COMPTON ROCKETS: RADIATIVE ACCELERATION OF A RELATIVISTIC FLUID

S. L. O'Dell
Physics Dept., Virginia Tech
Blacksburg, VA 24061 USA

Summary. Unless a plasma moves at relativistic bulk speeds, the Compton radiative lifetime for relativistic electrons near a luminous object is less than the transit time from the source. Acceleration by adiabatic decompression is too slow to preserve much of the electrons' energy. However, the Compton-rocket thrust and the radiatively induced pressure gradient can accelerate a relativistic fluid to relativistic bulk speeds on a time scale comparable to that for radiative loss. Consequently, severe Compton losses are not only reduced by relativistic bulk motion, but can in fact effect such motion.

Relativistic electrons of proper Lorentz factor γ_{e*}, in a fluid moving with speed $c\beta$ away from a source of luminosity L, lose energy via single Thomson scattering at an average rate

$$\frac{d\,\ln\langle\gamma_{e*}-1\rangle}{d\,\ln r} = -\frac{2}{3}\frac{\langle\gamma_{e*}^2-1\rangle}{\langle\gamma_{e*}-1\rangle}\,\Lambda_1\left(\frac{r_1}{r}\right)\frac{(1-\beta)}{\gamma\beta(1+\beta)} \quad ,$$

where r_1 is a fiducial distance and the parameter

$$\Lambda_1 \equiv \frac{\sigma_T L}{2\pi m c^3 r_1} = \left(\frac{m_H}{m}\right)\left(\frac{r_S}{r_1}\right)\frac{(L/M)}{(L/M)_E} = 4.3\,(L_{45}/r_{15}) \ ,$$

with r_S and $(L/M)_E$, respectively, the Schwarzschild radius and Eddington light-to-mass limit for Thomson scattering, and $L_{45} \equiv L/(10^{45}$ erg/s) and $r_{15} \equiv r/(10^{15}$ cm). Clearly, Compton radiative losses near r_1 are quite severe (cf. Hoyle, Burbidge, and Sargent 1966) unless, or until, $\gamma^3(1+\beta)^2\beta \gtrsim \Lambda_1\langle\gamma_{e*}^2-1\rangle/\langle\gamma_{e*}-1\rangle \longrightarrow \Lambda_1\langle\gamma_{e*}^2\rangle/\langle\gamma_{e*}\rangle$ for $\langle\gamma_{e*}^2\rangle \gg \langle\gamma_{e*}\rangle \gg 1$.

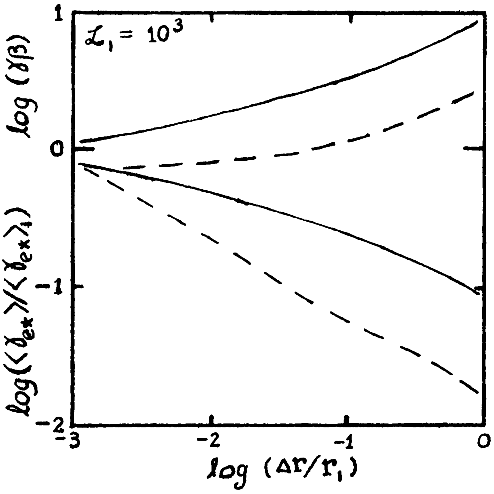
Relativistic bulk motion thus mitigates the Compton problem (e.g., Shklovsky 1964; Woltjer 1966; Rees and Simon 1968). Adiabatic decompression is, however, too slow since it requires a distance $\sim r$ to be effective. On the other hand, if the enthalpy of the fluid is concentrated in or can be transferred sufficiently rapidly to the relativistic electrons, the dynamics are very different. First, the rapid radiative loss of internal kinetic energy induces a steep pressure gradient which accelerates the fluid in the direction of flow. Second, the Compton-rocket thrust (O'Dell 1981), resulting from the anisotropic loss of internal energy via Thomson scattering, accelerates the fluid away from

D. S. Heeschen and C. M. Wade (eds.), Extragalactic Radio Sources, 365–366.

the source of incident radiation (Cheng and O'Dell 1981). These two effects are usually comparable and can accelerate an ultrarelativistic fluid to relativistic bulk speeds over a radiative-loss time scale.

To see this explicitly, consider a spherically symmetric, steady-state, relativistic wind starting with speed $\beta_1=\sqrt{1/3}$ at r_1. For simplicity, take $(\langle\gamma_{e*}^2\rangle/\langle\gamma_{e*}\rangle^2) = (\langle\gamma_{e*}^2\rangle_1/\langle\gamma_{e*}\rangle_1^2)$ fixed and define $\mathcal{L}_1 \equiv \Lambda_1(\langle\gamma_{e*}^2\rangle_1/\langle\gamma_{e*}\rangle_1)$ and $\Delta r \equiv (r - r_1)$. Figure 1 shows that the combined effects of the radiatively induced pressure gradient and the Compton-rocket thrust substantially reduce the Compton losses compared with those sustained if the electrons are confined to an adiabatic mesh. The initial parameter $\mathcal{L}_1=10^3$ is about the maximum appropriate to observed radio sources near a quiescent quasar. However, during an outburst of an OVV quasar or a blazar, or in the formation of a compact radio component or jet, larger values of $\mathcal{L}_1$ can occur. Figure 2 shows $\langle\gamma_{e*}\rangle_2$ and $(\gamma\beta)_2$ at $r_2=2r_1$ for a range of $\mathcal{L}_1$.

References:
Cheng, A.Y.S., and O'Dell, S. L. : 1981, Ap. J. (Letters), in the press.
Hoyle, F., Burbidge, G. R., and Sargent, W.L.W. : 1966, Nature, 209, pp. 751-753.
O'Dell, S. L. : 1981, Ap. J. (Letters), 243, pp. L147-L149.
Rees, M. J., and Simon, M. : 1968, Ap. J. (Letters), 152, pp. L145-L148.
Shklovsky, I. S. : 1964, Soviet Astr.--AJ, 8, pp. 132-133.
Woltjer, L. : 1966, Ap. J., 146, pp. 597-599.



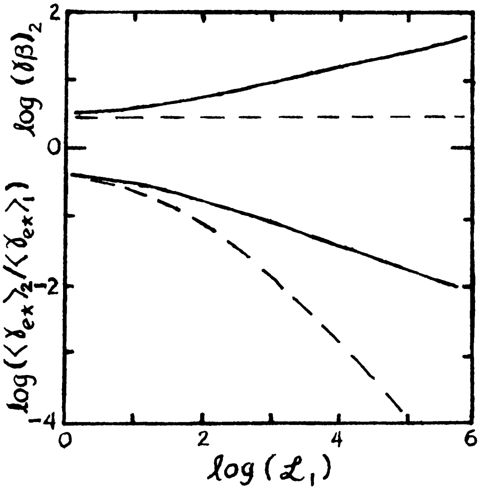


Fig. 1. Dependence of fractional residual energy $(\langle\gamma_{e*}\rangle/\langle\gamma_{e*}\rangle_1)$ and bulk unitary speed $(\gamma\beta)$ upon distance $\Delta r = (r - r_1)$ for $\mathcal{L}_1=10^3$. Dashed and solid lines denote adiabatic and radiative dynamics, respectively.
Fig. 2. Dependence of fractional residual energy $(\langle\gamma_{e*}\rangle_2/\langle\gamma_{e*}\rangle_1)$ and bulk unitary speed $(\gamma\beta)_2$ at $r_2=2r_1$ upon $\mathcal{L}_1$. Symbols are as in fig. 1.