AGN FEEDBACK:
THE HEATING MECHANISM OF THE INTERGALACTIC MEDIUM

CAPSTONE THESIS INTERIM REPORT

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1 Introduction

Active Galactic Nuclei (AGN) constitute a class of astrophysical phenomena characterized by the luminous emission originating from the central region of galaxies, powered by mass accretion onto a supermassive black hole (SMBH). This emission spans various electromagnetic wavelengths, from radio waves to gamma rays. Investigating AGN is paramount for understanding the interplay between the energetic processes occurring in galactic cores and their impact on the surrounding intergalactic medium (IGM).

The central engine of AGN, harboring an SMBH with masses reaching millions to billions of times that of our Sun, exerts an influence on the evolution of galaxies. The gravitational interaction between the SMBH and its host galaxy, coupled with the AGN's energy output, leads to a dynamic feedback mechanism. This AGN feedback, encompassing both radiative and mechanical processes, modulates the formation and evolution of galaxies and has far-reaching consequences for the broader cosmic environment.

This study focuses on exploring the details of AGN feedback, specifically emphasizing its role as a heating mechanism for the IGM. Understanding the processes by which AGNs inject energy into their surroundings is essential for comprehending the thermal state, ionization, and enrichment of the IGM. This investigation holds implications for broader astrophysical phenomena, such as galaxy formation, the cosmic web, and the universe's large-scale structure.

As we delve into this exploration, we aim to examine critical relationships, such as the Magorrian Relation and the Kormendy Relation, which provide empirical links between SMBH mass and host galaxy properties. Additionally, we will discuss methodologies for measuring SMBH masses, the black hole mass function, and the correlation between galaxy type, environment, and AGN activity. The use of tools like TOPCAT for data visualization will be outlined, and the emissions and radiation mechanisms associated with AGN will be scrutinized.

2 Magorrian Relation

The Magorrian Relation, established by Magorrian et al. (1998), empirically correlates the mass of a central supermassive black hole (SMBH) in a galaxy with the properties of its host bulge. The relation is expressed mathematically as:

$$M_{\text{BH}} \propto M_{\text{bulge}}^{1.12}$$

Where M_{BH} is the mass of the supermassive black hole, and M_{bulge} is the bulge mass of the host galaxy.

1. **Connection Between SMBH and Galaxy Evolution:** The Magorrian Relation underscores the intrinsic connection between the growth of supermassive black holes and the evolution of their host galaxies, specifically the bulge component. This correlation suggests a mutual co-evolution, where the SMBH and bulge mass evolve in tandem.

2. **Observational Implications:** Observationally, this relation has been substantiated through various galaxy surveys and studies, utilizing methods such as reverberation mapping and stellar velocity dispersion. It implies a systematic relationship that provides insights into the underlying processes governing the formation and growth of galaxies and their central black holes.

3. **Implications for AGN Feedback:** Understanding the Magorrian Relation is pivotal in the context of AGN feedback. The correlation hints at a dynamic interplay between the supermassive black hole's growth and the galactic bulge's properties. This interaction is crucial in elucidating the mechanisms by which AGNs influence their host environments.

Recent advancements in observational techniques, including high-resolution imaging and spectroscopy, have allowed more accurate measurements of SMBH masses and bulge properties. Additionally, multi-wavelength surveys have provided a wealth of data for statistical analyses, further refining our understanding of the Magorrian Relation across different galaxy populations.

Despite its robustness, challenges remain in precisely measuring bulge masses and accounting for other factors influencing the correlation. Future work involves addressing these challenges and exploring the Magorrian Relation in the context of diverse galaxy populations, including high-redshift and low-mass galaxies, to grasp the universality of this connection comprehensively.

3 Kormendy Relation

The Kormendy Relation, formulated by Kormendy in 1977, establishes a quantitative connection between the structural properties of a galaxy's bulge and its central supermassive black hole (SMBH) characteristics. Mathematically, the relation is expressed as:

$$\log\left(\frac{M_{\text{BH}}}{M_\odot}\right) = a \cdot \log\left(\frac{M_{\text{bulge}}}{10^9 M_\odot}\right) + b$$

Where M_{BH} is the mass of the SMBH, M_{bulge} is the mass of the galactic bulge, $M_\odot$ is the solar mass, and a and b are empirical coefficients.

1. **Linking SMBHs with Bulge Structure:** The Kormendy Relation establishes a statistically significant correlation between the mass of the central black hole and the properties of the galactic bulge. This implies a co-evolutionary connection, indicating that the formation and growth of the SMBH are intricately linked to the structural evolution of the host galaxy.
2. **Observational Support:** Observational studies, employing techniques such as high-resolution imaging and spectroscopy, consistently validate the existence of a tight correlation between SMBH mass and bulge properties. The Kormendy Relation is particularly robust in elliptical and lenticular galaxies, providing empirical evidence for the coexistence of SMBHs and their host bulges.

Recent advancements in observational capabilities, such as adaptive optics and integral field spectroscopy, have facilitated more precise measurements of bulge properties and SMBH masses. This has enabled a refined scrutiny of the Kormendy Relation across a diverse range of galaxy types, redshifts, and luminosities.

4 Methods for Measuring Supermassive Black Hole Masses

Accurate measurement of supermassive black hole (SMBH) masses is pivotal for understanding their role in galactic dynamics and evolution. Several methodologies have been developed to quantify these masses, each with inherent strengths and limitations.

4.1 Reverberation Mapping

Reverberation mapping relies on analyzing temporal variations in the luminosity of the broad emission lines from the accretion disk surrounding the SMBH. The method capitalizes on the time delay between changes in the ionizing continuum emitted by the accretion disk and the subsequent response of the broad emission lines. The formula for estimating SMBH mass using reverberation mapping is:

$$M_{\text{BH}} \approx f \cdot R_{\text{BLR}} \cdot \Delta V^2$$

Here, M_{BH} is the SMBH mass, R_{BLR} is the radius of the Broad Line Region, ΔV is the line-of-sight velocity of the gas, and f is a dimensionless scale factor.

Strengths and Limitations:

1. Reverberation mapping can be applied to active galactic nuclei (AGN) at various redshifts.
2. It provides a direct measurement of the SMBH mass.

3. Requires long-term monitoring, limiting its applicability to a subset of AGN.
4. Sensitivity to geometry and physical conditions in the Broad Line Region introduces uncertainties.

4.2 Stellar Dynamics

Stellar dynamics leverages the motion of stars within the gravitational potential of the SMBH to infer its mass. The fundamental equation for stellar dynamics is:

$$M_{\mathrm{BH}} \approx \frac{R \cdot \sigma^2}{G}$$

Where R is the spatial scale of the stellar distribution, σ is the stellar velocity dispersion, and G is the gravitational constant.

Strengths and Limitations:

1. Applicable to quiescent galaxies and those lacking broad emission lines.
2. Provides a measurement of the enclosed mass within the stellar orbit.
3. Restricted to galaxies with discernible stellar kinematics.
4. Requires high spatial resolution for accurate measurements.

4.3 Maser Observations

Observing maser emission from molecular gas in the accretion disk allows for precise measurements of SMBH masses. The formula for estimating mass using maser observations is:

$$M_{\mathrm{BH}} = \frac{f \cdot R \cdot \Delta V^2}{G}$$

Here, f is a geometrical factor, R is the maser disk radius, ΔV is the linewidth, and G is the gravitational constant.

Strengths and Limitations:

1. Highly accurate measurements can be achieved.
2. Applicable to galaxies with active maser sources.
3. Limited to galaxies with detectable maser emission.
4. Observational challenges associated with maser variability.

5 Black Hole Mass Function

The black hole mass function (BHMF) is a statistical distribution that characterizes the occurrence frequency of black holes with respect to their masses within a population or a given volume of the universe. This function provides insights into the underlying mechanisms governing the formation and evolution of black holes across cosmic scales.

The mathematical formulation of the BHMF is expressed as:

$$\Phi(M_{\rm BH}) = \frac{dN}{d\log M_{\rm BH}}$$

Where $\Phi(M_{\rm BH})$ is the black hole mass function, $M_{\rm BH}$ is the black hole mass, and $\frac{dN}{d\log M_{\rm BH}}$ represents the number density of black holes per logarithmic mass interval.

Significance:

1. **Galactic and Cosmic Evolution:** The BHMF is a crucial tool for understanding the distribution of black hole masses and how they evolve. It sheds light on the processes of forming and growing black holes within galaxies and contributes to broader studies of cosmic structure and evolution.
2. **Probing Formation Mechanisms:** By examining the shape and evolution of the BHMF, astronomers can infer the dominant formation mechanisms of black holes, such as stellar collapse, mergers, or accretion processes. This information is fundamental for refining theoretical models of black hole formation and growth.

Observational Challenges:

1. **Selection Biases:** Observing black holes, especially those not actively accreting matter, introduces selection biases. This can result in underestimating the abundance of low-mass or quiescent black holes in observational samples.
2. **Mass Measurement Uncertainties:** Accurately measuring the masses of black holes, particularly in distant or faint objects, poses a significant challenge. Different measurement techniques, such as stellar dynamics or reverberation mapping, come with inherent uncertainties that can affect the precision of the BHMF.

Recent Developments:

1. **Gravitational Wave Observations:** The advent of gravitational wave astronomy has revolutionized our ability to detect and measure the masses of merging black hole binaries directly. This has provided unprecedented data for constraining the BHMF in the high-mass regime.

2. **Improved X-ray and Radio Surveys:** Ongoing advancements in X-ray and radio surveys have expanded our observational capabilities, enabling the detection of faint or obscured black holes. These surveys contribute to a more comprehensive understanding of the low-mass end of the BHMF.

6 Galaxy Type and Environment

Understanding the correlation between galaxy type and the environment in which galaxies reside is fundamental to unraveling the intricate processes governing galaxy formation and evolution. This section delves into the known relationships between galaxy properties and their surrounding environments.

Galaxies exhibit diverse morphological classifications, commonly categorized as elliptical, spiral, or irregular. The distribution of these morphological types is not uniform across the cosmic landscape but exhibits discernible trends with environmental density.

Empirically, the fraction of elliptical galaxies tends to increase in dense environments such as galaxy clusters, while spiral galaxies are more prevalent in lower-density regions. This phenomenon, known as the morphology-density relation, suggests that environmental factors play a role in shaping the structural characteristics of galaxies.

The relation is often expressed quantitatively using the following formula:

$$\frac{dN}{dV} \propto \rho^{\alpha}$$

Here, $\frac{dN}{dV}$ represents the number density of galaxies per unit volume, ρ denotes the environmental density, and α is an empirical parameter indicating the strength of the correlation.

Galaxy color, indicative of the stellar populations within galaxies, is another property influenced by the galactic environment. Observationally, galaxies in denser regions exhibit redder colors, suggesting a prevalence of older stellar populations. In contrast, bluer colors are associated with galaxies in lower-density environments, indicating ongoing star formation.

The color-density relation can be expressed mathematically as:

$$\langle \text{Color} \rangle \propto \rho^{\beta}$$

Here, $\langle \text{Color} \rangle$ represents the average color of galaxies, and β quantifies the strength of the correlation between color and environmental density.

The presence of active galactic nuclei (AGN) is also linked to the galactic environment. Observations suggest that AGN are more prevalent in denser environments, such as galaxy groups and clusters. The exact mechanisms driving this correlation remain an area of active research but may involve interactions between galaxies, gas accretion, and environmental processes.

Quantifying the environmental impact on AGN activity involves statistical analyses and assessments of the AGN fraction in different density regimes.

Several indicators are used to measure the environmental density around galaxies, including local galaxy density, cluster-centric distance, and large-scale structure analyses. These metrics contribute to a quantitative understanding of how the local and global environments influence galaxy properties.

7 Measuring the Galaxy Environment

Accurately characterizing the environment in which galaxies reside is crucial for understanding the underlying physical processes governing their formation, evolution, and interactions. Several quantitative methods are employed to measure the galaxy environment, providing insights into the larger-scale structures of the universe.

Galaxy Clustering

Galaxy clustering involves analyzing the spatial distribution of galaxies to identify patterns and quantify the degree of their aggregation. One widely used statistical measure is the two-point correlation function ($\xi(r)$), which describes the excess probability of finding a galaxy at a given separation distance r compared to a random distribution. Mathematically, the correlation function is defined as:

$$\xi(r) = \frac{DD(r) - 2DR(r) + RR(r)}{RR(r)}$$

Here, $DD(r)$ represents the number of galaxy pairs at a distance r in the observed data, $DR(r)$ and $RR(r)$ are the corresponding pairs in the data-random and random-random distributions, respectively.

Density Fields

Density fields provide a continuous representation of the galaxy distribution across space. These fields are constructed by estimating the local galaxy number density at different points in the universe. The overdensity (δ) at a given location is expressed as:

$$\delta(\mathbf{r}) = \frac{\rho(\mathbf{r}) - \bar{\rho}}{\bar{\rho}}$$

Here, $\rho(\mathbf{r})$ is the local galaxy number density at position $\mathbf{r}$, and $\bar{\rho}$ is the mean density of the universe.

Large-Scale Structure Analysis

Large-scale structure analysis involves studying the distribution of galaxies on cosmological scales, examining features such as voids, filaments, and galaxy superclusters. The power spectrum ($P(k)$) is a standard tool in this analysis, representing the distribution of power as a function of spatial frequency k in Fourier space.

$$P(k) \propto |\delta_k|^2$$

Here, δ_k is the Fourier transform of the galaxy density field.

The galaxy environment significantly influences the activity of active galactic nuclei (AGN). Studies have shown a correlation between the density of the galactic environment and the prevalence of AGN. The likelihood of AGN activity is higher in denser regions, such as galaxy clusters. The exact mechanisms behind this correlation remain an area of ongoing research.

Potential explanations include galaxy interactions, enhanced gas accretion, and the influence of large-scale structures on the availability of fuel for AGN. Understanding the environment's impact on AGN activity provides valuable insights into the intricate interplay between the cosmic web and the energetic processes occurring within galaxies.

8 TOPCAT Fundamentals

TOPCAT (Tool for OPerations on Catalogues And Tables) is a powerful and versatile software tool designed for the interactive analysis and manipulation of astronomical catalog data. Developed by the Starlink project, TOPCAT is particularly valuable for researchers dealing with large datasets and conducting analyses that involve cross-matching, filtering, and visualizing astronomical tables.

TOPCAT's significance lies in its ability to handle diverse astronomical data formats and perform a wide range of operations on catalog data. It offers a user-friendly interface, facilitating efficient and interactive exploration of datasets essential for gaining insights into complex astrophysical phenomena.

8.1 Essential TOPCAT Functionalities

To harness the capabilities of TOPCAT for your research, it's crucial to familiarize yourself with some fundamental functionalities:

- **Loading Data:** Import data in various formats, including FITS, VOTable, and ASCII. Use the "Load Table" option to bring in your datasets.
- **Cross-Matching:** Employ the cross-match tool to compare datasets based on celestial coordinates. Customize matching criteria and explore matched sources.
- **Filtering and Sorting:** Apply filters to narrow down data based on specific criteria. Sort tables according to desired parameters.
- **Visualizations:** Generate scatter plots, histograms, and other visualizations to explore data distributions. Utilize the 2D plot window for interactive exploration.
- **Column Operations:** Perform mathematical operations on columns to derive new parameters. Use the expression editor for custom calculations.
- **Subset Selection:** Create subsets of data based on user-defined conditions. Explore subsets to analyze specific regions of interest.
- **Saving Results:** Save manipulated or filtered datasets for future reference. Export results in various formats for compatibility with other tools.
- **Scripting and Automation:** TOPCAT supports scripting in various languages (such as STILTS command scripts). Automate repetitive tasks to enhance workflow efficiency.

8.2 TOPCAT in Action

This section demonstrates some basic use of TOPCAT with SDSS DR7 Data Products “gal_info" and “gal_line".

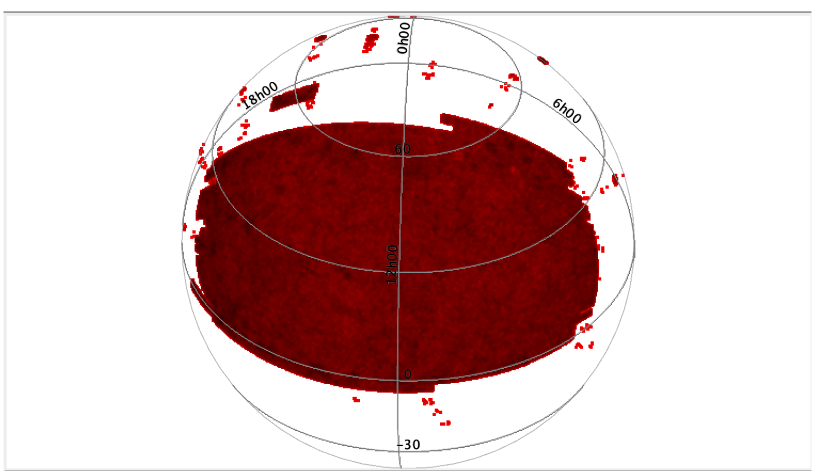

Figure 1: In this plot, we see the Sky Plot for the “gal_info" data table. The `Data Sky System` is set as ‘galactic’ and Longitude and Latitude are ‘RA’ and ‘Dec’, respectively.

The Sky Plot is a graphical representation of the positions of celestial objects in the galaxy. In this plot, the Data Sky System is set to ’galactic’ which means that the location of each object is determined with respect to the Milky Way's center. The Longitude and Latitude axes are labeled as 'Right Ascension' (RA) and 'Declination' (Dec), respectively, indicating the angular distance of each object from the celestial equator in the galactic coordinate system.

The Sky Plot provides a comprehensive view of the distribution of objects in the galactic plane, making it easier to identify patterns and trends in celestial data. The plot is particularly useful in identifying the location of star clusters, interstellar clouds, and other astronomical objects distributed across the galactic plane.

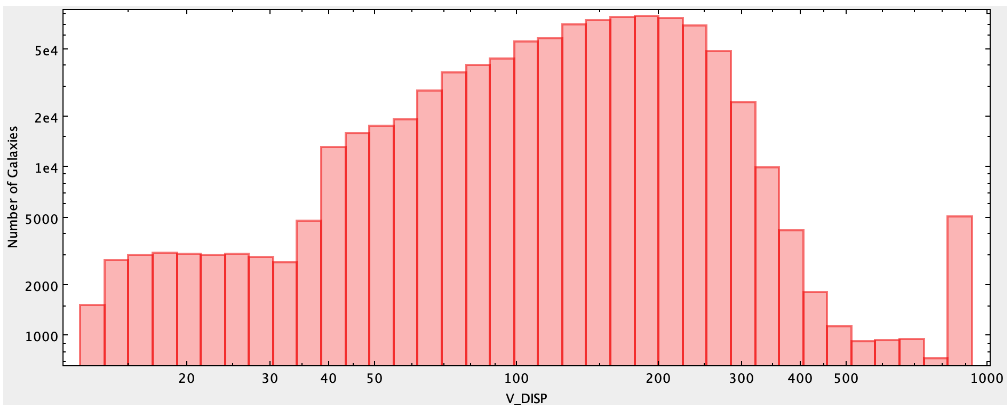

Figure 2: In this plot, we can observe the Velocity Dispersion value obtained from Schlegel's research, which is a fundamental parameter provided in the "gal_info" data table.

Velocity Dispersion refers to the spread of galaxy velocities around their mean velocity. This parameter is crucial in studying the physical properties of galaxies, such as their mass, size, and luminosity. Therefore, the value of Velocity Dispersion is an essential piece of information in analyzing the characteristics of galaxies.

9 AGN Emissions

Active Galactic Nuclei (AGN) exhibit a diverse range of emissions across the electromagnetic spectrum, originating from processes associated with accretion onto the central supermassive black hole (SMBH). Understanding these emissions is pivotal for probing the physical conditions near the SMBH and deciphering the impact of AGN on their surrounding environments.

9.1 Continuum Emissions

The continuum emissions from AGN cover a broad spectral range and are primarily associated with thermal and non-thermal processes. The accretion disk, heated by the gravitational energy released during mass accretion onto the SMBH, emits a thermal continuum, peaking in the ultraviolet to soft X-ray regime. Non-thermal emissions from relativistic particles in jets contribute to radio, optical, and X-ray continuum emissions.

The Planck function can represent the mathematical expression for the thermal continuum emission from the accretion disk:

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \cdot \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

Here, $B_\nu(T)$ is the spectral radiance, h is Planck's constant, ν is the frequency, c is the speed of light, k is the Boltzmann constant, and T is the temperature of the accretion disk.

9.2 Line Emissions

AGN spectra often feature prominent emission lines from the ionized gas near the SMBH. These include the Balmer series, forbidden lines like [O III], and Lyman-alpha. The line emissions provide valuable diagnostics for determining the emitting gas's physical conditions, such as temperature and density, of the emitting gas.

The intensity of a spectral line (I_λ) is related to the number density of emitting particles (n), the line's emissivity (j_λ), and the path length (ds) through the emitting region:

$$I_\lambda = \int j_\lambda \cdot n \cdot ds$$

9.3 X-ray Emissions

X-ray emissions from AGN arise from high-energy processes near the SMBH, such as Compton scattering in the accretion disk corona and X-ray binaries. Observations in the X-ray band provide insights into the properties of the hot, energetic regions close to the SMBH, complementing information obtained from other wavelengths.

9.4 Radio Emissions

Radio emissions in AGN result from synchrotron radiation produced by relativistic electrons spiraling along magnetic field lines in jets. The observed radio emission depends on factors such as the magnetic field strength (B), electron Lorentz factor (γ), and observing frequency (ν):

$$P_\nu \propto B^{(\gamma+1)/2} \cdot \nu^{-(\gamma-1)/2}$$

Here, P_ν is the power per unit frequency.

The emissions from AGN play a crucial role in understanding the feedback processes influencing the intergalactic medium (IGM). High-energy emissions, particularly X-rays, have the potential to heat and ionize the surrounding gas, affecting the thermodynamics and chemical composition of the IGM. Additionally, the mechanical energy carried by AGN jets can drive shocks and outflows, influencing the IGM on larger scales.

10 Radiation Mechanism

Understanding the mechanisms through which radiation from Active Galactic Nuclei (AGN) interacts with the intergalactic medium (IGM) is essential for unraveling the complex astrophysical processes shaping the broader cosmic environment. This section delves into the intricacies of AGN radiation and its impact on the IGM.

10.1 Radiation from AGN

AGN emits radiation across various wavelengths, encompassing radio, optical, ultraviolet, X-ray, and gamma-ray bands. The primary sources of this radiation are the accretion disk, where gravitational energy is converted into thermal radiation, and relativistic jets, producing non-thermal emissions through processes such as synchrotron radiation.

Mathematically, the total luminosity (L) of an AGN can be expressed as the sum of the thermal (L_{thermal}) and non-thermal ($L_{\text{non-thermal}}$) components:

$$L = L_{\text{thermal}} + L_{\text{non-thermal}}$$

10.2 Bremsstrahlung and Synchrotron Radiation

Bremsstrahlung, meaning "braking radiation" in German, is a process by which charged particles, typically electrons, emit radiation when decelerated by the electric field of atomic nuclei. In astrophysical contexts, bremsstrahlung is particularly relevant in hot, ionized plasmas in environments such as stellar atmospheres, galaxy clusters, and the interstellar medium.

The bremsstrahlung emissivity (j_ν) for a single electron in a plasma can be expressed as:

$$j_\nu \propto n_e^2 T^{-1/2} e^{-\dfrac{h\nu}{kT}}$$

Here, n_e is the electron density, T is the temperature, h is Planck's constant, k is the Boltzmann constant, and ν is the frequency of the emitted radiation.

Bremsstrahlung is a continuous process, producing a broad spectrum of radiation from radio to X-ray wavelengths, depending on the temperature of the emitting plasma. It is a crucial mechanism for studying the thermal properties of ionized gases in astrophysical systems.

Synchrotron radiation is emitted by charged particles, typically electrons, spiraling along curved paths in strong magnetic fields. This process is prevalent in astrophysical environments with powerful magnetic fields, such as accretion disks around black holes, pulsar wind nebulae, and relativistic jets from active galaxies.

The Larmor formula can describe the synchrotron power emitted by a single electron:

$$P_{\text{syn}} \propto B^2 E^2$$

Here, P_{syn} is the synchrotron power, B is the magnetic field strength, and E is the energy of the radiating electron.

The emitted synchrotron radiation exhibits a characteristic spectrum, with the intensity peaking at a frequency determined by the strength of the magnetic field. A power-law often describes The spectral energy distribution, making synchrotron radiation a distinctive signature in astrophysical observations.

Both bremsstrahlung and synchrotron radiation are essential processes in astrophysics, providing valuable insights into the physical conditions and dynamics of celestial objects.

10.3 Interaction with the Intergalactic Medium (IGM)

The radiation from AGN interacts with the IGM through various channels, influencing its thermal and ionization state. The key mechanisms are:

- **Photoionization:** High-energy photons, particularly in the ultraviolet and X-ray bands, can ionize the IGM by ejecting electrons from atoms, particularly in the ultraviolet and X-ray bands. The photoionization rate (Γ) can be described as:

  $$\Gamma = \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} \sigma_{\text{ion}} d\nu$$

  Here, L_ν is the spectral luminosity, h is Planck's constant, ν is the frequency, and σ_{ion} is the ionization cross-section.

- **Compton Heating:** In regions with a high density of soft photons, Compton scattering of high-energy photons can transfer energy to the IGM, leading to heating. The Compton heating rate ($\dot{q}_{\text{Compton}}$) is given by:

$$\dot{q}_{\text{Compton}} = n_e \int_{\nu_1}^{\infty} \frac{L_\nu}{h\nu} \sigma_{\text{T}} \left(\frac{h\nu}{m_e c^2} \right) d\nu$$

Here, n_e is the electron density, σ_{T} is the Thomson cross-section, m_e is the electron mass, and c is the speed of light.

- **Heating through Cosmic Rays:** Non-thermal particles, such as cosmic rays produced in AGN jets, can deposit energy into the IGM through interactions with ambient gas. The heating rate ($\dot{q}_{\text{CR}}$) can be expressed as:

$$\dot{q}_{\text{CR}} = \zeta n_{\text{gas}}$$

Here, ζ is the cosmic ray energy deposition rate per unit volume, and n_{gas} is the gas density.

10.4 Implications for the Surrounding Environment

The interaction of AGN radiation with the IGM has profound implications for the surrounding environment:

- **Thermal and Ionization Balance:** The heating processes influence the thermal and ionization balance of the IGM, impacting its temperature, density, and ionization state.
- **Cosmic Structure Formation:** AGN feedback contributes to regulating cosmic structure formation by influencing the gas properties within galaxies and galaxy clusters.
- **Enrichment of the IGM:** The ionization of the IGM by AGN radiation can lead to the enrichment of the cosmic medium, affecting the abundance of elements and contributing to the overall chemical evolution of the universe.