A 'SINGLE ELECTRON' SYNCHROTRON RADIATION MODEL AND THE QUASI-STELLAR OBJECTS

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Abstract. In this synchrotron radiation model, the essential feature is that the basic form of the theoretical continuum is a characteristic of the energy evolution of a single electron. The model may be applied to sources containing high magnetic field regions where electrons have radiation lifetimes short compared with typical observation times; the electrons are generated in condensations of material which also amplify magnetic fields to values required for the emission of optical synchrotron radiation. A more specialized version of the model can provide a description of the QSOs that is consistent with their cosmological interpretation.

The optical radiation continua of the QSOs may be represented by $F(\nu) \propto \nu^{-n}$. The usual explanation for a spectral index of any given value is that it results from synchrotron radiation, in a uniform magnetic field, by electrons having a power-law energy spectrum with an index directly related to n. We discuss here a theoretical model in which the particular values $n=\frac{1}{2}$ and $n=1$ can be given a completely different interpretation; the essential feature of the model is that the basic form of the theoretical continuum obtained is a characteristic of the energy evolution of a single electron (Falla, 1970).

The synchrotron radiation power spectrum, for an electron of energy γmc^2 in a magnetic field H, is described by the characteristic frequency

$$\nu_c = (3eH/4\pi mc)\,\gamma^2 . \tag{1}$$

For x defined as ν/ν_c, the power spectrum is given approximately by

$$P(\nu) \propto Hx^{1/3}, \quad \text{for} \quad x \leqslant \tfrac{1}{3}, \tag{2a}$$

and

$$P(\nu) \propto H \exp(-ax^{2/3}), \quad \text{for} \quad x > \tfrac{1}{3}, \tag{2b}$$

where a is a constant. The expression for the electron energy as a function of time,

$$\gamma = \gamma_0/(1 + \beta H^2 \gamma_0 t), \tag{3}$$

where γ_0 represents the initial electron energy and β is a constant, gives the radiation half-life for the electron as

$$t_{1/2} = (\beta H^2 \gamma_0)^{-1} . \tag{4}$$

The corresponding evolution of the synchrotron power spectrum can be represented by the variation of characteristic frequency with time,

$$\nu_c = (\nu_c)_0/(1 + t/t_{1/2})^2 \tag{5}$$

where $(\nu_c)_0$ is the value of ν_c for $\gamma=\gamma_0$.

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It is normally assumed that ν_c does not change appreciably over a given time interval Δt, which we take here to be the period of observation, so that the radiation continuum can be derived by combining the synchrotron power spectrum with the electron energy spectrum. We examine here the opposite situation, for which a significant change in ν_c occurs during the relevant time interval and thereby causes an appreciable evolution of the synchrotron power spectrum. We suggest that for the change in ν_c to be significant, $\Delta t \gtrsim t_{1/2}$. From the above equations, $t_{1/2}$ can be expressed in terms of H and ν_c for the observed radiation. In the radio region ($\nu_c \sim 10^9$ Hz), a magnetic field $H \sim 10^{-4}$ G gives $\Delta t \gtrsim 10^6$ yr: clearly, evolutionary effects are insignificant for an electron radiating in this region. In the optical region, however, larger magnetic fields may be expected to occur. For the QSOs 3C 273 and 3C 446, as discussed by Burbidge and Burbidge (1967), the existence of magnetic fields $H \sim 10$–100 G is required if these objects are to be given a cosmological interpretation, and if synchrotron radiation is to dominate that by the inverse Compton process. We find that these values of H give $\Delta t \gtrsim 10^2$–10^3 sec, which are time intervals that are comparable with photographic plate exposure times, so that in this case our condition for a significant evolutionary effect is fulfilled. The same applies to the low-energy X-ray region, for which magnetic fields of the same orders of magnitude give $\Delta t \gtrsim 1$–10 sec, which are time intervals that are certainly exceeded in X-ray photon detection.

For electrons in high magnetic fields, the radiation mean free paths are short compared with the estimated dimensions of the objects: electron generation *in situ* is therefore required. We consider pion decay to be the principal source of these electrons. Pions of low energy ($\lesssim 100$ MeV) produce decay electrons with a most probable energy given by $\gamma_0 = 75$; these electrons radiate in the optical region if magnetic fields $H \sim 10^4$–10^5 G are available, and have $t_{1/2} \ll 1$ s.

We consider, for one of these decay electrons, an evolving power spectrum of the

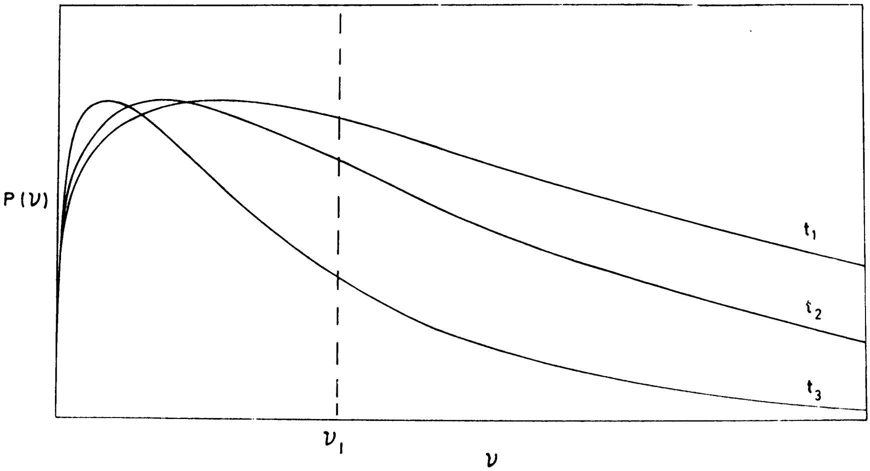

Fig. 1. Power spectra at times t_1, t_2, and t_3 from Equations (2).

form (2), in which ν_c changes with time according to (4) and (5): the evolutionary effect is illustrated in Figure 1, in which the power spectrum is shown for successive moments of time t_1, t_2, and t_3. The total radiation continuum has been derived by taking the frequency ν as an independent parameter and at each of its values, (for example, ν_1 in Figure 1), computing the integral of the evolving power spectrum over the whole radiation lifetime of the electron. Figure 2(a) shows the radiation continuum

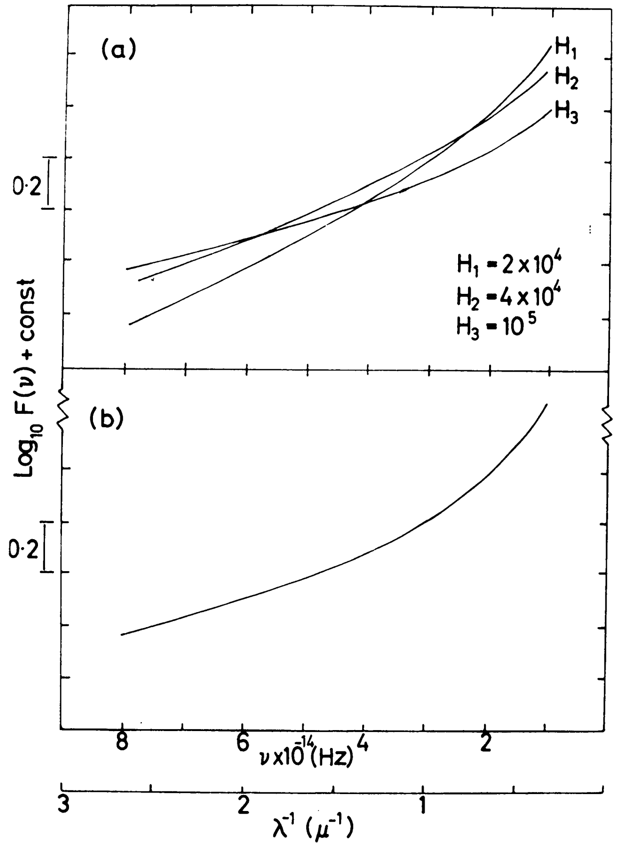

Fig. 2. (a) Single electron radiation continua. (b) Locus of maxima for optimum H.

for the optical and near infrared regions, computed for $\gamma_0 = 75$, for several magnetic field values in the range from 2×10^4 G to 10^5 G: each curve gives the radiation continuum produced by a single electron.

If we perform the integration by an analytical method we find that, provided that γ_0 is sufficiently high, (a condition that can be expressed by the inequality $H\gamma_0^2 \gg 10^9$ G for the optical region, and which is easily fulfilled for the high values of H taken), the integral can be written in the simple asymptotic form

$$F(\nu) = 2.63 \times 10^{-10} (\nu H)^{-1/2} \,\mathrm{erg\,Hz}^{-1}. \tag{6}$$

If the above condition for γ_0 is not satisfied then the expression (6) is only an approximation; in this case the more general formula used in obtaining the curves of Figure 2(a) has to be taken.

The requirements for the validity of the theory described are that the electron should be confined to a uniform magnetic field region, and be observed for the whole of its radiation lifetime. Furthermore, the theoretical radiation continuum does not depend upon the initial energy of the electron: this has the important consequence that the spectral index n is independent of the initial energy spectrum of the electrons.

For a complete radiation source it is necessary to integrate the computed radiation continua over an appropriate magnetic field distribution. In principle, any distribution of high magnetic fields could be taken and its parameters adjusted to fit the observational value of n: this approach would be similar to that of Hoyle and Burbidge (1966) to the radio spectrum of 3C 273, but with the difference that for high magnetic fields the electron energy spectrum would no longer be important. We consider now only one particular case, – a flat distribution, in which all magnetic field values are equally probable. Inspection of the curves in Figure 2(a) reveals that for any frequency there exists an optimum H value at which the computed flux is a maximum; the locus of these maxima is the upper envelope of the curves and is shown in Figure 2(b). We take the envelope plotted in Figure 2(b) as being an approximate representation of the total radiation continuum; for the optical and near infrared regions, this curve can be described by the spectral index $n \approx 1$. We suggest, therefore, that this value of n has a special significance: it could indicate that we are observing cosmic systems in which the different high magnetic field values occur with equal probability, and in which the radiating electrons have synchrotron power spectra for which evolutionary effects are appreciable.

High magnetic fields may be produced by the localized condensation of material initially associated with fields of much lower intensity (Ginzburg, 1964; Hoyle, 1969). Dyson's concept of a QSO, in which there occurs a random succession of local gravitational collapse events (Dyson, 1968), might be relevant to our model if magnetic field amplification were also included.

In our model, the electrons are generated in the interactions of high-energy protons incident upon the condensed material. Their rate of generation from a given proton flux is approximately proportional to the mass of the condensation, and does not depend upon the magnetic field contained by it; for the situation where the mass and magnetic field are completely uncorrelated, the suggested flat magnetic field distribution would be obtained. We would expect this type of model to apply to all cosmic systems containing a flux of high-energy protons, together with condensations of material where there are high magnetic fields and where electron production can occur.

For the particular case of the QSOs, a slightly more specialized version of the model is required. Burbidge and Burbidge (1967) have concluded that "if the QSOs are assumed to be at cosmological distances then their magnetic fields must be very large; the relativistic particles must be generated or accelerated *in situ*; and the very large number of subregions... must be phased together". Regarding this third requirement, we see that if these subregions are identified with the condensations that we have considered here, then the necessary correlation of the radiation from the subregions may be obtained by locating them around a well-defined source, (perhaps a central physical object), from which, as suggested by Hillier (1966), the interacting protons are emitted. Alternatively, following Dyson's random local collapse model, we might suggest that each condensation itself becomes a source of fast protons at some stage of its lifetime. This more specialized version of our model, in either of the two forms suggested, would seem to provide a consistent physical description of the QSOs that has all the properties demanded by their cosmological interpretation.

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