Stellar Evolution in Active Galactic Nuclei (AGN) Disks

Introduction

The study of stellar evolution in Active Galactic Nuclei (AGN) disks presents an interesting perspective on how stars evolve within extreme environments, such as in the areas around supermassive black holes (SMBHs). These environments are "extreme" because surrounding an AGN is a highly energetic and dense region, caused by the SMBH accretes stellar material such as gas and dust onto itself, emitting intense heat and radiation. This circumstance vastly differs from a "normal" case for stellar evolution, creating opportunities for unique physical processes, lifetimes, and final states for stars within the AGN disks that have never been observed. This literature review focuses on stellar evolution in AGN disks, emphasizing the unique boundary conditions, accretion processes, and implications for our understanding of stellar physics.

Background: What is an AGN?

An AGN is a region at the center of a galaxy where a supermassive black hole ($M_{bh} \sim 10^{6-10} M\odot$) accretes surrounding stellar materials like gas and dust at a ferocious rate; thus forming a geometrically thin disk surrounding itself. This accretion process generates enormous luminosities and releases intense radiation across the electromagnetic spectrum. The intense spiral motion of matter near the SMBH can also generate a large, helical-shaped magnetic field that further accelerates particles and ejects them along the black hole's rotational axis, creating streams of outflowing jets. The luminosity from the AGN is so high that it often outshines its host galaxy over a wide range of wavelengths from radio to X-ray. However, not all SMBHs display AGN characteristics, as active accretion only occurs in a fraction of them (Kormendy & Ho, 2013).

AGN disks are extreme environments, known for their abnormally high temperatures, densities, and accretion rates. These factors create unique conditions for star formation and affect stellar evolution differently than in environments where stellar evolution is usually observed such as in the interstellar medium (Cantiello et al., 2021). Stars in the AGN disks can be formed in situ due to gravitational instabilities (which create supermassive stars due to the dense and hot environment) or are captured from nearby regions. Since these AGN disks are rich in accreted stellar materials, combined with the unique conditions, AGN stars' evolutionary paths are altered vastly from what is expected normally.

The Stellar Evolution Process in AGN Disks

Stellar evolution in AGN disks is characterized by high-rated mass accretion and mass loss thanks to the impact of the AGN accretion process, which distinguishes it from the typical stellar evolution where stars evolve in a vacuum. This section outlines the critical stages in AGN stars' evolution, including accretion mechanisms, internal mixing, mass loss, and boundary conditions.

1. Accretion and Mass Loss Mechanisms: AGN stars undergo rapid mass accretion, growing to as much as 100 $M_\odot$ due to experiencing enhanced mass accretion from the AGN disks (Cantiello et al., 2021). AGN stars accrete mass at a rate

$$\dot{M}_B = \eta\pi R^2_B \rho_{AGN} c_{s,AGN},$$

where η is an efficiency factor, ρ_{AGN} is the AGN disk density, $c_{s,AGN}$ is the local sound speed in the disk, and R_B is the Bondi radius of the star defined as

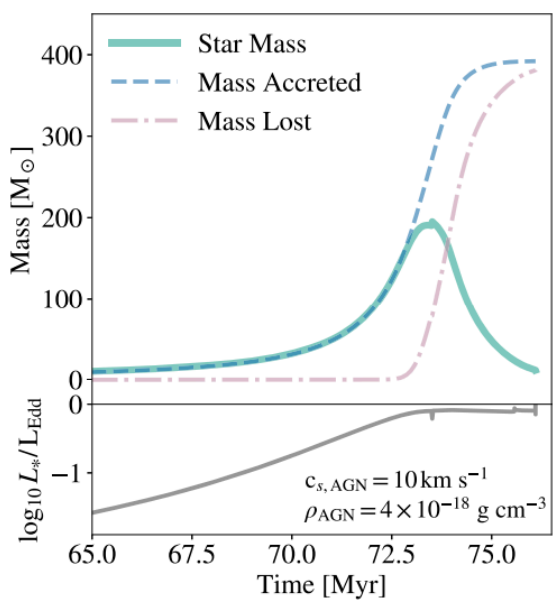
$$R_B = \frac{2GM_*}{c^2_{s,AGN}}.$$

The Bondi radius is the distance that defines the gravitational zone of influence around a celestial object. As shown in the equation above, the accretion rates are mainly influenced by local conditions, such as the disk density and local sound speed. The equation also speculates that the accretion rates follow the Bondi accretion mechanism, where accretion rates depend on the star's Bondi radius (Bondi, 1952).

For typical AGN conditions ($\rho_{AGN} = 4e - 18\ g\ cm^{-3}$, $c_{s,AGN} = 10\ km\ s^{-1}$), AGN stars can grow up to approximately 200 $M_\odot$ in only 73 Myr (Cantiello et al., 2021). However, as a result, these massive AGN stars soon approach the Eddington luminosity by the end of their lifetime. The Eddington luminosity is the threshold where radiation pressure balances gravitational pull. This leads to substantial mass loss through super-Eddington stellar winds, expelling the nuclear-processed material from the star into the AGN disk (Owocki & Shaviv, 2012). This balance between accretion and mass loss is the key characteristic of AGN stars' evolutionary pathway. Eventually, mass loss dominates accretion and strips the AGN stars down to ~10 $M_\odot$, as the stars undergo gravitational collapse. This often leaves them as compact remnants or black holes within the AGN disk (Cantiello et al., 2021).

2. Internal Mixing and Homogeneous Evolution: As the AGN stars accrete materials and become massive, they undergo extensive internal mixing. This occurs for several reasons. First, AGN stars are supermassive stars. As we have learned in class, high-mass stars have convective cores in the center and radiative envelope. This will make the stars' core well-mixed by convection. Second, the radiative envelope grows as the stars accrete more mass, which makes them highly radiation-dominated. Thanks to the unusual surface boundary conditions of the AGN disk environment, AGN stars become highly unstable, making even radiative regions prone to the mixing process (Cantiello et al., 2021). As a result, hydrogen mixes throughout the star, extending the hydrogen-burning phase and preventing typical compositional layering. This *quasi-chemically homogeneous evolution* leads to a continuous, nearly uniform composition throughout the star, distinct from the standard layered structure seen in stars on the Hertzsprung-Russell (HR) diagram (Maeder, 1987).

3. Boundary Conditions in AGN Stars: The evolution of AGN stars is heavily influenced by their unusual boundary conditions, which vastly differ from the typical stellar environments we have discussed in class. Since these stars are located within a dense and high-temperature AGN disk, they are constantly affected by extreme external pressures and heat from their surroundings. These conditions allow the stars to maintain high surface temperatures and pressures, resulting in increasingly unstable stars, and accelerating their internal mixing processes. The high-temperature environments also prevent standard cooling and contraction within the stars, halt the formation of distinct compositional layers, and sustain quasi-homogeneous evolution.



The figure above shows the mass budget and accretion versus the mass-loss rate of an AGN star at the temperature of 186K. This figure demonstrates the competition between mass accretion and mass loss, emphasizing the boundary conditions' role in shaping AGN stars' stellar evolution.

Comparison to Standard Stellar Evolution

In class, we mostly explored stellar evolution through the HR diagram and discussed the balance between nuclear burning and gravitational forces in stars. AGN stars diverge significantly from this standard model. Their stellar evolution is mostly driven by external accretion and mass-loss process due to super-Eddington winds. Combined with internal mixing, AGN stars completely derailed from the normal HR diagram's classical paths as compositional layers can no longer form. However, AGN stars can still achieve equilibrium at high masses once their accretion rate is roughly equivalent to their mass-loss rate. This will create "main-sequence" stars with masses far beyond what is usually observed (Goodman & Tan, 2004).

Outcomes and Remnants of AGN Stars

The study predicts that AGN stars will eventually undergo core collapse once their materials are stripped away from super-Eddington winds, producing compact remnants such as black holes. Some AGN stars reach masses up to 1000 $M\odot$ through *runaway accretion*, which occurs when mass accretion surpasses nuclear fusion. This runaway growth can lead to two outcomes: either the star will reach its Eddington luminosity and experience mass loss, or it will collapse directly into a black hole. The remnants of these AGN stars contribute to the population of compact matters such as black holes and neutron stars in galactic centers. These remnants could be potential sources for gravitational waves detectable by observatories like LIGO-Virgo (Cantiello et al., 2021).

Observational Signatures and Implications

Though AGN stars' evolutionary pathways are hypothetical, their predicted characteristics could explain observed high metallicities in some AGN environments, as mass loss from these stars enriches the AGN disk. Observationally, stars in AGN disks might be detected as luminous sources in infrared wavelengths due to the high temperatures of their environment. Furthermore, the compact remnants of AGN stars could potentially create gravitational wave events by colliding within the dense disk, radiating detectable signals and contributing to unique black hole mass distribution observed in AGNs (Cantiello et al., 2021; Kormendy & Ho, 2013).

Conclusion

Stellar evolution within AGN disks presents an interesting new possibility for the typical stellar processes we have learned in class. It is a very insightful look into how stars could evolve in different environments than just the vacuum of space. The intense accretion, rapid mass loss, and extensive internal mixing in AGN stars offer a broader view of traditional stellar evolutionary models. These stars are significant contributors to the metallic enrichment of AGNs and potential gravitational wave sources waiting to be discovered. Future observations of AGN environments, combined with the advancements in gravitational wave detection and infrared astronomy hopefully, will one day help verify the hypothetical predictions of this model, refining our understanding of stellar evolution under extreme conditions. I am excited to learn more about what we will uncover from future observations.

References

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