``The Restless Nature of AGN: 10 years later” June 26-30, 2023, Napoli, Italy

Modeling variable diffuse continuum from dusty/dustless plasma using CLOUDY

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Abstract

We present results of our photoionization modeling of dusty and dustless broad-line region (BLR) clouds using CLOUDY code. We simulated the BLR spectra for a grid of models in local cloudy density, log n_H, and the incident radiation flux, log Φ_H, parameter space. We investigated the total diffuse continuum for dusty and dustless clouds and observed that for dusty BLR clouds, the Balmer and Paschen jumps almost vanished at lower densities, whereas at higher densities, the Balmer jump decreases but the Paschen jump does not change. We derived equivalent widths of emission lines and compared them with observed values for NGC 5548. We discussed in details the Hβ line properties using the observed time delay.

Introduction

Dust is one of the key constituents of the Active Galactic Nuclei (AGN). The presence of the dust in AGN is well established by spectroscopic observations and direct interferometric mapping of nearby AGN (Nenkova et al. 2008; Guise et al. 2022; García-Bernete et al. 2022). Even though the majority of the dust is undoubtedly outside the BLR, some of it might actually be inside it if it is adequately shielded from nuclear emissions. The need for the dust within BLR was claimed on the basis of the measured ratio of the Hβ to Hα (Osterbrock 1981).

Based on the dust presence in BLR, two theoretically motivated models were proposed for BLR clouds. (1) Failed Radiatively Accelerated Dusty Outflow (FRADO; Czerny & Hryniewicz (2011)) model, which is the dynamical model of the BLR clouds which are launched from the outer parts of the accretion disk under the radiation pressure acting on dust (Naddaf & Czerny 2022). (2) the static model of Baskin & Laor (2018) in which the dust inside the disk affects its structure, the disk remains in hydrostatic equilibrium (for most radii, where the model can be calculated). In this model, part of the disk remains dustless, but the shielded part remains dusty.

The presence of dust in (some) BLR clouds can affect the BLR emissivity, and thus can be important in several contexts. Dust modifies gas line emissivity which might be important for the determination of the BLR covering factor (see e.g. Baskin & Laor 2018). Dust can also modify the continuum emission from the BLR, and this, in turn, is important for the potential measurements of the intrinsic continuum time delays which requires subtraction of the BLR contamination (see Netzer 2022; Jaiswal et al. 2023).

Therefore, in this work, we systematically compare the emissivity of the BLR with and without the dust in the BLR clouds.

Method

Using the photoionization code **CLOUDY** (version 22.01; Ferland et al. 2017), we generated a grid of models for individual clouds in a plane-parallel approximation. We parameterized the solutions with the local density of the cloud, log n_H, and the incident radiation flux, log Φ_H. The parameter range is adopted as in (Korista & Goad 2019): $7 \leq \log n_H(\mathrm{cm}^{-3}) \leq 14$, and $17 \leq \log \Phi_H(\mathrm{cm}^{-2}\mathrm{s}^{-1}) \leq 24$ with a step size of 0.2 in the logarithm of each parameter yielding a total of 1296 models. We adopted a fixed hydrogen column density of log N_H = 23 cm^{-2} for our simulations. We assumed solar abundance for the BLR clouds.

For the incident radiation, we adopted the continuum spectral energy distribution (SED) for well-studied AGN NGC 5548 from Mehdipour et al. (2015).

For a comparison of the dust effect, we developed model solutions for both dusty and dustless clouds. For the computation of dusty BLR models, we employ graphite dust grains with a size distribution similar to Orion. The composition and physics of grains are described in van Hoof et al. (2004), and Weingartner et al. (2006). The dust cannot survive at very high temperatures and it is destroyed in a very short timescale. The dust sublimation temperature is a parameter of the model, we often set to 2000 K (Baskin & Laor 2018).

Results and discussion

1. Properties of the continuum

We computed the total diffuse continuum emission which includes contributions from the reflected incident continuum and the diffuse continuum emission from the outward-facing cloud face for all our CLOUDY solutions. We include the lines in our discussion of the continua since actually, some lines do form pseudo-continua, for example, Fe II lines (Czerny et al. 2023). We illustrate the issue in Figure 1. The intense lines like Hβ and Mg II are clearly seen as separate lines, and the remaining lines contribute to what was traditionally described as the ‘small blue bump’, consisting mostly of Fe II and Balmer continuum.

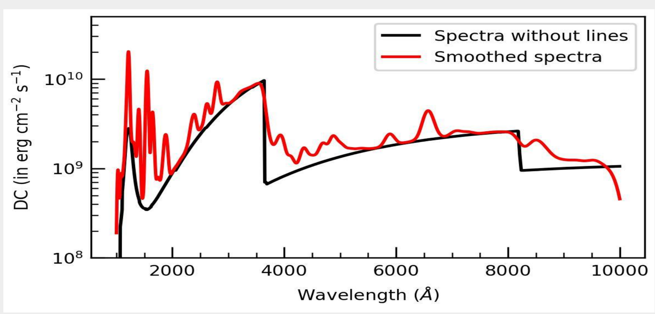

Fig. 1. A sample spectrum for diffuse continuum without lines and with lines smeared with the velocity appropriate for NGC 5548 (~4000 km/s for Hbeta (Pei et al. 2017)). log Φ_H= 20 cm^{-2}s^{-1}, log n_H = 12 cm^{-3}

We illustrate the role of dust by plotting the continua (see Fig. 2) for a few selected models in dustless and dusty cases, for the other parameters kept the same. The spectral features are strongly affected for the lowest density: the Balmer and Paschen discontinuity almost disappear for density 10^8 cm^{-3} in the presence of the dust. At higher densities, the Balmer edge is always reduced while the Paschen edge is almost unaffected.

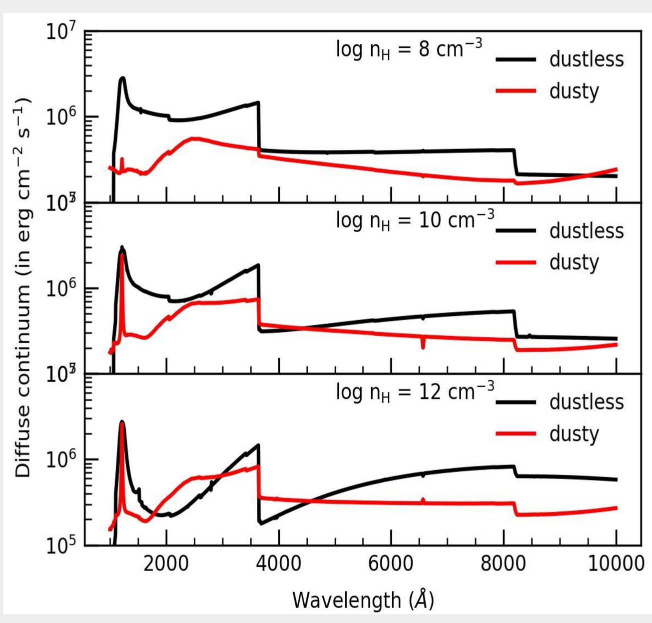

Fig. 2. The examples of the continua for dusty and dustless clouds for log Φ_H= 17 cm^{-2}s^{-1} and three values of the local density.

2. Properties of the emission lines

The dusty region in Fig. 3 is present only at very low values of the incident flux, Φ_H, which might imply that BLR with such parameters cannot be responsible for the Low Ionization Lines like Hβ or Mg II. We therefore calculated the line intensities from our grid of CLOUDY models with, and without dust, and determined their equivalent widths (EW) with respect to the incident continuum. The EW contours are shown in Fig. 3. Given that the models are computed in a plane-parallel geometry, the estimated EWs have a 100% covering factor.

We compared these values with the observed values of the EWs in NGC 5548. We collected them from the literature and summarized in Table 1. We see that the values of EW for Hβ are comparable to the measured values in NGC 5548 or much smaller when the incident radiation flux log Φ_H is larger than 20 cm^{-2} s^{-1}. Actually, since the measured EW should include a covering factor f_c usually considered to be of the order of 0.1 - 0.3 (Baldwin et al. 1995; Korista & Goad 2019).

$$EW_{obs} = f_c EW_{model}$$

Line	EW [Å]
Mg II (2795)	60.9
H_β (4861)	79.8
He II (1640)	9.3
C IV (1548)	106.5
Lyman-alpha (1215)	114

Table 1. Observationally determined representative values EW of selected lines in NGC 5548. UV data are from Goad & Koratkar (1998), and the Hβ is taken as the average value from Peterson et al. (2002).

Hβ EW from the model should be of the order of 266 - 798 Å. Values higher than 750 Å are found in Fig. 3 in the dustless region. Thus, if the covering factor f_c is indeed as low as 0.1, the dust present in the BLR is not possible. However, if f_c is rather of order of 0.2 (EW requested from the model is then 400 Å) there is a parameter region with n ~ $10^{11} - 10^{12}$ cm^{-3} and Φ_H ~ 3 × 10^{17} which can give such a line intensity.

The high density requested for the LIL region is not surprising as many recent works obtained such values on the basis of modelling line properties (Bruhweiler & Verner 2008; Garnica et al. 2022; Czerny et al. 2023) or just theoretical argument of radiation pressure confinement (Baskin & Laor 2018).

Whether the region is dusty or dustless, the values of log Φ_H should be rather smaller than 19 for the density 10^{12} cm^{-3}, and smaller than 6 × 10^{19} for unlikely high cloud density 10^{14} cm^{-3}.

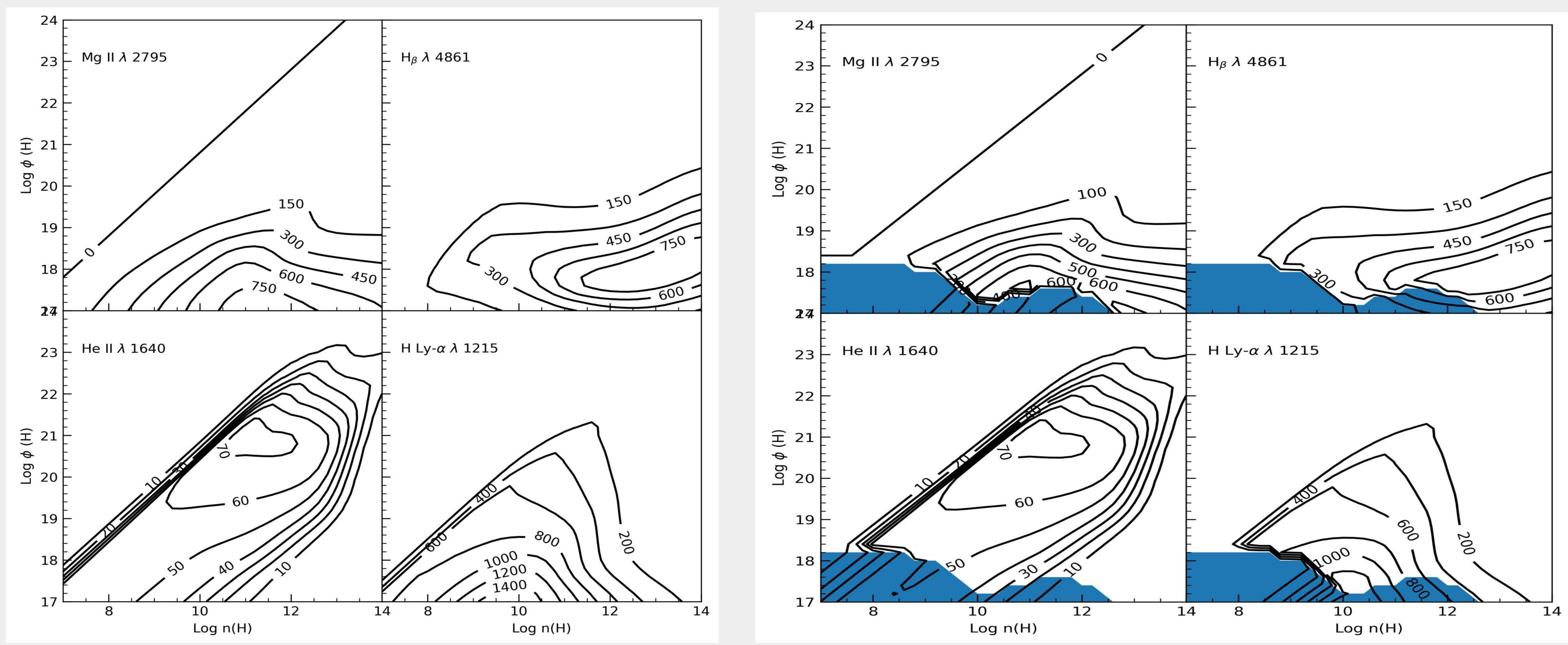

Fig. 3. Equivalent widths contours for different emission lines for dustless (left) and dusty (right) solutions. The EWs for Mg II, He II, and H Ly-α are measured with respect to the incident continuum flux at their line centres, while for H β, EW is measured with respect to the 5100 Å continuum. The shaded region in the right panel represents the solutions for the dusty cloud for a sublimation temperature of 2000 K.

3. Time delay constraints for the effective radius of Hβ line.

The time delay for the Hβ line in NGC 5548 was extensively studied over the years. Here, we use a mean time delay of 17.0±3.9 days from the AGN Watch campaign (Peterson et al. 2002). If the BLR sees the same radiation as the observer, then the incident photon flux at this distance should be

$$\phi = \frac{1}{2\pi R_{BLR}^2} \int_{13.6eV}^{\infty} \frac{L_\nu}{h\nu} d\nu$$

For the incident radiation flux normalized to the ionizing luminosity of 1.17 × 10^{44} erg s^{-1} as estimated by Mehdipour et al. (2016) for unabsorbed flux luminosity, the distance corresponding to Hβ time delay is equal 3.99 × 10^{18} (~ 18.6 in log scale) photons cm^{-2} s^{-1}.

If the incident continuum is unabsorbed, the BLR should be dustless and the EW of Hβ matches observations with moderate covering factor. **However, if the BLR receives strongly absorbed continuum, dusty BLR might be possible.**

Summary

- We generated a grid of photoionization models using incident SED of a well studied AGN NGC 5548 for a range of incident radiation flux and local density of cloud.
- We compared th diffuse continuum for dusty and dustless clouds and found that the dust affects the spectral shape for log n_H ~ 7-12.5 cm^{-3} and log Φ_H~ 17-18.2 cm^{-2} s^{-1}.
- **The work is still in progress, since we still must consider the case when the incident continuum seen by the BLR is filtered by the absorber closer than BLR or within BLR.**

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Acknowledgements. This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation program (grant agreement No. [951549]). Part of this work was supported by the Polish Funding Agency National Science Centre, project 2017/26/A/ST9/00756 (MAESTRO 9).

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Thank you for your time !