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Original scientific paper

SIMULATIONS OF THE BROAD LINE REGION OF NGC 5548 WITH CLOUDY CODE: TEMPERATURE DETERMINATION

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SUMMARY: In this paper an analysis of the physical properties of the Broad Line Region (BLR) of the active galaxy NGC 5548 is presented. Using the photoionization code CLOUDY and the measurements of Peterson et al. (2002), the physical conditions of the BLR are simulated and the BLR temperature is obtained. This temperature was compared to the temperature estimated with the Boltzmann-Plot (BP) method (Popović et al. 2007). It was shown that the measured variability in the BLR temperature could be due to the change in the hydrogen density.

Key words. Galaxies: active – Galaxies: individual: NGC 5548 – Galaxies: Seyfert – Line: formation – Plasmas

1. INTRODUCTION

Active Galactic Nuclei (AGN) and their emission-line spectra are undoubtedly among the most intriguing and studied phenomena in astrophysics today. Their Broad Line Region (BLR) – where Broad Emission Lines (BELs) originate - is of particular interest, due to the fact that its physics and kinematics are not yet fully understood. This region is very close to the central engine of AGN (i.e. probably a black hole with an accretion disk), thus is under influence of the strong gravitational field. Furthermore, the physical conditions in the BLR – are probably more similar to the conditions in stellar atmospheres than in photoionized nebulae (Osterbrock 1989). Therefore, common techniques used for diagnostics of the physical properties of photoionized nebulae could not be used in the case of the BLR. There are few methods that could probe the physics of the BLR directly from the measured BELs, that are the only signature of this region. Recently, Laor (2006) suggested one such method. This method determines the physical parameters of the BLR by fitting the emission line wings, but a disadvantage is that it can be applied only to the BELs with the exponential line wings, that is, in the case of low luminosity AGN. On the other hand, Popović (2003, 2006ab) suggested that by applying a Boltzmann-plot (BP) onto the broad Balmer lines of some AGN, a temperature can be estimated. This method was applied in several cases (see Popović et al. 2002, 2003, Ilić et al. 2006, La Mura et al. 2007, Popović et al. 2007).

The aim of this paper is to investigate the physical properties of the galaxy NGC 5548, one of the best observed variable Seyfert 1 galaxy (see Shapovalova et al. 2004, and references therein) using the photoionization code CLOUDY (Ferland 2006) and the BP method (Popović 2003, 2006a). The idea is to compare the simulated temperature with the temperature estimated with the BP method, and to try to explain the variability measured in the BLR temperature.

2. THE PHYSICS OF THE BLR IN NGC 5548

The broad lines spectrum, and thus, the broad line region (BLR) of NGC 5548, have been a subject of numerous studies. Most importantly this galaxy was the focus of an intense 13-year campaign by the International AGN Watch consortium (Peterson et al. 2002) with the aim to study the variations in the optical continuum and Hβ line flux. As a result, using the reverberation mapping technique, the size of its BLR is measured from the time delay between variations in the continuum flux and broad-line fluxes. It is estimated that BLR size was changing in the period 1989 - 2001 in the range 6 - 26 light days (Peterson et al. 2002). In addition, the mean mass of the central black hole was estimated to be $M_\bullet \approx 7 \times 10^7 M_\odot$ (Peterson and Wandel 1999, Bentz et al. 2007).

It was shown that the pure photoionization model may not be adequate for the BLR of this galaxy, as there is, for example, an energy budget problem, so that a non-radiatively heated region could as well contribute to the BLR spectrum (Dumont, Collin-Souffrin and Nazarova 1998). On the other hand, some authors claim that the model of "locally optimally emitting clouds" (LOCs) of Baldwin et al. (1995) is valid for the BLR of NGC 5548, e.g. Korista and Goad (2000) simulated the light curves of UV emission-lines using this approach and they found a good agreement between the predicted and observed light curves and time lags.

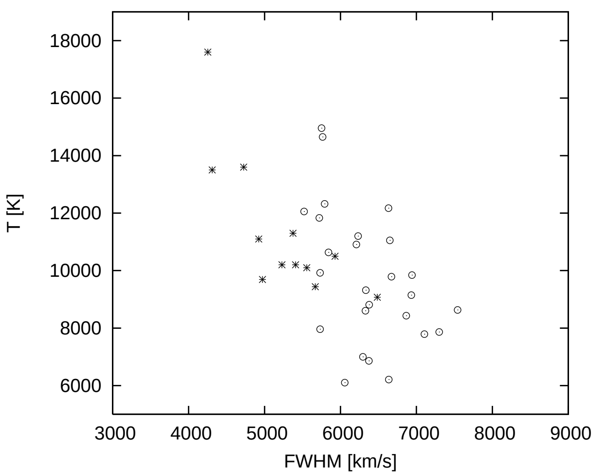

Fig. 1. *The BLR temperature as a function of the FWHM. The circles represent the measured values taken from Popović et al. (2007), while the asterisks are the simulated values using the input data of Peterson et al. (2002), where the BLR temperature is predicted by the CLOUDY code and the velocity is calculated with the virial equilibrium assumption.*

3. CLOUDY SIMULATIONS

The spectral simulation code CLOUDY is a numerical code designed to simulate emission-line regions (version 06.02; Ferland et al. 1998; Ferland 2006). It determines the physical conditions (temperature, level of ionization, and chemical state) within a non-equilibrium gas, possibly exposed to an external source of radiation, and predicts the resulting spectrum. Detailed instructions on how to download, install and run the code can be found in Ferland (2006) or on the website `http://www.nublado.org/`.

We used this code to estimate the BLR average temperature, and to compare it with the temperature estimated by the BP method. The aim of these numerical simulations is not to find the best fit for the observed data, but rather the physical reason of the variation measured in the BLR temperature.

The main input parameters of these models are the radius of the BLR ($R_{\rm BLR}$), the ionizing photons flux ($Q_{\rm h}$), and hydrogen density ($n_{\rm H}$). The radius of the BLR is taken from reverberation results of Peterson et al. (2002)[1], while for the calculations of the ionizing photons flux the optical continuum mean flux F_λ(5100 Å) from Peterson et al. (2002) and the correlation between the $Q_{\rm h}$ and the bolometric luminosity $L_{\rm bol}$ (Padovani and Rafanelli 1988) are used, assuming that the bolometric luminosity is $L_{\rm bol} \approx 9 \times \lambda \times L_\lambda$, where $\lambda = 5100$ Å (Collin and Hure 2001). For the calculation of the distance to the galaxy the following cosmological parameters are assumed $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$ and $\Omega_\lambda = 0.7$. The temperature averaged over the BLR radius is one of the outputs of these numerical simulations, and that temperature is used for further analysis.

In order to calculate the velocity (represented with Full Width Half Maximum - FWHM), the mean value for the mass of the black hole $M_\bullet = 7 \times 10^7 M_\odot$ (Peterson and Wandel 1999) is taken, along with the assumption that the BLR is in the virial equilibrium. The mean optical continuum flux is corrected for the host galaxy starlight contribution at λ =5100 Å, $F_{\rm gal} = 3.4 \times 10^{-15}$ ergs s^{-1} cm^{-2} (Romanishin et al. 1995). For the simulations it is assumed that all clouds have a single column density $N_{\rm H} = 10^{23}\,{\rm cm}^{-2}$ (Dumont et al. 1998, Korista and Goad 2000, 2004).

First, the models were constructed by fixing the hydrogen density to e.g. $n_{\rm H} = 10^9\,{\rm cm}^{-3}$, but the temperature variability could not be reproduced only with the variation of the continuum flux. Therefore, further simulations are performed, assuming that the hydrogen density $n_{\rm H}$ varies from $n_{\rm H} = 10^{8.8}\,{\rm cm}^{-3}$ up to $n_{\rm H} = 10^{10}\,{\rm cm}^{-3}$ for the maximum and minimum continuum flux, respectively.

[1]From the data set, the measurements in the Year 12 (2000) are not considered since the value of the BLR radius was very low.

4. RESULTS AND DISCUSSION

If we take the Balmer series for which the population of the upper energy states ($n \geq 3$) is described with Saha-Boltzmann distribution, then the temperature can be obtained from the following equation (Popović 2003, 2006a):

$$\log_{10}(F_n) = \log_{10} \frac{F_{ul} \cdot \lambda}{g_u A_{ul}} = B - AE_u \qquad (1)$$

where F_n is normalized flux, B and A are BP parameters, with $A = 5040/kT$ being temperature indicator from which we can estimate the temperature. This is the basic principle of the so-called Baltzmann-plot (BP) method. We should emphasize that the BP method (Popović 2003) only assumes the physics in the BLR, i.e. that the Balmer lines originate in the same emitting region. The method includes the intensities of all lines from Balmer series, not only the ratio of two or three lines, as usually considered, and should not be mistaken with the Balmer decrement.

Applying the BP method on the fluxes of broad Balmer lines, measured in the period of 8 years (1996-2004) (see Table 2 in Popović et al. 2007 for details) the temperature of the region where these lines originate is obtained. The determined temperature is changing up to 50% in the considered period and the averaged temperature is ≈10000 K. Moreover, the average FWHMs of the Hα and Hβ were measured for the same sample.

The results are presented in Fig. 1, where the BLR temperature is given as a function of the FWHM. From Fig. 1 it is clear that the calculated results resemble the trend of the temperatures measured by the BP method. One should emphasize that small variations in the hydrogen density could produce wider range in the temperature. The lowest measured temperatures (most of the data below $T = 8000\,\mathrm{K}$) are from the period between 2000 and 2003 for which Peterson et al. (2002) did not make reverberation measurements, hence there were no attempts to reproduce those data with the models. Also, it is interesting to see how this difference between the mean temperature predicted by the code, $\mathrm{T}_{\mathrm{model}}$, and the temperature determined when BP method is applied to the predicted Balmer line ratios T_{BP}, changes with the column density, that basically determines the optical depth of the Lyα line, given a fixed hydrogen density. From Fig. 2 it can be seen that the ratio of these temperatures is in most of the cases close to unity and does not depend on the Lyα optical depth. Therefore, we can say that the difference between the mean temperature predicted by the CLOUDY and the temperature determined with BP method is not significant, especially for the lowest values of the hydrogen density.

Due to the increase of the hydrogen density, the intensity of the Hα increases with respect to the Hβ line, while other Balmer lines are less influenced, since the collisional processes contribute more to the lower excitation levels. The difference between the two temperatures in case of higher densities could be due to the fact that the line ratios could not be explained only by a photoionization model (Dumont et al. 1998), or it might be that not just collisional processes contribute to line formation. In any case, the change in the temperature could be explained by the change of the hydrogen density, but one should be very careful when choosing the input parameters in the simulations.

5. CONCLUSIONS

We have studied the physical properties in the BLR of the variable galaxy NGC 5548. The BLR was simulated with the photoionization code CLOUDY for different time periods. The main conclusions are:

i) the BLR temperature of NGC 5548 estimated by the BP method can be reproduced by the CLOUDY simulations;

ii) the change in the BLR temperature is real, and one explanation could be that the change is due to hydrogen density fluctuation;

iii) the results of the CLOUDY simulations lead to the conclusion that the BP method could be used in some cases as a probe for temperature in the BLR (see Ilić et al 2007).

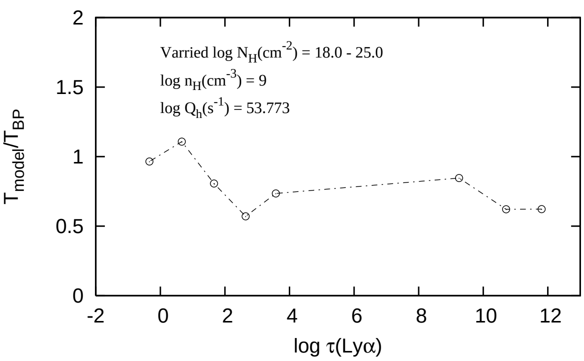

Fig. 2. *The difference between the mean temperature predicted by the code,* T_{model}*, and the temperature determined when BP method is applied to the predicted Balmer line ratios* T_{BP} *, as a function of the Ly*α *optical depth, for the fixed hydrogen density* $n_{\mathrm{H}} = 10^9\,\mathrm{cm}^{-3}$ *and the ionizing photons flux* $Q_{\mathrm{h}} = 10^{53.773}\,\mathrm{s}^{-1}$*, where the column density* N_{H} *was varied from* 10^{18} *to* $10^{25}\,\mathrm{cm}^{-2}$.

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НУМЕРИЧКЕ СИМУЛАЦИЈЕ ШИРОКОЛИНИЈСКОГ РЕГИОНА NGC 5548 ПОМОЋУ КОДА CLOUDY: ОДРЕЂИВАЊЕ ТЕМПЕРАТУРЕ

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Оригинални научни рад

У овом раду је дата анализа физичких карактеристика широколинијске области активне галаксије NGC 5548. Користећи нумерички код CLOUDY и мерења Peterson et al. (2002), симулирани су физички услови у широколинијској области и одређена је њена температура. Ова температура је затим упоређена са температуром процењеном уз помоћ Boltzmann-plot (BP) метода (Popović et al. 2007). Показано је да измерена променљивост температуре широколинијске области може бити последица промене концентрације водоника.