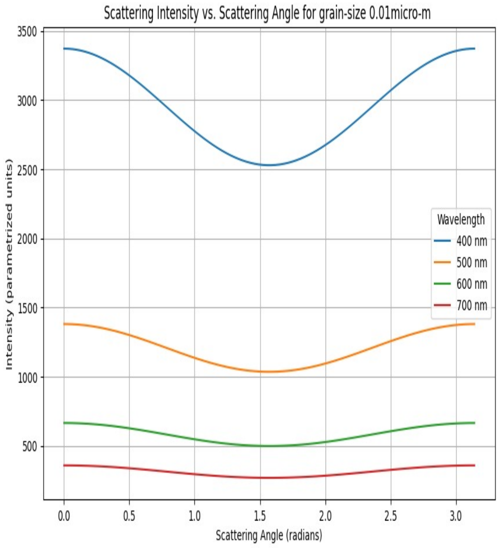
The boundary condition at a large depth is:

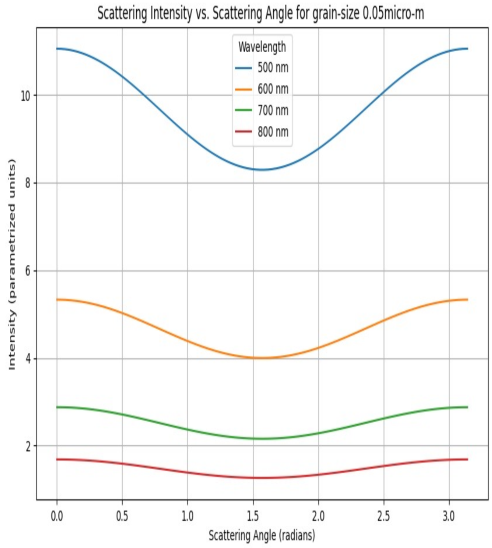
$$\frac{dI_v}{ds} = \to 0 \tag{5.13}$$

To solve the differential equation for radiative transfer using Eddington approximation and Rayleigh scattering with boundary conditions at $s = 0$ and $s \to \infty$, we use numerical methods like finite differences in Python software. Based on the above two conditions for the interaction between radiation and dust particles, we consider scatter and absorption.

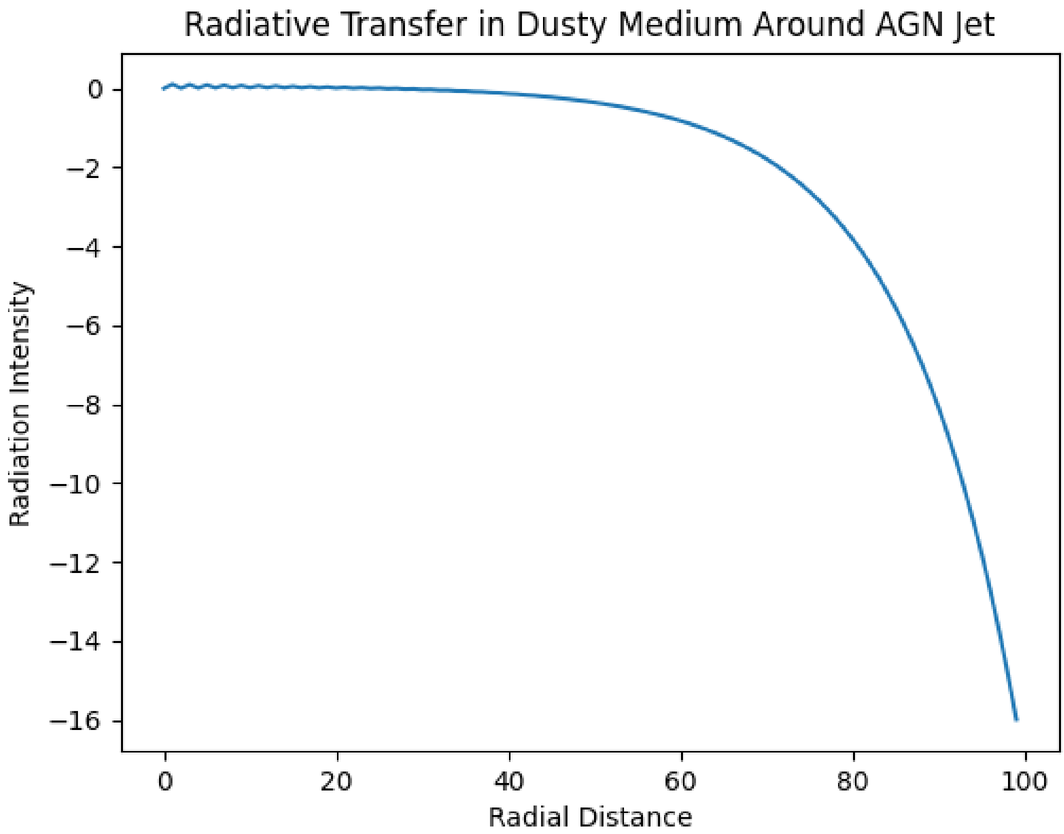
For scattered radiation based on dust grains:

$$\frac{dI_v}{ds} = \left(1 + \left(1 + \frac{\cos^2\theta}{2R^2}\right)\right)\left(\frac{2\pi}{\lambda}\right)^4\left(\frac{n^2-1}{n+2}\right)^2 V \tag{5.14}$$





→ From the left graph, we see a small dust grain size, but the intensity is high.
→ From the right graph, it has a large dust grain size, but the intensity is very low when we compare it with the left graph.
→ Generally, from the above plot, we understand that the radiation of jets is high at small dust grains.
Depending on the interstellar dust interaction with jets emitted from AGN, we consider the extinction effect of dust on AGN jets.



The relationship between radiation intensity I_v and radial distance for a jet released from an Active Galactic Nucleus (AGN) is represented by the plotted graph. According to the graph:

Optical Depth (Radial Distance): The optical depth of the medium that radiation is traveling through is represented by this axis. It rises to higher values from a minimum starting point.

Radiative Intensity I_v: This axis shows the radiation's particular intensity at various optical depths or radial distance. As radial distance increases, it begins at a maximum value and declines inversely.

The graph shows that the particular intensity I_v drops in an inverse relationship with increasing optical depth or radial distance. This pattern fits nicely with our first idea that radiation attenuates with the increasing optical depth of the medium it passes through.

In summary, the graph shows how, for a jet emanating from an AGN, specific intensity varies with optical depth in the case of the dust effect.

6

Summary and Conclusion

The extinction effect on jets emitted from galactic nuclei demonstrates that interstellar dust significantly affects the characteristics of jets that arise from galactic nuclei. A detailed investigation and simulation demonstrate that dust extinction modifies the polarization signatures, intensity profiles, and spectral properties of these jets. The importance of accounting for interstellar dust impacts in extra-galactic phenomena involving AGN jets is highlighted by this.

Finally, by examining the effects of interstellar dust on jet emissions at different spatial scales in AGN environments, this study illuminates a yet-studied facet of AGN physics. Important insights into the complex interaction between dust-rich galactic environments and the energetic mechanisms driving jet production near supermassive black holes have been obtained by theoretical simulations. The results of this thesis lay the groundwork for future research into how interstellar dust shapes cosmic architecture and further our understanding of the astrophysical phenomena linked to AGN activity.

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