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MODELING X-RAY POLARIMETRY WHILE FLYING AROUND THE MISALIGNED OUTFLOW OF NGC 1068

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Abstract. In contrast to the standard unified model, the ionized outflow in the nucleus of the Seyfert-2 galaxy NGC 1068 is claimed to be tilted with respect to the symmetry axis of the dusty torus. We compute the broad-band X-ray spectrum and polarization emerging from multiple reprocessing in an asymmetric model setup of NGC 1068. Considering different azimuthal viewing directions, we show that the slope of the polarization angle between the soft X-ray and the hard X-ray bands allows us to distinguish a clock-wise from a counter clock-wise tilt of the wind with respect to the torus axis. We also find that equatorial scattering in the outer accretion flow has a minor impact on the X-ray polarization of typical Seyfert-2 nuclei.

Keywords: Galaxies: active, Galaxies: Seyfert, Galaxies: individual: NGC 1068, Radiative transfer, Polarization, Scattering

1 Introduction

Accreting supermassive black holes in thermal active galactic nuclei (AGN) are known to redirect a large fraction of the accretion flow into strong outflows. Neither the ejection mechanism nor the geometry of these winds are well-constrained yet. According to the unified scheme of AGN (Antonucci 1993) the wind in type-2 objects – those that do not show broad Balmer emission lines – should be seen from the side, in contrast to type-1 objects where the wind is observed in transmission. The standard unified model is assumed to be axis-symmetric, but there has been a recent claim by Raban et al. (2009) that the ionized wind in the well-studied Seyfert-2 galaxy NGC 1068 is misaligned with respect to the axis of the dusty torus and the accretion disk.

Raban et al. (2009) infer the ejection direction of the outflow in NGC 1068 somewhat indirectly; the authors implicitly assume that the more distant narrow line region is aligned with the wind base situated much closer to the black hole. In Goosmann & Matt (2011) we present a model of the expected X-ray polarization of NGC 1068 and we argue that a soft X-ray polarization measurement would unambiguously constrain the flow direction (projected on the plane of the sky) at the wind base. We further show how the tilting angle of the wind with respect to the torus axis can be constrained by broad-band X-ray polarimetry.

So far, we have only presented spectra and polarization properties at one azimuthal viewing angle. In this note, we therefore consider a more general viewing direction toward the asymmetric model setup of NGC 1068.

2 Modeling results for different azimuthal viewing directions

Our modeling is carried out using the latest version of the radiative transfer code STOKES. The code and the model are described in more detail in Goosmann & Matt (2011) and we summarize the setup in Fig. 1 and the parameters in Table 1. The model comprises an irradiated accretion disk, a dusty torus and a bi-conical outflow with an angular offset of 18° with respect to the torus axis. We investigate two cases that either include an equatorial scattering disk (model B) or not (model A). A primary spectrum with a power-law shape $F_{\rm E} \propto E^{-\alpha}$ and $\alpha = 1$ is assumed. The spectrum cuts off at 1 keV and 100 keV. We introduce a Cartesian coordinate system with the z-axis being the common symmetry axis of the torus and the accretion disk. All reprocessing

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irradiated accretion disk	dusty torus	bi-conical, polar outflow	flared disk
on-axis source at height 0.0001 pc	$R_{\rm min} = 0.1$ pc	$R_{\rm min} = 0.3$ pc	$R_{\rm min} = 0.02$ pc
$R_{\rm disk} = 0.0004$ pc	$R_{\rm max} = 0.5$ pc	$R_{\rm max} = 1.8$ pc	$R_{\rm max} = 0.04$ pc
$h_{\rm disk} = 3.25 \times 10^{-7}$pc	half-open. ang. $= 60°$	half-open. ang. $= 40°$, tilted by $18°$	half-open. ang. $= 20°$
vertical opt. depth > 600	equat. opt. depth $= 750$	radial opt. depth $= 0.3$	radial opt. depth $= 1$
neutral reprocessing	neutral reprocessing	electron scattering	electron scattering

Table 1. Parameters of the model components. The primary X-ray source subtends a half-angle of $\sim 75°$ with the disk. For the polar outflow, the half-opening angle is measured with respect to its symmetry axis, while for the flared disk the half-opening angle is taken with respect to the equatorial plane. Model B includes the flared disk, model A does not.

regions are centered on the coordinate origin and the wind axis is tilted inside the yz-plane leaning towards the positive y-axis. The observer's inclination and the tilting angle of the outflow are measured from the z-axis. The azimuthal viewing angle, ϕ, is taken inside the xy-plane with respect to the negative y-axis. In Goosmann & Matt (2011), ϕ was set to $\sim 90°$, which corresponds to the view shown in Fig. 1.

The results for the models A and B are shown in Figs. 2 and 3. The inclination $i \sim 18°$ features a type-1 object, at $i \sim 63°$ the line-of-sight lies just below the torus horizon, while $i \sim 76°$ and $i \sim 87°$ represent type-2 objects. We cover half a round in azimuth at $\phi = 35°$, $\phi = 80°$, $\phi = 125°$, and $\phi = 170°$; we extend the results to a full round for the polarization angle ψ. For $\psi = 0°$, the polarization is perpendicular to the z-axis; it rotates clock-wise with rising ψ until it is aligned with the projected z-axis at $\psi = 90°$.
The spectral flux does not depend strongly on ϕ, which is due to the system's still limited divergence from axis-symmetry. But the polarization below 10 keV is very sensitive to scattering in the tilted outflow and ψ shows a systematic behavior as one goes around in azimuth. At an extreme type-2 view, the soft X-ray polarization is strictly perpendicular to the projected wind axis (at the type-1 inclination, the polarization partly is very low and the Monte Carlo results suffer a bit from insufficient statistics).
Above 10 keV, Compton scattering in the dusty torus and the accretion disk competes with the electron scattering in the wind. The polarization angle shows some dependency on this competition around 30 keV. Note that when comparing ψ at azimuthal viewing angles that are symmetric with respect to the yz-plane one can derive in which direction the wind is leaning: if it is rotated clock-wise (counter clock-wise) with respect to the z-axis, the polarization angle increases (decreases) with photon energy (this relation inverts should ψ be defined in the opposite direction).

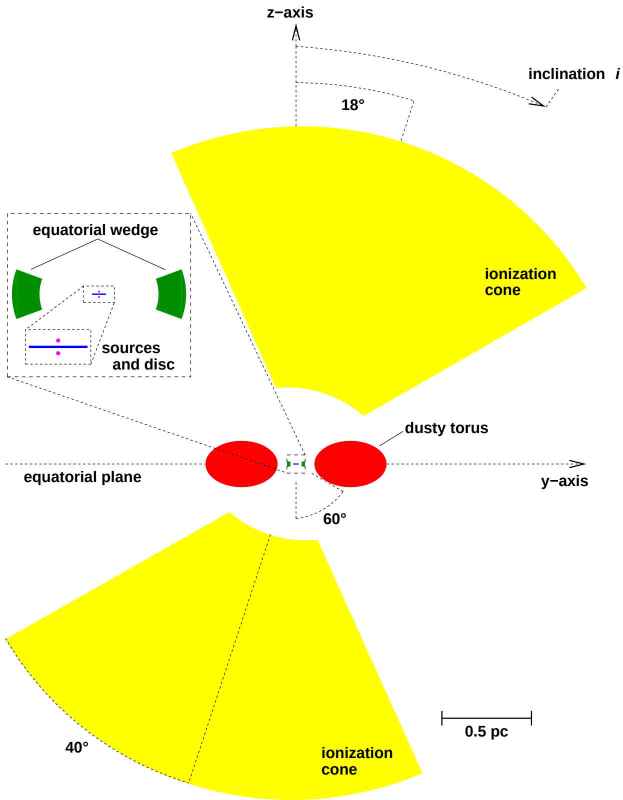

Fig. 1. Edge-on view ($i = 90°$) of our model setup at the azimuthal viewing angle $\phi = 90°$ (see Goosmann & Matt 2011, for more details).

The equatorial scattering disk has a significant impact on the X-ray polarization only at type-1 viewing angles. Since the equatorial scattering modifies the irradiation pattern of the inner torus surfaces, one could suspect that the hard X-ray polarization at type-2 viewing angles should be different when the flared disk is included. Careful comparison between model A and model B shows that there are indeed minor shifts in the polarization spectra at type-2 view; but the effect turns out to be rather weak. At type-1 view or at the limit of a type-1/type-2 view, the flared disk produces strong polarization at a different polarization angle than the outflow. This is visible in both polarization features (percentage and position angle). Note that the presence of the flared disk also increases the total soft X-ray flux by scattering primary photons into the line-of-sight.

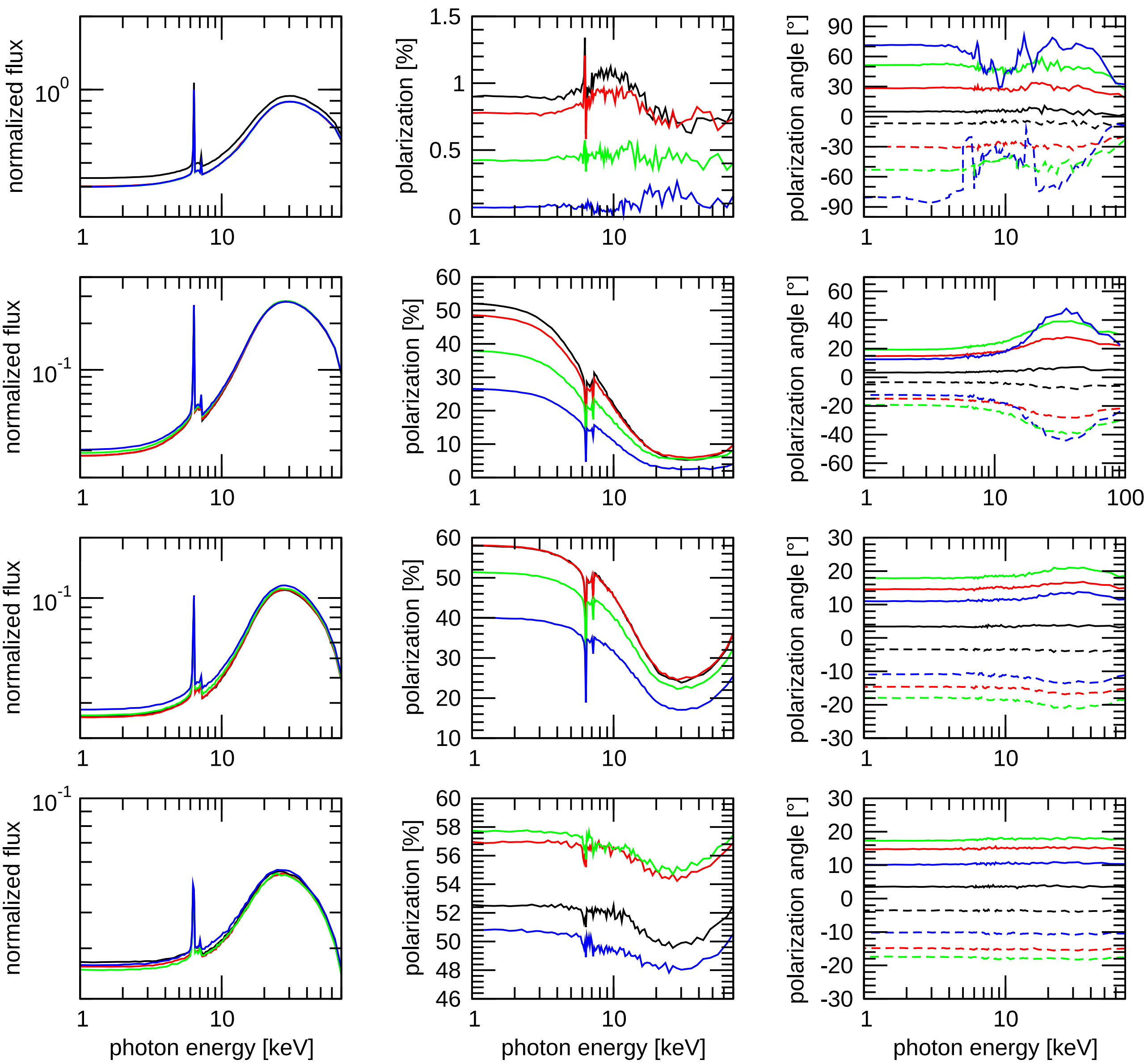

Fig. 2. Results for Model A (no equatorial scattering disk). From top to bottom the panels represent the inclinations $i \sim 18°$, $i \sim 63°$, $i \sim 76°$, and $i \sim 87°$. We plot the spectral flux (left), the polarization percentage (middle), and the polarization angle ψ (right) at four azimuthal angles (half a round) measured from the negative y-axis: $\phi = 35°$ (blue), $\phi = 80°$ (green), $\phi = 125°$ (red), and $\phi = 170°$ (black). The spectral flux is always normalized to the source flux emitted into the same line-of-sight. The polarization angle ψ is shown also for the symmetric azimuth $\phi' = -\phi$ (dashed lines). For $\psi = 0°$, the polarization is perpendicular to the z-axis; it rotates clock-wise with rising ψ.

3 Summary and conclusions

We have added new results to our previous modeling of the X-ray polarization induced by complex reprocessing in NGC 1068. Presuming that the double-conical outflow is tilted with respect to the symmetry axis of the dusty torus, we explore the polarization results at different azimuthal viewing angles and inclinations of the observer; it turns out that in particular the behavior of the polarization position angle as a function of photon energy can help to determine the viewing direction towards the asymmetric model. However, this rather requires broad-band polarimetry capability, which is already technically feasible (Tagliaferri et al. 2011) and hopefully will be included in a future X-ray mission.

An equatorial scattering region situated between the accretion disk and the inner edge of the dusty torus has

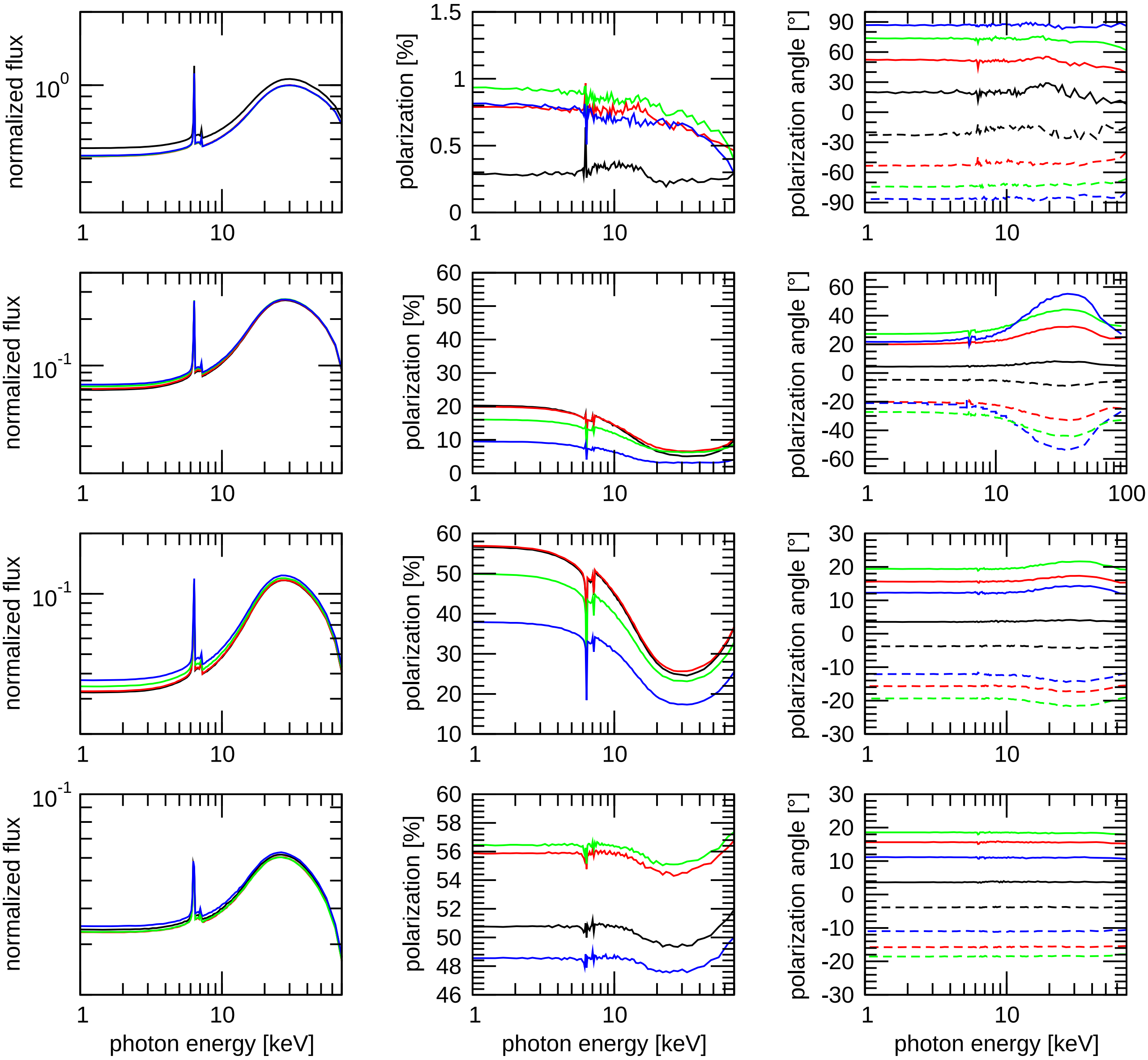

Fig. 3. The same denominations as for Fig. 2, but for model B that includes scattering inside an equatorial, flared disk.

an impact in particular at type-1 or limiting type-1/type-2 viewing angles. The equatorial scattering increases the total soft X-ray flux and modifies the polarization in competition with other reprocessing regions. At type-2 viewing angles, the effect of equatorial scattering is minor. The soft X-ray polarization of X-ray bright AGN can soon be probed with the *NASA* GEMS mission (Kallman et al. 2010) to be launched in 2014.

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