Modelling the polarization dichotomy of Active Galactic Nuclei

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ABSTRACT
I present polarization modelling of Active Galactic Nuclei in the optical/UV range. The modelling is conducted using the Monte-Carlo radiative transfer code Stokes, which self-consistently models the polarization signature of a complex model arrangement for an active nucleus. In this work I include three different scattering regions around the central source: an equatorial electron scattering disk, an equatorial obscuring dusty torus, and polar electron scattering cones. I investigate the resulting dependencies of the V-band polarization for different optical depths of the scattering cones, different dust compositions inside the torus, and various half-opening angles of the torus/polar cones. The observed polarization dichotomy can be successfully reproduced by the model.

Keywords: galaxies: active – radiative transfer – polarization

1 INTRODUCTION
The research of Active Galactic Nuclei (AGN) started with the discovery of separate types of objects that nowadays we gather under the AGN-class: Seyfert galaxies, radio galaxies, quasars, blazars, etc... An important common property among the various types is the very strong luminosity produced inside a small spatial region at the centre of the host galaxy. The standard model of the AGN phenomenon assumes accretion onto a supermassive black hole as the fundamental mechanism for producing the strong radiation. The central black hole and the accretion flow are surrounded by several additional media such as the broad line and narrow line regions. A key assumption of this so-called unified scheme for AGN is the existence of a dusty torus (see e.g. Antonucci, 1993). It divides AGN into two classes: “type-1” objects, which are seen close to face-on, and “type-2” objects seen rather edge-on. In type-1 AGN the central energy source and the broad line region can be seen directly, whilst in type-2 AGN the torus blocks the view toward the centre.

Current observational technology in the optical and UV waveband does not allow to resolve the inner regions of AGN. However, the light of AGN is polarized...
over a broad wavelength range, which allows to put important constraints on the geometry of the emitting and scattering regions. When light is scattered, the angle of polarization depends on the direction of the last scattering, so one expects the angle of polarization to be related to the structure of the AGN. Stockman et al. (1979) made the seminal discovery that for low-polarization, high optical luminosity, radio-loud AGN, the optical polarization position angles tend to align parallel to the large-scale radio structure. Antonucci (1982) pointed out that whilst many radio galaxies showed a similar parallel alignment of the polarization and radio axes, there was, unexpectedly, a population showing a perpendicular relationship. It was subsequently shown (Antonucci, 1983) that relatively-radio-quiet Seyfert galaxies show a similar dichotomy between the predominantly, but not exclusively, parallel polarization in face-on type-1 Seyferts and the perpendicular polarization of type-2 Seyferts (see Antonucci, 1993, 2002 for reviews).

Applying the radiative transfer code Stokes, we have presented theoretical modelling of individual scattering regions in AGN (Goosmann and Gaskell, 2007; Goosmann et al., 2007a,b). In these papers, we considered dusty torii, polar electron cones, and equatorial scattering wedges individually calculating their polarization signatures for various viewing angles. For the present proceedings note I expand on this type of modelling combining the individual regions to obtain an approach to the unified scheme of AGN. With Stokes such modelling is done consistently as the code automatically includes the effects of multiple scattering. In Sect. 2, I briefly summarize the basic properties of Stokes. In Sect. 3, I describe the model setup. The modelling results are then presented in Sect. 4 and discussed in Sect. 5.

2 THE RADIATIVE TRANSFER CODE STOKES

The computer program Stokes performs simulations of radiative transfer, including the treatment of polarization, for AGN and related objects. The code is publicly available and 100% shareware¹. It is based on the Monte Carlo method and follows single photons inside the source region through various scattering processes until they become absorbed or escape from the model region (Fig. 1).

Photons are created inside the source regions, which can be defined by different geometries. The continuum radiation is set by the index $\alpha$ of an $F_\nu \propto \nu^{-\alpha}$ power law. The Stokes vectors of the emitted photons are initially set to the values of completely unpolarized light. Various scattering regions can be arranged around the source regions. The program offers e.g. toroidal, cylindrical, spherical or conical shapes. These regions can contain free electrons or dust consisting of “astronomical silicate” and graphite. A photon works its way through the model region and generally undergoes several scattering events. The emission directions, path lengths between scattering events, and the scattering angles are sampled by Monte Carlo routines based on classical intensity distributions. During each scattering event the Stokes vector is changed by multiplication with the corresponding Mueller matrix.

¹ http://www.stokes-program.info/
For dust scattering, absorption is important, and a large fraction of the photons does not reach the virtual observer. The relevant cross sections and matrix elements for dust scattering and absorption are computed on the basis of Mie theory applied to size distributions of spherical graphite and silicate grains.

When a photon escapes from the model region, it is registered by a web of virtual detectors arranged in a spherical geometry around the source. The flux and polarization information of each detector is obtained by adding up the Stokes parameters of all detected photons. If the model is completely axially symmetric these can be azimuthally integrated and, if there is plane symmetry, the top and bottom halves are combined. The object can be analyzed in total flux, in polarized flux, percentage of polarization, and the position angle at each viewing angle.

3 MODELLING THE UNIFIED SCHEME

Our setup for the united model of AGN is shown in Fig. 2. We include the equatorial dusty torus and the polar electron scattering cones. In addition to that an equatorial electron scattering wedge is defined. Such a region produces the correct (parallel) polarization of type-1 AGN. The polarization properties of flat equatorial scattering disks have been investigated in a series of papers by Young (2000) and Smith et al. (2002, 2004, 2005) as well as in Goosmann and Gaskell (2007).

We assume that the central source of the AGN is point-like and emits a flat intrinsic spectrum around $\lambda = 5500 \, \text{Å}$. We define a half-opening angle, $\theta_{\text{disk}}$, of the flared electron disk of $\theta_{\text{disk}} = 25^\circ$. For this half-opening angle a high percentage of
Figure 2. Illustration of the setup for a unified scheme model of AGN. The central source is surrounded by a flared electron scattering disk (wedge), a dusty torus, and by polar electron cones.

Table 1. Parameterization of the dust models

| Type   | Graphite | Silicate | $a_{\text{min}}$ (µm) | $a_{\text{max}}$ (µm) | $\alpha_s$ |
|--------|----------|----------|------------------------|------------------------|------------|
| Galactic | 62.5%    | 37.5%    | 0.005 µm               | 0.250 µm              | -3.5       |
| AGN    | 85%      | 15%      | 0.005 µm               | 0.200 µm              | -2.05      |

type-1 polarization is expected (Goosmann and Gaskell, 2007). The radial Thomson optical depth of the wedge is set to unity. The half-opening angle $\theta_0$ of the torus and the cone are set equal, which corresponds to the interpretation that the ionized outflow is collimated by the torus. We consider two cases for the Thomson optical depth of the scattering cones, which is measured along the symmetry axis of a single cone and set to $\tau_{\text{cone}} = 0.01$ and $\tau_{\text{cone}} = 0.1$ respectively. The radial optical depth of the dusty torus in the equatorial plane is set to 750 for the V-band. The dust models (table 1) assume a mixture of graphite and “astronomical silicate” and a grain radii distribution $n(a) \propto a_\ast^\alpha$ between $a_{\text{min}}$ and $a_{\text{max}}$.

The “Galactic dust” model reproduces the interstellar extinction for $R_V = 3.1$ whilst the “AGN dust” parameterization is obtained from quasar extinction curves derived by Gaskell et al. (2004). This latter dust type favours larger grain sizes.
Using Stokes we consistently model the resulting polarization spectrum of the entire model setup for various inclinations, $i$, of the observer and for four different values of $\theta_0$ between $30^\circ$ and $45^\circ$.

4 RESULTS

We investigate the dependence of the polarization in the visual band on the half-opening angle of the dusty torus/polar cones. In Fig. 3 and Fig. 4 we show the resulting percentage of polarization, $P$, versus $i$ for the two values of $\tau$ and for the two types of dust. The relation has a similar shape for all cases shown and reproduces the observed type-1/type-2 polarization dichotomy: the polarization position angle is oriented parallel to the projected symmetry axis when the line of sight is above the horizon of the torus, i.e. for $i < \theta_0$, and switches to a perpendicular orientation for $i > \theta_0$. In the figures, the two different orientations of the polarization vector are denoted by negative (type-1) and positive (type-2) values of $P$. The type-1 values of $P$ are moderate and reach maximum absolute values of $\sim 2.5\%$. They rise with $i$ until the polarization vector switches to the type-2 orientation. In the type-2 case $P$ continues to increase with $i$ and saturates for edge-on viewing angles at a level that depends on $\theta_0$.

The combined effect of all scattering regions on the total polarization value can be partly understood from the results we obtained when modelling the individual regions in Goosmann and Gaskell (2007). However, the fact that all regions are radiatively coupled adds more complexity to the model. The polar scattering regions have a strong impact on the result, in particular for type-2 viewing angles. With increasing $\theta_0$ the resulting type-2 polarization becomes lower because it is averaged over a broader distribution of polarization position angles. An increasing optical depth of the cones raises $P$ for the type-2 case because more photons are scattered by the cones.

For nearly face-on viewing directions, the polar cones have less impact as they cause mainly forward or backward scattering producing low polarization. In these cases the resulting polarization is mainly determined by the geometry and optical depth of the equatorial scattering disk. However, these two regions compete against each other, as they produce different orientations of the polarization vector. For higher optical depth the impact of the polar cones becomes stronger and lowers the resulting type-1 polarization, as can be seen when comparing the top with the bottom panels in Figs. 3 and 4.

In the central parts of the model region, the optically thick torus, and the scattering wedge are strongly interconnected by multi-scattering. This explains the significant impact of the dust composition and grain size distribution on the resulting polarization profile. For AGN dust the obtained type-2 polarization percentages for intermediate viewing angles are lower than for the Galactic dust torus. For this range of $i$ the reflection off the torus has an important influence while toward edge-on values of $i$ the polar scattering is again more important.
Figure 3. Polarization degree $P$ at 5500 Å as a function of the disk inclination $i$. The upper panels denote an optical depth $\tau = 0.01$ of the polar electron cones, the lower ones denote $\tau = 0.1$. On the left side, the results for a torus with Galactic dust are given, on the right side the results are for AGN dust. From left to right the four curves of each panel mark increasing half-opening angles $\theta_0$ of the system. Positive values of the polarization degree denote an orientation of the polarization position angle, which is perpendicular to the symmetry axis, negative values stand for parallel polarization.

5 SUMMARY AND DISCUSSION

In this proceedings note, we have investigated the optical polarization imprint of an active nucleus. Our model is geared toward the unified scheme of AGN includ-
Figure 4. Same as in Fig. 3 but zoomed in and limited to disk inclinations of 60°.
type-2 polarization. They are considered to be dominated by polar instead of equatorial scattering. In our model, we have set the half-opening angle and the optical depth of the equatorial wedge in such a way that a maximum type-1 polarization percentage is obtained. We then vary the optical depth of the polar scattering cones. The resulting distribution of the polarization position angle as a function of the inclination must correspond to the observed number densities of Seyfert-1 galaxies that are dominated by polar and by equatorial scattering. In principle, it is thus possible to put constraints on the optical depth of the polar cones.

But our modelling shows that there is also a significant impact of the dusty torus on the resulting polarization, especially for intermediate viewing angles. The resulting polarization changes with the dust type. From the given number density of AGN with different spectral and polarization types it is thus not straightforward to find relations between the properties of the various scattering regions. It rather requires more detailed modelling over a broader spectral range and within a larger parameter space than presented here. We intend to conduct such investigations in the future.

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REFERENCES

Antonucci, R. R. J. (1982), Optical polarization position angle versus radio source axis in radio galaxies, *Nature*, 299, pp. 605–606.

Antonucci, R. R. J. (1983), Optical polarization position angle versus radio structure axis in Seyfert galaxies, *Nature*, 303, pp. 158–159.

Antonucci, R. R. J. (1993), Unified models for active galactic nuclei and quasars, *ARA&A*, 31, pp. 473–521.

Antonucci, R. R. J. (2002), Polarization insights for active galactic nuclei, in J. Trujillo-Bueno, F. Moreno-Insertis and F. Sánchez, editors, *Astrophysical Spectropolarimetry*, pp. 151–175.

Gaskell, C. M., Goosmann, R. W., Antonucci, R. R. J. and Whysong, D. H. (2004), The Nuclear Reddening Curve for Active Galactic Nuclei and the Shape of the Infrared to X-Ray Spectral Energy Distribution, *ApJ*, 616, pp. 147–156, arXiv:astro-ph/0309595.

Goosmann, R. W. and Gaskell, C. M. (2007a), Modeling optical and UV polarization of AGNs. I. Imprints of individual scattering regions, *A&A*, 465, pp. 129–145.

Goosmann, R. W., Gaskell, C. M. and Shoji, M. (2007b), AGN polarization modeling with Stokes, in V. Karas and G. Matt, editors, *IAU Symposium*, volume 238 of *IAU Symposium*, pp. 375–376.

Goosmann, R. W., Gaskell, C. M. and Shoji, M. (2007b), Modeling the Polarization of Dusty Scattering Cones in Active Galactic Nuclei, *ArXiv Astrophysics e-prints*, astro-ph/0701163.
Smith, J. E., Robinson, A., Alexander, D. M., Young, S., Axon, D. J. and Corbett, E. A. (2004), Seyferts on the edge: polar scattering and orientation-dependent polarization in Seyfert 1 nuclei, *MNRAS*, **350**, pp. 140–160, arXiv:astro-ph/0401496.

Smith, J. E., Robinson, A., Young, S., Axon, D. J. and Corbett, E. A. (2005), Equatorial scattering and the structure of the broad-line region in Seyfert nuclei: evidence for a rotating disc, *MNRAS*, **359**, pp. 846–864, arXiv:astro-ph/0501640.

Smith, J. E., Young, S., Robinson, A., Corbett, E. A., Giannuzzo, M. E., Axon, D. J. and Hough, J. H. (2002), A spectropolarimetric atlas of Seyfert 1 galaxies, *MNRAS*, **335**, pp. 773–798, arXiv:astro-ph/0205204.

Stockman, H. S., Angel, J. R. P. and Miley, G. K. (1979), Alignment of the optical polarization with the radio structure of QSOs, *ApJL*, **227**, pp. L55–L58.

Young, S. (2000), A generic scattering model for AGN, *MNRAS*, **312**, pp. 567–578.
