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Characteristics of Accreting Sources in the Universe

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SRIVIPRA PROJECT 2024

Title: Characteristics of Accreting Sources in the Universe

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Certificate of Originality

This is to certify that the aforementioned students from Sri Venkateswara College have participated in the summer project SVP-2416 titled "*Characteristics of Accreting Sources in the Universe* ". The participants have carried out the research project work under my guidance and supervision from 1st July, 2024 to 30th September 2024. The work carried out is original and carried out in an online/offline/hybrid mode.

Signature of Mentor

Acknowledgements

We would like to express our heartfelt gratitude to Dr. Main Pal and Dr. Pankaj Kushwaha for their invaluable guidance and support throughout our summer internship, "Characteristics of Accreting Sources in the Universe - Understanding the Power Law Emission: A Theoretical and Simulative Analysis," conducted from 1st July 2024 to 30th September 2024. Under their mentorship, we were able to deepen our understanding of accreting sources and their spectral energy distributions, acquaint ourselves with and perform data modelling for power law emissions, and explore the Gaussian curve.

We had a highly fruitful and engaging time working on the project, with all three of us discussing, collaborating and assisting each other in successfully executing the research work and completing the project.

This experience has been immensely educational and rewarding, and we are grateful for the opportunity to work on this project under such excellent supervision.

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Abstract

Accreting sources, including black holes, neutron stars, and white dwarfs, are among the most energetic objects in the universe, emitting radiation across the electromagnetic spectrum. This report investigates the formation, radiation mechanisms, and emission characteristics of accretion discs surrounding these compact objects. We studied how accretion discs form due to the transfer of mass and angular momentum, radiating energy and applied it in our simulations. The study focuses on the power-law emission observed in high-energy regions, often associated with inverse Compton scattering, and the Gaussian emission lines resulting from atomic transitions within the disc. Understanding the radiation from these sources is crucial for probing high-energy astrophysical processes, testing general relativity in strong gravitational fields, and examining the role of compact objects in galactic evolution. By simulating power-law and Gaussian curves, we highlight the interactions between continuous and discrete emission components, offering insights into the energy distribution and dynamics of accreting systems in the universe.

KEY WORDS- accretion, accretion discs, power law emission, gaussian emission, photon index, active galactic nuclei (AGNs), black holes, spectral energy distribution (SED)

1. Introduction

1.1. Accretion and Accretion Discs

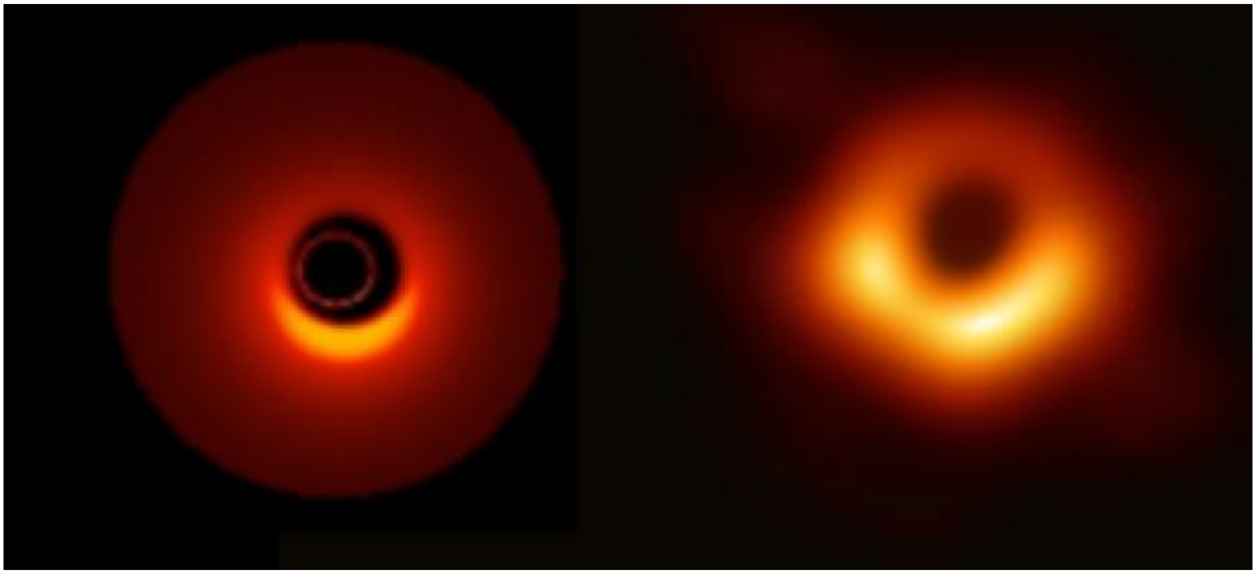


Fig1. First-ever image of a black hole as produced by the Event Horizon Telescope (EHT) captured in 2017 (the super luminous signature observed is that of its accretion disc)

The universe and its ability to amaze humankind has been a story of centuries now. There are certain processes in the universe that have been discussed, researched on and presented many times, processes that have always been the centre of many important findings and continue to still be a mystery for scientists around the globe. **Accretion**, which is one of the fundamental processes in the cosmos, has been one such case. It is a by-product of gravity wherein matter is drawn toward a massive object, typically a compact object like a black hole, neutron star, or white dwarf, due to gravitational attraction. The importance of studying accretion comes from the fact that when matter accretes, it forms objects and thus, accretion and formation are very closely related in astronomy. Apart from this, the extraction of gravitational potential energy from material which accretes onto a gravitating body is now known to be the principal source of power in several types of close binary systems, and is widely believed to provide the power supply in active galactic nuclei and quasars.

As the matter falls to a central object, the conservation of angular momentum forces the accreted matter to form a disc-like structure around it which is referred to as '**Accretion Disc'**. The disc is typically denser and hotter in the inner regions, near the compact object, and cooler and less dense in the outer regions. Friction and viscous forces within the disc cause the material to gradually spiral inward, transferring angular momentum outward and converting gravitational potential energy into heat and radiation.

1.2. Emission and its Importance

The inflowing material dissipates energy via friction and viscosity, ultimately radiating a **significant amount of energy across the electromagnetic spectrum**.
Accretion discs appear in a wide variety of astrophysical environments such as white dwarfs, binary star systems and Active Galactic Nuclei (AGN). Accreting systems are observed to emit copious radiation in the X-ray energy range which suggests emission from the innermost regions of an accretion disc. [X-Ray reflected spectra from accretion disc models]. Studying the radiation from such accreting sources proves of much importance, like offering deep insights into some of the most extreme and fundamental processes in astrophysics, understanding physical characteristics of compact objects and cosmic evolution which are a few pointers in the long list.

1.3. Types and Examples

Some examples of accreting sources are-

1. **Active Galactic Nuclei (AGN)**: Supermassive black holes at the centres of galaxies, accreting matter from their host galaxy. AGN produces powerful X-ray, UV, and radio emissions.
2. **X-ray Binaries**: Systems where a neutron star or black hole accretes matter from a companion star. These systems are known for their strong X-ray emission.
3. **Cataclysmic Variables**: Systems where a white dwarf accretes matter from a low-mass companion, producing optical, UV, and X-ray outbursts.

2. Background and History

2.1. On Accretion and Accretion Discs

The concept of the process of accretion in general - that is **gravitational attraction resulting in an accumulation of particles into a massive object** - was introduced initially as a model for the formation of Earth and other terrestrial planets from meteoric material in *1944* by *Otto Schmidt*. Further developments and theories in the *1960s* expanded on the same, but none of them could achieve complete success and were more descriptive than observational and based on data.

However, *Safronov* in *1969* further developed *Schmidt*'s model quantitatively and further numerical simulations have been applied to the same to study the accumulation. Subsequent research revealed gravitational collapse of interstellar gas as the causative agent for the formation of stars - where the collapse of gas-rich molecular clouds, results in loss of potential energy but the gain of kinetic energy and the conservation of angular momentum results in the cloud forming a flattened accretion disc. *Accretion discs* are structures or phenomena that are observed ubiquitously - be it **gamma ray bursts (GRBs), protoplanetary discs, quasars or active galactic nuclei (AGNs)**. It was as late as in *2003*, when the first observations of the outskirts of a supermassive black hole's accretion disc were made by a team of astronomers using the **Gemini Near-Infrared Spectrograph** (GNIRS).

2.2. Key Models and the Role of Observational Astrophysics

The study of binary star systems, one of the earliest of which was **Hercules X-1** in *1971* proved to be pivotal in terms of identification of accreting sources - where a neutron star accreted material from its companion star, producing periodic X-ray emissions. Works such as these in the *1970s* along with other discoveries such as that of **Cygnus X-1** prompted development of models to describe the process of accretion or "funnelling" of matter into the accretion disc and the gravitational energy of the same matter gets converted into radiation, which can be observed as X-rays in case of compact, highly dense objects of the ilk of black holes and neutron stars.

Shakura and Sunyaev's **alpha-disc model** provided crucial insight into the mechanism behind the inwards spiralling of matter due to the transfer of angular momentum and its consequent heating up, resulting in emission of radiation across various wavelengths on the spectrum.

Pioneering theories and models were supported in parallel with advancements in observational astrophysics - particularly with in-space X-ray observatories like **UHURU** *(1970-1973)*, **CXO** *(Chandra X-Ray Observatory, 1999 - present)* and **XMM-Newton** *(1999 - present).*

These observatories in space paved way to accurate observations of accreting sources at high energies, while radio and infrared observatories have made the study of AGNs possible.

2.3. <u>About Active Galactic Nuclei (AGNs)</u>

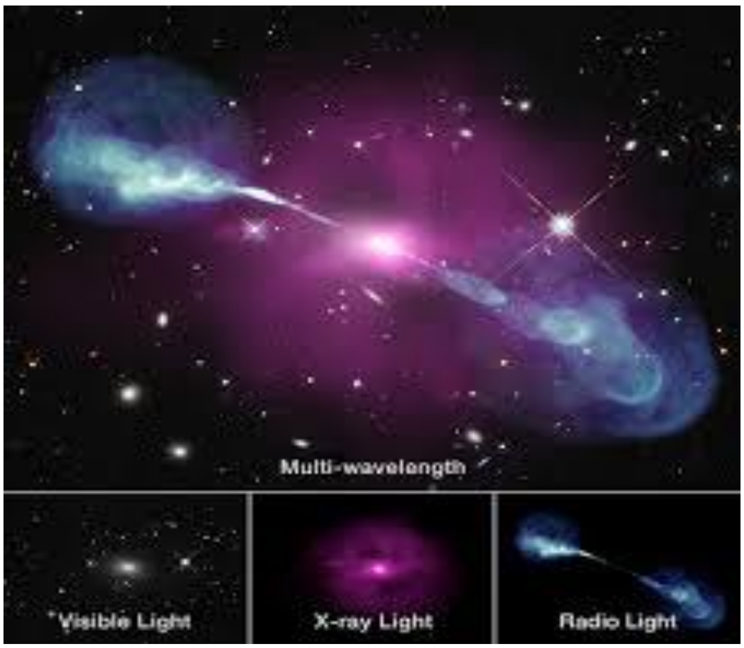


Fig2. Hercules A, with its AGN observed under different spectra

While characteristic signatures of AGN emissions had been detected as early as early-to-mid twentieth century based on photographic observations and subsequent spectroscopic studies that also indicated some aberrational and unusual emission lines in some galactic nuclei, it was the advent of radio astronomy that catalysed an improved understanding of AGNs.

AGNs are compact and highly luminous objects, arguably powered by mass accretion onto massive blackholes (greater than million times the Solar mass). The efficiency in the conversion of energies (both potential and kinetic) into radiation and the high Eddington luminosity of the associated blackhole is theorized to be responsible for the high persistent luminosity.

The first time that AGNs were introduced in the mainstream consciousness was by Viktor Ambartsumian in 1958, promoting them as a cornerstone in the understanding and theories of galactic evolution, which was initially met with scepticism.

AGNs serve as excellent candidates for the study of accretion due to multiple factors:

- High luminosity and consequently powerful emissions which are spread across the entirety of the electromagnetic spectrum
- Diverse observable time variability which can be observed by observing changes in brightness and SEDs and can be utilized to model the movement and evolution of matter during the course of its approach to the supermassive black hole
- Provide a longer timeframe to study accretion in comparison to stellar accretion
- Relatively ideal due to ease of resolution of these relatively massive, and long-term stable systems, besides an intriguing feedback mechanism that can influence our understanding of galactic formation
- The presence of jets and outflows helps further the understanding of energy transport mechanisms in accreting systems.

2.4. Characteristics of Accreting Sources

Accreting sources found in the universe display several characteristic emissions and physical processes. These characteristic properties are extensively studied both via observation and theories. Some of such characteristics are-

1. **POWER LAW EMISSION-** In many accreting sources, X-ray spectra show a power-law shape, indicating high-energy non-thermal processes such as Compton scattering, where lower-energy photons are boosted to higher energies by interactions with relativistic particles. The power-law emission often dominates the high-energy part of the spectrum and is linked to processes near the event horizon of black holes or in relativistic jets in AGN.
2. **THERMAL(BLACKBODY) EMISSION-** The inner regions of accretion discs can emit blackbody radiation, particularly in systems like neutron stars and white dwarfs where the surface is directly observable.
3. **GAUSSIAN EMISSION LINES-** One of the most significant features in the X-ray spectra of accreting black holes and AGNs is the iron Kα emission line around 6.4 keV. This line often appears broadened and skewed due to relativistic effects in the accretion disc. The emission lines are broadened by the high velocity of material in the inner accretion disc and are distorted by gravitational redshift and Doppler effects near the black hole.
4. **JETS AND OUTFLOWS-** Some accreting sources, especially AGNs and micro quasars (stellar-mass black holes), launch relativistic jets. These jets produce

synchrotron emission, which can follow a power-law spectrum from radio to X-rays.

5. **EDDINGTON LUMINOSITY-**Accretion is regulated by the Eddington limit, the balance between the gravitational pull of the central object and the outward pressure from radiation. When an object accretes near this limit, it emits significant radiation, leading to characteristic X-ray or optical outbursts.
6. **ACCRETION RATE-**The rate of mass accretion influences the luminosity and spectral characteristics of the source. High accretion rates lead to more luminous and harder X-ray spectra, whereas low accretion rates can produce softer spectra dominated by thermal processes.
7. **TIMING PROPERTIES -** Variability in accreting sources refers to the changes in brightness, spectral characteristics, or emission features of astronomical objects over time. Variability is one of the hallmark features of AGNs, observed across the electromagnetic spectrum. AGNs can exhibit fluctuations in their brightness over timescales ranging from hours to years. These variations offer insights into the size of the emitting region and the physical processes at play near the supermassive black hole.

3. Theoretical Background

3.1. Power Law Emission

Power law is a functional nonlinear relation in which the function varies as the nth power of x. The main characteristic of power law is that it appears as a straight line in the log-log plot. It is a relation with a general form as-

$$f(x) = a\,x^n.\,f(x)$$

Accretion discs surrounding compact objects such as black holes, neutron stars, white dwarfs act as a source of radiation which often display power law characteristics. These arise from physical processes occurring in different regions of the disc and its surrounding environment like inverse Compton scattering (scattering of low energy photons to high energies by ultra relativistic electrons so that the photons gain and the electrons lose energy), synchrotron radiation(when relativistic electrons spiral around magnetic field lines in the accretion disc or the jet) and Bremsstrahlung radiation(from electrons decelerating in the electric fields of ions within the accretion disc).
For AGNs, hard X-ray spectra are usually decomposed into an underlying primary power law, a Compton reflection hump and an iron line. The power law component, is characterized by the spectral slope α or photon index $\boldsymbol{\Gamma = \alpha + 1}$. Power law photon indices have been measured in different AGN samples, with typical values lying in the $\boldsymbol{\Gamma \sim 1.5 - 2.5}$ **range.**
The general form of power law emission is given by-

$$I(E) \propto E^{-\alpha}$$

where,
I(E) is the intensity (or flux) of the radiation at energy E.
E is the photon energy (or frequency, depending on the context).
α is the **spectral index** or **power-law index**, which determines how steeply the intensity falls off with increasing energy.

3.1.1. Importance

The relationship between power law slope and different parameters like blackhole mass and accretion rates have been extensively studied, especially for various AGN samples.

Photon index have also been correlated with the Eddington ratio L/LE by several papers (Porquet et al. 2004; Piconcelli et al. 2005; Shemmer et al. 2006, 2008). Several researches from the past two decades have studied such relationships existing between power law slope, photon index and other important accretion parameters.

3.2. Gaussian Line Emission

Gaussian line Emission refers to the emission lines in the spectrum of an astronomical object that can be described by a gaussian function. These emission lines are usually the result of specific transitions of electrons between energy levels in atoms or molecules.

3.2.1. Mathematical Representation

A gaussian function describing an emission line can be written as:

$$f(\lambda) = A \exp\left(-\frac{(\lambda - \lambda_0)^2}{2\sigma^2}\right)$$

where,

· λ is the wavelength.
· λ_o is the central wavelength of the emission line.
· A is the amplitude of the Gaussian, related to the intensity of the emission line.
· σ is the standard deviation, related to the width of the emission line.

3.2.2. Physical Principles

I. **Emission Lines:**

Emission lines in astrophysical spectra arise when electrons in atoms or molecules transition from a higher energy level to a lower energy level, emitting a photon with energy equal to the difference between the two levels. Each element has a unique set of energy levels, leading to a characteristic set of emission lines often referred as its spectral signature.
For AGNs in general, the optical lines have larger equivalent widths simply because there is relatively less continuum emission per unit wavelength under the optical lines.

II. **Gaussian Profile:**

The shape of an emission line can often be approximated by a gaussian function due to various broadening mechanisms, such as thermal and doppler broadening.

4. Methodology

4.1. Setup:

In this project, all simulations and analyses were performed using:

- **Python** - A popular programming language that can be used for web development, software development, mathematics, system scripting and more.
- **Jupyter Notebook** - A web application that allows you to create and share computational documents with code, text, and output.
- **NumPy** - A Python library that provides a multidimensional array object and fast operations on arrays.
- **SciPy -** A scientific computation library that uses NumPy underneath and provides more utility functions for optimization, stats and signal processing.
- **Matplotlib -** A comprehensive library for creating static, animated, and interactive visualizations in Python.

4.2. Data Fitting and Simulation:

As a part of this project, we investigated power law emission using two approaches: modelling the spectral energy distribution (SED) by simulation and by examining its relationship with the Gaussian emission curve.

Here are the plots that we simulated:

4.2.1. Linear Plot for Power Law Emission

We applied power law as a tool to model and simulate the emissions and the spectral energy distribution (SED) as a plot of frequency versus the emission. Simulated external noise was added to the data in order to examine the influences and consequences of the same. Further, we used various photon indices (alpha) to observe the effect of various photon indices on the curve, in a linear plot.

- ***Import Libraries:***

```
# Linear plot of power-law emission

# Importing Libraries
import numpy as np
import matplotlib.pyplot as plt
```

- ***Define the Power law function:***

```
# Defining  the power-law function
def power(mu, k, alpha, error):
    return k * (mu + error)**(-alpha)
```

- ***Assigning values to variables:***

```
# Assigning values to variables
x=np.linspace(1,50,100)
k = 1 # constant
mu = np.linspace(1, 50, 100) # frequency
error = 0.03 * mu * np.random.randn(100) # added noise
alpha_v = [1, 1.5, 2.5, 3] #  photon indices
```

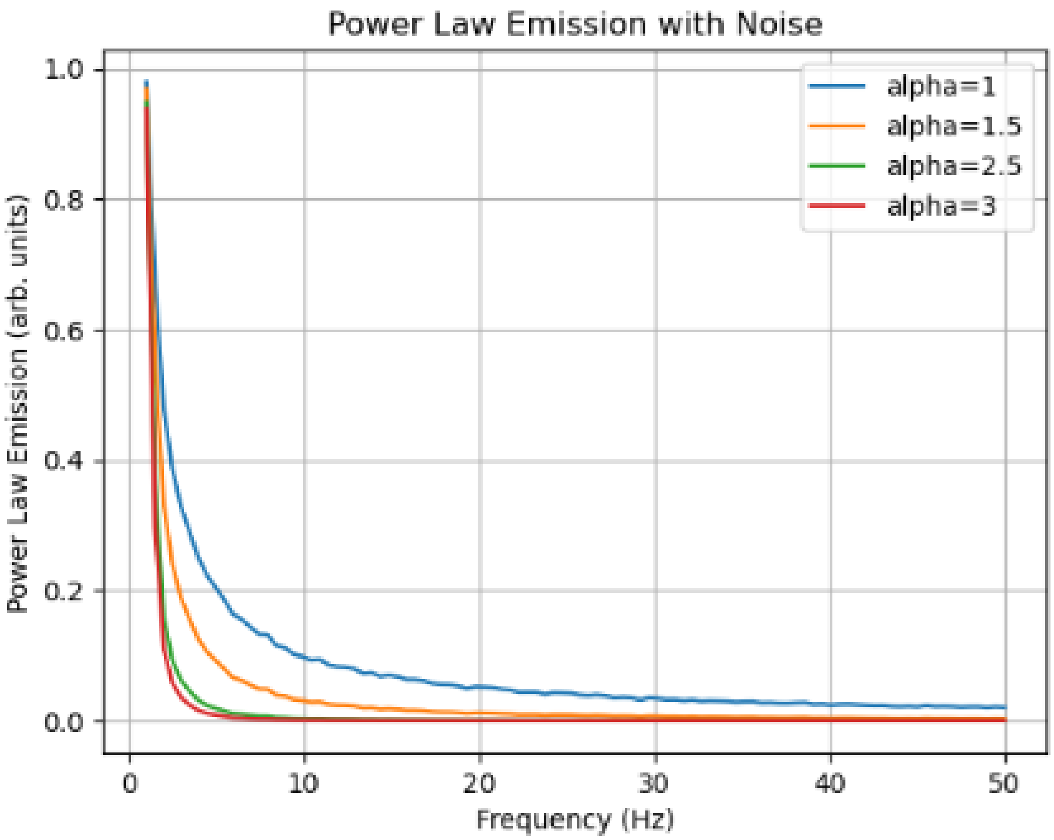
- ***Using for loop and plotting:***

```
# Plot the power-law emission with noise for different alpha values
for alpha in alpha_v:
    powerf = power(mu, k, alpha, error)
    plt.plot(mu, powerf, label=f'alpha={alpha}')
```

- ***Assigning names for axes and title:***

```
# Plotting the power-law emission with and without noise
plt.xlabel('Frequency (Hz)')
plt.ylabel('Power Law Emission (arb. units)')
plt.title('Power Law Emission with Noise')
plt.legend()
plt.grid(True)
plt.show()
```

4.2.1.1. <u>Output</u>



4.2.2. <u>Log-Log plot for Power-Law Emission</u>

We applied power law as a tool to model and simulate the emissions and the spectral energy distribution (SED) as a plot of frequency versus the flux density. Simulated external noise was added to the data in order to examine the influences and consequences of the same. Further, we used multiple photon indices (alpha) to observe the effect of various photon indices on the curve, in a log-log plot. Here break and cutoff frequency take influence of and account for Compton scattering and Bremsstrahlung frequency respectively.

- ***Import Libraries:***

```
# Log-Log plot of power law emission

import numpy as np
import matplotlib.pyplot as plt
```

- ***Define the Power law function:***

```
# Defining the power law function
def power_law_spectral(nu, alpha1, alpha2, nu_b, nu_c):
    return nu**(-alpha1) * (1 - np.exp(-nu/nu_c)) * (nu/nu_b)**(-alpha2)
```

- ***Assigning values to variables:***

```
# Define the parameters
alpha1 = 1.5 # photon indices
alpha2 = 2.5 # photon indices
nu_b = 1e14  # Break frequency (Hz) - due to Bremmstrahlung radiation
nu_c = 1e15  # cutoff frequency (Hz) - due to Compton scattering
```

- ***Generate frequency array***

```
# Generate frequency array
nu = np.logspace(12, 18, 100)
```

- ***Assigning the flux***

```
# Calculate SED
flux = power_law_spectral(nu, alpha1, alpha2, nu_b, nu_c)
```

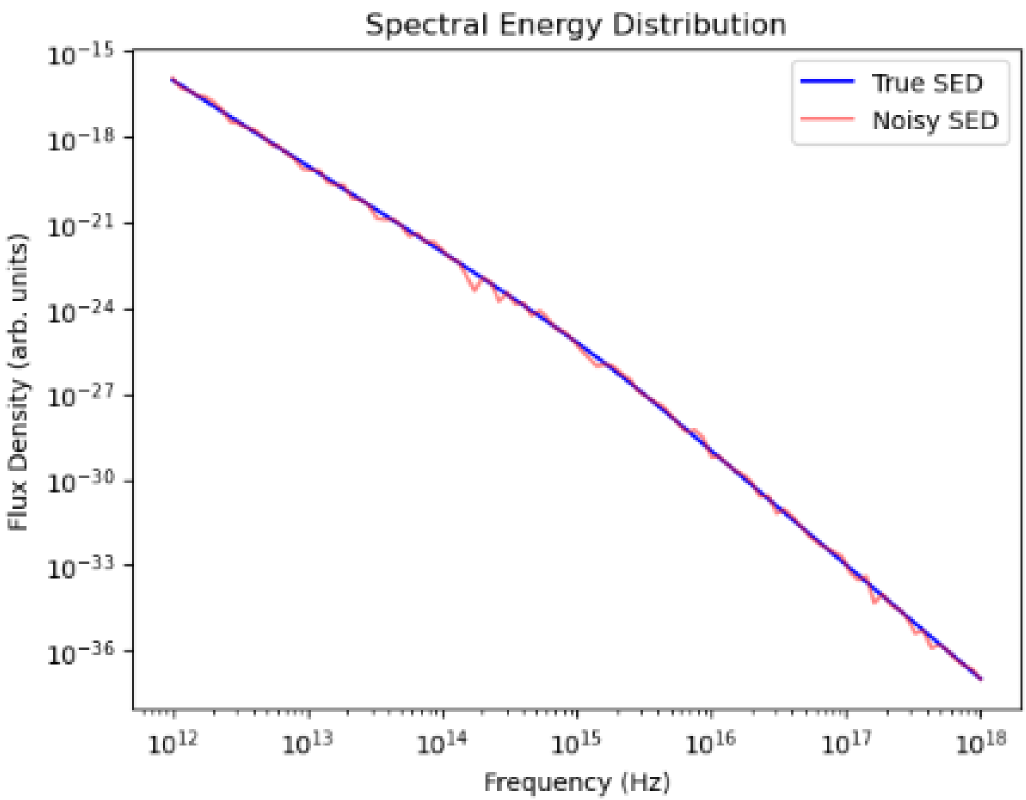
- ***Adding noise***

```
# Add noise (error)
noise_level = 0.28  # Adjust this value to change the noise level
flux_noisy = flux * (1 + noise_level * np.random.randn(len(flux)))
```

- ***Plotting with and without noise***

```
# Plot SED with and without noise
plt.loglog(nu, flux, label='True SED', color="blue")
plt.loglog(nu, flux_noisy, label='Noisy SED', alpha=0.5, color="red")
plt.xlabel('Frequency (Hz)')
plt.ylabel('Flux Density (arb. units)')
plt.title('Spectral Energy Distribution')
plt.legend()
plt.show()
```

4.2.2.1. Output



4.2.3. Log-log plot of power law emission with Gaussian curve

The power law emission plots modelled earlier, were replicated with the addition of the Gaussian curve to study the behaviour and influence of the same on the emission, as well as its significance.

- ***Import Libraries:***

```python
# Power Law Emission with noise and added Gaussian Curve - a log-log plot

# Importing Libraries
import numpy as np
import matplotlib.pyplot as plt
from scipy.stats import norm
```

- ***Define the Power law function:***

```python
# Defining the power-law function
def power(mu, k, alpha, error):
    return k * (mu + error) ** (-alpha)

y_power_law = power(mu, k, alpha, error)
```

mu: represents frequency.
k: A constant factor for scaling the power law**.**
alpha: The spectral index or the photon index (power-law exponent).
error: An array to simulate noise or perturbations**.**

- ***Assigning values to variables:***

```python
# Assigning the variables
x = np.logspace(0,3,1000)
k = 1                           # constant
mu = np.logspace (0,3,1000) # frequency
error = 0.03 * mu * np.random.randn(1000) # added noise
alpha = 1.5 # photon index
```

- ***Gaussian Parameters:***

```python
# The Gaussian Parameters
mean = 100
amplitude = 1e3
stddev = 10
```

- ***Define Gaussian Line function:***

```python
# Defining the Gaussian function using SciPy
def gaussian_line(x, mean, amplitude, stddev):
    return amplitude * norm.pdf(x, mean, stddev)

y_gaussian = gaussian_line(x, mean, amplitude, stddev)
```

- ***Combined Power-Law and Gaussian Function:***

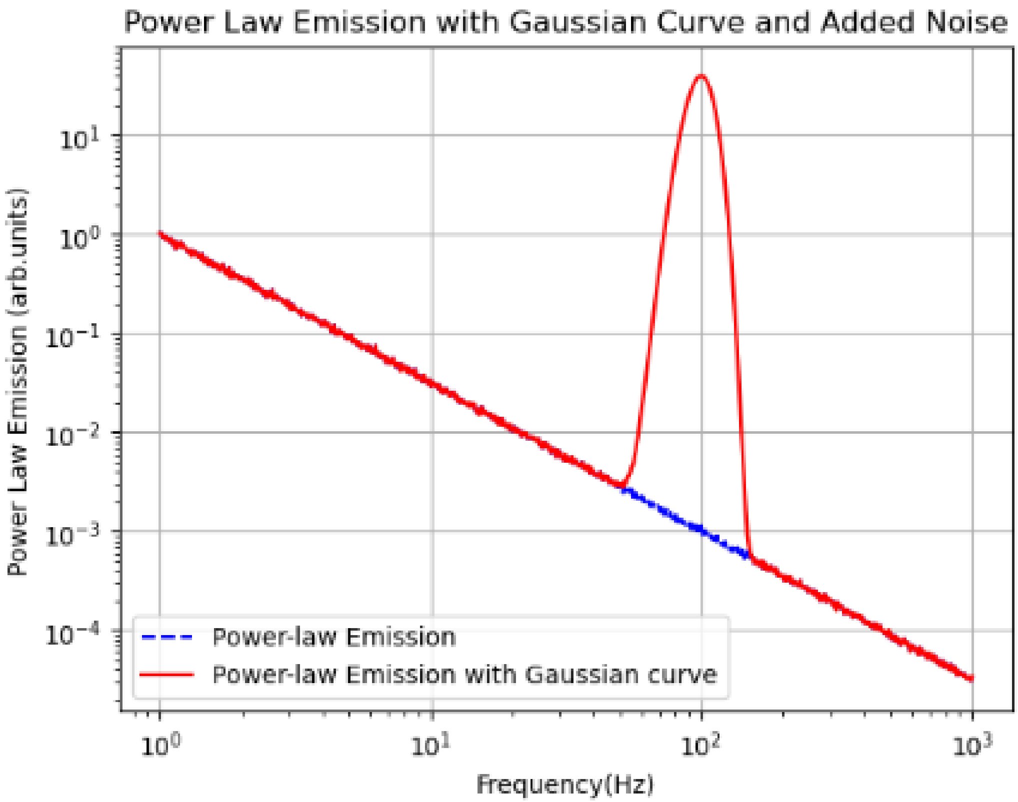
```python
# Adding the power law curve with the Gaussian curve

y_total = y_power_law + y_gaussian
```

- ***Plotting the Power Law emission (with and without Gaussian line):***

```python
# Plotting the power-law emission with the Gaussian Curve
plt.loglog(x, y_power_law, label="Power-law Emission", linestyle='--', color = 'blue')
plt.loglog(x, y_total, label="Power-law Emission with Gaussian curve", color = 'red')
plt.xlabel("Frequency(Hz)")
plt.ylabel("Power Law Emission (arb.units)")
plt.title("Power Law Emission with Gaussian Curve and Added Noise")
plt.legend()
plt.grid(True)
plt.show()
```

4.2.3.1. **Output**



Power Law Emission with Gaussian Curve and Added Noise
Power Law Emission (arb.units)
Frequency(Hz)
Power-law Emission
Power-law Emission with Gaussian curve
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{0}
10^{1}
10^{2}
10^{3}

5. Results

5.1. Simulation of power-law emission:

The simulations and its subsequent analysis revealed the nature of the power-law function to appear as a straight line in a log-log plot, with the slope (steepness) of the line relating directly to the associated photon index. It was also observed that steeper slopes signify the concentration of the energy to a greater extent in lower frequencies while flatter slopes indicate emission of more higher energy photons and consequently higher frequencies.

In real accreting sources such as AGNs or binaries, this manifests itself in the form of soft and hard X-rays respectively, since the high-energy electrons created from non-thermal processes cause the power-law spectrum to be seen in the X-ray to Gamma-ray range. It was observed that the flux density decreases with an increase in frequency, in agreement with the typical characteristics of such non-thermal emissions, due to the energy loss mechanisms of the emitting particles.

5.2. Introduction of the Gaussian curve to the simulation:

The introduction of the Gaussian curve helped in the analysis of spectral emission. The Gaussian peak, which in the aforementioned simulation was at around 100 Hz signified an excess at that frequency due to specific emission processes - essentially a quasi-periodic oscillation (QPO). QPOs are coherent oscillation or variability in the source's emission at the frequency which could be due to physical processes such as pulsations or structural reasons, particularly in the inner regions of these accreting systems.

5.3. Limitations

While considering the simulative analysis we have performed, it is evident that there may be limitations due to various factors, as listed:

1. Due to the simulative considerations, it may not have been possible to consider all potential contributing emissions and their respective contributions accurately, as a consequence of which there may be deviations from the potential real curves.
2. Again, compared to real astronomical data, the simulated noise added is significantly less random and more uniform, due to which aberrations and unexpectedly high spikes such as those due to cosmic rays among others might not be observed as well.
3. While the power law is an excellent mathematical tool to model and simulate the emissions to a high degree of accuracy, it is yet insufficient particularly in providing

information regarding electromagnetic and other factors, making the normalization of the spectrum ambiguous to interpret.

4. Each and every individual astrophysical source would show variations in terms of energy mechanisms as well as the spectral range. While we intend to create a generalized simulation, it fails to elucidate and perfectly describe specific sources.
5. At the higher as well as lower extremities, the fitting may be misleading and lead to incorrect conclusions about the source’s emission properties.
6. Power law emission, while highly descriptive, is only a segment of the overall emission, and fails to provide the overall picture regarding the spectral energy distribution (SED).

6. __Analysis and Discussion__

6.1. __Power Law Curve__

The power law is simulated for different values of alpha. As discussed earlier this is specifically due to the non-thermal physical processes that occur in the accretion discs. *For the log-log plot*, it follows a typical negative slope (alpha) indicative of some common high energy processes, such as synchrotron radiation or inverse Compton scattering. The straight line across a log-log plot indicates that the emission behaves consistently across a wide range of frequencies. The steepness of the curve varies with changing values of alpha (higher representing a steeper slope). Simulating power-law emission for different α values on a log-log plot helps visualize how changes in the energy distribution of particles or accretion conditions affect the emitted spectrum.

6.2. __Power Law with Gaussian Line__

The simulation of power law with gaussian line superimposed can help in exploration of both non-thermal processes (power law emission) and specific thermal features (gaussian emission) in accreting sources simultaneously. The addition of the gaussian line shows a sharp localized peak. This represents specific emission from the accretion disc not associated with the processes that majorly contributes to power law emission (like quasi-periodic oscillation (QPO)).*The gaussian peak distorts the smooth power law at certain frequencies, highlighting the presence of other specific processes that contributes to the overall emission.*

The superimposed simulation of power-law describes the extended, energetic processes in accreting sources while gaussian lines (localized) provide information about the inner regions of the accretion disc, often revealing the dynamics close to the central object such as atomic transitions.
The addition of noise to our simulation helped us get a closer result to actual observations.

7. <u>Conclusion and Future Prospects</u>

Power law and gaussian emission spectrum is crucial for understanding the physical processes at work in accreting systems. Simulation of power-law and Gaussian emissions mimics the behaviour of real astronomical systems, such as Active Galactic Nuclei (AGN), X-ray binaries, or neutron stars. The simulation allows us to isolate and study the individual physical processes responsible for these emissions. These simulations can be directly compared with data from X-ray telescopes like Chandra or XMM-Newton, which observe accreting systems.

Observational data from accreting sources are often complex and noisy. The superimposed simulation gave us an idea of how to decompose real spectra into different components to isolate and study the processes behind them.

Simulations help to determine physical properties of the accreting system. By fitting the simulated curves to observed data, one can infer:

- The mass of the black hole or neutron star: The slope of the power-law emission can be tied to the mass of the compact object.
- The accretion rate: The power-law slope and overall intensity provide clues about how much matter is being funnelled into the compact object.
- disc geometry and ionization state: The Gaussian lines provide information about the inner accretion disc, including the ionization level and the Doppler shifts caused by material moving at relativistic speeds near the black hole.
- Black hole spin: By modelling relativistic broadening of emission lines, one can measure the spin of the black hole, which is important for understanding the nature of the accretion process and the evolution of the black hole itself.

Such simulations also help testing predictions from theoretical models, deviations from simulated data can signal gaps in our understanding or the presence of additional factors. Simulating the spectrum of accreting sources with both power-law and Gaussian emission helps **link theory with observations**, offering a framework for interpreting real astronomical data. This process allows for the extraction of crucial physical information about the compact object, the accretion disc, and the emission processes. Ultimately, it helps refine our understanding of how **accreting black holes, neutron stars, and other compact objects** evolve and radiate across the universe.

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