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AN OPTICALLY-THIN, STRONG MAGNETIC FIELD MODEL FOR THE ENERGY DISTRIBUTION AND TIME-VARIABILITY OF BLAZARS

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RESUMO: A forma do espectro e as escalas de tempo de variabilidade de "blazars" são interpretados em termos de um modelo opticamente fino de radiação sincrotônica, no qual os elétrons são injetados na fonte na forma de pulsos de alta energia, e se propagam através do espectro de energia devido às perdas de energia por radiação. A escala de tempo de variabilidade, observada em qualquer comprimento de onda, é igual ao tempo de perda de energia por radiação sincrotônica. O modelo requer campos magnéticos da ordem de 10 a 100 gauss.

ABSTRACT: The energy distributions and time-scales of variability of "blazars" are interpreted in terms of an optically thin synchrotron radiation model, in which the electrons are injected into the source in the form of high-energy bursts, and flow down along the energy spectrum due to radiation loss. The time scale of variability observed at any wavelength is the time for synchrotron-radiation decay of electron energy. The model requires magnetic fields of the order of 10 - 100 gauss.

Key words: active nuclei, synchrotron radiation

I. INTRODUCTION

The term "blazar" has been recently introduced in the literature (e.g. Gear et al., 1984), to designate highly compact and variable sources, associated with QSOs, BL Lac objects or nuclei of Seyfert galaxies. Common characteristics of these objects are the presence of jets and superluminal motions (Cohen et al. 1979), large and variable polarization, and an energy distribution which is flat in the radio region and gradually steeps to $\alpha \simeq 0.7$ in the near-infrared-optical region. These similarities can be understood from the fact that the synchrotron radiation of the compact cores of the objects dominates the whole spectrum, so that the nature of the underlying galaxy is of secondary importance.

A widely accepted model to explain flat radio spectra, like those of blazars, first proposed by Kellermann and Pauliny Toth (1969), supposes that the emission originates in a number of homogeneous components which reach their maxima at different frequencies, due to differences in frequency of self-absorption. A variant of this model (e.g. Condon and Dressel, 1973) considers a single but inhomogeneous source. These models receive some support from the traditional interpretation of the time scales of variability, which associates fast variability to small compact components ($R \lesssim C\tau$), since observation of different time scales of variability at different wavelengths seem to confirm the existence of several components.

We discuss in this work a model which does not make use of a combination of regions of different opacities to reproduce the spectrum. The whole emitting region is considered to be optically thin, so that the spectrum is only related to the energy distribution of the electrons, and the geometry is not relevant. The energy distribution of electrons which reproduces the radiation spectrum of a blazar, which is distinct from a power law, can be obtained from high energy injection of the electrons into the source, followed by energy loss by synchrotron radiation. We consider that the time scale of variability of the objects is the time-scale for decay of electron energy by radiation loss. We also discuss some interesting implications of our model.

II. THE ENERGY DISTRIBUTION

A single relativistic electron with Lorentz factor γ, in a magnetic field B (gauss) and with pitch angle ε looses energy at a rate (e.g. Tucker, 1975):

$$\frac{d\gamma}{dt} \simeq -2.0\ \gamma^2 B^2 \sin^2 \varepsilon \qquad (1)$$

The single electron spectrum is strongly peaked at the frequency:

$$\nu_m \simeq 3 \times 10^6\ B\ \gamma^2 \sin \varepsilon \quad \mathrm{Hz} \qquad (2)$$

and the characteristic time of energy decay is:

$$\tau \simeq \gamma/(d\gamma/dt) \simeq 8 \times 10^{11}\ B^{-3/2}\ \nu_m^{-1/2} \sin^{-3/2} \varepsilon \qquad (3)$$

If the relativistic electrons are injected into the source at high energies at a constant rate, and subsequently flow down along the energy spectrum, the conservation of electron flow in a stationnary condition ($\frac{dN(\gamma)}{dt} = 0$) gives $N(\gamma) \propto \gamma^{-2}$, and the resulting spectral index of the radiation is 0.5. We reproduce in fig. 1 the spectrum of the typical blazar 0735+178, from simultaneous multifrequency measurements by Bregman et al. (1984). We note that $\alpha \simeq 0.5$ is the spectral index of the far infrared region

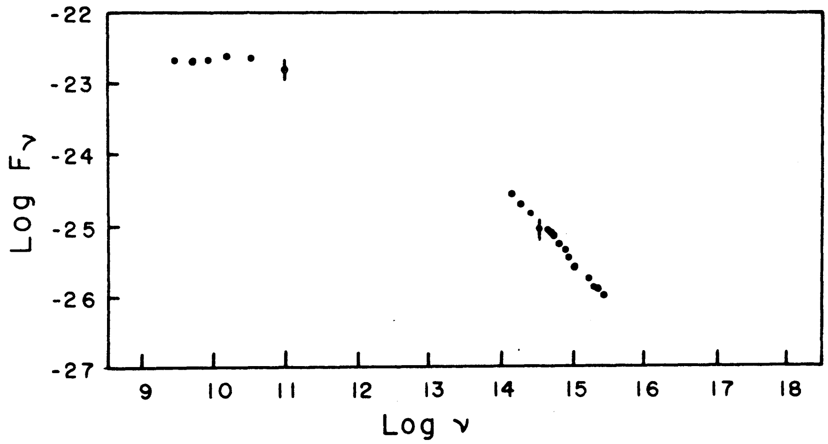

Fig. 1 - The spectrum of the blazar 0735+178, from simultaneous measurements made by Bregman et al. (1984).

of the spectrum; we must therefore explain both the steeper indexes at shorter wavelengths, and the flatter spectra at radio wavelengths. Equation (1) suggests two possibilities which result equivalent to $\frac{d\gamma}{dt} \propto - \gamma^k$ with $k > 2$: a) the effective magnetic field may decrease as γ decreases, as the electrons move away from the injection region, and b) the electrons may be injected at almost right angles to the magnetic field and evolve to smaller pitch angles. On the other hand, there is a straightforward explanation to the flat spectrum at radio wavelengths: at low electron energies, the synchrotron losses given by equation (1) become very inefficient, and are overcome by expansion losses. A possible solution in the case of uniform expansion is $\frac{d\gamma}{dt} \propto - \gamma/t$ (Tucker, 1975), which implies a flat energy spectrum and $\alpha \simeq -0.5$ for the radiation spectrum; $\alpha \simeq 0$ can easily be obtained if the expansion is not uniform.

III. TIME VARIABILITY

If the injection of relativistic electrons into the source takes place in the form of a series of bursts, instead of the steady process considered in the previous section, excesses of electron densities $N(\gamma)$ appear at a number of energies, corresponding to individual bursts. These density excesses propagate to lower energies due to radiation loss, and their corresponding humps in the radiation spectrum move towards longer wavelengths. The variability observed at a fixed wavelength is the result of the passage of successive humps; both rise time and decay time of the fastest events must be of the same order of the characteristic time of energy decay given by equation 3. We suppose that the fluctuations in the injection rate span a large range of time scales (at least from days to years); the characteristic time of energy decay $\tau(\lambda)$ acts like a filter which does not allow fluctuations faster than it to propagate to longer wavelengths. The phase-lag between two variability curves obtained at reasonably different wavelengths must be of the order of τ estimated at the longer wavelength.

We next compare the above predictions with the observed properties of variability curves. Many blazars have been monitored for several years at optical wavelengths (e.g. Usher et al., 1974; Pollock et al., 1979, Pica et al., 1980, Barbieri et al., 1982); they usually show short-term flickering with about 10% amplitude and time-scales of days, as well as longer term variations. Many of the same objects were monitored at radio wavelengths, by Andrew et al. (1978) at 6.7 GHz and 10.7 GHz, by Dent and Kojoian (1972) at 7.8 GHz, by Dent et al. (1974) at 15 GHz, and by Landau et al. (1980) at 90 GHz; typical time-scales of variations are about one year. No monitoration has been made at near-infrared wavelengths, but some estimates of the infrared time-scales of variability are provided by Lepine et al. (1985).

We first remark from optical and radio variability curves that statistically the rise time and decay time of events are similar. That could not be so if the electrons were also injected at low energy into the source (like a power law injection energy distribution) since in that case the rise time of events would depend on the injection mechanism, while the decay time would be that of radiation loss. In the case of 0735+178, which is one of the best studied blazars, the shortest time-scales ($\tau = \frac{d \ln F_\nu}{dt}$) observed are about 2 years at 15 GHz, 2-3 weeks in K (2.2 μm) and 1 week in B, which is in reasonable agreement with the $\nu_m^{-1/2}$ dependence in equation (3), and implies a magnetic field of about 30 Gauss.

The phase lag between radio and optical variability curves is difficult to be measured, for the following reasons: 1) it requires long-term monitoration at both frequency ranges; 2) the radio curves are smoothed by the filtering effect already mentioned, and 3) when many events of similar amplitude are present, the correspondence between optical and radio events may not be clear. Nevertheless a few cases have been well studied. Pomphrey et al. (1976) concluded from a cross-correlation analysis of the variability curves of 0336-019 that the phase-lag of the 2.8 cm radio emission with respect to the optical curve was one year. The investigation at many wavelengths of a proeminent event which occured in the BL Lac object OJ 287 (Usher, 1979) showed the maximum of the event at 3.5 mm to be delayed about 6 months with respect to the optical maximum, while the 2.8 cm radiation was delayed about 18 months. These numbers are in agreeemnt with the $\nu^{1/2}$ dependence of the phase lag.

IV. DISCUSSION

The optically thin model of synchrotron radiation that we discussed, in which the electrons are injected into the emitting region at high energies in the form of bursts, can explain both the energy distribution and wavelength dependence of variability of blazars. The magnetic field, rather than the size of the source, is directly derived from the time-scale of variability. In the case of 0735+178, we obtain B $\simeq$ 30 gauss; if we consider the source moving toward the observer with a bulk Lorentz factor $\Gamma = 10$ with respect to an external medium at $z = 0.424$, the estimated magnetic field in the reference frame of the source is increased by a factor of 14.

Our interpretation of the variability allows us to put some restrictions to the injection mechanism. Since the radiation of 0735+178 is strongly variable in the U band, but the X-ray emission is not variable within the observational limits (Bregman et al., 1984), the injection energy must be about 10 Gev, so that the corresponding ν_m is in the range of 10^{16} - 10^{17} Hz, between UV and X-rays. The X-ray emission, in this case, is attributed to inverse Compton scattering of radio frequency photons. In the above hypothesis, the source being moving toward the observer with $\Gamma = 10$, the required injection energy would be less than 1 Gev. If the injection energy corresponds to $\nu_m \simeq 10^{16} - 10^{17}$ Hz, the 10-15% flickering on time-scales of a day observed in the B band must be reminiscent of 100% fluctuations at the injection energy, filtered by the synchrotron decay time. We conclude therefore that there are some evidences that the electrons are injected into the emitting regions in the form of pulsed beams with energies of the order of Gevs, the duration of individual pulses being a day or less.

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