REFLKERR

These models compute relativistic reflection spectra from a disc around a Kerr black hole. `reflkerr_lp` is for the lamppost geometry, `reflkerr` is for a broken power-law radial emissivity profile, approximating a disc corona. The hybrid model of the rest-frame reflection from a photoionized medium (used in both geometries), `hreflect`, combines `xillver` (García & Kallman, 2010, ApJ, 718, 695; García et al., 2014, ApJ, 782, 76; García et al., 2016, MNRAS, 462, 751) in the soft X-ray range with `ireflect` (the `xspec` implementation of the exact model for Compton reflection of Magdziarz & Zdziarski, 1995, MNRAS, 273, 837) in the hard X-ray range. For details see Niedźwiecki, Szanecki & Zdziarski, 2019, MNRAS, 485, 2942 (NSZ19). `reflkerr_lpbb` extends `reflkerr_lp` by accounting for (1) the re-emission of the irradiating flux absorbed by the disc taking place as quasi-thermal emission satisfying the Stefan-Boltzmann law, and (2) intrinsic disc emission, due to the viscous dissipation.

Installation

This version of the `REFLKERR` package has been tested with version 6.22.1 of `HEASOFT`[1].

1. Download the source code and the table files from `users.camk.edu.pl/mitsza/reflkerr` and unpack them in your `<PATH>` directory:
   ```
   $cd <PATH>
   $tar -xvf reflkerr.tar.gz
   $tar -xvf reflkerr_tables.tar.gz
   ```
2. Initialize the `HEASOFT` package:
   ```
   $heainit
   ```
3. Compile the model:
   ```
   $./compile_reflkerr.csh
   ```
4. Run `xspec` and load `reflkerr` package:
   ```
   $xspec
   XSPEC>lmod reflkerr .
   ```
5. `reflkerr` models should be seen in the list:
   ```
   XSPEC>mo
   ```
   The source code and model tables can be placed in different directories, in such a case set the `REFLKERR_TABLES` environment variable:
6. ```
   $export REFLKERR_TABLES=<PATH_TO_TABLES>
   ```
   If `xspec` is run from a directory different than `<PATH>`, use
7. ```
   XSPEC>lmod reflkerr <PATH>
   ```
   for loading the model.

Notes

- The `ireflect` component can be neglected by using `xset RUSEIREF 0` in `xspec` or `xspec_xset("RUSEIREF", "0")` in `ISIS`. In this case the `xillver` reflection spectrum will be used in the full energy range. Using `ireflect` increases the execution time by about 50%.
- The models take into account reflection from matter within ISCO. Its contribution will be included when `Rin` is set smaller than $R_{\rm ISCO}(a)$.
- In all models `rel_refl`< 0 gives only the reflection component.
- Additional information can be displayed for the LP geometry by setting:
  ```
  XSPEC>xset SHOW_ALL 1
  ```
  This will display, in particular, the reduction factor of photon trapping and the internal compactness of the X-ray source. The latter requires the distance, the black hole mass (for the $R_{\rm g}$-scaled size of the source) and the fitted normalization of the model, which in `xspec` is not available inside the model function and must by typed in:
  ```
  XSPEC>xset RMBH <unit of M_sun>
  XSPEC>xset RDIST <unit of pc>
  XSPEC>xset RNORM <type in the model normalization>
  ```

[1] heasarc.nasa.gov/lheasoft/

- To neglect the contribution from the black body component in LP models, set:
  XSPEC>xset RNOBB 1

compps and ireflect are standard xspec models. xillver is a part of the relxill[2] model. We adopted the tables for ionized reflection, xillver-a-Ec5.fits, xillver-comp.fits, xillverD-4.fits, and functions reading them, interpolating their parameters and determining the reflection normalization, i.e. xilbase.c, xilltable.c, xilmodels.c, donthcomp.c, xilutility.c, common.h, xilbase.h, xilltable.h, xilmodels.h, xilutility.h, from version 1.2 of relxill; the functions are modified by removing their parts related with relativistic transfer of radiation. reflkerr is written in Fortran 90 and it was originally written to use the earlier (also written in fortran) functions of relxill (needed for the use of xillver). Then, some parts of our code have a structure similar to that of relxill ver. 0.5.

The primary spectrum is given by either an e-folded power law (in models denoted with suffix 'Exp') or a thermal Comptonization of soft blackbody photons. The Comptonization spectrum is computed with the compps model (Poutanen & Svensson, 1996, ApJ, 470, 249), and parametrized using the original compps parameters, i.e. the seed photons temperature, $kT_{\rm bb}$, the electon temperature, $kT_{\rm e}$, and either the optical depth, τ, or the Compton parameter, y. In models denoted with suffix 'G', the spectral index, Γ, is used instead of τ or y and $kT_{\rm bb}$ is fixed at 1 eV.

Suffix 'D' denotes models using xillverD tables for a high density accretion disc; other versions use a fixed density of 10^{15} cm^{-3}. Note that xillverD assumes an e-folded power-law spectrum with a fixed cut-off at 300 keV. Then, parameters kTe or Ecut of these models (i.e. 'D') do not affect the low energy part of the reflection spectrum.

The accuracy parameter determines the number of $\mu_{\rm d}$ values used for the convolution in equation (6) in NSZ18. The most accurate version uses 10 values of $\mu_{\rm d}$, but lower accuracy can be used to speed up the fitting; this concerns only LP models, other models are much faster and always use the most accurate version. The simple LP mode for delta=0 neglects the bottom lamp and photons circling around BH.

[2] http://www.sternwarte.uni-erlangen.de/ dauser/research/relxill/

REFLKERR models and model parameters

Lamppost models

reflkerr_lp	LP model with the primary spectrum computed by compps with a sphere geometry and using its original parametrization (i.e. τ or y). Low energy part of reflection computed by xillverCp
reflkerr_lpbb	LP model, the same as reflkerr_lp, but extending it by including the quasi-thermal component due to irradiation and internal dissipation in the disc
reflkerrD_lp	LP model similar to reflkerr_lp but low energy part of reflection computed by xillverD
reflkerrG_lp	LP model similar to reflkerr_lp but parametrized by Γ
reflkerrDG_lp	LP model similar to reflkerr_lp but low energy part of reflection computed by xillverD and the primary spectrum parametrized by Γ
reflkerrExp_lp	LP model with the primary spectrum computed by a power-law with exponential cut-off. Low energy part of reflection computed by xillver
reflkerrExpD_lp	LP model similar to reflkerrExp_lp but low energy part of reflection computed by xillverD
reflkerrline_lp	Relativistically smeared line in LP geometry

reflkerr_lp	
h	LP height, $\leq 100 R_{\rm g}$; unit of $R_{\rm g}$ if > 0, $R_{\rm hor}$ if < 0
a	BH spin
Incl	inclination angle in degrees
Rin	inner radius; unit of $R_{\rm ISCO}$ if < 0, $R_{\rm g}$ if > 0
Rout	outer radius; unit $R_{\rm g}$
tau_y	τ if > 0, y if < 0
Afe	iron abundance in units of solar
kTe	electron temperature in keV
kTbb	temperature of blackbody soft photons in keV
geometry	-5, -4, 0, 4 or 5; definition follows compps
logxi	disc ionization parameter
z	redshift
rel_refl	scaling parameter of reflection, = 1 for physical LP normalization
xillver_ver	switch between Cp and Ec xillver tables: 0 for xillver-comp.fits, 1 for xillver-a-Ec5.fits
delta	attenuation of the bottom lamp; between 0 (bottom lamp neglected) and 1 (full contribution)
accuracy	controls the speed and accuracy by choosing the number of bins in $\mu_{\rm d}$, see above. Between 0 (the least accurate and fastest) and 4 (the most accurate and slowest)

reflkerrD_lp, reflkerrDG_lp, reflkerrExpD_lp	
logN	density of reflecting medium; N between 10^{15} and 10^{19} cm^{-3}

reflkerrG_lp, reflkerrDG_lp, reflkerrExp_lp	
Gamma	photon spectral index

reflkerrExp_lp, reflkerrExpD_lp	
Ecut	folding energy

reflkerr_lpbb	
d	distance [kpc]
M	BH mass [Msun]
albedo	albedo for backscattering
f_col	color correction
delta_mu	correction of angular distribution; = 0 for locally isotropic emission, $I(\mu) = $ const, and $= 2.06$ for the electron scattering limit, $I(\mu) \propto 1 + 2.06\mu$
f	fraction of the dissipated power which is transferred to the X-ray source
therm_frac	scaling of quasi-thermal emission due to irradiation, similar to refl_frac = 1 for actual LP irradiation therm_frac = refl_frac should be set for the consistency of reflection and quasi-thermal emission

Disc corona models

reflkerr	Disc corona model with the primary spectrum computed by compps with a slab geometry and using its original parametrization (i.e. τ or y). Low energy part of reflection computed by xillverCp
reflkerrD	Disc corona model similar to reflkerr but low energy part of reflection computed by xillverD
reflkerrG	Disc corona model similar to reflkerr but parametrized by Γ
reflkerrDG	Disc corona model similar to reflkerr but low energy part of reflection computed by xillverD and the primary spectrum parametrized by Γ
reflkerrExp	Disc corona model with the primary spectrum computed by a power-law with exponential cut-off. Low energy part of reflection computed by xillver
reflkerrExpD	Disc corona model similar to reflkerrExp but low energy part of reflection computed by xillverD
reflkerrline	Relativistically smeared line in coronal geometry

reflkerr	
Index1	emissivity index for $r < R_{\rm br}$
Index2	emissivity index for $r > R_{\rm br}$
Rbr	breaking radius $R_{\rm br}$; unit $R_{\rm g}$
a	BH spin
Incl	inclination angle in degrees
Rin	inner radius; unit of $R_{\rm ISCO}$ if < 0, $R_{\rm g}$ if > 0
Rout	outer radius; unit $R_{\rm g}$
tau_y	τ if > 0, y if < 0
Afe	iron abundance in units of solar
kTe	electron temperature in keV
kTbb	temperature of blackbody soft photons in keV
geometry	-5, -4, 0, 1, 4 or 5; definition follows compps
logxi	disc ionization parameter
z	redshift
rel_refl	scaling parameter of reflection, definition follows R of compps
xillver_ver	switch between Cp and Ec xillver tables: 0 for xillver-comp.fits, 1 for xillver-a-Ec5.fits

reflkerrD, reflkerrDG and reflkerrExpD	
logN	density of reflecting medium; N between 10^{15} and 10^{19} cm^{-3}

reflkerrG, reflkerrDG and reflkerrExp	
Gamma	photon spectral index

reflkerrExp and reflkerrExpD	
Ecut	folding energy

Static models

`hreflect`	Nonrel. model with the primary spectrum computed by `compps` using its original parametrization (τ or y). Low energy part of reflection computed by `xillverCp`
`hreflectG`	Nonrel. model similar to `hreflect` but parametrized by Γ
`hreflectD`	Nonrel. model similar to `hreflect` but the low energy part of reflection computed by `xillverD`
`hreflectDG`	Nonrel. model similar to `hreflect` but the low energy part of reflection computed by `xillverD` and the primary spectrum parametrized by Γ
`hreflectExp`	Nonrel. model with the primary spectrum computed by a power-law with exponential cut-off. Low energy part of reflection computed by `xillver`
`hreflectExpD`	Nonrel. model similar to `hreflectExp` but low energy part of reflection computed by `xillverD`

`hreflect`	
`tau_y`	τ if > 0, y if < 0
`Afe`	iron abundance in units of solar
`kTe`	electron temperature in keV
`logxi`	disc ionization parameter
`z`	redshift
`Incl`	inclination angle in degrees
`kTbb`	temperature of blackbody soft photons in keV
`geometry`	-5, -4, 0, 1, 4 or 5; definition follows `compps`
`rel_refl`	scaling parameter of reflection, definition follows R of `compps`
`xillver_ver`	switch between Cp and Ec `xillver` tables: 0 for `xillver-comp.fits`, 1 for `xillver-a-Ec5.fits`

`hreflectD`, `hreflectDG`, `hreflectExpD`	
`logN`	density of reflecting medium; N between 10^{15} and 10^{19} cm^{-3}

`hreflectG`, `hreflectDG`, `hreflectExp`	
`Gamma`	photon spectral index

`hreflectExp`, `hreflectExpD`	
`Ecut`	folding energy