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Coherence Inherent in an Incoherent Synchrotron Radio Source

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Abstract. We show that a partial coherence due to antenna mechanism can be inherently present in any compact synchrotron source, which resolves many long-standing problems in the spectra and variability of compact extragalactic radio sources.

Key words. Galaxies: active—quasars: general—radiation mechanisms: non-thermal—radio continuum: general.

1. Introduction

It is well known that synchrotron radiation mechanism does not allow MASER type coherent emission (Pacholczyk 1970). Here we show that coherence can naturally occur in a synchrotron case by the antenna mechanism, without any need of a specific mechanism to form localized bunches of like charges.

In a synchrotron source, the radiated power lies in a cone of opening angle $\sim 1/\gamma$ about the instantaneous direction of motion of the charge. Thus only charges contributing effectively to the radiation at any instant are the ones that are moving within a narrow angle $\psi \sim 1/\gamma$ with respect to the line-of-sight to the observer. All other charges can be ignored, and can be treated as if they are not there, for the purpose of radiation towards the observer at that instant. One then effectively sees a 'sea of parallel moving charges' in the direction towards the observer.

Even in an overall neutral plasma the radiation fields of parallel moving electrons and positrons do not cancel each other. The electric field of a charge e, gyrating with acceleration $\dot{\boldsymbol{\beta}} = e\boldsymbol{\beta} \times \mathbf{B}/mc\gamma$ in a magnetic field $\mathbf{B}$, is given by

$$\mathbf{E} = \frac{e^2}{mc^2}\left[\frac{\mathbf{n} \times \{(\mathbf{n} - \boldsymbol{\beta}) \times (\boldsymbol{\beta} \times \mathbf{B})\}}{\gamma R(1 - \boldsymbol{\beta} \cdot \mathbf{n})^3}\right]_{\rm ret}, \tag{1}$$

which is independent of the sign of the charge.

2. Coherence volume and the number densities

As all quantities within the square brackets in equation (1) are at the retarded time, and the synchrotron radiation at the observer's location consists of a series of narrow pulses of duration $\sim\lambda/c$, the pulse windows of the two charges will overlap (with

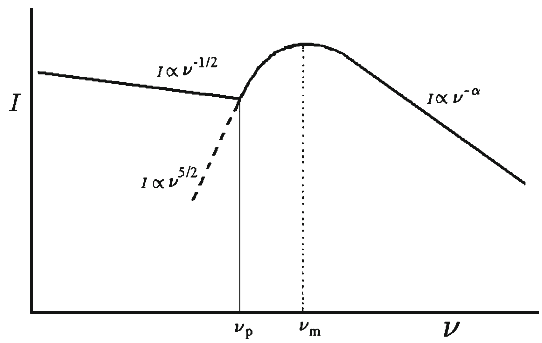

Figure 1. Synchrotron spectrum modified due to coherence.

Fourier components adding in phase) only if their projected distance along the line of sight $d \lesssim \lambda$. Thus for coherence to occur there has to be more than one charge lying within a region of length $\sim\lambda$, radiating in phase towards the observer. The lateral width W of the coherence volume for charges radiating in a cone of opening angle $\psi \sim 1/\gamma$, can be calculated from the condition $W\psi \sim \lambda$ or $W \sim \gamma\lambda$. The coherence volume will be in the shape of a chapati[1], with a thickness λ and a lateral cross-section $\pi W^2 \sim \pi\gamma^2\lambda^2$, implying a coherence volume $V_c \sim \pi\gamma^2\lambda^3$. A somewhat more rigorous approach yields $V_c \sim \gamma^2\lambda^3/\pi$ (Melrose 1992).

We can make an order of magnitude estimate of M, the number of particles in the coherence volume, by noting that near the spectral turnover, where $T_b \sim 10^{11.5}$ K, there is an equipartition of energy between particles and magnetic fields (Singal 1986, 2009). Also this is the region where the energy density of photons, W_p, approaches that of magnetic fields (Kellermann & Pauliny-Toth 1969). Then

$$W_p = \frac{4\pi}{c}\int I_\nu \, d\nu \approx \frac{4\pi}{c} I_m \, \nu_m = \frac{8\pi}{c^3}\, kT_m \, \nu_m^3. \tag{2}$$

One can get the number density of radiating charges $Nmc^2\gamma \approx W_p \approx 8\pi kT_m/\lambda_m^3$, and with $3kT_m \sim kT_e = mc^2\gamma$, we get $N \sim 8\pi/3\lambda_m^3$. However out of these only $1/4\gamma^2$ charges will be radiating towards the observer. To compute the number of charges that may be radiating coherently we multiply this number with the coherence volume V_c, to get $M \sim (2/3)(\lambda/\lambda_m)^3$. Thus we see that though near the spectral turnover $\lambda \sim \lambda_m$ there may hardly be any coherence, it could become increasingly effective at longer wavelengths because $M \propto \lambda^3$.

There may be an order of magnitude uncertainty in our estimates of M near the spectral turnover. For one thing we have not taken into account the spread in γ and might have thereby somewhat over-estimated M. However, since the λ^3 dependence of M still remains valid there will be a certain wavelength $\lambda_p > \lambda_m$ where M will become unity. The partial-coherence frequency $\nu_p = c/\lambda_p$, lying within the optically thick region (Fig. 1), then divides the synchrotron spectrum into an incoherent

[1] A thin flat circular unleavened Indian bread.

region (for $\nu > \nu_p$) where $M < 1$ with the maximum brightness temperature limited by $\sim 10^{11.5}$ K, and the partial-coherence region ($\nu < \nu_p$ or $\lambda > \lambda_p$) where coherence can give rise to much high brightness temperatures with the coherence factor $M = (\nu/\nu_p)^{-3}$ or $(\lambda/\lambda_p)^3$. As the incoherent brightness temperature limit of $\sim 10^{11.5}$ K occurs around ν_m, we may find much higher brightness temperatures at lower frequencies (depending upon ν/ν_p). This could then explain the high brightness temperatures observed by the space VLBI (Linfield *et al.* 1989; Frey *et al.* 2000; Horiuchi *et al.* 2004).

3. Flat spectra – A cosmic conspiracy!

A large number of compact unresolved, and presumably self-absorbed sources show spectra which are flat ($\alpha \lesssim 0.5$), from mm to metre wavelengths (see Owen *et al.* 1980). The observed spectra hardly ever show a theoretical slope of -2.5, and generally show a complex structure with an average slope close to zero. It is generally thought that this could be due to superposition of self-absorbed spectra of multiple components within the volume that gives rise to such a flat spectrum. The curious fact that distributions of the intensities and the turnover frequencies of the multiple components almost always 'conspire' to yield about zero spectrum slope has been sometimes called in the literature a 'cosmic conspiracy' (Cotton *et al.* 1980). Although one cannot rule out the presence of such multiple components in some individual cases, this cosmic conspiracy is resolved more naturally when coherence is invoked. Due to coherence, the maximum possible brightness temperature will get enhanced above the kinetic temperature T_e of individual particle by a factor M. Starting from the turnover point λ_m as we go to higher wavelengths, initially for $M \lesssim 1$ the spectrum may be that of an incoherent source ($I \propto \lambda^{-2.5}$) and the fall in intensity may continue up to λ_p but then the intensity will start rising with $M \propto \lambda^3$ making the intensity vary as $\lambda^{0.5}$ or $\nu^{-0.5}$ (Fig. 1). Thus the partial coherence can explain not only the non-observance of the spectral slope of -2.5, but also why a flatter value, 0.5, is seen observationally, a fact that has hitherto remained without a viable theoretical explanation.

4. A simple model for variability

We envisage a simple scenario for variability where a large number of additional charges are injected into the radiating region. Depending upon the ratio λ/λ_p, which could be $10 - 10^3$, we can get very large brightness temperatures, with coherence factors $\sim 10^{2.5-7.5}$.

The synchrotron half-life time of an electron is $t_{1/2} = 16\,\gamma^{-1}B^{-2}$ years and with $\gamma \sim 10^{2.5}$ and $B \sim 10^{-2.5}$ Gauss, we get $t_{1/2} \lesssim 10^4$ years. In the case of coherence $t_{1/2}$ will be shortened by the coherence factor $\sim 10^{2.5-7.5}$. Thus depending upon case to case, the electrons could lose energy in less than a day to years, which fits with the observed variability time scales.

For high brightness temperatures arising out of a coherent phenomenon, not only the synchrotron losses go up, but also the inverse Compton losses go up by the same factor, so the ratio of the inverse Compton and the synchrotron losses remains unchanged. That means one can expect a sort of correlation in radiation from inverse Compton (i.e., at optical or X-rays) and coherent synchrotron losses, since many more radio photons now become available for inverse Comptonization. This seems to be in accordance with the correlation observed in optical X-rays and radio variability (Wagner & Witzel 1995).

5. Conclusions

We have demonstrated that in a synchrotron radiation source there exists a certain partial-coherence frequency ν_{p}, its value depending upon the number density in the source, which divides the spectrum into two distinct regions – an incoherent region for $\nu > \nu_{\mathrm{p}}$ where emission is that of the usual incoherent synchrotron source, and a partial-coherence region at $\nu < \nu_{\mathrm{p}}$ where the emission would be higher by the coherence factor $(\nu/\nu_{\mathrm{p}})^{-3}$. This principle of partial coherence in a synchrotron radiation resolves a large number of long-standings problems of observed spectrum, variability and high brightness temperatures beyond the theoretical limit.

References

Cotton, W. D. *et al.* 1980, *Astrophys. J.*, **238**, L123.
Frey, S. *et al.* 2000, *Pub. Astr. Soc. Japan*, **58**, 217.
Horiuchi, S. *et al.* 2004, *Astrophys. J.*, **616**, 110.
Kellermann, K. I., Pauliny-Toth, I. I. K. 1969, *Astrophys. J.*, **155**, L71.
Linfield, R. P. *et al.* 1989, *Astrophys. J.*, **336**, 1105.
Melrose, D. B. 1992, *Philos. Trans. R. Soc. London*, **A341**, 105.
Owen, F. N., Spangler, S. R., Cotton, W. D. 1980, *Astr. J.*, **85**, 351.
Pacholczyk, A. G. 1970, *Radio Astrophysics* (Freeman, San Francisco).
Singal, A. K. 1986, *Astron. Astrophys.*, **155**, 242.
Singal, A. K. 2009, *Astrophys. J.*, **703**, L109.
Wagner, S. J., Witzel, A. 1995, *Ann. Rev. Astr. Astrophys.*, **33**, 163.