Shocks and Particle Energization in Supermassive Black Hole Coronae

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The recent identification of the Seyfert galaxy NGC 1068 as a source of high-energy neutrinos by the IceCube Neutrino Observatory presents a major challenge to standard high-energy astrophysical models. The detected neutrino flux, unaccompanied by a comparable flux of TeV gamma-rays, points to a particle acceleration environment that is transparent to neutrinos but opaque to gamma-rays: likely the hot coronal region surrounding the supermassive black hole (BH). However, the dominant particle acceleration mechanism in such environments remains established. Diffusive Shock Acceleration (DSA) has emerged as a leading candidate, particularly given recent observations indicating weak coronal magnetic fields (and thus a high plasma β environment unfavorable to magnetic reconnection).

This thesis investigates the microphysics of DSA in black hole coronae through a comprehensive suite of first-principles, one-dimensional Particle-in-Cell (PIC) simulations. We aim to resolve the critical uncertainty regarding the viability of DSA: specifically, whether shocks can accelerate protons to ~ 100 TeV with $\sim 10\%$ efficiency under realistic coronal conditions. To address the poorly understood regimes of low sonic Mach number (M_s) and non-equilibrium temperatures (The ion temperature and electron temperature are not equal, $T_i \neq T_e$), we systematically survey the parameter space of M_s, Alfvénic Mach number (M_A), shock velocity, and the temperature ratio T_i/T_e.

First, we demonstrate that quasi-parallel collisionless shocks are robust proton accelerators. We find that DSA consistently converts approximately 10% of the shock wave's kinetic energy into non-thermal ions. This holds true even in the low-Mach-number regime ($M_s \approx 2$), which was traditionally considered inefficient. Furthermore, we verify that the acceleration rates are sufficient to reach the requisite ~ 100 TeV energies, providing the necessary reservoir for hadronic neutrino production.

Second, we characterize the self-generated magnetic turbulence driven by non-resonant (Bell) and resonant streaming instabilities. Crucially, we link strong magnetic amplification to the suppression of primary electron acceleration. In regimes of high amplification, the shock front becomes locally superluminal, trapping thermal electrons and inhibiting their injection into the DSA cycle. We also found that if the initial T_e is sufficiently small compared to T_i, as expected in coronal plasmas, it can further reduce electron acceleration efficiency.

Third, we extend our analysis to pair-enriched plasmas, as positrons are expected secondary products of the hadronic cascade. By simulating positron-ion-electron shocks, we reveal a preferential acceleration of positrons relative to electrons. This deviation from standard electron-proton dynamics challenges the radiative models that assume identical behavior for both lepton species.

Finally, we discuss the multi-messenger implications of these micro-physical constraints. In particular, we examine the potential for neutrino production in BH coronae and the associated consequences of shock acceleration for the radiative spectra of leptons (electrons and positrons).