Polarization by scattering off relativistic jets – Application to blazars

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Abstract. We analyze the polarization properties of radiation Comptonized by cold electrons with relativistic bulk velocities. We consider "pencil" and "cone" distributions of electron velocities and assume that the background radiation is isotropic and has a power law spectrum. Our results are discussed in the context of jets formed close to the black hole, the scattering by the jet of radiation produced in the accretion flow can be responsible for IR-optical polarization in blazars.

I. ASSUMPTIONS
We assume that: (i) the background radiation is isotropic, possesses a power-law spectrum, $I_0 \propto \nu^{-\alpha}$, and is unpolarized; and (ii) the jet is optically thin ($\tau_{\text{Thomson}} < 1$) and relativistic ($\gamma > 2$). For relativistic electron velocities the background radiation as seen in the electron rest frame is strongly beamed into $-\nu_e$ direction and we adopt the approximation that the incident radiation is unidirectional in the electron frame.

II. POLARIZATIONS
The scattered radiation in the electron rest frame is smoothly distributed over all directions ($d\sigma/d\Omega = (1 + \cos^2\theta)$, where $\theta$ is the angle between the incident and scattered directions), with the degree of polarization varying between 0 and nearly 100% as the scattering angle varies between $0^\circ/180^\circ$ and $90^\circ$. The degree of polarization of a light ray is, of course, invariant under Lorentz transformation, hence the high degree of polarization of most of the rays is preserved when the scattered radiation is observed in the laboratory frame. Note, however, that most of the scattered rays are now compressed into a cone of half-angle $\sim \gamma^{-1}$, hence the degree of polarization is very sensitive to the precise viewing angle within the Doppler beaming cone. This argument is little affected by anisotropy in the ambient radiation field, provided that the source of the incident radiation subtends an angle greater than $\gamma^{-1}$ as viewed by a stationary observer located in the scattering region.

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III. RESULTS

The results presented on Figs. 1 and 2 have been obtained according to the formulas for Stokes parameters, presented in the paper by Begelman & Sikora (1986, in preparation).

Fig. 1. The percentage polarization $P$ (solid line) and the intensity ratio $I_{sc}/I_B$ (dotted line) versus the viewing angle $\theta_0$ for pencil beams. ($I_{sc}$ is the intensity of the scattered radiation, $I_B$ is the intensity of the background radiation and $\tau$ is the optical thickness for scattering.) The curves were obtained for the electron distribution, $n(\theta, \gamma) = \delta(\gamma - \gamma_C) \cdot \exp[-k_\theta(\theta - \theta_C)^2]$ with $\gamma_C = 5$, $\theta_C = 0$ and (a) $k_\theta = \infty$, (b) $k_\theta = 64$, and (c) $k_\theta = 16$.

Fig. 2. As in Fig. 1, but for "hollow cone" beams with $\theta_C = 30^\circ$ (Figs. a-c), and $\theta_C = 45^\circ$ (Figs. d-f). In (a) and (d), the cone has zero thickness ($k_\theta = \infty$); in (b) and (e) $k_\theta = 64$; and in the case of (c) and (f) $k_\theta = 16$. For the center peaks, the polarization is parallel to the projected cone axis.
IV. DISCUSSION

Relativistic outflows thought to occur near the black holes in AGNs may be sufficiently well ordered that radiation scattered by them has a high degree of polarization. Such outflows may be formed in the funnels of two-temperature tori, where the Poynting flux generated by a rotating magnetized black hole accelerates matter which is created there or is swept from the torus walls (Phinney 1983); or in magnetospheres above optically thick accretion disks, where cold winds along open magnetic field lines can propagate (Blandford & Payne 1982). In either case, unpolarized ambient radiation from an accretion flow is available to be scattered by the outflow.

What $\tau$ is required for the scattered radiation to dominate over the isotropic ambient radiation? Since the energy of each photon is amplified on average by a factor $\gamma^2$ via scattering, the energy of the scattered radiation is $g\gamma^2$ times the energy of the background radiation, where $g$ is a geometrical factor describing the fraction of the background radiation field that is traversed by the relativistic electrons. Because the scattered radiation is simultaneously collimated along the jet, characterized by the solid angle $\Omega_j$, the distant observer located in $\Omega_j$ will detect the following ratio of scattered to primary radiation flux:

$$\frac{F_s(v)}{F_b(v)} \sim g\gamma^2 \frac{4\pi}{\Omega_j}$$

Since $d\nu_o/d\nu \sim \nu_o/\nu \sim \gamma^2$, and the ambient spectrum has the form $F_b(v) = v^{-\alpha}$, at the fixed frequency $\nu_o$ we have

$$\frac{F_s(v)}{F_b(v)} \sim g\gamma^2 \frac{2\alpha}{\Omega_j}$$

Thus the component of the scattered radiation will dominate over the isotropic component, if $\tau > g^{-2\alpha} [(\Omega_j/4\pi)g]$. Normally, we expect the term in parentheses to be of order one.

V. CONCLUSIONS

We have found that even "weak" jets ($\tau < 1, \gamma \sim 3$) can scatter ambient radiation to a beam of polarized radiation, which dominates over isotropic components for observers located in the beam. In at least some blazars (AGN believed to emit jets to our direction), we expect that the strongly polarized infrared-optical radiation is due in part to scattering, by the jet, of radiation produced in the far-middle infrared by the accretion flow.

Research supported by National Science Foundation Grant AST83-51997.

REFERENCES
