ON THE LAMPPOST MODEL OF ACCRETING BLACK HOLES

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ABSTRACT

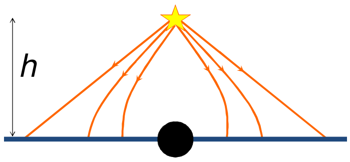
We study the lamppost model, in which the X-ray source in accreting black hole (BH) systems is located on the rotation axis close to the horizon. Many published fitting results give the source distances from the horizon within a few gravitational radii. If those results were correct, most of the photons produced in the lamppost would be trapped by the BH, and the luminosity generated in the source as measured at infinity would be much larger than that observed. This is in conflict with, e.g., the observed smooth state transitions between the hard and soft states of X-ray binaries. The required increase of the accretion rate and the associated efficiency reduction also present a problem for AGN. Furthermore, those models imply the luminosity measured in the *local* frame is still much higher, due to time dilation and redshift, and the electron temperature is significantly higher than that observed. These conditions imply that the fitted sources are out of $e^{\pm}$ pair equilibrium. Finally, we point out a number of inconsistencies in the lamppost model `relxilllp`, e.g., neglecting the redshift of the photons emitted by the lamppost that are directly observed.

ACCRETION EFFICIENCY AND MASS ACCRETION RATE

For emission close to horizon, a large fraction of the emitted photons cross it, due to light bending. E.g. the parameters of the lamppost model for NGC 4151, a = 0.98 and h = 1.3 (Keck et al. 2015), yield the fraction of photons escaping to infinity $\eta_{esc} \simeq 0.01$. This implies that the source is strongly photon-advection dominated, with the actual luminosity as measured at infinity ≃ 50 times larger than that observed. For the observed luminosity of NGC 4151 $\sim 10^{-2}\, L_{\rm Edd}$, the implied $\dot{M} \gtrsim 1.5 L_{\rm Edd}/c^2$ (for the accretion efficiency neglecting advection $\varepsilon \lesssim 0.3$). Then the radiative efficiency, $L/\dot{M}c^2$, is $\lesssim 10^{-3}$. Such low radiative efficiencies cannot be common in AGNs, given their average accretion efficiency of $\gtrsim 0.1$ (e.g. Sołtan 1982).

A similar reduction of the efficiency due to photon advection is implied for the hard state of the BH-binary Cyg X-1 by the lamppost best fit, with $h \simeq 1$ and $a \simeq 1$, of Parker et al. (2015; their fig. 7). This presents a major problem for our current understanding of state transitions. The standard soft-state model is an optically thick disk extending to the ISCO, with minor photon-advection reduction of the efficiency. Thus, the lamppost model implies the accretion rate in the hard state *higher* than in the soft state. This is highly unlikely.

LAMPPOST MODEL



A point-like X-ray source is located on the BH rotation axis perpendicular to a surrounding flat disk truncated at an inner radius $r_{\rm in} = r_{\rm ISCO}$, where ISCO is the innermost stable circular orbit. The height of the source, h, is in units of the gravitational radius, $R_g \equiv GM/c^2$, where M is the BH mass, and a is the BH dimensionless angular momentum.

The `relxilllp` model implementing this geometry has been used to model X-ray emission from accreting BHs and the lamp height was found to be within a few R_g from the horizon in many sources, including the BH binaries Cyg X-1 (Parker et al. 2015) and GX 339–4 (Fürst et al. 2015) and the Seyfert galaxies Mrk 335 (Parker et al. 2014) and NGC 4151 (Keck et al. 2015).

PAIR EQUILIBRIUM

Locations of the X-ray sources within a few R_g from the horizon imply that the luminosity measured in the *local* frame is much higher than that observed due to photon advection, time dilation and redshift. The electron temperature is also higher than that observed due to the redshift. This implies that the pair production rate is much higher than the annihilation rate.

The condition of equilibrium between production and annihilation of $e^{\pm}$ pairs in the radiation field from thermal Comptonization is $\ell \lesssim 10^2$–10^3, 0.1–1 at kT_e = 0.1, 1 MeV, respectively, where ℓ is the compactness parameter

$$\ell \equiv \frac{L_{\rm intr}\,\sigma_{\rm T}}{d R_{\rm g} m_{\rm e} c^2} = \frac{4\pi m_{\rm p} L_{\rm intr}\,\sigma_{\rm T}}{d m_{\rm e} L_{\rm Edd}},$$

d is the characteristic size in unit of R_g, $L_{\rm intr}$ is the luminosity in the local frame, σ_T is the Thomson cross section.
For NGC 4151, the lamppost model (a = 0.98, h = 1.3) implies:

- the photon-advection factor of $(0.5/\eta_{esc}) \approx 50$,
- the redshift of the primary radiation of $z \approx 6$,
- $d \lesssim 0.1$, since the size of the lamppost has to be small (Dovčiak & Done 2016).

Then, the actual plasma temperature is $(1+z) \approx 7$ times higher than that estimated from the observed spectrum and $L_{\rm intr}$ is higher by a factor $\approx 2\times10^3$ than the observed L, and thus $L_{\rm intr} \gtrsim 20 L_{\rm Edd}$ and $kT_e \gtrsim 1$ MeV ($kT_e/(1+z) \gtrsim 150$ keV). We thus find $\ell \gtrsim 3\times10^6$. This places that model very deep in the region forbidden by pair equilibrium, at which the production rate is orders of magnitude higher than the annihilation rate.

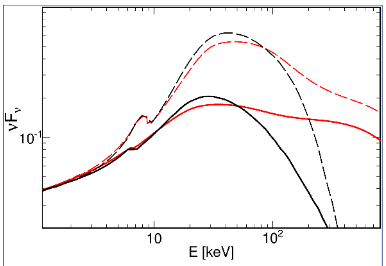


Fig. 1. Observed spectra (direct + reflection) for h = 1.3, a = 0.98, computed with `relxilllp` (red) and with `reflkerr` (black). The heavy solid and thin dashed curves are for inclination angle i = 18° and 76°, respectively. The direct spectrum has Γ = 1.75 and E_c = 1 MeV.

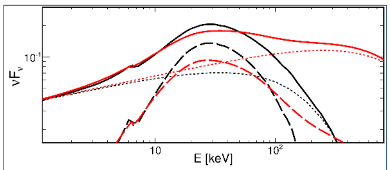


Fig. 2 Spectral components for i = 18° of Fig. 1. The solid black curve gives the actual total spectrum (obtained with `reflkerr` including the 2nd order reflection, same as the solid black curve in Fig. 1). The red solid curve is the result of `relxilllp`. The dotted and dashed curves give the direct and reflected components, respectively.

Inconsistencies in `relxilllp`

Some of the inconsistencies in the lamppost model `relxilllp` are:

The spectrum of the emitted radiation, both that reaching the observer and that irradiating the disk, is not redshifted. This causes the intrinsic cutoffs in the direct spectrum to be substantially underestimated. In particular, the e-folding energy, E_c, fitted using `relxilllp` has to be multiplied by $(1 + z)$ to get its intrinsic value. Also, the neglect of the redshift of the radiation irradiating the disk (which is different from that of the radiation directly received, and radius-dependent) strongly impacts the shape of the observed reflected component.
The related inaccuracies are illustrated in Figures 1-2, where the results of `relxilllp` are compared with those of the code `reflkerr` of Niedźwiecki & Życki (2008); the latter involves the exact treatment of the photon transfer, including the source-to-infinity and source-to-disc redshifts.

Another issue is due to `relxilllp` not taking into account the disk irradiation by returning (due to light bending) reflected radiation. At $a > 0.95$ and $r_{\rm in} = r_{\rm ISCO}$, including the 2nd-order reflection significantly increases the amplitude (up to a factor of ~5 at a = 0.998 and h = 1.3) and changes the reflection spectrum.

We are working on including ionized reflection in our model `reflkerr` and incorporating the model into `xspec`. The code will also return the fraction of photons crossing the horizon, the redshift of direct photons and the compactness parameter. This will allow the user to check the self-consistency of the fitted model. We hope to make it public soon.

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