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MULTI-WAVELENGTH POLARIMETRY: A POWERFUL TOOL TO STUDY THE PHYSICS OF ACTIVE GALACTIC NUCLEI

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Abstract. Accreting supermassive black holes reside in a very complex environment and the inner structure and dynamics of active galactic nuclei (AGN) are not well understood yet. In this note, I point out the important role that multi-wavelength polarimetry can play in understanding AGN. In addition to spectroscopy, the measurement of the polarization percentage and position angle provides two more observables that are sensitive to the geometry and kinematics of emission and scattering regions. Furthermore, time-dependent polarimetry allows to measure spatial distances between emission regions and scattering mirrors by applying a reverberation technique. For radiation coming from the direct vicinity of the black hole, the polarization also contains information about the space-time metric. Spectropolarimetry observations of AGN are obtained in the radio, the infrared, the optical, and the ultraviolet wave bands and in the future they are going be available also in the X-ray range. To interpret these observations in a coherent way, it is necessary to study models that do not only reproduce the broad-band spectroscopy properties of AGN but also their multi-wavelength polarization signature. I present a first step towards such models for the case of radio-quiet AGN. The modeling reveals the optical/UV and X-ray polarization properties of the reprocessed radiation coming from the obscuring torus. The discussion about the implications of such models includes prospects for the up-coming technique of X-ray (spectro-)polarimetry.

1 Observing and modeling the optical/UV and X-ray polarization of active galactic nuclei

Polarimetry and spectropolarimetry are powerful techniques to disentangle the complex structure and dynamics of the various media close to accreting supermassive black holes. In the optical waveband, polarimetry provided major support for the standard unification model of active galactic nuclei (AGN), when Antonucci & Miller (1984) found the first hidden type-1 nucleus in the Seyfert-2 galaxy NGC 1068 by revealing broad optical emission lines in the polarized flux spectrum. Many more hidden type-1 nuclei were then found by polarimetry. The technique enables a periscope view around the obscuring torus revealing the central ionizing source and the broad line region of a type-2 AGN. This periscope view is possible due to the scattering-induced polarization that originates mostly in the polar ionization cones of the AGN scheme. The analysis and modeling of large samples of Seyfert galaxies has further constrained the geometry and dynamics of the various scattering components that are relevant to the polarization of the continuum and the broad emission lines (see Smith et al. 2005 and references therein). A new dimension was added to the polarimetry technique when Gaskell et al. (2007) presented a reverberation of the optical polarization coming from the Seyfert galaxy NGC 4151. The reverberation time scale allowed to constrain the spatial distance between the illuminating source region and the polarizing mirrors. For NGC 4151 it was found that the size of the polarizing mirror should be comparable to the size of the low-ionization broad line region, while it was ruled out that the polarization arises from dust scattering by the inner surface of the much larger obscuring torus.

To correctly interpret the results of polarization measurements, it is important to conduct detailed and coherent modeling. Almost any interaction between radiation and matter leaves an imprint in the polarization signal coding information about the composition, dynamics and the geometry of the scattering mirror(s). In the complex environment of accreting black holes one therefore expects a strong impact of multiple scattering on the observed polarization spectrum. All these aspects should be considered in a polarization model, which is why the Monte-Carlo STOKES was written (Goosmann & Gaskell 2007) and continues to be developed.

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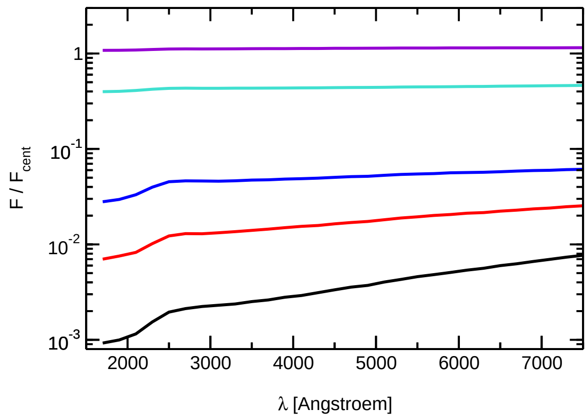

Fig. 1. Modeling the optical/UV dust extinction by a centrally illuminated large torus with an elliptical cross-section and half-opening angle $\theta_0 = 30°$. The fraction, F/F_*, of the central flux, F_*, seen at different viewing angles, i, and wavelengths, λ, is shown. From top to bottom i takes the values $i = 18°$ (purple, face-on view), $i = 32°$ (cyan), $i = 41°$ (blue), $i = 49°$ (red), and $i = 57°$ (black, intermediate viewing angle).

A first release of the code working in the optical/UV spectral range is publicly available and featured on the world wide web[1]. Recently, the code has been extended into the X-ray range by implementing a prescription of Compton scattering, X-ray photo-absorption and the production of iron Kα and Kβ lines. Now, it is thus possible to compute the polarization properties of a given AGN model simultaneously in the optical/UV and the X-ray band. This should give important constraints as several components of an active nucleus, such as the polar ionized outflows or the obscuring torus, reprocess both the optical/UV and the X-ray radiation.

2 Modeling the reprocessed optical/UV and X-ray spectra of the dusty torus

As a first step, I am going to focus on modeling the polarization properties of the reprocessed radiation emerging from the optically thick, dusty torus only. In the optical/UV range, the reprocessing has been extensively modeled with STOKES before (Goosmann & Gaskell 2007). Model setups for various torus geometries, half-opening angles, and dust compositions where examined. Here I apply again the model of a centrally irradiated torus with a large elliptical cross-section and a half-opening angle of $\theta_0 = 30°$. The size of the optical/UV emitting parts of the accretion disk is very small when compared to the size of the inner torus radius. Therefore, the central source is defined to be point-like. The incident radiation is supposed to be unpolarized and constant with wavelength λ. The dust composition follows a prescription for standard Galactic dust. The resulting scattering spectra as a function of the viewing angle i are recalled in Fig. 1. Note that the dust temperature must be below 1500 K for the dust being able to exist. Therefore, one does not expect any thermal re-emission in the optical/UV range considered here. The peak of the dust re-emission actually lies in the infrared waveband.

Next, I compute the X-ray reprocessing of the irradiated torus using the latest version of the STOKES code. In the X-ray range the sub-structure of the irradiating source should not be treated as simply as for the optical/UV band. The X-ray spectrum of AGN shows significant variability on very fast time-scales. It is therefore necessary to conclude that the X-ray emission comes from very compact regions close to the central black hole. One further assumes that a significant fraction of this primary radiation is being reprocessed by the accreting disk. Such a reflection from the disk polarizes the radiation, so that the X-ray spectrum impinging on the torus is no longer unpolarized. We take this fact into account by modeling self-consistently the multiple-reprocessing by the disk and the torus. For both regions we assume neutral reprocessing by an optically thick medium with solar elemental abundances. The disk is located at the symmetry center of the torus and being irradiated by a slightly elevated primary X-ray source (so-called lamp-post geometry). The size of the

[1] http://www.stokes-program.info/

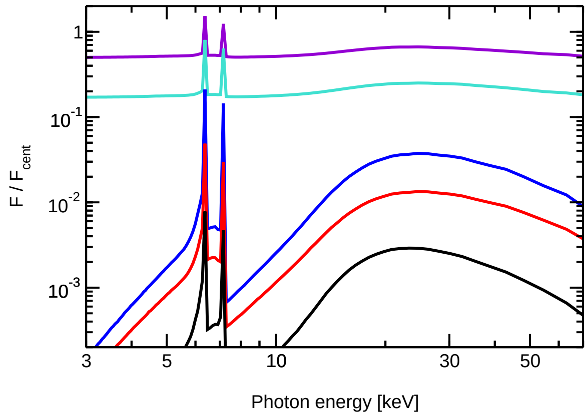

Fig. 2. Modeling the X-ray reprocessing from a system of a centrally illuminated disk situated inside the funnel of a large torus with an elliptical cross-section and half-opening angle $\theta_0 = 30°$. The denotations are as in Fig. 1.

reprocessing disk is small with respect to the inner radius of the torus. The height of the primary source above the disk is small against the disk size. The source isotropically emits a constant spectrum in photon energy.

The spectral results for the X-ray modeling are shown in Fig. 2. The reprocessed spectrum shows standard features, such as photo-absorption in the soft X-ray range, fluorescent Kα and Kβ lines at 6.4 keV and 7.1 keV and the characteristic reflection hump due to Compton down-scattering around 20—30 keV. At low inclination angles, when the observer can directly see the central source, the spectrum is dominated by the primary contribution. The reprocessing features are much more pronounced at higher inclinations when the primary source disappears below the torus horizon.

In Fig. 3, I show the spectrum of the resulting polarization degree for the X-ray and the optical/UV range. The X-ray data is now converted to photon wavelength. In both bands the polarization is positive and thus the polarization position angle is oriented perpendicularly to the symmetry axis of the system. For the X-ray range this is not necessarily obvious, as for a small irradiated X-ray region the position angle of the resulting polarization can also be aligned to the (projected) symmetry axis (Goosmann 2009). In this case, however, we assume the disk to be large with respect to the height of the primary source. A scattering torus with a half-opening angle of 30° can only produce perpendicular polarization in both wavebands considered.

It it interesting to compare the polarization degree P in both bands: the polarization is always weak at low inclinations when the spectrum is dominated by the unpolarized primary radiation. The situation is very different at higher inclinations. The highest polarization percentages appear in the soft X-ray range. Comparison with Fig. 2 shows that the strong polarization corresponds to fluxes decreasing toward low X-ray energies (longer wavelengths). The fluxes are more significant closer to the iron line complex, i.e. at 5—6 keV. Across the iron line, the polarization drops due to dilution by the unpolarized line emission. The Compton hump is significantly polarized. Across the hump maximum, P is slightly reduced due to the multiple Compton scattering that has a depolarizing effect. But the hard X-ray polarization always remains above ~ 10 %. In the optical/UV band the wavelength dependence of the polarization degree is influenced by the dust composition but the dominating effect is the torus half-opening angle (Goosmann & Gaskell 2007).

3 Future prospects for multi-wavelength polarimetry

The results presented in this note are first steps on the way to provide consistent and simultaneous polarization models for AGN in the optical/UV and the X-ray band. The advantage of using a flexible Monte-Carlo method like in STOKES lies in the possibility to coherently combine various reprocessing regions. For X-ray polarization emerging from close to the last stable orbit of the accretion disk, relativistic effects play an important role and the STOKES results have to be combined with a relativistic ray-tracing method - which then allows to probe the space-time structure in the direct vicinity of the black hole (Dovčiak et al. 2008).

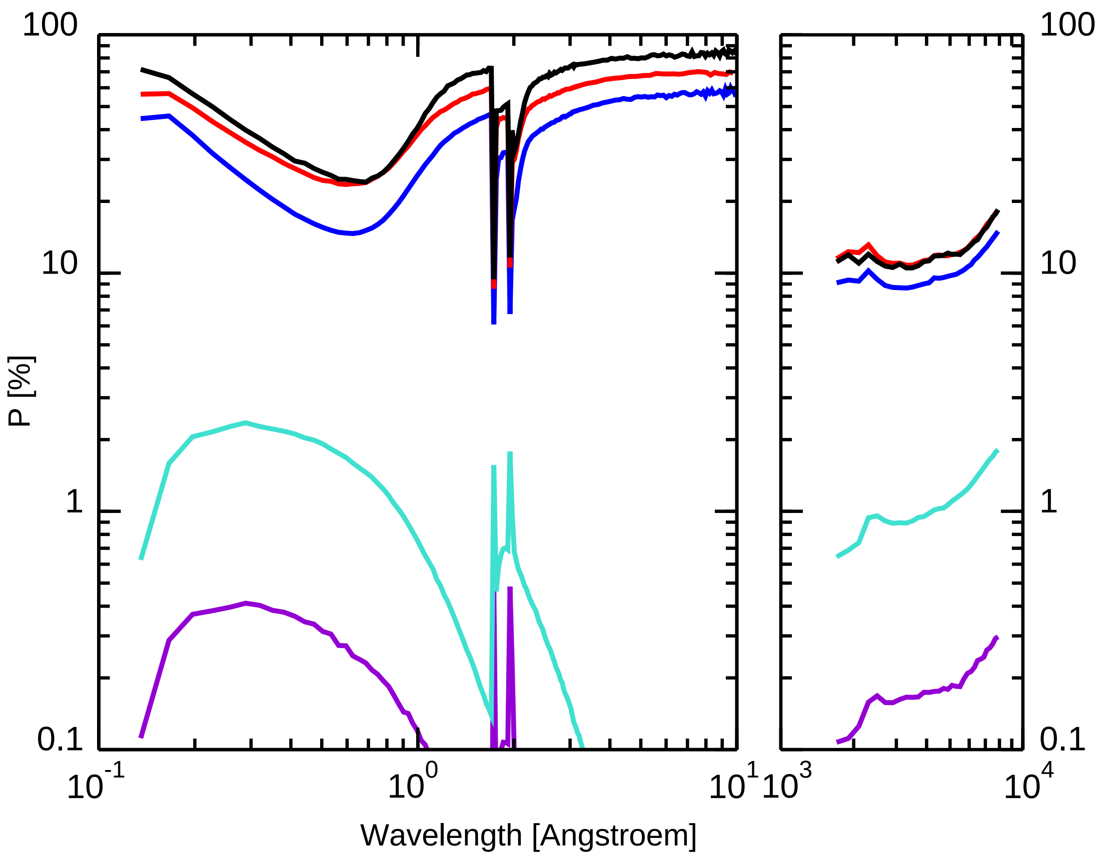

Fig. 3. Polarization degree, P, induced by the irradiated torus (see text) for the X-ray and the optical/UV band as a function of the photon wavelength, λ, and the viewing angle, i. From top to bottom i takes the values $i = 57^\circ$ (black, intermediate viewing angle), $i = 49^\circ$ (red), $i = 41^\circ$ (blue), $i = 32^\circ$ (cyan), and $i = 18^\circ$ (purple, face-on view).

While polarimetry is an established technique in the optical waveband, we are still at the edge of the X-ray polarimetry era. The coming age of satellite-based X-ray polarimeters like the NASA GEM SMEX satellite (Swank et al. 2008) or the Italian mission project POLARIX (Costa et al. 2006) will enable us to test the type of modeling of which only a beginning is laid out here. In the future it is necessary to further explore the available parameter space by considering multiple reprocessing components and by varying their geometry and dynamics. Of course the number of model parameter increases - but so does the number of (polarimetry) observables as well as the spectral coverage of both, models and observations. Therefore, multi-wavelength polarimetry is a promising tool to further disentangle the complexity around accreting supermassive black holes.

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