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ARE THE OBSERVED FILAMENTS IN EXTENDED RADIO SOURCES DUE TO SYNCHROTRON RADIATION THERMAL INSTABILITIES?

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RESUMEN. Se estudia un modelo en el cual la estructura filamentaria observada en chorros y lóbulos de las fuentes de radio extragalácticas extendidas se produce por inestabilidades térmicas debidas a las pérdidas por efecto Compton sincrotónico inverso del plasma expandido, el cual se supuso que tiene dos componentes de gas (una componente térmica y una de partículas relativísticas). Se muestra que el valor mínimo de $\beta = P_o/P_{Mo}$ bajo condiciones isobáricas para el crecimiento de una inestabilidad térmica Compton sincrotónica inversa (ITS) es $\beta_m = 3/2\ (2\nu_e/3 + 2/\tau_c)/(-2\nu_e + 3(2\eta_o-1)/4\tau_c)$, donde P_o es la presión electrónica, P_{Mo} la presión magnética, ν_e la tasa de expansión transversal del chorro, τ_c es el tiempo radiativo de enfriamiento y $\eta_o = (1 + U_{pho}/P_{Mo})^{-1}$, en donde U_{pho} es la densidad de energía en el campo de radiación ambiente. La aplicación del modelo al chorro de CenA muestra que las condensaciones con contraste de densidad no lineales $\rho_p/\rho_o \approx 2$-8 se forman y parecen ser suficientes para explicar los filamentos brillantes observados, en donde $\rho_p(\rho_o)$ es la densidad en la región (ambiente) perturbada.

ABSTRACT. We study a model in which the filamentary structure observed in jets and lobes of extended extragalactic radio sources is produced by thermal instabilities driven by the synchrotron-inverse-Compton losses of the expanding plasma assumed to have two gas components (a thermal and a relativistic particle component). We show that the minimum value of $\beta = P_o/P_{Mo}$ under isobaric conditions for the growth of a Synchrotron-inverse-Compton Thermal Instability (STI) is $\beta_m = 3/2\ (2\nu_e/3 + 2/\tau_c)/(-2\nu_e + 3(2\eta_o-1)/4\tau_c)$, where P_o is the electronic pressure, P_{Mo} the magnetic pressure, ν_e the rate of transverse expansion of the jet, τ_c the radiative cooling time and $\eta_o = (1 + U_{pho}/P_{Mo})^{-1}$, where U_{pho} is the energy density of the ambient radiation field. The application of the model to the CenA jet showed that condensations with nonlinear density contrasts $\rho_p/\rho_o \approx 2 - 8$ are formed and appear to be sufficient to explain the observed bright filaments, where ρ_p (ρ_o) is the density at the perturbed (ambient) region.

Key words: PLASMAS — RADIO SOURCES-GENERAL — SYNCHROTRON

I. INTRODUCTION

Recent observational evidence of filamentary structure in radio jets and lobes of extended extragalactic radio sources (e.g., CenA, Clarke et al. 1986) are indications that thermal instabilities may play an important role in extended radio sources. A general discussion of the various types of thermal instabilities that can be relevant in astrophysical phenomena was first given by Field (1965) and subsequently by Simon and Axford (1967), Eilek and Caroff (1979), Marscher (1980), Bodo et al. 1985, and others. Recently, we performed linear and nonlinear analysis of the formation of the observed filamentary structure in extended extragalactic radio sources (Gouveia Dal Pino and Opher 1989a - GOI), in the Crab Nebula (Gouveia Dal Pino and Opher 1989b - GOII), and in superluminal sources (Gouveia Dal Pino and Opher - GOIII) by a thermal instability driven by the synchrotron-inverse-Compton losses of the relativistic flow. In this work, we summarize our main results obtained for the CenA jet and present new curves.

II. THE MODEL

A detailed description of our basic assumptions is given in GOI. We consider an expanding jet with an optically thin plasma in which the major part of the internal energy of the system is due to the relativistic electrons emitting synchrotron and inverse Compton radiation. A cold component, although containing a negligible internal energy, provides the major part of the mass density and inertia of the system. The magnetic field lines are assumed to be frozen into the plasma and parallel to the z-axis of the jet. The border of the jet describes a cone of constant average half-opening angle θ, such that the transverse velocity V_R of the border is given by $V_R = V_J \tan\theta$ and the radius is $R(t) = V_R t + R(o)$, where $R(o)$ is the jet radius at $t = 0$ and V_J is the velocity of the fluid along the jet axis. In our model, the volume element of plasma to be perturbed is a field-aligned cylinder moving with the expanding jet. We restrict the analysis to transverse perturbations to the magnetic field, since the growth of longitudinal perturbations tends to be inhibited by the thermal conductivity of the relativistic particles, which is very large parallel to the magnetic field. We separate out the ambient (equilibrium) and the perturbed quantities which we designate with subscripts "0" and "1", respectively. We assume that the heating rate per unit volume of the gas, the gain function G, is independent of the local physical parameters of the perturbed region (GOI).

For the evaluation of the energy losses of the plasma due to synchrotron radiation and inverse Compton losses of the relativistic electrons, L_{sc}, we assume (similar to Simon and Axford (1967)) that the distribution of the electrons is isotropic and given by a relativistic Maxwellian distribution characterized by an electronic pressure P. (Although we know that the emitted synchrotron radiation indicates a power-law distribution, what is primarily important is the ratio $3P/L_{sc}$, which defines the electron cooling time τ_c, and is the same for both distributions (GOI)). The total loss function for the relativistic electrons is thus

$$L_{sc} = \frac{8\pi\, c_s\, P_{Mo}\, P^2}{n\eta} \qquad (\text{ergs cm}^{-3}\ \text{s}^{-1}) \tag{1}$$

where $c_s = 1.89 \times 10^{-2}$ in cgs units, $\eta = (U_{ph}(t)/P_M(t) + 1)^{-1}$, U_{ph} is the energy density of the background radiation, $P_M = B^2/8\pi$ the magnetic pressure, and n the electronic number density.

III. LINEAR THEORY

The MHD equations of motion appropriate to the scenario described are given in GOI. Assuming cylindrically symmetric perturbations with cosine density profile (GOI) we first examine the effect of small perturbations on the plasma in the equilibrium state. Under isobaric conditions the linear equations of the perturbation have an analytical solution which results in the following condition in order to have a synchrotron-inverse-Compton driven thermal instability:

$$\beta \geq \frac{3}{2}\ \frac{2\nu_e/3 + 2/\tau_c}{-2\nu_e + 3(2\eta_o - 1)/4\tau_c} \tag{2}$$

where $\beta = P_o/P_{Mo}$, $\nu_e = V_J \tan\theta/R(t)$ is the rate of transverse expansion of the jet. Eq.(2) and Fig. 1 indicate that in the absence of inverse-Compton losses ($\eta_o = 1$) the growth of the condensation by thermal instability is more efficient than when they are present ($\eta_o < 1$).

IV. NONLINEAR THEORY

Because the linear theory does not permit a deduction of the true density enhancements, we performed a nonlinear study of the growth of the thermal instability. The nonlinear equations for the perturbed quantities are described in detail in GOI.

V. NONLINEAR RESULTS FOR THE CEN A JET

The model described above was applied to the inner 40" radio jet of Cen A where a complex filamentary structure has been detected in the region between knots A1 and A4 (Clarke et al. 1986). In order to follow the magnetohydrodynamic development of a perturbed region in the jet, we used as initial values for the ambient parameters (extracted from observational data): $R(0) = 2x10^{20}$ cm (radius of the jet in the region of the A1 knot), $\theta = 6^o$, $P(0) = 10^{-10}$ dy/cm^2, $L_{sco}(0)=10^{-21}$ ergs cm^{-3} s, V_J=5000 km/s, and $\beta(0)$=5.49 (Burns et al. 1983; GOI).

The nonlinear evolution of the density contrast between the perturbed and the ambient regions $\rho_p/\rho_o = (\rho_1 + \rho_o)/\rho_o$ (with initial density perturbations $\alpha_\rho = \rho_1(o)/\rho_o(o)$ = 0.05, 0.1, 0.2 and 0.3) is shown in Fig. 2, which corresponds approximately to the distance ($=V_J\Delta t$) between the knots A1 and A4. We note that the different initial perturbations produce the same maximum density contrast at $t \sim 2.0 \times 10^5$ yr. This maximum density contrast corresponds to an average contrast of the synchrotron emissivity of the condensed and adjacent regions L_{sp}/L_{so} = 10 (GOI) which is in reasonable agreement with the values inferred from the observed filaments. These results indicate that thermal instability appears to be sufficient to explain the filaments in the inner CenA jet.

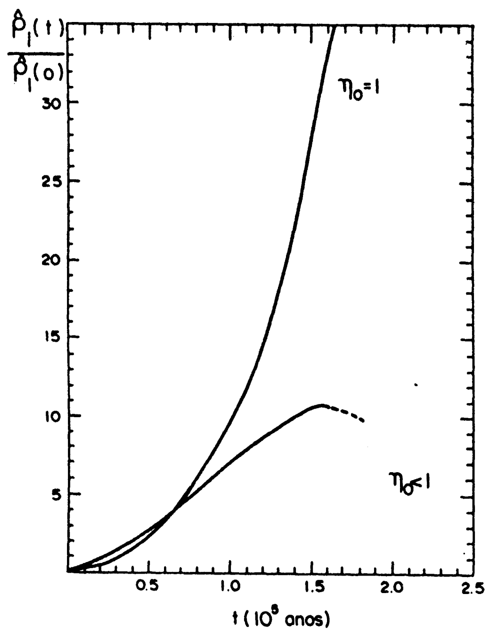

Fig. 1: Linear evolution of $\rho_1(t)/\rho_o(t)$ in the inner jet of Cen A for an initial density perturbation α_ρ $(\equiv \rho_1(0)/\rho_o(0)) = 10^{-5}$, and: a) η_o = 0.98 and b) η_o = 1.

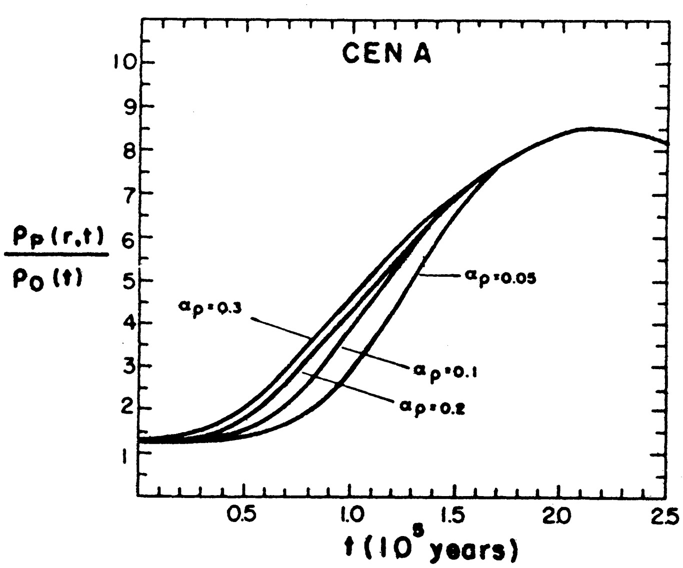

Fig. 2: Nonlinear growth curves of the total density contrast of the perturbed region $\rho_p/\rho_o (= (\rho_1+\rho_o)/\rho_o)$ in the inner jet of Cen A for initial density perturbations $\alpha_\rho \simeq$ 0.05, 0.1, 0.2, and 0.3.

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