A POSSIBLE MECHANISM TO EXPLAIN THE NARROW LINE VARIABILITY OF SEYFERT GALAXIES ON TIMESCALES OF MONTHS

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ABSTRACT. Gas in the shadow of clouds in the outer parts of the broad line region can radiate a considerable fraction (dozens of percent) of the narrow emission line flux. The variability of the X-ray luminosity of the central source should result in significant variations of the gas emission on a timescale of months. Particularly strong changes of line intensities and column densities of gas in the shadow ($\sim 10^{23}$ cm^{-2}) can be produced by phase transfer between two thermally stable fluids with temperatures 10-20×10^3 K and 40-100×10^3 K, which can exist in the shadow of clouds.

Several papers have been published about observed variations of the narrow emission lines of Seyfert galaxies (Pronik, 1980), including variations on short timescales. Fairall (1983) and Merkulova and Pronik (1983) reported probable fast variations of the N1 and N2 (5007 and 4959 Å) lines of [OIII]. These data are very doubtful. Nevertheless at least 3 mechanisms were found which can produce such variability.

Pronik and Pronik (this volume) consider the formation of the [OIII] lines in the BLR. In the dense HI parts of the BLR ($N_H > 10^9$ cm^{-3}) oxygen can be ionized by X-rays (Auger effect) with $n_e \approx 10^{6-7}$ cm^{-3}. In this case the volume emissivity of the [OIII] lines is so large that they are mostly formed in the BLR and can exhibit variability similar to that of the broad lines.

Fabrika (1986) suggests that in some cases gas can be optically thick in forbidden lines. In this case optical thickness and shape of line profiles "feel" the variations of the continuum without time delay, and the timescale of the line variations are determined by the lifetime of excited ion levels and the timescale of variations of the continuum and can be as small as ~ 30 min.

A third mechanism was discussed briefly by Bochkarev (1974, 1979, 1980). He considered gas regions which are illuminated by X-rays without the soft ($h\nu <$ 100-1000 eV) part of the spectrum (such conditions take place in some regions of AGNs, see below). Under these conditions the gas can be present in several thermally stable phases

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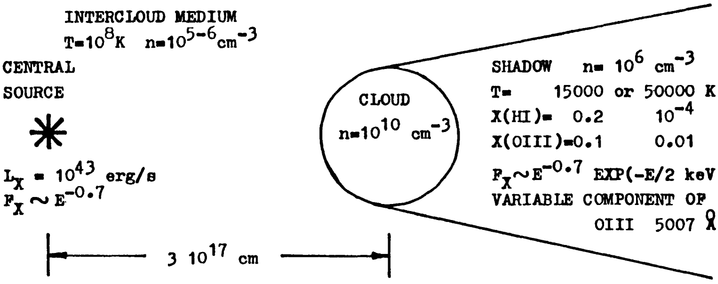
with temperatures T = 10-20×10^3 K, 40-100×10^3 K and $\gtrsim 10^6$ K. Small variations of X-ray flux can initiate phase transfer. Dielectron recombinations and collision excitations produce non-monotonous variations of volume emissivity ε on timescales of $3\times10^{12}/n_e$ sec. It can produce variations of line profiles during $\Delta t \sim$ month.

Let us consider this mechanism in detail. BLR-gas is located in high density gas clouds ($n_e \approx 10^{10}$ cm^{-3}). It is heated and ionized by X-ray and hard UV radiation from a central source. Approximately half ($\eta \approx 50\%$) of the galaxies with active nuclei and small X-ray luminosity $L_X < 10^{43.5}$ erg/s have a low energy cut-off in the X-ray spectrum near $h\nu \approx 2$ keV (Elvis and Lawrence, 1985). There are two arguments that the absorption is produced by the inner parts of AGNs. First, Keel (1980) showed an absence of any dependence of the visibility of the nuclei of normal galaxies on the orientation of the parent galaxy axes. This means that the X-ray absorption is probably not connected with the galaxy body. Secondly the observed variations of column density of the absorbing matter during several months (Barr et al., 1977; Elvis and Lawrence, 1985) certainly show deep location of the absorption, which means that BLR clouds are optically thick for soft X-rays and produce shadows which are free of low-energy X-rays.

BROAD LINE REGION



PHYSICAL CONDITIONS IN SHADOWS OF BLR-CLOUDS

The one month delay between changes of optical continuum and broad emission line variations (Cherepashchuk and Lyutyi, 1973; Lyutyi and Cherepashchuk, 1974) indicates an average distance of BLR clouds from the central source of $r \approx 10^{17}$ cm. The clouds are probably distributed at distances ranging from less than 10^{17} cm to several times more, maybe up to 3×10^{18} cm for QSOs.

The space between the clouds is possibly filled by the intercloud matter, considerably less dense and much hotter than the clouds (Zentsova, 1985). X-rays fully ionize the gas and heat it to temperatures close to maximum for Compton heating, $kT = \langle h\nu\rangle/4 \sim 10^8$ K, where $\langle h\nu\rangle$ is the average energy of photons interacting with the intercloud medium.

In the case of pressure equilibrium the number density of intercloud matter is $n \sim 10^6$ cm^{-3}. This is an upper limit of the intercloud matter number density; it corresponds to Compton column density ($\tau_T = 1$) for Sy 1 BLRs with $r \approx 10^{18}$ cm. Nevertheless observations of fast ($\sim 1^d$) variations of the optical continuum and even faster changes of X-ray flux show that $\tau_T = 1$ can take place only in a region $r \lesssim 10^{15}$ cm and that the regions with $r > 10^{15}$ cm have $\tau_T << 1$. The soft X-ray spectrum in NGC 4151 corresponds to ~ 90% covered X-ray source (Elvis and Lawrence, 1985). This means that the electron scattering reradiates less than 10% X-ray photons and $\tau_T \lesssim 0.1$. The pressure of the intercloud gas can be less than in clouds, i.e. $n \lesssim 10^6$ cm^{-3}. Very small n is impossible, because in that case evaporation of clouds increases n in the intercloud medium. Thus, we can suggest that the intercloud matter has $n \approx 10^{5-6}$ cm^{-3}.

In the shadows of clouds the number density is approximately the same as (or a few times more than) in other parts of the intercloud regions as far as the hydrodynamical timescale of gas compression in the shadows, $t \approx r_c/c_s \sim 10^8$ sec (r_c is cloud size, c_s is sound speed in the shadows) is comparable to the time of the cloud movement through the BLR. For non-radial movements the intercloud matter spends still less time in the shadows. Therefore the matter in the shadows is suggested to have $n \approx 10^6$ cm^{-3} and to be illuminated only by hard X-rays ($h\nu \gtrsim 2$ keV). The properties of the gas were studied by Bochkarev (1979, 1980). This gas can exist at least in two thermally stable phases with $T = 10\text{-}20 \times 10^3$ K and $40\text{-}100 \times 10^3$ K. For Sy 1 - Sy 1.5 galaxies with X-ray luminosities $L(> 2\ \text{keV}) \approx 10^{43}$ erg/s the medium with $n = 10^6$ cm^{-3} can co-exist in these phases in the outer parts of the BLR with thickness $\Delta r \approx r \approx 3 \times 10^{17}$ cm. The X-ray flux scattered by intercloud matter is probably small in the shadows.

If the probability of covering of the central sources is about $\eta \approx 50\%$, the fraction of the BLR volume occupied by the shadows is expected to be ~ 50%. The volume emission measure of the gas in the shadows is $MV \approx (4/3)\pi r^3 \eta n^2 \sim 10^{65}$ cm^{-3}. The colder phase ($T \approx 10^4$ K) has an efficiency of [OIII] 5007 Å line emission $\lambda \approx 3 \times 10^{-24}$ x_{OIII} cm^3/sec, where x_{OIII} is the fractional abundance of O^{++}. According to Bochkarev (1979, 1980) the hotter phase has $\lambda \approx 1.5 \times 10^{-25}$ cm^3/sec. Taking into account charge-transfer reactions of oxygen ions with hydrogen, OII and OIII dominate in the cold phase. Therefore we expect $x_{OIII} \gtrsim 0.1$ and OIII line luminosity $L(OIII) = \lambda . MV \approx 3 \times 10^{40}\text{-}10^{41}$ erg/s. This is a significant part L(OIII) of typical Sy 1.5.

X-ray flux variations of a factor of ~ 1.5 during weeks or months, which is typical for e.g. NGC 4151 (Elvis, 1976) result in ~ 20-30% changes of λ (Bochkarev and Pudenko, 1975) and in ~ 10% variations of L(OIII). The timescale of the variations is $r/c \sim 100^d$ (c is the light speed). Changes in the shadow of the cloud covering the X-ray source are observed without this time delay.

The phase transfers, which can be initiated by the X-ray flux variation, develop during a time interval $t_T = 3 \times 10^{12}/n_e$ sec $\approx 100^d$ and can result in even more changes of L(OIII), especially taking into account non-monotonous variation of the forbidden line volume emissivity ε during the phase transfer with high maximum (Bochkarev, 1979, 1980). The hydrodynamical timescale (years) is significantly more than T_t. Therefore the phase transfer takes place with approximately constant density.

During the phase transfer the hydrogen column density N_H of gas in the shadows can vary between $(0.3 \text{ and } 1) \times 10^{23}$ cm^{-3}, because of variations of hydrogen degree of ionization between $n(H^+)/n(H^0) \approx 0.1$ and 0.3 in the cold phase and $n(H^+)/n(H^0) \ll 1$ in the hot one. This means that observed variations of N_H are probably produced by the phase transfer rather than by the tangential movements of clouds suggested by Elvis and Lawrence (1985). The gas in the shadows has not sufficient time to change N_H during fast bursts of X-ray flux (with several days duration. This can explain the absence of N_H variations during X-ray flares on timescales of days in NGC 4151 reported by Mushotzky et al. (1978).

For a mass $M = 10^7$-10^8 $M_\odot$ of nuclei of Sy 1 - Sy 1.5 galaxies the virial velocity v is 600-2000 km/sec for typical sizes of $r \sim 3\times10^{17}$ cm. Thus v is close to the thermal velocity of the intercloud gas with $T \sim 10^8$ K. This means that the variable part of narrow line profiles is not near the central maximum. Thus, the gas in the shadows of the clouds in the outer part of the BLR can radiate a significant part (dozens of percent) of emission in sufficiently narrow components of forbidden and allowed lines and can show variability on timescales of months as a result of relaxation of both thermal and ionization conditions during slow variations of X-ray luminosity of the active nuclei and phase transfer between thermally stable phases with temperatures $T = (1\text{-}2)\times10^4$ K and $(4\text{-}10)\times10^4$ K.

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