1994ApJS...92..607P

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 92:607–609, 1994 June
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RELATIVISTIC JETS IN BLAZARS: POLARIZATION OF RADIATION

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Received 1993 May 4; accepted 1993 July 15

ABSTRACT

I consider polarization of radiation in two processes which can be responsible for the radiation of the active galactic nuclei from infrared to X-ray frequencies. The first one is optically thin synchrotron self-Compton emission from an isotropic distribution of relativistic electrons with a power-law energy spectrum in aligned magnetic field. It is shown that the polarization degree of the scattered radiation is angle dependent in contrast to the initial synchrotron radiation. The second process is radiation from an accretion flow scattered off a relativistic jet. In that case I assume that electrons have a relativistic Maxwellian distribution in the frame of reference connected with the jet. The dependence of polarization on angles for different electron temperatures is obtained.

Subject headings: BL Lacertae objects: general — galaxies: jets — polarization

1. INTRODUCTION

The class of blazars (BL Lacertae objects and OVV's) is characterized by a high degree of polarization and rapid variability. Their multiwaveband spectra are generally interpreted in terms of synchrotron self-Compton emission in relativistic jets. The Compton scattering by the jet of the unpolarized ambient radiation produced by the central region of the accretion disk can also contribute significantly to the X-ray spectra of active galactic nuclei (AGNs).

The spectral and polarization properties of the synchrotron radiation are well-known (Ginzburg & Syrovatskii 1965; Björnsson & Blumenthal 1982). Observations in the optical region of the frequency-dependent polarization give the information about the magnetic field structure in the source. The timescale of the flux variability tells about the size of the emission region. Polarimetric observations in the X-ray region will be possible after the launch of the Spectrum-X-Gamma satellite (in 1995) with the X-ray polarimeter (Kaaret et al. 1990). High degree of polarization in blazars (up to ~40%) may compensate for the low sensitivity of the scattering polarimeter due to the low flux of these objects in the 6–12 keV range (Piro et al. 1991).

2. SCATTERING MATRIX

Let ν, ν_1 be the photon frequencies after and before the scattering, respectively; μ is the cosine of the scattering angle, γ is the electron energy in units of $m_e c^2$. The Compton scattering matrix for the isotropic electron distribution has the following form:

$$\hat{S}(\nu, \nu_1, \mu) = \begin{pmatrix} S & S_I & 0 & 0 \\ S_I & S_Q & 0 & 0 \\ 0 & 0 & S_U & 0 \\ 0 & 0 & 0 & S_V \end{pmatrix} . \quad (1)$$

The methods of calculation of this matrix in the particular case of the Maxwellian electron distribution were proposed by Nagirner & Poutanen (1993a). For the power-law electron distribution in energies $dN = n_e K \gamma^{-p} d\gamma$, $\gamma > \gamma_{\min} \gg 1$ the components of the scattering matrix are (Bonometto, Cazzola, & Saggion 1970; Nagirner & Poutanen 1993b)

$$S = A\left(\frac{1}{p+1} - \frac{2\Delta}{p+3} + \frac{2\Delta^2}{p+5}\right), \quad S_I = 0 ,$$

$$S_Q = -S_U = A\frac{\Delta^2}{p+5}, \quad S_V = A\left(\frac{1}{p+1} - \frac{2\Delta}{p+3}\right), \quad (2)$$

where

$$A = \frac{3K}{16\pi}\frac{m_e c^2}{h\nu}[\max\{\gamma_*, \gamma_{\min}\}]^{-(p+1)} ,$$

$$\Delta = \min\left\{1, \frac{\gamma_*^2}{\gamma_{\min}^2}\right\} ,$$

$$\gamma_* = \left[\frac{2\nu_1(1-\mu)}{\nu}\right]^{-1/2} .$$

The expressions (2) are valid if $h\nu_1 \ll h\nu \ll \gamma_{\min} m_e c^2$, $h\nu_1 h\nu \ll (m_e c^2)^2$.

3. SYNCHROTRON SELF-COMPTON POLARIZATION: OPTICALLY THIN CASE

We consider the spherical homogeneous cloud of electrons with isotropic power-law energy distribution. We assume that magnetic field H is aligned. It is known that the emissivity of the synchrotron process (Ginzburg & Syrovatskii 1965) is

$$\tilde{\epsilon}(\nu, \zeta) = \begin{pmatrix} \epsilon_I \\ \epsilon_Q \end{pmatrix} \sim \sin\zeta \left(\frac{\nu_H \sin\zeta}{\nu}\right)^{\alpha} \begin{pmatrix} 1 \\ -P_s \end{pmatrix} , \quad (3)$$

where ζ is the angle between the magnetic field and the photon propagation, ν_H is the characteristic frequency $\nu_H = 3eH/4\pi mc$, $\alpha = (p-1)/2$ and the degree of polarization $P_s = (p+1)/(p+7/3)$ is independent of ζ.

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The inverse Compton scattered polarized flux is

$$\tilde{H}_1(\nu, \zeta) \sim \pi\tau\nu^2 \int_0^\infty \frac{d\nu_1}{\nu_1^2}\left(\frac{\nu_H}{\nu_1}\right)^\alpha \int_0^{2\pi} d\phi \int_{-1}^{1} d\mu$$

$$\times (1-\eta^2)^{(\alpha+1)/2}\begin{pmatrix} S(\nu, \nu_1, \mu) \\ -P_s S_Q(\nu, \nu_1, \mu)\cos 2(\chi_1+\phi)\end{pmatrix}, \quad (4)$$

where $\tau = n_e\sigma_T R$ is the optical radius of the cloud in respect to the Thomson scattering, ζ is the angle between the magnetic field and the photon propagation (after scattering), $\eta = \mu\cos\zeta + \sqrt{1-\mu^2}\sin\zeta\cos\phi$ is the cosine of the angle between momentum of the initial photon and magnetic field, μ is the cosine of the scattering angle, and

$$\cos 2\chi_1 = 2\frac{(\cos\zeta - \mu\eta)^2}{(1-\eta^2)(1-\mu^2)} - 1 . \quad (5)$$

The polarization degree of scattered radiation P_{sc} can be approximated by a simple formula:

$$P_{sc} \approx P_s \frac{(p+1)(p+3)}{p^2+4p+11}\sin\zeta . \quad (6)$$

The results of calculations for one set of parameters are presented in Figures 1*a* and 1*b*.

4. SCATTERING OF AMBIENT RADIATION

We consider the scattering of the blackbody unpolarized ambient radiation by the relativistic jet. We assume that in the jet rest frame electrons have Maxwellian distribution with some temperature T_e. The Lorentz factor of jet is Γ. The incident radiation in the jet rest frame is concentrated in a cone of half-opening angle $\approx\Gamma^{-1}$, therefore for $\Gamma \gg 1$ the "head-on" approximation can be adopted. The initial photon frequency in this frame $\nu' \approx 2\Gamma\nu$. If the ambient radiation is blackbody with the temperature T_{ph} then the energy distribution of initial radiation in the jet rest frame can be approximated by Planck function with temperature $T'_{ph} \approx 2\Gamma T_{ph}$. The Stokes vector of the scattered radiation in the jet rest frame is

$$\tilde{I}_1(\nu_1, \mu) \sim \nu_1^2 \int_0^\infty \frac{\nu' d\nu'}{e^{h\nu'/kT'_{ph}} - 1}\begin{bmatrix} S(\nu_1, \nu', \mu) \\ S_I(\nu_1, \nu', \mu)\end{bmatrix}. \quad (7)$$

If the electrons in the jet are cold then the scattered radiation is highly polarized (Begelman & Sikora 1987). But if the temperature of the electron gas (in the frame of reference connected with relativistic jet) is high then the exact Compton scattering matrix is quite different from the Rayleigh matrix and the first one predicts smaller polarization degree than the second one (Poutanen & Vilhu 1993). As an example, we consider the scattering of blackbody radiation with $T_{ph} = 0.01$ keV by jet ($\Gamma = 5$) with electron temperature (in jet rest frame) T_e = 0, 50, 100, and 200 keV. Calculations have shown that polarization of the scattered component does not depend on frequency and decreases when electron temperature increases. The dependence of polarization on scattering angle for different temperatures is presented in Figure 2.

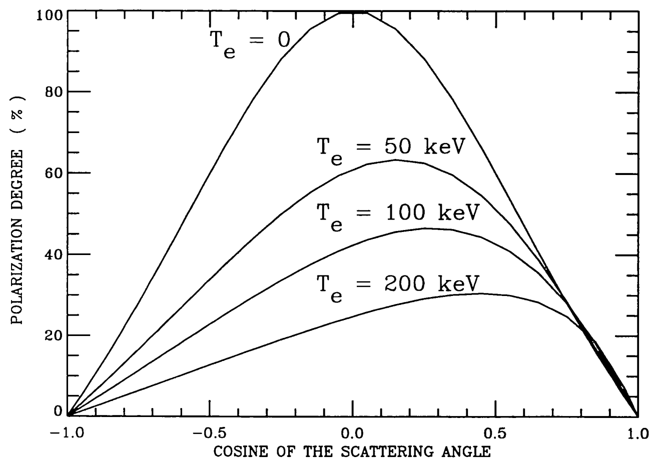

FIG. 2.—Polarization degree of radiation scattered by relativistic jet as a function of the cosine of the scattering angle.

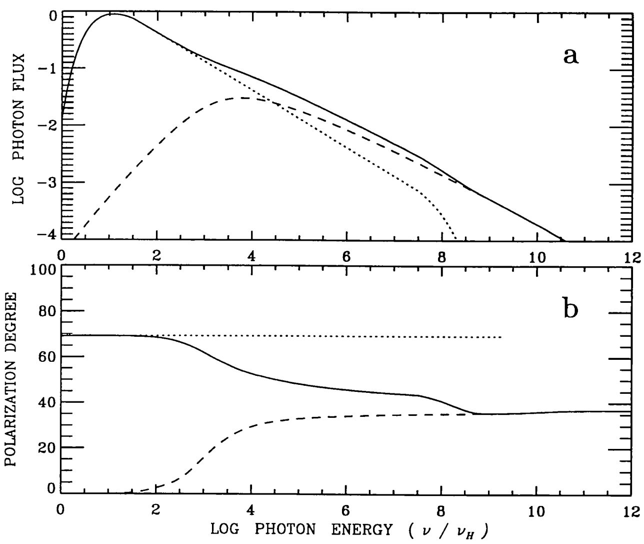

FIG. 1.—(*a*) Intensity and (*b*) polarization of synchrotron self-Compton radiation. *Dotted lines*—initial synchrotron radiation; *dashed lines*—inverse Compton scattered radiation; *solid lines*—intensity and polarization of the total radiation. Here $\tau = 0.1$, $\alpha = 0.5$, $\sin\zeta = 1$, and $\gamma_{min} = 10$.

5. CONCLUSIONS

We have considered two simple models for the important processes that can contribute significantly to the X-ray luminosity:

1. Synchrotron self-Compton radiation (power-law electrons);
2. Compton scattering of the ambient radiation by relativistic jet with Maxwellian distribution of the *random* electron velocities.

We have calculated the polarization degree and the intensity of the scattered radiation in the frame of references connected with the jet. In the first case it is shown that the polarization degree of the total radiation is frequency- and angle-depen-

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dent, although the polarization of synchrotron radiation for the power-law electron distribution does not depend on the frequency and angles.

In the second case we have shown that if the electron gas (in the jet rest frame) is not cold, then the polarization degree is quite different from one that the Rayleigh matrix predicts.

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