# Matter content in AGN jets: constraint from cocoon dynamics?

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**Abstract.**
The matter content of jets in active galactic nuclei is examined in a new way. We model the dynamical expansion of its cocoon embedded in the intra-cluster medium (ICM). By comparing the observed shape of the cocoon with that expected from the theoretical model, we estimate the total pressure ($P_c$) and electron temperature ($T_e$) of the cocoon. The number density of the total electrons ($n_{e^-}$) is constrained by using the non-thermal spectrum of the hot spot and the analysis of the momentum balance between the jet thrust and the rum pressure of ICM. Together with the obtained $P_c$, $T_e$ and $n_{e^-}$, we constrain the matter content in the jets. We find that, in the case of Cygnus A, the ratio of number density of protons to that of electrons is of order of $10^{-3}$ . This implies the existence of a large number of positron in the jet.

## INTRODUCTION

The matter content in extragalactic jet is one of the primal issues for resolving the jet formation mechanism in active galactic nuclei (AGNs) [2]. However it has been a longstanding problem over the years, since it is hard to get the electromagnetic signal from the component such as *thermal electrons and/or protons* co-existing with non-thermal electrons. So far, at the sub-pc scale inner jet, mainly three approach have been proposed to constrain the plasma content in AGN jets. They are based on the (i) synchrotron self-absorption analysis [7, 12, 8], (ii) the observed circular polarization [17], and (iii) the constraint from the absence of bulk-Compton emission [14]. As a complementary approach, the constraints from the hydrodynamical interaction between the large scale jet (100kpc-Mpc) and intra-cluster medium (ICM) has been recently proposed [9]. In the proceeding, a new approach to constrain on the matter content is presented, by the combination of cocoon dynamics and non-thermal emission analysis at the hot spot (see Fig. 1).

## THE COCOON MODEL

Here we define a key parameter $\eta$ describing the degree of baryon loading

$$n_p \equiv \eta n_{e^-}, \tag{1}$$

where $n_p$ and $n_{e^-}$ are the total number densities of protons and electrons in the cocoon, respectively. The case of $\eta = 0$ corresponds to pure $e^\pm$ plasma while $\eta = 1$ corresponds

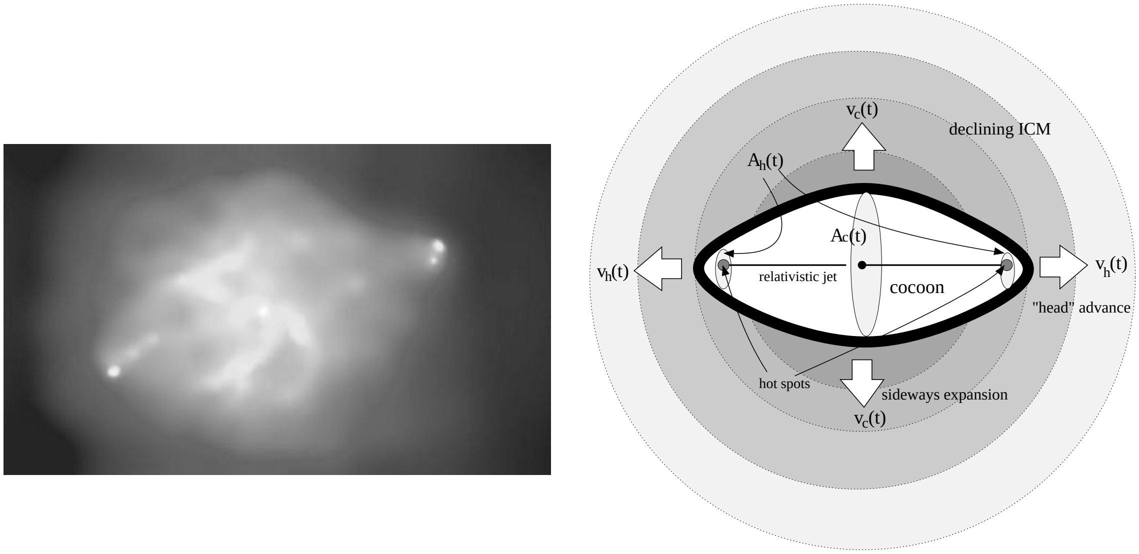


**FIGURE 1.** Left: X-ray image of Cygnus A by *Chandra* [16]. Right: A cartoon of the cocoon expansion in powerful FR II source [3, 10].

to the pure electron-proton plasma. The total number densities of positron is expressed as $n_{e^+} = (1-\eta)n_{e^-}$ by the charge neutral condition. The number density of non-thermal (hereafter "NT") electrons is written as $n_e^{\rm NT}$. Main assumptions in this work are as follows; (i) a jet velocity $v_{\rm j}(=\beta_{\rm j}c)$ is a relativistic one, (ii) the kinetic power $L_{\rm j}$ and mass flux $J_{\rm j}$ of the jet is constant in time, (iii) $L_{\rm j}$ is all deposited into the cocoon as the internal energy [13], (iv) the shocked matter pressure is dominated by thermal plasma, and (v) the electrons and protons are separately thermalized by shock heating and they become two temparature phase (i.e., $(T_e = \frac{m_e}{m_p}T_p)$ where $T_e$ and $T_p$ are the electron (and positron) temperature and proton temperature).

The time-averaged mass and energy injection from the relativistic jet into the cocoon, which govern pressure $P_{\rm c}$ and mass density $\rho_{\rm c}$ of the cocoon are written as

$$\frac{1}{\hat{\gamma}_c - 1}\frac{P_{\rm c}V_c}{t_{\rm age}} = T_{\rm j}^{01}A_{\rm j}, \qquad \frac{\rho_{\rm c}V_c}{t_{\rm age}} = J_{\rm j}A_{\rm j}, \tag{2}$$

where $\hat{\gamma}_c$, $V_{\rm c}$, $t_{\rm age}$, $T_{\rm j}^{01}$, $J_{\rm j}$, $A_{\rm j}$, are the adiabatic index of the plasma in the cocoon, the volume of the cocoon, the source age, the energy and mass flux of the jet, and the cross-sectional area of the jet, respectively. The condition of cold jet lead to $T_{\rm j}^{01} = \rho_{\rm j}c^2\Gamma_{\rm j}^2 v_{\rm j}$, $J_{\rm j} = \rho_{\rm j}\Gamma_{\rm j}v_{\rm j}$ where $\rho_{\rm j}$, and $\Gamma_{\rm j}$ are mass density and bulk Lorentz factor of the jet [4]. It is useful to define the ratio of "the volume swept by the unshocked relativistic jet" to "the volume of cocoon" which is written as $\mathscr{A} \equiv (A_{\rm j}v_{\rm j}t_{\rm age})/V_{\rm c}$. Here we set $A_{\rm j} = \pi R_{\rm hs}^2$ and $V_{\rm c} = (2\pi/3)\mathscr{R}^2 l_{\rm hs}^3$, where $R_{\rm hs}$, $\mathscr{R}$, and $l_{\rm hs}$ are the size of the hot spot, the aspect-ratio of the cocoon and the distance from the central core to the hot spot, respectively. Together with these basic equations and two temperature condition, we can express $T_e$, $T_p$, $n_e$, and

$n_p$ as

$$3\Gamma_j c^2 = \frac{kT_e}{m_e} = \frac{kT_p}{m_p}, \quad n_{e^-} = \frac{\Gamma_j \rho_j \mathscr{A}}{(2-\eta)m_e + \eta m_p}, \quad n_p = \eta n_{e^-}. \tag{3}$$

## CONSTRAINTS ON THE BARYON LOADING

In principle, we can determine $\eta$ if we know the value of $T_e$, $n_{e^-}$, and $P_{\rm c}$, since the sum of the pressures of electrons, positrons and protons is written as $P_{\rm c} = (n_{e^-} + n_{e^+})kT_e + n_p kT_p = (2-\eta)n_{e^-}kT_e + \eta n_{e^-}(m_p/m_e)kT_e$. Regarding $kT_e$, we have directly obtained the result of $kT_e = 3\Gamma_{\rm j} m_e c^2$ (in Eq. (3)). As for $P_{\rm c}$, we independently obtained it by solving the dynamics of cocoon expansion [10]. $n_{e^-}$ can be constrained with the aid of the observational property of the hot spot (see details in [9, 10]). In general, the number density of NT electron is smaller than that of total particles. From this, we can estimate the minimum value of the total electron as $n_{e^-,{\rm min}} = min[\Gamma_{\rm j} n_{\rm j,e^-} \mathscr{A}] \simeq 5 \times 10^{-5}(n_e^{\rm NT}/10^{-3}{\rm cm}^{-3})(\mathscr{A}/0.05)$ where $n_e^{\rm NT}$ is the number density of NT electrons in the hot spot. Here we used the relativistic shock junction between the jet and hot spot [5]. The upper limit of the number density of total electrons can be obtained by solving the balance between the thrust of the jet and the ram pressure of the ICM. The maximum $n_{e^-}$ corresponds to the case of pure $e^{\pm}$ plasma sustaining the ram pressure of the ICM. $n_{e^-,max} = max[\Gamma_{\rm j}\rho_{\rm j}\mathscr{A}/m_e] \simeq 1 \times 10^{-3}(\Gamma_{\rm j}/10)(\mathscr{A}/0.05)(n_{ICM}/10^{-2}{\rm cm}^{-3})$. Here the mass-density ratio can be estimated as $\rho_{\rm j,max}/\rho_{\rm ICM} = (\beta_{hs}/\Gamma_j)^2 \sim 10^{-4}$ (Eq. (8) in [9]).

In Fig. 2, we show the resultant $n_{e^-}$ and $n_p$ of Cygnus A. Based our study of Cygnus A [10, 11], we estimate the allowed range of $P_{\rm c}$ as $8 \times 10^{-10}{\rm dyn\ cm}^{-2} < P_{\rm c} < 4 \times 10^{-9}{\rm dyn\ cm}^{-2}$ is $P_{\rm c}$ (in gray-color) which is consistent with other estimate of [3, 6]. Since we do not have a consistent value of $n_{e^-}$ below $P_c = 8 \times 10^{-10}{\rm dyn\ cm}^{-3}$, the region below it is ruled out. It is useful to define the critical cocoon pressure as $P_{\rm c}^* \equiv max[2n_{e^-}kT_e] = 3 \times 10^{-8}{\rm dyn\ cm}^{-2}$. When $P_c > P_{\rm c}^*$ is satisfied, the baryon loading $\eta$ is determined by $\eta = (2m_e/m_p)(P_c - P_{\rm c}^*)/P_{\rm c}^*$. In other words, the baryon loading is inevitably required to support the cocoon. Furthermore, because of the condition of $n_p kT_p > (n_{e^-} + n_{e^+})kT_e$, “proton-supported” cocoon will be realized. Below $P_{\rm c}^*$, $\eta$ only has an upper limit such as $0 \le \eta < (2m_e/m_p)(P_c - P_{\rm c}^*)/P_{\rm c}^*$. We find that the Cygnus A corresponds to this regime and the baryon loading is $\eta \sim \mathscr{O}(10^{-3})$.

## SUMMARY AND DISCUSSION

The matter content of jets in active galactic nuclei is examined. The key point is that the quantities of $T_e$, $n_{e^-}$, and $P_{\rm c}$ can be constrained independently. By comparing theoretical model of cocoon expansion and observation, we constrain the $P_{\rm c}$ and $T_e$. The value of $n_{e^-}$ is constrained is constrained by using the non-thermal spectrum of the hot spot and the analysis of the momentum balance between the jet thrust and the rum pressure of ICM. Combining these quantities, we constrain the matter content in the jets. The analysis is

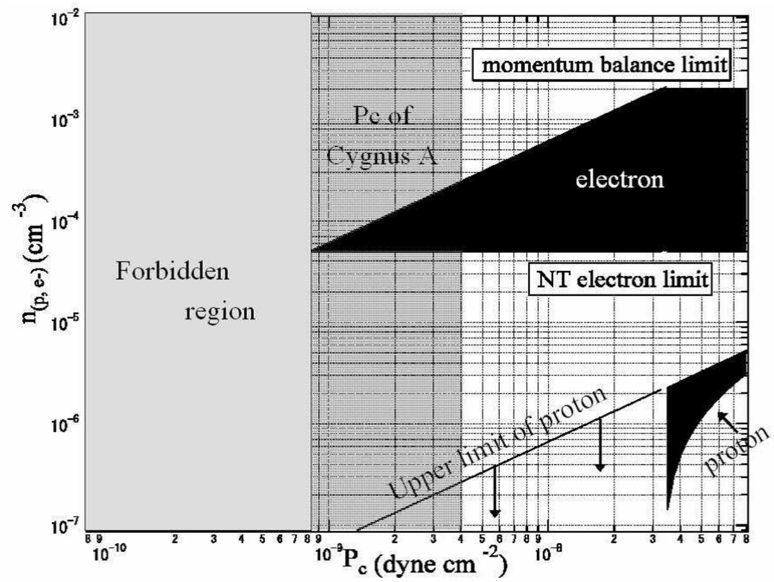


**FIGURE 2.** The number densities of electrons and protons in Cygnus A. The ICM pressure is estimated as $P_a = 8 \times 10^{-11}$dyne cm$^{-2}$ [1]. The proton number density is order of $\sim 10^{-3}$ of electrons.

focused on Cygnus A. We find that $\eta \sim \mathscr{O}(10^{-3})$ in the case of Cygnus A. As for the number density, this agree with the suggestion of larger number density of $e^- e^+$ plasma by [9, 14, 15]. Furthermore [14, 15] suggest that kinetic power of baryon is larger than that of leptons. We keep this as the important future investigation.

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