Abstract. We demonstrate that the disk-wind model for the broad-line region (BLR) can explain the variability from single-peaked to double-peaked emission line (DPEL) profiles observed in some active galactic nuclei (AGNs) and can produce realistic single-peaked line profiles if the inclination and size of the line-emitting region are restricted. The main drivers of differences in the line profile is the radial density distribution in the wind, which is likely related to the accretion rate of the AGN. We exploit the extreme case of AGNs with DPELs in order to test different models of perturbations in the accretion disk, and find evidences that the outer regions of the disk are likely unstable to self-gravity. Finally, we devise a new monitoring strategy in order to build a rich dataset in a short time.

Key words: galaxies: active – quasars: emission lines

1. INTRODUCTION

Broad emission lines are an ubiquitous feature of Active Galactic Nuclei (AGN). Observations have pinpointed some properties of the broad line-emitting gas, which have refuted the originally proposed geometry, a collection of dense clouds, and helped to revise our understanding of the physical conditions of the broad-line regions (BLRs). Establishing a new paradigm for BLRs is essential since the properties of broad emission lines are commonly used to estimate the mass of the central supermassive black hole ($M_{BH}$) (e.g., Greene & Ho 2007), albeit by employing a scale factor ($f$) that depends on the geometry and kinematics of the BLR (Peterson 2010).

The theory, steadily gaining support in the AGN community, accepts that the source of the broad lines is the accretion flow itself. This model is particularly appealing because it does not require the addition of a new component to the current paradigm of AGN structure. However, line production in the accretion disk should generate double-peaked broad emission lines (DPEL), which are observed only in 3% of AGNs in the Sloan Digital Sky Survey (SDSS) spectra (Strateva et al. 2003). Some AGNs were observed to have line profiles varying from single-peaked to double-peaked in a few years, suggesting that these two types of line profiles are intimately connected.
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Radiative line transfer effects through a disk-wind can distort the line profile produced by the accretion disk into a single-peaked line profile and produce realistic single-peaked line profiles. Double-peaked emission lines are then produced when the disk-wind is weak and gives us a direct view of the accretion disk. The variability of the double-peaked line profile, which is uncorrelated with the line or continuum flux, then traces changes in the accretion disk and can be used to look for the presence of density perturbations in the disk.

2. THE DISK-WIND MODEL

The effects of radiative line transfer through the disk-wind can be approximated by the Chiang & Murray (1996) model. In this model, the optical depth is proportional to the wind density and inversely proportional to the strain tensor projected along the line of sight. The main term of the strain tensor is the radial velocity gradient of the line-emitting gas, hence photons whose radial velocity gradient is directed towards or away from the observer will be more likely to escape through the disk-wind. These photons are produced near zero projected velocity and contribute to the emission line cores. Hence, as the density of the wind and the optical depth increases, the line core is enhanced relative to the peaks and wings, producing a single-peaked emission line (see Figure 1).

![Fig. 1. The profile of the Hα emission line with increasing optical depth through the disk-wind. The increase in optical depth from one profile to another is one order of magnitude.](image)

In order to determine whether the disk-wind model for the BLR produces realistic line profiles, we created a database of profiles spanning a realistic range of model parameters. Then we measured line profile parameters of the simulated profiles (Marziani et al. 1996), namely the asymmetry index (A.I.), kurtosis index (K.I.), shift of the line centroid and FWHM. The range of line profile parameters in our database was compared with the observed line profile parameters for a set of AGNs in the SDSS (Zamfir et al. 2010). From this comparison, we find that some model parameters must be restricted within specific ranges to produce realistic line profiles. In particular, the inclination has to be $i \leq 45^\circ$, the inner radius of the line-emitting region $r_{\text{in}} \leq 2000 \, r_g$, and the outer radius $r_{\text{out}} \geq 5000 \, r_g$ (Flohic et al. 2011). Such parameter restrictions produce the distribution of the line profile parameters similar to those obtained from observations (Figure 2).
Fig. 2. Distributions of the simulated line profile parameters, after restricting the parameter range to $i \leq 45^\circ$, $r_{in} \leq 2000 \, r_g$, $r_{out} \geq 5000 \, r_g$ and $r_{h} \geq 10^{-3}$, are shown by the solid lines. The observed distributions from Zamfir et al. (2010) are plotted as the dashed lines.

Fig. 3. The simulated (solid line) and observed (dashed line) Hα emission line profiles. The observed line profile is the average of profiles for populations A (left) and B (right), adapted from Sulentic et al. (2009). The simulated line profiles are not fitted to the observed line profiles, but were chosen to have realistic model parameter values. Only the radial density profile of the wind and the outer radius of the line-emitting region differ between the two simulated line profiles.

With typical choices of the model parameters, we can reproduce the two main types of emission line profiles (Figure 3). A Lorentzian profile, such as observed in AGNs of population A (Sulentic et al. 2009), can be produced with a steep radial density profile and large outer radius of the line-emitting region. A double
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Gaussian profile, such as observed in AGNs of population B, are produced with a flatter density profile and smaller $r_{\text{out}}$. We emphasize that the simulated line profiles in Figure 3 were produced with the same inclination, inner radius and optical depth, meaning that the outer radius of the line-emitting region and the density profile of the wind are the main drivers of line profile differences. The probable reason leading to differing disk sizes and wind properties is the accretion rate of the AGN, since higher-accretion rate objects have stronger winds (Proga et al. 2000). Sulentic et al. (2009) also points to the accretion rate as the main driver of differences between populations A and B based on other observational results.

3. MODELING OF DOUBLE-PEAKED LINE VARIABILITY

In the context of the disk-wind model of the BLRs, AGNs with DPELs are the extreme case where the wind is very weak and does not distort the lines produced in the disk. DPELs thus give us a direct view of the accretion disk. The line profile of the DPELs is seen to vary on a dynamical timescale of the disk, and this variability is uncorrelated with the variability of the flux of the line or ionizing continuum. The DPEL variability thus likely traces changes in the structure of the accretion disk itself (Popović et al. 2011).

Our group has been monitoring $\sim$40 AGNs with DPELs twice a year for 10 years on average (Gezari et al. 2007; Lewis et al. 2010; Flohic 2008). We sometimes detected some long time-scale, large amplitude variability that can be explained by a spiral arm in the accretion disk, but most of the variability has short timescales and small amplitudes.

We developed a stochastically perturbed accretion disk model and tested whether it could reproduce the observed small-amplitude variability (Flohic & Eracleous 2008). Such stochastic perturbations could be produced by star/disk collisions, by baroclinic vortices in the disk, or by condensations in the disk under the effect of self-gravity. These different mechanisms of perturbations lead to different perturbation properties, in particular their shearing properties, their lifetimes and radial distribution.

We produced simulated line profile series for a large range of model parameters and compared the character of the variability of the simulated series with those observed in AGNs with DPELs. In order to do such a comparison, a large number of spectra are required in the observed series in order to place significant constraints on the model parameters. We compared our simulated line profile series with the two best-sampled double-peaked emitters, namely Arp 102B and 3C 390.3. We were able to place tight constraints on the properties of perturbations in the accretion disk of Arp 102B: the perturbations need to be non-shearing, in the outer regions of the accretion disk, and need to have a high density. Such properties are consistent with stochastic perturbations produced by gravitational collapse of the disk past the radius of marginal self-gravity (Goodman & Tan 2004). For 3C 390.3, we were not able to put any constraints on the perturbations in the disk, most likely because we did not have enough spectra in the series to characterize the small-amplitude variability (38, as opposed to 92 for Arp 102B). Jovanović et al. (2010) were able to model large-amplitude variability of the H$\beta$ line of 3C 390.3 with two bright spots, which they interpret as fragments of a spiral arm in the accretion disk. Such spiral arms can form due to close passage of a massive object (such as another supermassive black hole or a star cluster, Lewis et al. 2010) or
due to self-gravity. Thus we are forming a theory of accretion disk structure where self-gravity can play an important role.

4. NEW MONITORING STRATEGY

To further test our stochastically perturbed accretion disk model and other models of accretion disk structure, we need to build other datasets of double-peaked line profile variability as rich as that available for Arp120B. We have ongoing observations of AGNs with double-peaked lines twice a year, but still it will take many years to build a sufficiently rich dataset. Observing during a year more frequently would produce more spectra, but this will not necessary lead to new interesting information: then we would sample at a rate much smaller than the dynamical time-scale of the accretion disk, what will reduce the probability to see any variability.

In order to build rich datasets faster, it would be more judicious to target AGNs with low dynamical time-scales. Since this scales with the black hole mass, by targeting an AGN with $M_{\text{BH}} \sim 10^7 M_\odot$ once a week for 2 yr, we would be able to build a dataset comparable to that of Arp102B, an AGN with a $3 \times 10^8 M_\odot$ black hole, observed for over 20 years. We are currently finishing such a monitoring campaign for an AGN with $M_{\text{BH}} = 4 \times 10^7 M_\odot$ and double-peaked lines. Also we are searching for other candidates for such a 2-year monitoring campaign. We were awarded time in order to measure the black hole mass of double-peaked emitters using the $M - \sigma$ relation.

5. CONCLUSIONS

The disk-wind model provides a viable hypothesis for the structure of the broad-line region. It produces realistic line profiles within a certain range of model parameters and can explain observed transitions between double-peaked and single-peaked emission lines. In the low optical depth limit, the disk-wind model produces double-peaked emission line, whose variability can be used to infer the structure of the disk itself. The comparison of the richest variability dataset with a stochastically perturbed model hints at the importance of the self-gravity in the outer parts of the accretion disk. In order to build other rich datasets, continued monitoring of AGNs with high mass black hole is important, but targeting AGNs with low mass black hole will produce results in a much shorter time span.

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REFERENCES

Peterson B. 2010, in print, arxiv: 1001.3675