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Abstract

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ON THE POSSIBLE POLARIZATION OF BREMSSTRAHLUNG X-RADIATION OF SOLAR FLARES

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The hard X-radiation of solar flares in the region $\lambda \leqslant 8$ Å can in principle arise as the result of three radiation mechanisms: bremsstrahlung, synchrotron, and Compton. Having experimental data only on the spectral flux, it is difficult to indicate the dominant radiation mechanism for particular flares, since information on the energy spectrum of the accelerated electrons and on the physical conditions in the radiation region is still unreliable. Therefore it would be important to try to detect polarization of the hard X-radiation of flares.

In paper ([1]) the possible polarization of cosmic X-radiation is considered for the three radiation mechanisms indicated above. It is concluded there that the detection of appreciable linear polarization will mean either that the X-radiation is synchrotron, or that it has a bremsstrahlung nature if the angular distribution of the radiating electrons is anisotropic. Below the second possibility is considered, since in solar flares it is natural to expect the occurrence of sharply anisotropic beams of accelerated electrons.

For a parallel monoenergetic beam of low-energy electrons ($E_k \ll mc^2$) moving at an angle θ to the line of sight $\mathbf{k}$, the degree of linear polarization, as is not difficult to show, is determined by the expression (see, for example, ([2])):

$$\Pi = (\sigma_\perp - \sigma_\parallel)/(\sigma_\perp + \sigma_\parallel) = -B\sin^2\theta/(B\sin^2\theta + C), \tag{1}$$

where $\sigma_\perp$ is the bremsstrahlung cross section referring to photons polarized perpendicular to the plane of radiation (the plane ($\mathbf{pk}$)), θ is the angle between $\mathbf{p}$ and $\mathbf{k}$, and the quantities B and C are equal to

$$\begin{aligned} B &= (3x-2)\ln(1+\sqrt{1-x})/(1-\sqrt{1-x}) + 6\sqrt{1-x}, \\ C &= 2(2-x)\ln(1+\sqrt{1-x})/(1-\sqrt{1-x}) - 4\sqrt{1-x}, \end{aligned} \tag{2}$$

Fig. 1 and Fig. 2

Figure 1: Fig. 1 and Fig. 2

where $x = E_\gamma/E_k$, E_γ is the photon energy, and E_k is the kinetic energy of the electron. Formulas (1)–(2) were obtained in the Born approximation and neglecting screening.

Figure 1 gives the dependence of the degree of linear polarization Π and of the total radiation power P_ν on photon energy for different values of the angle θ. It is seen from the figure that in the region of soft photons ($x \ll 1$) the polarization is positive, i.e., the photons are polarized predominantly perpendicular to the plane of radiation, whereas hard photons ($x \lesssim 1$) are polarized in the plane of radiation. The degree of polarization reaches 100% in the two limiting cases indicated and passes through zero independently of the angle θ at $x = E_\gamma/E_k \approx 0.12$. This feature of the polarization of bremsstrahlung radiation makes it possible to distinguish it from synchrotron radiation. In the case of synchrotron radiation of a monoenergetic beam of relativistic electrons, the degree of polarization depends much more weakly on frequency and lies within the limits 50-100%, while the direction of preferential po-

polarization is determined by the projection of the magnetic field onto the plane of the sky (see, for example, ([3])).

It is natural to expect that electrons accelerated during flares possess some energy distribution. In this case the polarization properties of the radiation will also depend on the character of the energy spectrum. Figure 2 shows the dependence of the degree of polarization Π on $x_0 = E_\gamma/E_{k0}$ (E_{k0} is the boundary of the electron energy spectrum on the low-energy side) at $\theta = \pi/2$ for a power-law electron spectrum $E_k^{-\chi}$ for various values of χ. It is seen from the figure that for a steep energy

Fig. 1. **Fig. 2**

spectrum ($\chi \gg 1$) the degree of polarization still changes from $+1$ to -1, passing through zero near $E_\gamma \approx 0.12 E_{k0}$. As χ decreases, the zero point shifts into the region of larger values of x_0 and disappears for $\chi \lesssim 1$. If the electron energy spectrum falls off steeply or cuts off in the relativistic region $E_k \gg mc^2$, then, as is not difficult to show, the zero point is also absent, and all photons are polarized perpendicular to the plane of radiation.

The indicated polarization properties of bremsstrahlung radiation are valid only for a parallel beam of electrons. In flares another limiting case may also be realized, when the electrons are trapped by a regular magnetic field and a certain angular distribution of velocities is established in it. In this case the degree of polarization naturally decreases. Let us consider this important case using as an example a sinusoidal angular distribution of the form $\sin^n \alpha$, where α is the angle between the velocity and the magnetic field (or any other selected

Fig. 3

Figure 2: Fig. 3

direction). Such a distribution, or one close to it, is established, for example, in the radiation belts of the Earth and Jupiter ([4,5]). Averaging over the angular distribution, we obtain for the degree of polarization Π the expressions

$$\Pi_{n=2} = B \sin^2 \theta_0 / (4B + 5C - B \sin^2 \theta_0),$$

$$\Pi_{n=4} = B \sin^2 \theta_0 / (3B + 3.5C - B \sin^2 \theta_0), \qquad (3)$$

where θ_0 is the angle between the axis of symmetry of the distribution (the direction of the magnetic field) and the line of sight, and the coefficients B and C are still determined by (2). It follows from (3) that, in the presence of an angular distribution, the degree of polarization is smaller than for a parallel beam of electrons (see (1)). In this case Π is equal to zero if the axis of symmetry of the angular distribution coincides with the line of sight ($\theta_0 = 0$), and is maximal at $\theta_0 = \pi/2$.

Figure 3 shows the frequency dependence of the degree of polarization for the indicated particular case, for various values of the angle θ_0 and for values $n = 2$ and $n = 4$.

It is seen from the figure that averaging over the sinusoidal distribution does not change the characteristic properties of the polarization of bremsstrahlung radiation.

The degree of polarization Π still passes through zero near $E_\gamma \approx 0.12 E_\kappa$, independently of the angle θ_0, with soft photons being polarized predominantly in the plane passing through the axis of symmetry of the angular distribution and the line of sight. However, the magnitude of the maximum polarization is significantly smaller than for a parallel electron beam, and increases with increasing degree of anisotropy n. For example, at $n = 4$ the maximum polarization is attained in the hard-photon region at $\theta_0 = \pi/2$ and is equal to 50%.

Fig. 3

If the angular and energy distributions of the electrons are independent, it is not difficult to carry out averaging over both of these distributions. In this case, for the power-law energy spectrum and the sinusoidal angular distribution considered above, we obtain the same expressions (3), in which B and C should be replaced by b and c, respectively, where

$$b = \left(\frac{3}{2} \frac{2\kappa - 1}{2\kappa + 1} x_0 - 1 \right) l_0 + F_1 \left(3 - \frac{2}{2\kappa - 1} \frac{F_2}{F_1} + \frac{3(2\kappa - 1)}{(2\kappa + 1)^2} x_0 \frac{F_3}{F_1} \right), \qquad (4)$$

$$c = \left(2 - \frac{2\kappa - 1}{2\kappa + 1} x_0\right) l_0 - 2F_1 \left(1 - \frac{2}{2\kappa - 1} \frac{F_2}{F_1} + \frac{2\kappa - 1}{(2\kappa + 1)^2} x_0 \frac{F_3}{F_1}\right). \quad (5)$$

In (5) the following notation has been used:

$$x_0 = E_\gamma / E_{\kappa 0}, \qquad l_0 = \ln(1 + \sqrt{1 - x_0})/(1 - \sqrt{1 - x_0}),$$

$$F_1 = F(-{}^1/2, \kappa - {}^1/2, \kappa + {}^1/2, x_0), \quad (6)$$

$$F_2 = F({}^1/2, \kappa - {}^1/2, \kappa + {}^1/2, x_0), \qquad F_3 = F({}^1/2, \kappa + {}^1/2, \kappa + {}^3/2, x_0)$$

are hypergeometric functions.

In the limiting case of small values $x_0 \lesssim 0.2$, $F_1 \approx F_2 \approx F_3 \approx 1$, $l_0 \approx \ln(4/x_0)$, and therefore

$$b \approx \left(\frac{3}{2} \frac{2\kappa - 1}{2\kappa + 1} x_0 - 1\right) \ln \frac{4}{x_0} + \frac{6\kappa - 5}{2\kappa - 1},$$

$$c \approx 2 \left(\ln \frac{4}{x_0} - \frac{2\kappa - 3}{2\kappa - 1}\right). \quad (7)$$

In the opposite limiting case $E_\gamma \gtrsim E_{\kappa 0}$, one should put $x_0 = 1$ and $l_0 = 0$; then

$$b \approx \frac{4\sqrt{\pi}(\kappa - 1)\Gamma(\kappa - {}^1/2)}{2\kappa + 1} \frac{\Gamma(\kappa)}{\Gamma(\kappa)} = (\kappa - 1)c \quad (8)$$

(Γ denotes Euler’ s gamma functions).

As was to be expected, upon averaging over the angular and energy distributions, the maximum degree of polarization is still smaller and reaches relatively large values only at $\theta_0 = \pi/2$ and large values of κ. For example, from (3), (5)–(9) it follows that at $\theta_0 = \pi/2$ the degree of polarization Π reaches 37% at $\kappa = 6$ only in the hard-photon region, while in the soft-photon region it is considerably lower. However, even for this case one may hope that under real conditions the degree of polarization of bremsstrahlung radiation will turn out to be of the order of 10–20%, and one may hope to detect it.

If the energy spectrum of the electrons accelerated in a flare extends into the nonrelativistic region, then the bremsstrahlung will considerably exceed the two other types of radiation: Compton and synchrotron radiation [6]. In this case the X-ray radiation, as was shown above, may turn out to be linearly polarized, and the degree of polarization may in some cases reach 100%. The polarization of this radiation depends on frequency*, and, when the energy spectrum cuts off at some energy $E_{\kappa 0}$, has a very characteristic feature in the region $E_\gamma < E_{\kappa 0}$ (opposite signs for soft and hard photons), which makes it possible to distinguish bremsstrahlung from synchrotron radiation. Therefore, in order to determine the radiation mechanism when carrying out polarization observations, it is desirable to make observations in at least two photon-energy regions sufficiently far apart from one another.

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* For synchrotron radiation with a power-law energy distribution E^{-x}, the polarization of the radiation over a broad frequency range does not depend on frequency and is equal to $(x+1)/(x+7/3)$ (see, for example, [(3)]).