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Unveiling Black Holes: From Code to Cosmos

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Final Essay=What are the most likely electron-positron temperature models corresponding to observations of supermassive black holes

Introduction

Supermassive black holes (SMBHs) sit at the center of most galaxies, holding millions of times the Sun's mass within an unimaginably small region. Their high gravity bends spacetime, creating a point of no return known as the event horizon, from which not even light can escape. Despite their invisibility, SMBHs leave their mark on the universe through their interaction with surrounding matter. The infalling material forms a swirling disk, the accretion disk, where intense friction generates tremendous heat and electromagnetic radiation. This interaction between gravity and matter is the engine that powers some of the brightest objects in the cosmos, Active Galactic Nuclei (AGN) and quasars (May, 2022).

Understanding the physics within the accretion disk of an SMBH is a complex challenge. However, computer simulations are a powerful tool to look at SMBHs. By incorporating the laws of general relativity, magnetohydrodynamics (the study of magnetized fluids), and radiative energy (Balbus, 2002), these simulations allow us to explore the physics of the SMBHs by giving us the ability to test different models and parameters and see how the result compares to our actual observations of the SMBHs.

This paper delves into the realm of electron-positron temperatures around SMBHs. As matter falls towards the black hole, it gains energy and reaches extremely high temperatures. Under such extreme conditions, energetic photons can collide, leading to the creation of electron-positron pairs (Uzdensky 2014). The temperature of these electron-positron pairs plays a significant role in the overall energy balance and radiative signature of the accretion disk. Accurately modeling this temperature is essential for interpreting the electromagnetic radiation observed from SMBHs and unraveling the secrets of their mechanics.

Models

Now we look at the different proposed electron-positron temperature models for observations of supermassive black holes. These models attempt to consider the entire inflow-outflow structure governed by the SMBH.

1. R-Beta model

This model was originally conceptualized in (Quataert, 1999). They investigated how turbulence heats particles (electrons and protons) within Advection-Dominated Accretion Flows, which are hot, collisionless plasmas that form around accreting black holes. They argue that the fraction of turbulent energy heating electrons increases as the ratio of gas pressure to magnetic pressure decreases. A turbulent gas is one filled with chaotic motions, and an example of this is the hot swirling gas around a black hole. This turbulence can carry energy, similar to how waves carry energy in the ocean. The energy from the waves then can be transferred to the particles in the gas (electrons and protons).

There is an important distinction between how the protons and the electrons are heated. Electrons utilize a process called Landau Damping. Where the electrons "ride" the waves, effectively absorbing their energy. It works better for electrons because they're lighter and therefore more responsive to the waves. Protons, on the other hand, are heated through Transit-Time Damping. This is like particles bumping into the waves and getting a shove which transfers energy to the particles. It's more effective for heavier protons than for smaller electrons (Short, 1998).

Another important factor to consider is the strength of the magnetic field because that affects how the energy is transferred. Within strong magnetic fields, there is more Landau Damping, meaning electrons get heated more, while when there are weaker magnetic fields it allows for more Transit-Time Damping to occur, leading to more proton heating. They also point out a special type of wave called "whistler modes" that are generated when turbulence reaches a certain scale; these waves are particularly good at heating electrons (Short, 1998). This would mean that the fraction of energy heating electrons increases as the gas pressure becomes more dominant compared to the magnetic pressure.

2. Critical Beta Model

Originally formulated in (Anantua, 2020), this model takes a different approach to turbulent heating. This model assumes a critical value of beta (β_c), which represents the plasma pressure ratio (plasma pressure/magnetic pressure) that serves as a kind of tipping point. If the pressure balance (beta) flips past this point, the way the plasma heats changes dramatically.

Below βc, electrons are thought to be efficiently heated, while above βc, the heating efficiency decreases.

In equation form, it is [1], where Te and Ttot represent electron temperature and total temperature, respectively. f is a constant between 0 and 1, representing the maximum achievable Te/Ttot ratio at β = 0. β is the plasma pressure ratio (actual value), and βc is the critical beta value.

[1]

$$\frac{T_e}{T_e + T_i} = f e^{-\beta/\beta_c}$$

3. Constant Electron Beta Model:

The Constant Electron Beta Model (CEBM) rests on a few key ideas. First, the model assumes a continuous transfer of energy from the magnetic field to the electron population within a plasma. This implies that the energy stored in the magnetic field is constantly being used to heat the electrons, increasing their energy density. Second, the CEBM postulates a fixed proportional relationship between the electron energy density and the magnetic energy density. This essentially means that a constant fraction of the magnetic energy is always dedicated to heating the electrons. Third, since pressure is directly proportional to energy density, the CEBM translates the constant energy density relationship into a constant pressure relationship. This translates to a constant ratio between the electron pressure and the magnetic pressure.

The CEBM uses these principles to connect the magnetic field and the pressure exerted by the electrons. Since pressure is just another way to express energy density, the constant energy density relationship between electrons and the magnetic field translates to a similar constant pressure connection. This means there's a constant ratio between the pressure exerted by the energetic electrons and the pressure from the magnetic field. Essentially, the CEBM suggests the magnetic field pressure directly translates into a proportional increase in electron pressure, with β being the proportionality constant.(Falcke, 2000).

4. The Electron Evolution Model (EEM)

The Electron Evolution Model (EEM) offers the most detailed description of electron heating in astrophysical environments compared to its alternatives. The EEM tracks the evolution of electron temperature over time by using electron entropy, which accounts for various processes affecting electron energy. It takes into account Joule heating (the conversion of electrical energy into thermal energy through collisions), adiabatic heating/cooling (changes in electron temperature due to pressure variations), radiative losses (energy loss through emission of electromagnetic radiation), and turbulent heating (the energy transfer from plasma turbulence to electrons) (Ressler, 2015).

More specifically, when this model looks at turbulent heating, it incorporates the (Howes, 2010) prescription for turbulent heating, which is based on calculations of Landau damping, which describes the process where plasma waves interact with resonant particles (in this case, electrons) and transfer their energy. The Howes prescription provides a heating rate term within the electron entropy equation, accounting for the energy transfer from turbulence.

Another important note about this model is that it involves multiple key parameters to describe the temperature of the system. Those parameters are electron density, electron temperature, magnetic field strength, plasma beta (ratio of gas pressure to magnetic pressure), and turbulent cascade parameters (e.g., wave number spectrum). Due to the inclusion of turbulent heating calculations and multiple interacting parameters, the EEM is very complex when compared to other models.

5. Magnetic Bias Model:

The Magnetic Bias Model (MBM) builds upon the Constant Electron Beta Model (CEBM) but introduces a new generalization. It still has the assumptions of the CEBM: continuous energy transfer from the magnetic field to electrons, and the pressure relationship between electron and magnetic energies. The MBM additionally assumes that the electron pressure (Pe) scales with the magnetic pressure (PB) to a certain power, denoted by n (Anantua et al., 2020).

This variability allows for more flexibility in describing electron behavior compared to the CEBM, which assumes a fixed proportionality (n = 1). However, the choice of the power n is crucial and might require adjustments based on specific astrophysical environments and heating mechanisms. Unlike the CEBM with its single parameter (βe0), the MBM introduces an additional parameter (n) and potentially the normalization constant (Kn), increasing the complexity.

Observations

Investigating black holes does come with some difficulty. We cannot directly observe supermassive black holes due to their immense gravity and the event horizon. However, we can study their presence and properties indirectly through various methods.

First is Spectral Analysis, which by analyzing the electromagnetic radiation emitted across different wavelengths (radio, X-ray, gamma-ray), we can understand the temperature, density, and composition of the surrounding gas in the accretion disk. This radiation originates from processes like synchrotron emission (electrons spiraling in magnetic fields) and inverse Compton scattering (high-energy electrons interacting with low-energy photons). Additionally, the use of dynamical studies, studying the motions of gas near the event horizon using techniques like Doppler shifts and gravitational redshifting, allows us to estimate the black hole's mass and the dynamics of the accretion disk. Scientists also use Microlensing to learn about black holes. Gravitational microlensing events, where a massive object like a black hole bends the light of a background star, can reveal the presence and mass of the black hole (Harvard-Smithsonian Center for Astrophysics). To compare the various temperature models, and try to reach conclusions about their respective accuracy with reality we want to use these methods, to observe actual black holes and their respective physics.

The observations and comparisons of these models will be drawn from a series of papers by Dr. Richard Anantua looking at two different SMBHs and our observations of them (Anantua, 2020, and Anantua, 2023). The observations are based on the Event Horizon Telescope's (EHT) observations of two distinct black hole systems: Sagittarius A* (Sgr A*) and M87*. Sgr A* resides at the very heart of our Milky Way galaxy. It boasts a mass 4.14 million times that of our Sun and exhibits a very low accretion rate. On the other hand, M87*, located in the Messier 87 galaxy, is 55 million light-years away and presents a far more dramatic picture. With a mass 6.5 billion times that of our Sun, it has a much faster accretion rate. The paper utilizes general relativistic magnetohydrodynamics (GRMHD) simulations to model the accretion flows around the supermassive black holes in Sgr A* and M87. By analyzing these two very different black holes, I can aim to make my conclusions more generalizable to black holes in general, rather than potentially only applying to specific parameters.

It should be noted that the studies constrain the electron-positron gas temperature ranges within these black hole environments. For example, in Sgr A*, the estimated electron temperature is around 10^8-10^9 K, while in M87, it's significantly higher, reaching 10^10-10^11 K. The observations also put constraints on the electron-to-proton temperature ratio (Te/Tp). In some cases, the ratio is close to 1, suggesting similar temperatures for both particles. However, in other scenarios, the ratio might deviate from 1, indicating preferential heating of electrons through specific mechanisms. The studies also hint at the presence of different heating mechanisms operating within the accretion disks, such as magnetic reconnection (where magnetic field lines violently reconnect, releasing tremendous energy) and turbulence (chaotic motions of the plasma).

Comparisons

1. R-Beta Model:

The R-Beta model stands out for its emphasis on turbulence as a key mechanism for electron heating in positron-electron plasmas near black holes. It predicts a rising fraction of turbulent energy transferred to electrons as gas pressure asserts dominance over magnetic pressure. This aligns well with observational hints that turbulence plays a significant role, particularly in regimes where gas pressure reigns supreme. However, the R-Beta model might overestimate the contribution of hot electrons, especially in regions where magnetic pressure trumps thermal pressure. This can lead to simulations producing jets with a more uniform and hotter temperature profile than what's observed. For instance, Anantua 2020 which looked at Sgr A* suggests that models incorporating cooler electron populations better align with the collected data.

One key advantage of the R-Beta model lies in its ability to provide a nuanced perspective on how changes in the temperature ratio influence heating dynamics. Compared to other models, it offers a more detailed picture. This makes it particularly valuable for analyzing scenarios where gas pressure fluctuations are significant factors within the accretion disk dynamics under investigation.

Despite its strengths, the R-Beta model does have limitations. It rests upon certain theoretical assumptions and may not fully capture the intricate complexities of turbulent heating processes across diverse astrophysical environments. For example, the model assumes a uniform electron temperature, which might not always hold true. When observations point towards significant variations in electron temperature along the jet, the R-Beta model's premise of a more uniform hot population might not be suitable. Additionally, precisely quantifying the fraction of turbulent energy transferred to electrons proves challenging, potentially introducing uncertainties into the predicted temperature values.

2. Critical Beta Model (CBM)

The Critical Beta Model (CBM) introduces a critical beta value (β_c) that demarcates a significant shift in electron heating efficiency. Below β_c, electrons heat up efficiently, while above it, the efficiency plummets. Observational data partially supports this critical threshold, though the specific β_c value might fluctuate depending on the black hole's environment and other factors.

This model's strength lies in its flexibility. By strategically adjusting the critical temperature, researchers can explore more extreme variations within simulations compared to other models. This flexibility is particularly useful when observations suggest a jet with cooler electrons farther from the black hole, aligning with observational findings(Anantua, 2020). Additionally, CBM offers a simpler approach compared to models like R-Beta, requiring only a single critical parameter. This simplicity translates to greater computational efficiency.

However, the CBM's dependence on the critical temperature is also its Achilles' heel. The model's accuracy hinges on selecting the optimal critical temperature, which might necessitate further research and calibration with observations. Furthermore, assuming a single critical beta value might be an oversimplification. The actual transition could be more gradual or influenced by additional factors. This lack of detailed physics compared to other models could potentially lead to less accurate predictions in specific scenarios where pressure variations play a crucial role.

3. Constant Electron Beta Model (CEBM):

The Constant Electron Beta Model (CEBM) offers a simplified approach to modeling electron temperature in positron-electron plasmas, particularly near black holes. This model assumes a constant ratio ($\beta e0$) between electron pressure and magnetic pressure. This inherent assumption translates to a continuous transfer of energy from the magnetic field directly to the electrons. In simulations, the CEBM predicts a uniform electron temperature throughout the jet. However, a significant drawback of this model lies in its discrepancy with observations. Observation shows considerable variations in electron temperature within jets, highlighting the limitations of the CEBM's uniform temperature prediction(Anantua, 2023 and Anantua, 2020).

Despite its limitations, the CEBM offers certain advantages. Due to its single parameter ($\beta e0$) and the absence of intricate heating calculations, the CEBM is computationally efficient.

While its applicability might be restricted in scenarios requiring temperature variations, the model proves well-suited for analyzing environments dominated by magnetic reconnection, a phenomenon prevalent in jet regions.

However, the CEBM's core assumption of a fixed proportionality between electron and magnetic pressure might not be universally applicable. This simplification could lead to inaccurate temperature estimations. Additionally, the model neglects the potential influence of other heating mechanisms, such as turbulence, which can play a significant role in specific situations. As observations clearly demonstrate temperature variations within jets, the CEBM's uniform temperature approach renders it unsuitable for scenarios where such variations are a key characteristic.

4. Electron Evolution Model (EEM):

The Electron Evolution Model (EEM) stands out as the most intricate model for electron temperature in positron-electron plasmas. It surpasses other models in its comprehensiveness by incorporating a multitude of energy exchange processes. These processes include Joule heating, adiabatic heating/cooling, radiative losses, and, notably, turbulent heating described through the Howes prescription. As a consequence, the EEM offers the most detailed description of electron temperature evolution within the jet. However, this detailed approach comes at a cost – the EEM is computationally expensive. Additionally, the model's accuracy hinges heavily on the chosen parameters and the underlying assumptions made for the turbulent heating calculations.

Despite the computational burden, the EEM holds significant advantages. Anantua, 2020 and Anantua, 2023) compared various electron temperature parametrizations, including those inspired by the EEM. Their findings suggest that EEM-based models excel when they account for the dependence of electron temperature on magnetic field strength. This aligns remarkably well with observations, which indicate hotter electrons residing in regions with stronger magnetic fields. By incorporating various energy exchange processes, the EEM provides the most comprehensive description of electron heating, potentially achieving good agreement with diverse observational constraints. Compared to other models, the EEM offers the most detailed and dynamic picture of electron temperature evolution. However, this detail comes at a significant computational cost.

5. Magnetic Bias Model (MBM):

The Magnetic Bias Model (MBM) builds upon the Constant Electron beta model (CEBM) by introducing a variable power-law relationship between electron pressure and magnetic pressure. This flexibility allows the MBM to capture a wider range of physical scenarios compared to the CEBM's fixed proportionality. However, this added flexibility comes at the cost of increased complexity.

The MBM's key advantage lies in its ability to predict hotter electron temperatures in regions with stronger magnetic fields. This aligns well with observational data, as demonstrated by Anantua et al.'s simulations. This suggests a significant advantage over models like the R-Beta model, which assumes a more uniform temperature distribution. Additionally, the MBM offers a more nuanced approach than the CEBM by allowing for deviations from the fixed proportionality between electron and magnetic pressures. This potentially leads to more accurate predictions in environments where this simple relationship breaks down. Anantua et al.'s work provides a strong case for the MBM's ability to capture temperature variations within jets compared to models with a uniform temperature profile.

Despite its strengths, the MBM does have limitations. The introduction of a power-law exponent as an additional parameter increases computational complexity. Furthermore, the chosen power law might not accurately represent the underlying physics in all scenarios. Careful consideration of the specific astrophysical environment is crucial to ensure the chosen exponent reflects reality. Additionally, the MBM's accuracy relies heavily on accurately modeling the magnetic field within the jet, which can be a significant challenge. In conclusion, while the MBM offers significant advantages over simpler models in capturing the relationship between magnetic fields and electron temperatures, its increased complexity and reliance on accurate magnetic field modeling require careful consideration.

Conclusions

Choosing the optimal temperature model requires careful consideration. While each model offers unique strengths, researchers must navigate trade-offs between three key factors: complexity, computational efficiency, and specific applicability.

On one hand, highly detailed models like the Energy Exchange Model (EEM) provide the most comprehensive understanding of heating processes. They account for intricate details, allowing for highly accurate predictions. However, this complexity comes at a cost. Researchers need a deep grasp of the model's parameters, and the EEM demands significant computational resources to run simulations.

Conversely, simpler models like the CBM and the CEBM prioritize efficiency. Their straightforward nature makes them ideal for quick estimations or large-scale simulations. However, this simplicity can come at the expense of accuracy. These models might miss crucial details that more complex models capture.

The R-Beta model and MBM offer a compelling middle ground. They strike a balance between accuracy and complexity. The R-Beta model excels at capturing turbulence, while the MBM is well-suited for scenarios where the pressure relationship deviates from a fixed value. These models offer specific strengths without the overwhelming complexity of the EEM.

Ultimately, the best choice hinges on the specific research question at hand. If a balance between accuracy and computational cost is desired, the R-Beta model or MBM might be suitable. For quick estimations or large-scale simulations, the CBM or CEBM might be preferable. When a comprehensive understanding of heating mechanisms is crucial, the EEM remains the best option, despite its computational demands. By carefully considering the research question, computational resources available, and the trade-offs between complexity and efficiency, researchers can select the temperature model that best suits their specific needs.

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