X-ray radiative transfer in full 3D with SKIRT

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ABSTRACT

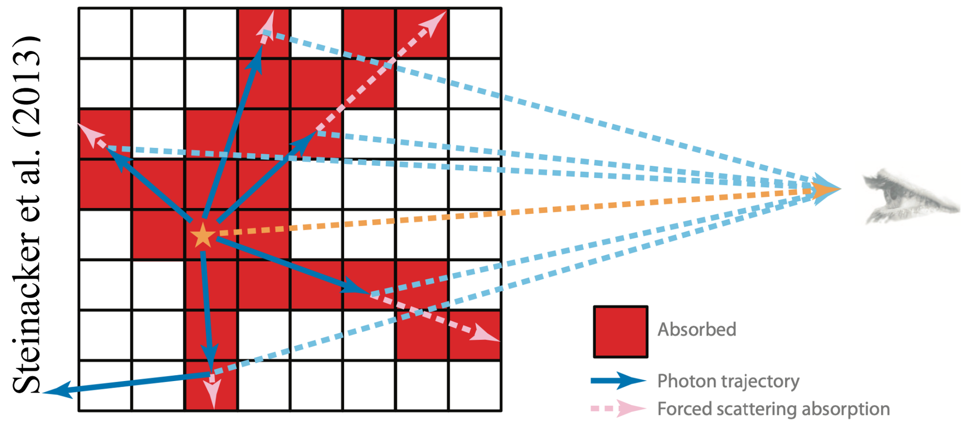
Large amounts of gas and dust can be found in the central regions of most active galaxies. These ambient media play a crucial role as they provide the accretion reservoir powering active galactic nuclei (AGN) and reprocess the optical, UV and X-ray emission of the central engine. **Here, we present the new X-ray functionalities of the SKIRT radiative transfer code, to study this gas and dust in the complex circumnuclear media of AGN.** Focusing on the X-ray broadband spectra of obscured AGN, we introduce radiation processes in free-electron, cold-gas and dust media, which goes beyond the X-ray physics that are currently implemented in most X-ray spectral models for AGN. By incorporating these X-ray processes, we obtain a high-performance radiative transfer code that can self-consistently model complex AGN media from infrared to X-ray energies.

MONTE CARLO RADIATIVE TRANSFER WITH SKIRT

SKIRT is a state-of-the-art Monte Carlo radiative transfer code to study absorption, scattering and re-emission in complex transfer media. The SKIRT code has been applied in different fields of astrophysics, modelling e.g. galaxies and AGN.

SKIRT offers built-in model geometries, radiation sources and transfer media, in addition to interfaces for post-processing hydrodynamical simulations. The latest version supports kinematics, modelling bulk velocities and velocity dispersions.

SKIRT implements many acceleration mechanisms and is fully parallelised, allowing efficient simulations on both laptops and supercomputers. The SKIRT code is open-source and well-documented, with tutorials for both users and developers.



Currently, SKIRT is operational in the sub-mm to FUV wavelength range. In this work, we extend the advanced treatment of radiative transfer into the X-ray range, obtaining an X-ray radiative transfer code with all benefits of the established SKIRT framework. This enables simulations that self-consistently cover the X-ray band and the IR-to-UV range, linking X-ray reprocessing to dust modelling in obscured AGN.

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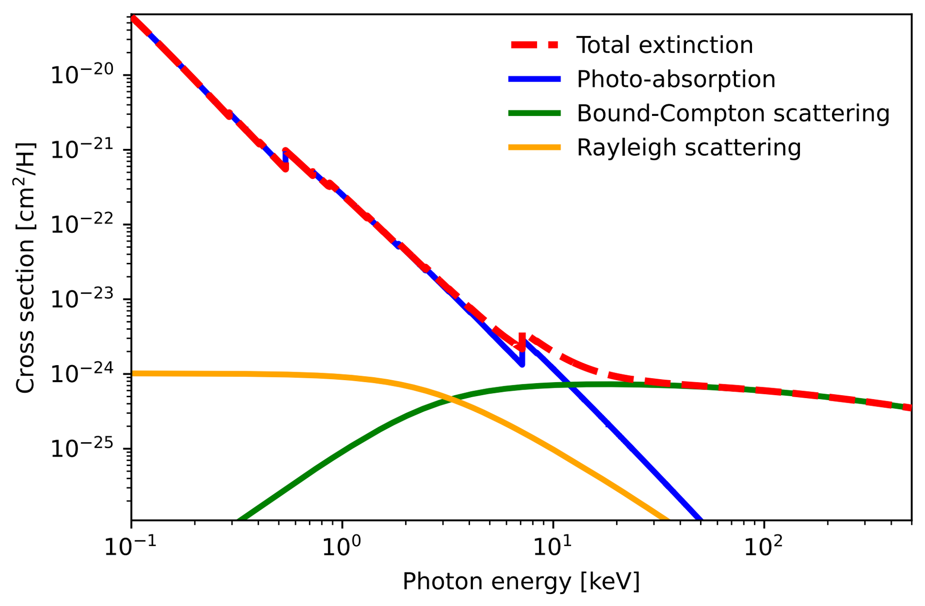
NEW X-RAY PHYSICS IN SKIRT

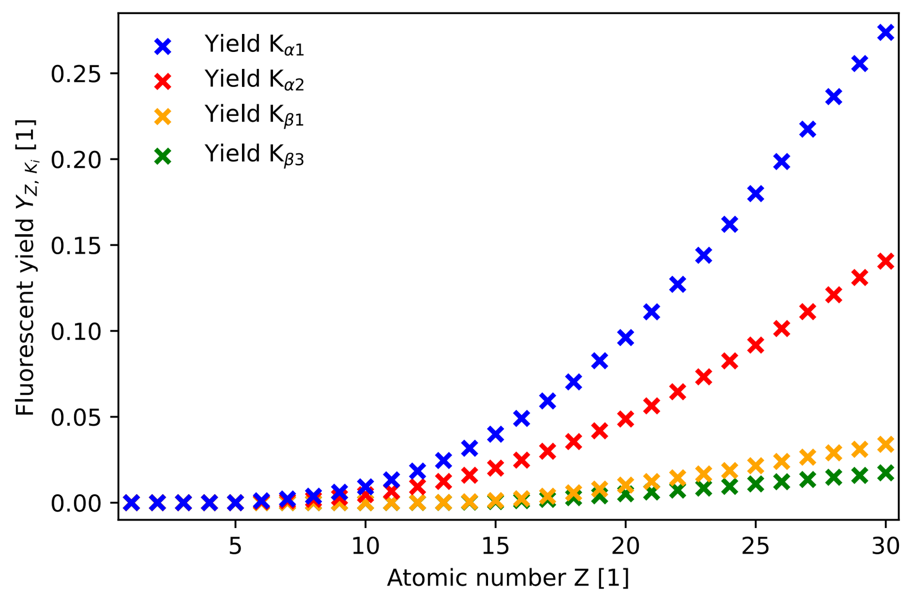
Focusing on the radiative processes that govern the broadband spectra of obscured AGN in the 0.1 to 500 keV range, we implement **Compton scattering** on free electrons, **photo-absorption** and **fluorescence** by cold atomic gas, **scattering on bound electrons** and **extinction by dust**. This includes a detailed description of anomalous Rayleigh scattering, and extreme-forward scattering by dust. For more details, we refer to the X-ray implementation paper by **Vander Meulen et al. (in prep.)**.



Cold-gas extinction

-Photo-absorption by all subshells for all Z ≤ 30

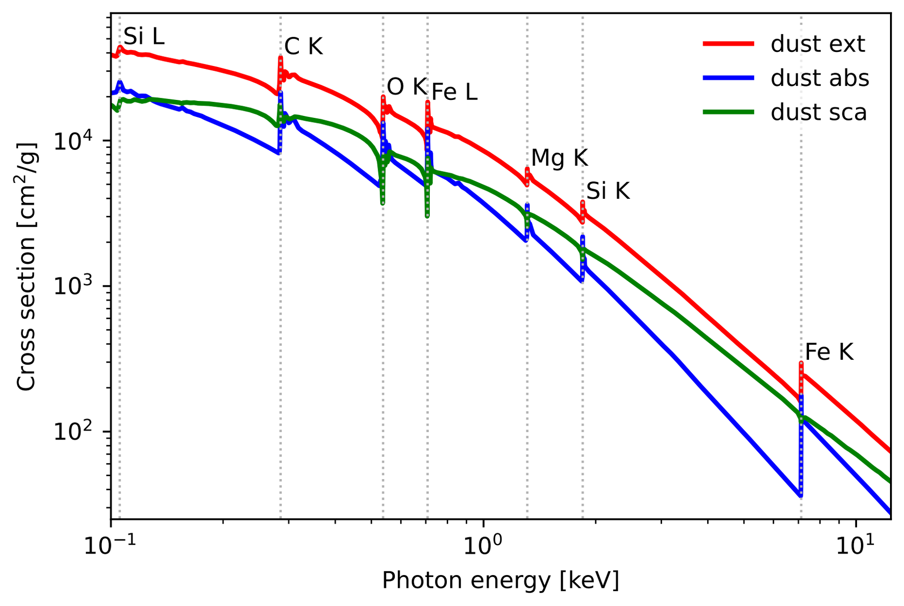
-Elastic and inelastic bound-electron scattering



Fluorescent yields

-Fluorescent line transitions for all Z ≤ 30

-Four different lines: $K_{\alpha1}$, $K_{\alpha2}$, $K_{\beta1}$ and $K_{\beta3}$



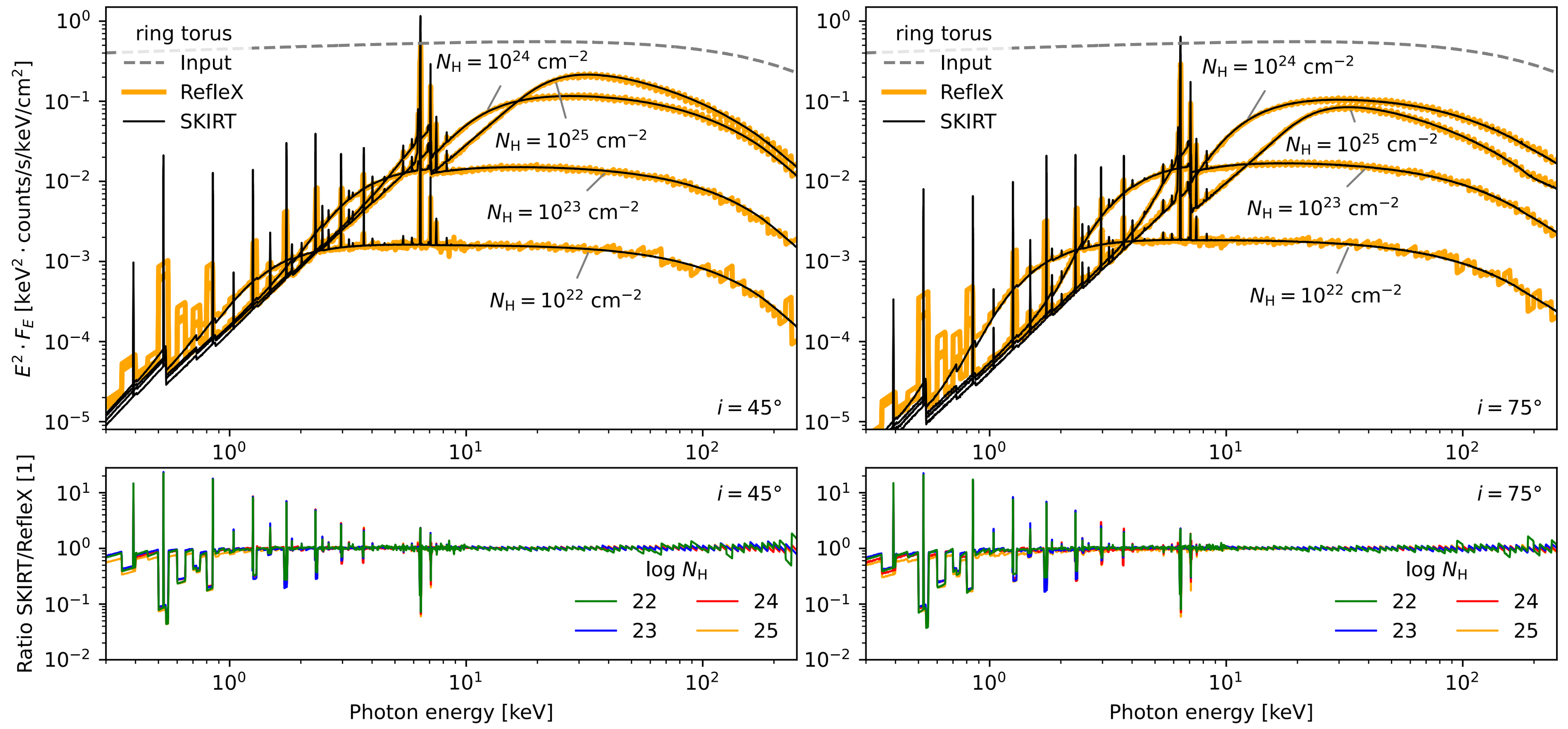
Dust extinction

-Detailed spectral features near absorption edges

-Advanced treatment of extreme forward scattering

SKIRT BENCHMARK IN 3D: REFLEX TORUS MODEL

We benchmark SKIRT against the RefleX code (Paltani & Ricci 2017) by running the same 3D torus model. We find an excellent agreement between both codes, with less photon counting noise and a higher spectral resolution in the SKIRT results. The SKIRT spectrum reveals additional structure in the Compton shoulder shape, and resolves the $K_{\alpha1}$ and $K_{\alpha2}$ sublines (below, right), which could be studied with microcalorimeter observations. The fluorescent line fluxes are perfectly consistent in both simulations (Table 1).



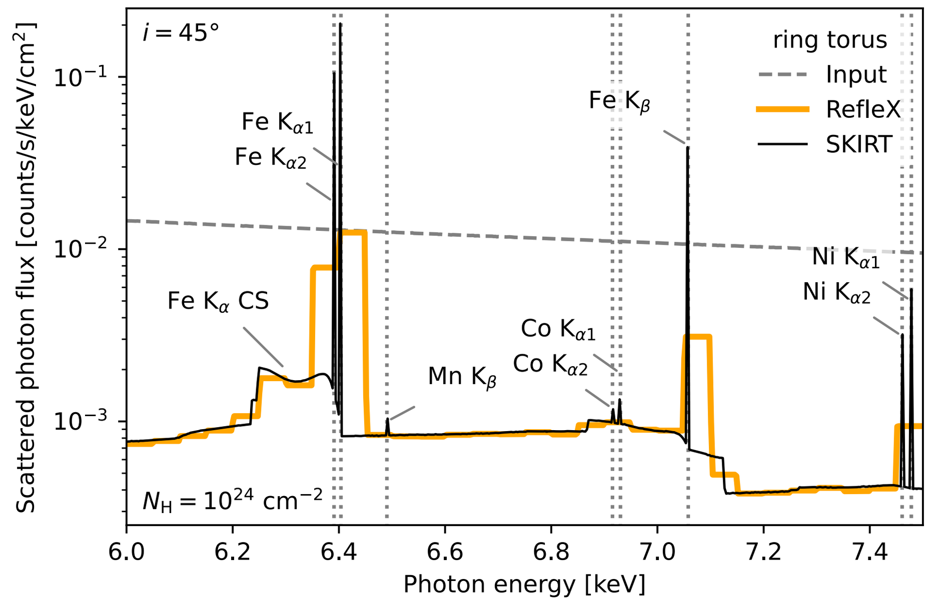
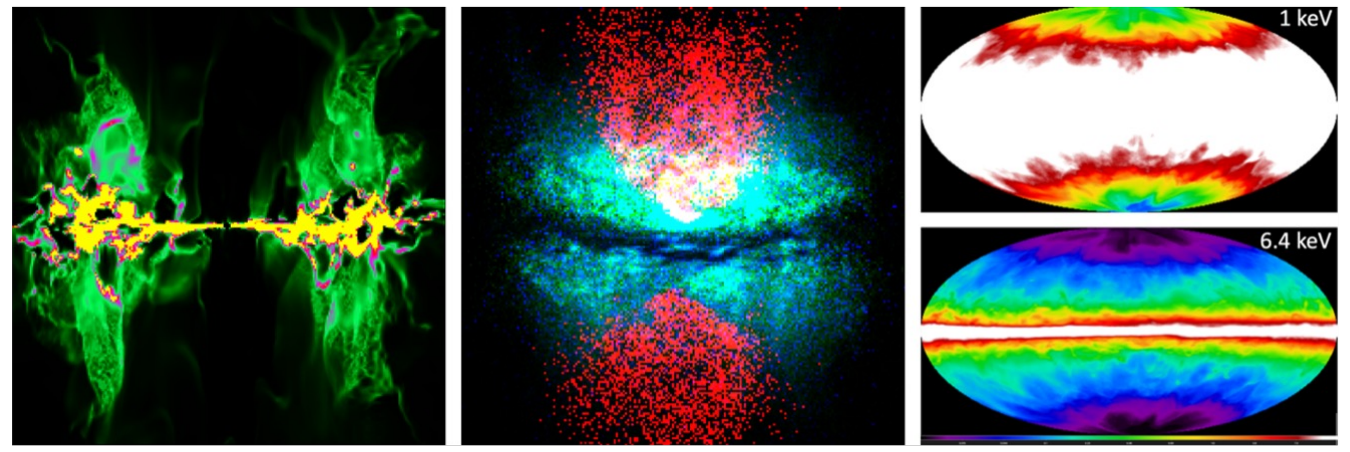


Table 1. Integrated line fluxes as calculated with SKIRT and REFLEX.

Line	F_{line} with SKIRT $[10^{-4}]$	F_{line} with REFLEX $[10^{-4}]$
Fe K_α	8.75 counts s^{-1} cm^{-2}	8.83 counts s^{-1} cm^{-2}
Fe K_β	1.21 counts s^{-1} cm^{-2}	1.20 counts s^{-1} cm^{-2}
Ni K_α	0.27 counts s^{-1} cm^{-2}	0.26 counts s^{-1} cm^{-2}

DEMONSTRATION

We demonstrate the full-3D capabilities of SKIRT by post-processing the hydrodynamical torus simulations of Wada (2016), representing an obscured AGN similar to Circinus galaxy. The left panel shows the distribution of cold gas as extracted from this simulation. The middle panel shows a synthetic X-ray image in red (1 keV), green (6.4 keV) and blue (10 keV), produced with SKIRT for an inclination of 75°. We observe a prominent absorption lane in the equatorial plane, and extended soft X-ray emission in the polar direction caused by bound-electron scattering. The right panel shows the all-sky optical depth map as calculated from the centre. The white colour indicates optical depths above 10, where virtually no photons can penetrate the torus. We find that the X-ray obscuring structure is more extended at 1 keV than it is at 6.4 keV.



CONCLUSIONS

SKIRT can now model X-ray radiative transfer, simulating Compton scattering, photo-absorption, fluorescence, bound-electron scattering and dust extinction. This results in a high-performance X-ray radiative transfer code, that can handle AGN media with complex distributions. Due to this computational efficiency, SKIRT will be ideal to experiment with new spectral models for AGN. In addition, SKIRT allows for model predictions covering both the X-ray band and the IR-to-UV range.

We tested the new X-ray implementation by comparing SKIRT simulation results to equivalent RefleX simulations, and found an excellent agreement over a wide range of N_H values. We demonstrated the full-3D capabilities of SKIRT by post-processing hydrodynamical torus simulations, and conclude that the SKIRT code can handle these complex three-dimensional transfer media.

CONTACT

Please get in touch to discuss, use or apply SKIRT:

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For more details, see Vander Meulen et al. (in prep.).