PROTON-PROTON COLLISIONS IN EXTRAGALACTIC RADIO SOURCES

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The majority of extragalactic radio sources are known to consist of two extended components straddling an optical galaxy or quasar with each component being maintained from the nucleus of the associated optical object through a beam or jet of relativistic plasma and magnetic fields. Hitherto, the energetics of radio source components have been considered essentially from the point of view of the cooling of the relativistic electrons through their interaction with ambient magnetic fields (synchrotron radiation) and with low energy photons (inverse Compton emission). Here we consider a hitherto neglected problem involving the mutual interactions between the fast particles themselves. (The results of a detailed investigation into these interactions will be reported elsewhere -- see Okoye and Okeke, 1982.)

We suggest that the beams or jets are essentially colliding nuclear beams involving high energy protons and electrons. At high energies, it is well known that proton-proton (p-p) collisions lead to pion emission. The pions, which are short-lived, quickly decay into muons which in turn quickly decay into electrons according to the following scheme:

$$pp \longrightarrow pp + \pi^+ \pi^- + \pi^0 \qquad (1a)$$

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu \qquad (1b)$$

$$\mu^- \longrightarrow e + \bar{\nu}_e + \nu_\mu \qquad (1c)$$

In the discussion which follows below, we shall attempt to show that the electrons produced in the above reaction will carry away a significant proportion of the energy of a typical colliding proton. Consequently, the p-p collision represents a plausible mechanism for high energy secondary electron injection into a radio source. It can be shown (see e.g. Rosser 1964) that the threshold energy for this reaction (i.e. p-p) to occur is 936 MeV in the rest frame of the beam or jet. Under the condition of a colliding pair of protons as would happen in a jet, hot spot or even radio lobe, the proton threshold energy (in the observer's frame) becomes $936\gamma_B$ MeV, where γ_B is the Lorentz factor associated with the beam. The total proton threshold energy is consequently $(936\gamma_B + 930)$ MeV. For non-relativistic beams,

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the threshold energy is $\sim$1.866 GeV. It is obvious from the above that the threshold energy is quite sensitive to assumptions made about the jet or beam (bulk) velocity. For example, for a highly relativistic jet, $\gamma_B \gg 1$, a very large threshold energy results which may be too high for the reactions (1) above to take place. According to current ideas, however (see e.g. Conway 1982; Readhead and Pearson 1982), the magnitude of the jet velocity is $\sim$0.2c-0.3c, at least for the nearby radio galaxies and quasars. This corresponds to a proton threshold energy of $\sim$2.19 GeV or a proton Lorentz factor, $\gamma_p \sim 2.4$. These values are reasonably low enough as to accommodate virtually the bulk of the energetic protons in a radio source in the p-p reactions.

We now turn to the issue of the proportion of the initial proton energy carried away by secondary electrons in the p-p interaction as described above. It is a straightforward matter to show from energy conservation considerations that the resulting new particles will carry away the following amounts of energy:

$$E_e / E_\mu \lesssim 103\gamma_e / 105\gamma_\mu \tag{2a}$$

$$E_\mu / E_\pi \lesssim 34\gamma_\mu / 140\gamma_\pi \tag{2b}$$

$$E_\pi / E_p \lesssim 2/3 \tag{2c}$$

where E_p, E_π, E_μ and E_e are the relativistic energies of the protons, pions, muons and electrons respectively. From (2a), (2b) and (2c) above we obtain

$$E_e / E_p \lesssim 0.15\,\gamma_e / \gamma_\pi \sim 0.15 \qquad \text{if } \gamma_e \sim \gamma_\pi \tag{3}$$

where γ_e, γ_μ, γ_π are the respective Lorentz factors of the electrons, muons and pions. Available radio source data suggest that electrons in the beam ejected from the galactic nucleii will have energies in the range, $1 < E_e/m_e c^2 < 10^5$. Assuming that the ratio of the proton to electron energies is similar to that found in cosmic rays (i.e. $1 < E_p/E_e < 100$), then the energy of the secondary electrons produced in the p-p collisions discussed above will be related to the energy of the original electrons ejected from the nucleus as

$$\gamma_e^s m_e c^2 \lesssim 15\gamma_e m_e c^2 \tag{4}$$

where γ_e^s is the Lorentz factor associated with the secondary electrons. Consequently, the p-p interactions constitute a plausible mechanism for the continuous injection of secondary electrons at various sites in an extragalactic radio source and covering roughly the same energy spectrum as the initial electron beam ejected by the galactic nucleii. If so, the need for electron reacceleration in the radio jet, hot spot and lobe, as recent observations demand, may become superfluous.

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