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Off-axis irradiation and the polarization of broad emission lines in active galactic nuclei

René W. Goosmann [a,*], C. Martin Gaskell [b,c], Frédéric Marin [a,d]

[a] *Observatoire Astronomique de Strasbourg, Université de Strasbourg, CNRS, UMR 7550, 11 rue de l'Université, 67000 Strasbourg, France*
[b] *Centro de Astrofísica de Valparaíso y Departamento de Física y Astronomía, Universidad de Valparaíso, Chile*
[c] *Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA*
[d] *Astronomical Institute of the Academy of Sciences, Boçní II 1401, CZ-14100 Prague 4, Czech Republic*

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Abstract

The STOKES Monte Carlo radiative transfer code has been extended to model the velocity dependence of the polarization of emission lines. We use STOKES to present improved modeling of the velocity-dependent polarization of broad emission lines in active galactic nuclei. We confirm that off-axis continuum emission can produce observed velocity dependencies of both the degree and position angle of polarization. The characteristic features are a dip in the percentage polarization and an S-shaped swing in the position angle of the polarization across the line profile. Some differences between our STOKES results and previous modeling of polarization due to off-axis emission are noted. In particular we find that the presence of an offset between the maximum in line flux and the dip in the percentage of polarization or the central velocity of the swing in position angle does not necessarily imply that the scattering material is moving radially. Our model is an alternative scenario to the equatorial scattering disk described by Smith et al. (2005). We discuss strategies to discriminate between both interpretations and to constrain their relative contributions to the observed velocity-resolved line and polarization.

Keywords: Polarization; Radiative transfer; Line profiles; Scattering; Galaxies: active

1. Introduction

As far as we know, all thermal active galactic nuclei, which we will refer to here simply as "AGNs", have a broad-line region (BLR) (see Antonucci, 2012 for a discussion of thermal versus non-thermal AGNs). The standard model assumes that all AGNs have BLRs but that in so-called type-2 AGNs the BLR is obscured by optically-thick dust located on our line of sight, while in type-1 AGNs we can see the BLR directly. Hence, the obscuring medium must be anisotropically distributed around the supermassive black hole and its accretion disk. In the simplest version of orientation unification (Antonucci, 1993), the obscuring medium is assumed to have a toroidal geometry. The BLR and accretion disc are the inner extension of the accretion flow from the torus (Gaskell et al., 2008; Gaskell, 2009).

It has generally been assumed in the unified scheme that the AGN is symmetric with respect to the axis of the circumnuclear dust. While this is a very natural assumption, there is now growing evidence that this is not the case. For example, a detailed spectroscopic analysis of the ionized outflows in the Seyfert-2 galaxy NGC 1068, suggests that the winds are not expelled along the axis of the torus (which is presumably close to the accretion disk axis) but are misaligned with respect to these axes (Raban et al., 2009). Furthermore, (Gaskell, 2008, 2010, 2011) argues that the energy generation of AGNs is fundamentally non-axisymmetric. The standard accretion disk model states that the spectral energy

* Corresponding author. Tel.: +33 3 68 85 23 93; fax: +33 3 68 85 24 32.
E-mail address: rene.goosmann@astro.unistra.fr (R.W. Goosmann).

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distribution in the optical/UV, the so-called big blue bump, is a continuous superposition of black body spectra following the radial temperature profile of the disk (see, for example Fig. 5 of Gaskell, 2011). As a consequence, variability of different spectral regions corresponds to variations at different disk radii. Because information cannot travel faster than light it is impossible for a given annulus of the disk to vary in a coherent manner and to produce the variability at a given wavelength on the observed time scales. Therefore, the energy dissipation must happen on spatial scales significantly smaller than the corresponding radius of the annulus, i.e. *the radiation is emitted in a rather localized region*. This idea laid the ground for the off-axis variability model presented in Gaskell (2010, 2011). This new interpretation of continuum and broad line variability solves a range of problems including line profiles and line profile variability (Jovanović et al., 2010), the conflicting kinematic signatures of the red and blue wings of broad lines observed in velocity-resolved reverberation mapping, the puzzling changes in reverberation lags between different continuum events, and the independent variability of different parts of BLR line profiles (Gaskell, 2008, 2010).

Polarization is highly sensitive to departure from rotational symmetry about the line of sight in the emission and reprocessing geometry of an astrophysical object and therefore the polarization percentage and position angle provide important information about asymmetries. The motions of the BLR are predominantly coherent. The dominant motion is rotation, with significant turbulence (see Gaskell, 2009) for a review of the BLR, probably with inflow (Gaskell and Goosmann, 2013). As a result of this there is a correspondence between a given velocity in the line profile and a region in the disc (see Fig. 6 of Gaskell, 2010). Because of this, the off-axis irradiation model makes strong predictions for the velocity dependence of the polarization of the broad emission lines. In this paper, we present some preliminary modeling of the expected intensity and polarization of broad emission lines produced by a BLR that is illuminated by both axially symmetric and off-axis sources. We provide the modeled intensity and polarization profile of the line as a function of the azimuthal position of the off-axis source and compare our results to spectropolarimetric data for type-1 AGN from the literature. We have been awarded VLT time for making further spectropolarimetric observations of line profiles and we will give a more detailed analysis of these and other data in subsequent work.

The remainder of the paper is organized as follows: in Section 2, we describe our model setup and the different modeling cases we consider. The results are then given in Section 3.1 and discussed in the context of spectropolarimetric data in Section 3.2. We draw some conclusions and give further perspectives of our work in Section 4.

2. Model setup

We model the spectropolarimetric signature of a broad emission line as it appears when the BLR is irradiated simultaneously by an axisymmetric continuum source and an off-axis one. The radiative transfer simulations are conducted with a new version of STOKES (Goosmann and Gaskell, 2007; Marin et al., 2012). The new version, which is not yet public, includes the necessary atomic physics to account for photo-absorption and radiative recombination. In our model, the BLR has the geometry of a flared disk centered on the origin of the model space. We define a spherical coordinate system, with the polar angle, i, measured from the symmetry axis of the BLR. The inner and outer boundary of the BLR are sphere segments with radii $r_{\rm out} = 4 \times r_{\rm in}$. Their half-opening angle of $\theta_{\rm BLR} = 25^\circ$ is measured with respect to the equatorial plane defined by $\cos i = 0$. The continuum source emits a spectrum that is constant in wavelength and the intensity is equally split between two point-like locations. The "symmetric" part comes from the origin of the model space, whereas the "off-axis" part is emitted by a point source situated inside the equatorial plane and at the inner edge of the BLR. The azimuthal orientation of the off-axis source with respect to the direction of the observer is measured by the angle ϕ. For $\phi_0 = 0^\circ$, the source lies "in front of" the symmetric source, at its closest approach to the observer (inferior conjunction). For $\phi = 180^\circ$ the off-axis source is at superior conjunction with the origin. The polar viewing angle, i_0, of the observer is set to $\mu_0 = \cos i_0 = 0.875$ or $i_0 \sim 29^\circ$. Around i_0 and ϕ_0, photons are integrated over $\Delta\mu = 0.05$ and $\Delta\phi = 15^\circ$.

We assume that photons can be absorbed at any position inside the BLR. At the absorption edge, the radial optical depth to photo-absorption between $r_{\rm in}$ and $r_{\rm out}$ is set to unity. After an absorption event, instantaneous recombination is assumed and a new, unpolarized line photon is emitted at the same location and into an arbitrary direction. Apart from photo-absorption, the BLR also allows for Thomson scattering with a radial optical depth of $\tau_{\rm Th} = 0.24$. All absorbing, re-emitting and scattering material shares a common rotational velocity field. Following Gaskell (2010) this is assuming that the BLR can be modeled as a collection of small clouds on Keplerian orbits at all possible inclinations $-\theta_{\rm BLR} < \theta < \theta_{\rm BLR}$ and orientations of the line of node. The tangential velocity along the orbits scales with $r^{-0.5}$ and is normalized to 1400 km/s at $r_{\rm in}$. The off-axis source shares the Keplerian rotation of the inner edge of the BLR. For a 10^5 solar mass black hole, the orbital period at the inner edge of the BLR assumed in this model is about 1 year. Hence, even for a relatively low mass of the supermassive black hole the azimuthal position of the off-axis source remains constant over typical spectropolarimetric observation