SUBRELATIVISTIC JET HEATING MECHANISMS

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ABSTRACT. Different physical processes, influencing the X-ray jet's thermal balance are considered. We focus on the problem of possible fast jet cooling via radiative losses. Thus, the contributions of each process to the jet thermal balance are calculated. We investigate the influence of shock wave propagation on jet heating, and the mechanism of jet kinetic energy transformation into heat via Coulomb collisions of jet and corona protons. Quantitative estimates are made for the case of Galactic microquasar SS433 based on previous results of the authors. The only important heating mechanism for this source turned out to be Coulomb collisions.

1. Introduction

Jets are quite frequent in the Universe and can have various sizes and shapes. Despite the fact that they were discovered decades ago, many questions regarding them remain unanswered. The main issues deal with jet formation, the mechanisms of jet collimation and heating. In the present paper we will focus on the last issue that requires jet thermal balance equation investigation. We consider the X-ray jet, i.e. the region close to the base of the jet, fully ionized, with temperatures around tens keV. Under these conditions the major energy loss mechanisms are bremsstrahlung and adiabatic expansion cooling. Jet temperature profile strongly depends on the bremsstrahlung to adiabatic losses ratio. In the case of SS433 we consider quite dense jet, surrounded by substantially less dense corona, emitting hard X-rays. It was demonstrated in [1] that the best fit of simulations to INTEGRAL data gives us jet to corona density ratio about 200 with only adiabatic cooling considered. But bremsstrahlung cooling at the bottom of the jet is several times greater than adiabatic cooling (about 3.5 times greater). In the absence of jet heating mechanisms it must lead to rapid jet cooling shifting the X-ray jet boundary closer to the bottom, in contradiction with observations. So, mechanisms supplying energy to the jet must be present to compensate for radiative cooling. Results of our detailed calculations of jet temperature profile, carried out in [2], are persented in Fig.1.

Here we investigate the most pronising, in our opinion, jet heating mechanisms: heating by shock wave energy dissipation generated at the bottom of the jet, heating by jet kinetic energy transformation into heat via jet and corona protons Coulomb collisions. Our calculations show the importance of the last mechanism in supporting the jet thermal balance only.

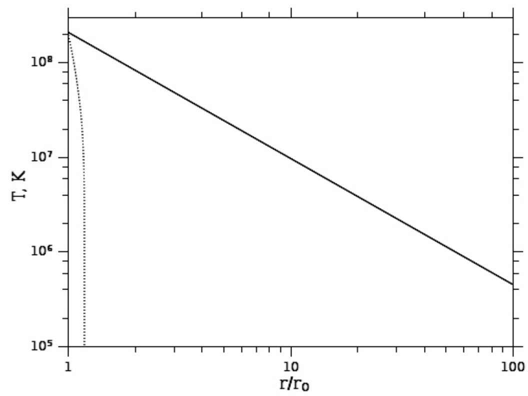

Figure 1. Jet temperature profiles without radiative cooling (solid line) and radiative cooling included (dotted line)

2. Heating by shock wave energy dissipation

Shock waves can be generated at the jet bottom by turbulent or convective motions. We will assume that a shock wave propagates along the jet generated at its bottom with given Mach number M. We have a stationary state, so we will assume a sequence of shock waves separated by given time interval. We will characterize this state by 'average' temperature T for this time interval. The value the time interval can be inferred from observations. For SS433 we set it to be equal to 1 second based on X-ray time variability observations [3]. We can write shock wave energy density balance equation governing the local Mach number evolution based on the fact that shock wave energy dissipates into heat behind shock wave front. Then we introduce shock wave heating term in the jet energy balance equation and obtain a system of two coupled equations for two unknown functions: temperature in the jet and local Mach number. We solved these equations numerically and obtained temparature and Mach munber profiles in the jet. The results of calculations for a shock wave originating at the bottom of the jet are presented in the Fig.2.

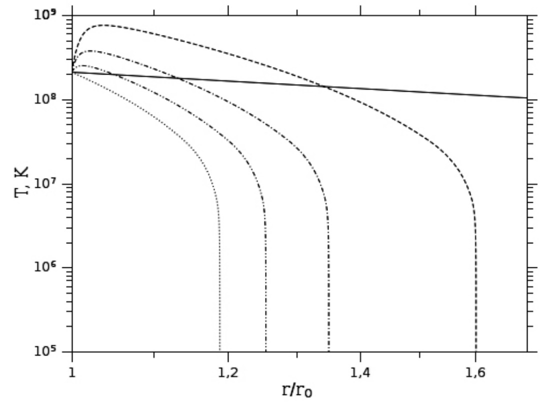

Figure 2. Jet temperature profiles with shock wave heating included. Dashed line corresponds to shock wave propagation with Mach number M=2, dash-dotted - to M=3, dash-dot-dotted - to M=5. Dotted line - temperature profile without heating, solid line — adiabatic cooling only.

It is clear that shock waves can heat the jet locally, near the place of generation. To heat the whole jet (up to 100r0) we need a system of shocks generated along the jet because of broad spectrum of initial perturbations or because of jet matter interaction with the surrounding medium. The last mechanism was mentioned in [4] to explain the heating of SS433 X-ray jet.

3. Proton-proton Coulomb collisions

Let us consider jet heating by Coulomb collisions of corona and jet protons. Thermal corona protons enter the jet where they serve as targets for jet protons moving at0.27c. As a result of scattering, jet protons lose part of their energy to corona protons thus transforming jet kinetic energy into heat. We estimate the maximum heating rate that can be produced by this mechanism as the number of protons with Maxwell distribution crossing unit surface per unit time multiplied by jet proton kinetic energy. We assume conical jet shape and corona and jet density profiles in the form of [1]. Then collisional heating to radiative cooling ratio at a distance equal to corona radius is maximal and equal to 34. This is the upper limit for this ratio because it is assumed that all jet kinetic energy is transformed into heat. Actually, jet is thin for corona protons with respect to Coulomb scattering, so collisional heating will reduce significantly if corona proton trajectory is straight line. But if magnetic field is present, proton trajectories are curved and they stay longer in the jet, increasing the effectiveness of collisional heating. Magnetic field of 0.13 mG is enough for proton gyroradius to be equal to jet radius [2]. In reality, magnetic field value B is several orders of magnitude greater, jet is thick for corona protons and collisional heating is effective. We do not know how magnetic field does vary with distance along the jet, so to model magnetic field radial dependence we introduce a phenomenological function a(r) characterizing the fraction of maximal hating rate in the collisional heating term. The results of calculations with collisional heating are presented in Fig.3.

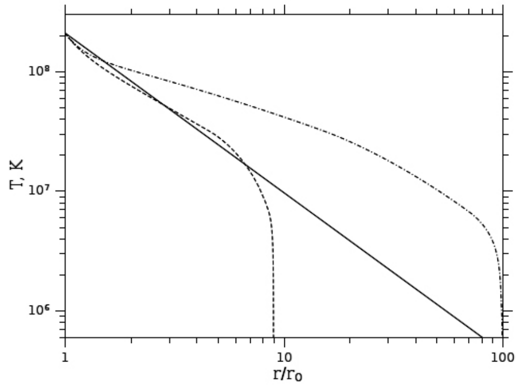

Figure 3. Jet temperature profile with radiative cooling and power-law collisional heating included. Power law index -3/2 (dashed line), -1.163 (dash-dotted line). Solid line — adiabatic cooling only.

It is clear from the figure that Coulomb collisions can heat the X-ray jet effectively. When jet temperature drops below 10 MK rapid cooling occurs because of significant increase of radiative losses. The dashed line in the figure explains the X-ray observations quite well [1], the dash-dotted line corresponds to excessive heating of the X-ray jet. Both cases require less than 1% of the jet kinetic luminosity conversion.

4. Conclusion

It was demonstrated that with radiative cooling taken into account in the jet energy balance equation using data obtained in [1] leads to fast jet cooling with distance. We have investigated possible jet heating mechanisms. Shock wave, propagating along the jet heat it locally, their energy is dissipated in a small interval close to their generation place. The whole jet can be heated by a system of shocks generated along the jet by broad spectrum of initial perturbations or by interaction of jet matter with the surrounding medium. The most promising mechanism of jet heating is jet kinetic energy transformation into heat by Coulomb collisions of jet and corona protons. In the presence of small magnetic field of about 0.1 - 1 G effective heating of the while X-ray jet region can be achieved requiring only a small fraction of jet kinetic energy flux (less than 1%). Because of that jet bulk motion speed decrease with distance due to heating is too small to be observable at the moment. More details about the calculations can be found in [2].

Reference:

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