STRUCTURE OF RADIATIVELY COOLED JETS

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Abstract. Radiative cooling strongly affects the thermal structure of dense jet, such as in SS433, through free-free emission. From the dynamical aspect, the beam width of a cooled jet does not expand, unlike from an adiabatic jet. From the thermal aspect, cooling efficiency determines the ratio of X-ray region of high temperature to optical one of low temperature. However, this ratio is influenced by the heating due to contained high-energy particles, which produce synchrotron radiation in the tail of the jet.

Extragalactic jets can also be considered in a similar way due to other energy loss mechanisms.

1. Introduction

The astrophysical jets are so slender that a mechanism of collimation would be working. Various mechanisms have been investigated until now; cocoon model of confinement by ambient gas, turbulent magnetic effect to cocoon model, line locking, coupling of magnetic field and rotation, and others (cf. Begelmann et al, 1984).

On the other hand, with respect to the thermal structure, astrophysical jets are composed of representative three regions; X-ray region of high temperature region, optical one of lower temperature, and radio tail of synchrotron emission. Therefore, it seems collimation mechnisms should act in any thermal situation, so that collimation mechanisms might correlate with thermal situation.

Then, from the aspect of formation of filaments or knots, thermal instability has been considered such that cooled filaments will appear in hot medium (Bode et al, 1985; Brinkmann et al, 1988; dal Pino et al, 1989). If a jet pass through vacume, however, we can expect contraction of cross section due to radiative energy loss even in thermally stable state.

2. Non-adiabaticity of Astrophysical Jets

In the case of SS433, the jet is relatively dense because no forbidden line is observed. Since free-bound emissions of hydrogen or line ones of oxygen are optically thick, dominant radiative cooling is free-free emissions. Then, the efficiency factor η of energy loss can be defined as the ratio of two time scales. One is the time scale t_p of passing a characteristic distance r_0 with the jet velocity V: $t_p = r_0/V$, where r_0 is likely a radius of an orifice. Another one is the cooling time scale t_c, given by c_pT/Q, where c_p and Q are the specific heat capacity and energy loss.

$$\eta = t_p/t_c = r_0Q/c_pTV$$

Since $Q \sim 5 \cdot 10^{20}\rho T^{1/2}$ for free-free emission and $V \sim c/4$, we get $\eta \sim 8.6 \cdot 10^{12}\dot{M}_{-6}/r_0T^{1/2}$, where $\dot{M}_{-6}$ means mass flux in unit of $10^{-6}M_{\odot}$/year. Hence, η

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of SS433 is around of 0.1, refered to the observational constraint (cf. Margon, 1984; Zwitter et al, 1990).

On the other hand, in the extragalactic case, radiative cooling is ineffective, because density is very thin. Then, synchrotron emission is possiblly effective(cf. Achterberg, 1989). However, heat conduction acts in effectiveness of $\eta \sim 1$. Moreover, relativistic nature has to play an essential role. Accordingly, the extragalactic case is not considered here.

3. Contraction of Radiatively Cooled Jets

To examine the cooling effect on jets, we set the situation where a jet flowes out vertically from horizontally layerd disk, the pessure of which steaply decreases, for example, as $exp(-5z/r_0)$. To compare a cooled jet with an adiabatic one, it is preferable to consider the steady state. Then, we will treat the steady hydrodynamical equtions, where all physical quantities are normalized by the values at the orifice, and vertical/radial distance by r_0. these equations include two basic parameters of the Mach number M and the cooling efficiency η.

We calculated the steady configuration of $M = 14.2$ and $\eta = 0.1$, by the method of characteristics (cf. Sanders, 1983). The results of two cases of adiabatic and cooled jets are shown in the figure.

3.1. The adiabatic jet

The so-called potential core is formed in the cone with the base of orifice, where all quantities keep the values of orifice, and stream lines keep vertically straight. Leaving the core, the jet expands rapidly, so that quantities decrease adiabatically. Although the core with high temperatureis observed as jet beam, the optical region of low-temperature tail would be not observed in the beam form.

3.2. The jet cooled by free-free emission

The potential core disappears because cooling let the temperature and pressure decrease. Consequently, the jet does not expand, keeping the high density near the orifice, as shown in the figure of density profile. From the observational aspect, the X-ray region is diminished and the optical one of low temperature is observable in the beam form.

In reality, there should be heating due to high energy particles, which collisionally ionize thermal gas. Accordingly, the fraction of high energy particles to normal gas determines the ratio of optical part to X-ray one. Then, these high energy particles emittes synchrotron radiation in the tail.

One of noted points is the horizontal stream, that appeared in both cases, which keeps the high velocity and contact tangentially to the static atmosphere of the disk. This stream should be unstable for the Kelvin-Helmholtz instability, in reality. Hence, turbulent gas would be blown off by this shear instability, emitting Balmer lines with broad line widths similar to the central lines of SS433. Nevertheless, this phenomena would not affect the central jetstream, differing from the case of coccon jet.

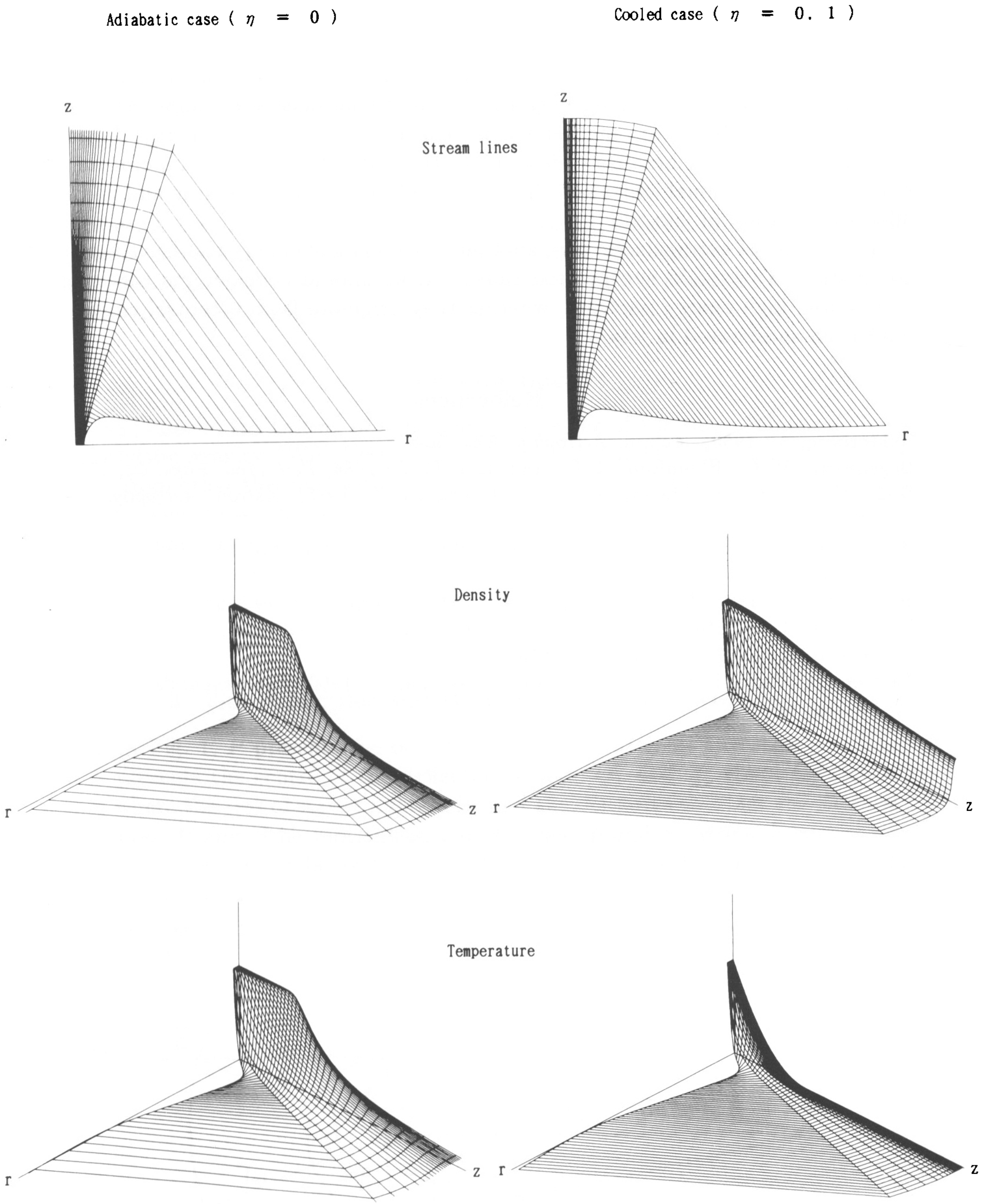

Fig. 1. Comparison between the adiabatic and the cooled case of $M = 14.2, \eta = 0.1$. Stream lines, density and temperature are shown. The scales of vertical z and radial r are in units of orifice.

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4. Conclusion

The cooling effect of free-free emission inhibits expansion of jets in such a way that the pressure of the potential core, that causes expansion, is diminished. Hence, any artificial mechanisms including magnetic or rotational effects are unnecessary for collimating jets. However, another effect of heating due to high energy particles should be considered, because it determines the state of the lower temperature region through collisional ionization. Hence, the relation between cooling and heating affects the nature of jets.

In the case of extragalactic jets, another mechanism of energy loss has to act for collimation. To explain synchrotron radiation, we should consider gas containing relativistic, high energy particles, whether they originate from a central engine or have been accelerated in jets.

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