CSIRO Publishing

Publications of the Astronomical Society of Australia

VOLUME 19, 2002

An international journal of astronomy and astrophysics

For editorial enquiries and manuscripts, please contact:
The Editor, PASA,
ATNF, CSIRO,
PO Box 76,
Epping, NSW 1710, Australia
Telephone: +61 2 9372 4590
Fax: +61 2 9372 4310
Email: Michelle.Storey@atnf.csiro.au

For general enquiries and subscriptions, please contact:
CSIRO Publishing
PO Box 1139 (150 Oxford St)
Collingwood, Vic. 3066, Australia
Telephone: +61 3 9662 7666
Fax: +61 3 9662 7555
Email: publishing.pasa@csiro.au

CSIRO PUBLISHING

Published by CSIRO Publishing
for the Astronomical Society of Australia

www.publish.csiro.au/journals/pasa

Publ. Astron. Soc. Aust., 2002, 19, 122–124

The Effect of Radiation Drag on Relativistic Bulk Flows in Active Galactic Nuclei

Qinghuan Luo

Research Centre for Theoretical Astrophysics, School of Physics, The University of Sydney, NSW 2006, Australia

Received 2001 October 5, accepted 2002 March 12

Abstract: The effect of radiation drag on relativistic bulk flows is re-examined. Highly relativistic bulk flows in the nuclear region are subject to Compton drag, i.e. radiation deceleration as a result of inverse Compton scattering of ambient soft photon fields from emission from the accretion disk, broad line region, or dusty torus. Possible observational consequences of X-/γ-ray emission produced from Compton drag are specifically discussed.

Keywords: scattering — plasmas — galaxies: active — galaxies: nuclei — galaxies: jets — radiation mechanisms: non-thermal

1 Introduction

Blazars (flat spectrum quasars [FSQs] and BL Lac objects) are a class of AGN that are thought to have relativistic jets directed at small angles to the line of sight (e.g. Urry & Padovani 1995). Although a number of models have been proposed for the jet formation and acceleration (e.g. Blandford 1990 and references therein), there is no single widely accepted model for the relativistic AGN jet. However, if the jet is formed sufficiently close to the black hole (BH) it must pass through the strong radiation fields from the central region and be subject to radiative deceleration through inverse Compton scattering (Phinney 1982, 1987; Sikora et al. 1996, hereafter SSBM). O'Dell (1981) first considered the radiative effect on relativistic jets and argued that a jet can be accelerated to a relativistic speed by radiation fields. Phinney (1982, 1987) reconsidered this effect and showed that the net effect is deceleration rather than acceleration due to the extended distribution of photon fields from an accretion disk. He further argued that radiation drag can impose an ultimate limit to the maximum jet speed.

The dynamic importance of drag has been further studied by several authors (for example, SSBM; Luo & Protheroe 1999; Renaud & Henri 1998). SSBM extended the calculation of radiation drag to include scattering of photons from reprocessed radiation originating from an extended region, such as the outer part of the accretion disk or the broad line region. They showed that the drag can be effective at a distance up to few $10^3 r_g$, where $r_g = 1.5 \times 10^{13}(M/10^8 M_\odot)$ cm is the gravitation radius and M is the BH mass, and suggested that it is dynamically important only for magnetically dominated jets. Luo & Protheroe (1999) and Renaud & Henri (1998) have calculated Compton drag in the Klein-Nishina regime.

In this paper, the effect of Compton drag on relativistic bulk flows is considered for external photon sources such as UV or IR radiation from the inner and extended disks and near-IR radiation from a dusty torus that absorbs radiation from the central source — the accretion disk near the BH. Since the mechanism for bulk acceleration of jets is not well understood, to focus on the radiative drag effect I assume that (1) the bulk acceleration occurs rapidly within a certain distance, which is referred to as the injection distance $r_{\rm inj}$ and is sufficiently close to the BH, and (2) at $r \geq r_{\rm inj}$ the bulk flow is affected by radiation drag. I discuss in particular the observational consequences of X-/γ-ray emission resulting from Compton drag.

2 Radiation Drag

To illustrate radiative deceleration consider a plasma blob moving in a photon field with a bulk Lorentz factor Γ. Assume the blob contains only electron–positron pairs that are isotropically distributed in the bulk rest frame. Individual electrons (positrons) within the blob lose energy through synchrotron radiation and inverse Compton scattering. To calculate the bulk motion, the electron distribution in the bulk frame is assumed to remain unchanged. This assumption is not realistic since electrons can cool very rapidly in the central region. Electrons emit synchrotron radiation isotropically, which does not affect the jet bulk motion. However, the bulk flows are affected by inverse Compton scattering as the scattering plasma sees an anisotropic external photon field and there is on average a net momentum transfer to the plasma. The evolution of the bulk Lorentz factor is given by (e.g. Phinney 1982; SSBM)

$$\frac{d\Gamma}{dt} = \frac{\beta_b f_r}{E} \tag{1}$$

where $\Gamma = (1-\beta_b^2)^{-1/2}$, f_r is the radiation force density, which can be obtained by calculation of average momentum transfer to the plasma blob through inverse Compton scattering, and E is the energy density in the blob. Both f_r and E are in the bulk rest frame.

Possible sources of soft photons include accretion disks (inner disk and extended outer disk) and possibly a dusty

 10.1071/AS01112 1323-3580/02/01122$05.00

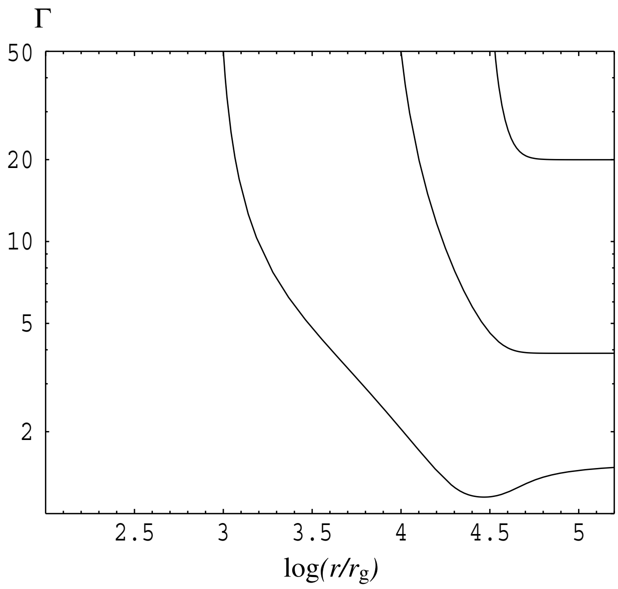

Figure 1 Plots of the bulk Lorentz factor vs distance from the BH. The plasma blob is injected at radii $r_{\rm inj} = 10^3 r_g$, $10^4 r_g$, and $3\times 10^4 r_g$ (from left to right) with $\Gamma = 50$, and electrons have an isotropical angular distribution with $n_e \propto \gamma'^{-p}$, $p \approx 2$, $\gamma'_{\rm min} = 1$, $\gamma'_{\rm max} = 10^5$ in the jet frame.

molecular torus. The latter possibility has been suggested by several authors (e.g. Barthel et al. 1989; Barthel 1989; Protheroe & Biermann 1996). A recent study by Xie, Zhang, & Fan (1997) showed that γ-ray luminosities are better correlated with the IR flux than the X-ray flux, suggesting that a hot dusty torus may be the source of IR photons.

Figure 1 shows Compton drag in a relativistic $e^\pm$ jet as a result of inverse Compton scattering of soft photons from both the accretion disk (inner disk and outer disk) and torus. I assume that the outer disk is optically thick and reprocesses 10% of radiation from the inner disk with the luminosity $L_d = 0.1 L_{\rm Edd}$, where $L_{\rm Edd} = 10^{46}(M/10^8 M_\odot)\,{\rm erg\,s^{-1}}$. The torus is assumed to be axisymmetric (about the jet axis) with inner radius $R_{\rm in} = 0.1\,{\rm pc}$, the outer radius $R_{\rm out} = 0.2\,{\rm pc}$, and the height 0.2 pc (e.g. Pier & Krolik 1992). I assume that the effective temperatures of the inner and outer surfaces are respectively $T_{\rm in} = 1100\,{\rm K}$ and $T_{\rm out} = 100\,{\rm K}$ (Pier & Krolik 1992). The top surface temperature has a power-law spatial distribution $T_s \propto R^{-\delta}$ where $R_{\rm in} \le R \le R_{\rm out}$ and $\delta = \ln(T_{\rm in}/T_{\rm out})/\ln(R_{\rm out}/R_{\rm in}) = 3.46$. The torus that shrouds the nucleus is assumed to absorb 20% of radiation from the central source and re-radiate it in thermal emission. The figure shows that the terminal Γ is not well constrained and strongly depends on the injection distance. The efficiency of drag reduces if a cooling electron spectrum is used. Compton drag becomes less effective as the injection distance increases, implying a larger terminal Γ. Here inclusion of a torus extends the effective distance of drag up to parsec regions.

3 Radiation Resulting from the Drag

A particle's kinetic energy is converted to radiation in X- or γ-rays through Compton drag. Consider a jet with the bulk Lorentz factor Γ. For electrons with γ' in the jet frame, the characteristic energy of scattered photons is $\varepsilon_s \approx \Gamma^2\gamma'^2\varepsilon_{\rm ph}$, where $\varepsilon_{\rm ph}$ is the soft photon energy, typically in UV or IR. Radiation from Compton drag is in the soft X-ray range for nonrelativistic or mildly relativistic electrons and in the hard X- or γ-ray range for ultrarelativistic electrons (in the comoving frame).

To estimate the luminosity of radiation arising from Compton drag the jet is assumed to contain only $e^\pm$ and magnetic fields with the initial bulk Lorentz factor Γ_0 at the injection distance $r_{\rm inj}$ and with the kinetic luminosity $L_k = \Gamma^2 A_j m_e c^2 \langle\gamma'\rangle c n'_e$, where A_j is the cross sectional area of the jet, and $n'_e = n_e/\Gamma$ is the electron density in the comoving frame. The average energy loss rate in the observer's frame is $d\varepsilon_e/dt \approx -(16/9)c\sigma_T\langle\gamma'^2\rangle\Gamma^2 U_{\rm ph}$, where γ' is the particle's Lorentz factor in the jet frame, $\langle\cdots\rangle$ is the average over the electron distribution, and $U_{\rm ph}$ is the energy density of the diffused soft photon field. The observable luminosity arising from Compton drag, $L_{\rm IC}$, is then given by

$$L_{\rm IC} \approx \frac{4}{\Delta\Theta_j^2}\int_{r_{\rm inj}}^{r_{\rm inj}+\Delta r_b} A_j\,dr\left|\frac{d\varepsilon_e}{dt}\right| n_e$$

$$= \frac{16\sigma_T\xi L_d}{9\pi\,\Delta\Theta_j^2 c}\int \frac{L_k}{m_e c^2}\frac{\langle\gamma'^2\rangle}{\langle\gamma'\rangle}\frac{\Gamma}{r^2}\,dr, \qquad (2)$$

where $\Delta\Theta_j$ is the opening angle of the jet, Δr_b is the deceleration distance, and the diffused photon field is assumed to be $U_{\rm ph} = \xi L_d/4\pi r^2 c$. If the longitudinal size, Δr_p, of the plasma blob is smaller than Δr_b and the injection time $r_{\rm inj}/c > r_b/c$, the integration range in (2) is then Δr_p. Note that the power received is different from the power radiated with the former depending on the beaming angle and the latter being a Lorentz invariant. In deriving equation (2) $n_e = L_k/A_j\Gamma m_e c^3\langle\gamma'\rangle$ is used. Due to Compton drag, $\Gamma(r)$ in equation (2) decreases with distance and can be obtained from equation (1).

In Figure 2 the observed luminosity due to Compton drag is plotted as a function of the injection distance ($r_{\rm inj}$). The two curves (upper and lower) correspond to a constant power-law distribution and a cold plasma, respectively. For a distribution with electron cooling, the result should be between these two extreme cases. The kinetic luminosity L_k is assumed to be constant (provided that pairs are continuously injected through a certain acceleration mechanism). For small $r_{\rm inj}$ one has $L_{\rm IC} \gg L_k$, the result similar to that of Ghisellini (1999), Sikora & Madejski (2000), and Sikora et al. (2001), but here the Compton drag is included in the estimate of the luminosity. Any observational limit to the X-ray or γ-ray luminosity can constrain either the jet kinetic luminosity (L_k) or the injection distance ($r_{\rm inj}$). For example, if the observed luminosity is about $10^{46}\,{\rm erg\,s^{-1}}$, one requires that $L_{\rm IC} \le 10^{46}\,{\rm erg\,s^{-1}}$. If the half of the

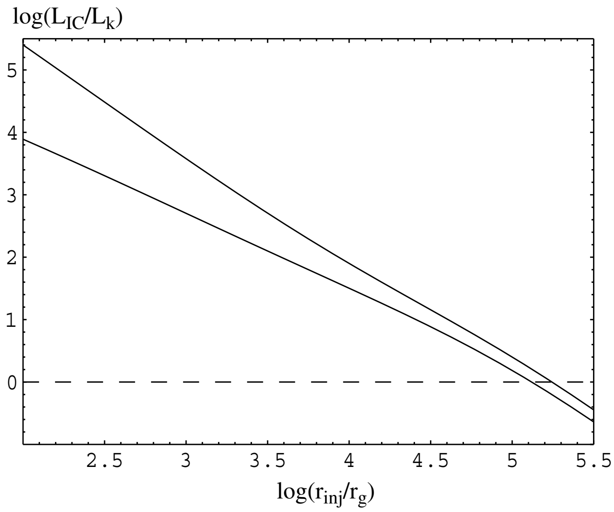

Figure 2 The observed luminosity (in L_k) against the injection distance. The upper and lower curves correspond respectively to the constant power-law distribution and a cold plasma. The horizontal dashed line is $L_{\rm IC} = L_k$. The power distribution of electrons in the jet frame is the same as that used in Figure 1.

jet luminosity is carried by $e^\pm$ (and the other half is magnetic, i.e. the luminosity associated with the Poynting flux $L_B \sim L_k$), then, to avoid overproduction of inverse Compton scattered photons, the kinetic luminosity of the jet, L_k, is constrained by $L_k \le 10^{-3} L_{\rm IC} \approx 10^{43}$ erg s^{-1} for $r_{\rm inj} = 10^3 r_g$, where the cold plasma case is considered. This constraint does not impose a problem for BL Lacs with low-luminosity jets. However, it does constrain radio loud quasars as they normally have jets of high luminosity.

It is possible to avoid overproducing X-/γ-rays by assuming that near the BH the jet luminosity is mainly in the Poynting flux, that is, $L_k \ll L_B \approx L_{\rm IC}$. Alternatively, the injection distance is considerably away from the BH, say $r_{\rm inj} \sim 10^5 r_g$, or the jet content is predominantly protons.

4 Discussion

Radiation drag on relativistic bulk flows in $e^\pm$ jets and the resultant high energy emission are discussed. The luminosity from Compton drag is estimated and compared to the observed blazar luminosity. Due to relativistic beaming, the observed luminosity in general is larger than the jet kinetic luminosity (L_k), implying that the jet kinetic luminosity is limited by $L_k \ll L_{\rm IC}$ with $L_{\rm IC}$ being no larger than the observed overall X-/γ-ray luminosity. This may impose a constraint on radio loud quasars with high luminosity jets as Compton drag can produce excess X-/γ-rays for injection too close to the BH. The overproduction of X-rays or γ-rays can be avoided by choosing either a large injection distance, or by the jet luminosity being predominantly in the Poynting flux or the jet containing a significant fraction of protons. The result is valid for any bulk acceleration mechanism that occurs within a sufficiently short distance ($\le r_{\rm inj}$), such as the mechanism proposed by Blandford & Znajek (1977).

For given L_k, the luminosity $L_{\rm IC}$ is not particularly sensitive to the initial bulk Lorentz factor Γ_0 due to the fact that the larger the value of Γ_0 the shorter the braking distance Δr_b. For the plasma blobs with the longitudinal size being much smaller than Δr_b the luminosity $L_{\rm IC}$ can be significantly reduced and the above constraint can be relaxed.

References

Barthel, P. D. 1989, ApJ, 336, 606
Barthel, P. D., et al. 1989, ApJ, 336, 601
Blandford, R. D. 1990, in Active Galactic Nuclei, eds R. D. Blandford, H. Netzer, & L. Woltjer (Berlin: Springer-Verlag), 161
Blandford, R. D., & Znajek, R. 1977, MNRAS, 179, 433
Ghisellini, G. 1999, in BL Lac Phenomenon, ASP Conf. Series 159, eds L. O. Takalo, & A. Sillanpää (San Francisco: ASP), 311
Luo, Q., & Protheroe, R. J. 1999, MNRAS, 304, 800
O'Dell, S. L. 1981, ApJ, 243, L147
Phinney, E. S. 1982, MNRAS, 198, 1109
Phinney, E. S. 1987, in Superluminal Radio Sources, eds J. A. Zensus, & T. J. Pearson (Cambridge: Cambridge University Press), 301
Pier, E. A., & Krolik, J. H. 1992, ApJ, 401, 99
Protheroe, R. J., & Biermann, P. L. 1996, APh, 6, 293
Renaud, N., & Henri, G. 1998, MNRAS, 300, 1047
Sikora, M., & Madejski, G. 2000, ApJ, 534, 109
Sikora, M., Blazejowski, M., Begelman, M. C., & Moderski, R. 2001, ApJ, 554, 1
Sikora, M., Sol, H., Begelman, M. C., & Madejski, G. M. 1996, MNRAS, 280, 781 (SSBM)
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Xie, G., Zhang, Y., & Fan, J. 1997, ApJ, 477, 114