THE AMPLITUDE–TIME LAG RELATION FOR EMISSION-LINE FLARES OF AGN

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Abstract. The amplitude–time lag ("ΔA–Δt") relation is considered in order to describe behaviour of the emission-line spectrum of an active galactic nucleus during a separate active event. Here ΔA, called the amplitude, is the maximum relative increment of the flux in a line, and Δt is the time lag between the maximum of the ionizing continuum flare and the maximum of the flare in a line. As suggested by Shevchenko (1988), the construction and analysis of such relations can be used to discriminate between broad-line region models. Comparison of theoretical "ΔA–Δt" relations with the observed one composed by data for flares in various lines during a separate active event, is proved to be a useful tool for investigating the geometry of a broad-line region, for studies of the form of phase functions of a typical line-emitting cloud in various lines, as well as for clearing up the duration and amplitude of the initial flare in the ionizing continuum. The advantage of this method is that it utilizes the most general observed characteristics of the emission-line flares and nevertheless provides basic information on the allowed BLR models before the detailed modelling of emission-line light curves is performed.

1. Introduction

Since the discovery of rapid emission-line variability of AGN in emission lines (Lyutyj and Cherepashchuk, 1971; Cherepashchuk and Lyutyj, 1973), this phenomenon has been extensively studied (cf. review by Peterson, 1993). It has been usually analyzed in the framework of the "reverberation mapping" approach, introduced by Blandford and McKee (1982). This technique requires detailed information on emission-line light curves. A supplementary approach consists in an attempt of interpretation of basic characteristics of emission-line variations such as time lags and amplitudes (Shevchenko, 1984, 1985a, 1988). Here the interrelation between these characteristics is discussed.

2. The model of a BLR and the phase functions

Hereafter the standard picture of a broad-line region is adopted, according to which the BLR is an aggregate of a large number of line-emitting clouds surrounding the central source of ionizing radiation; the line emission of an individual cloud responds to continuum variations instantaneously as compared to the light-crossing time of the BLR (cf. e.g. the review by Peterson, 1993). The duration of the ionizing flare is assumed to be much less than that of the accompanying line variation, i.e. the whole analysis is performed in a flare approximation. The dependence of the luminosity of a BLR cloud in a line upon the incident ionizing flux is represented

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by the power law $L \propto F^s$ ($s \geq 0$); the index of this power law is referred to as "the parameter s".

Let us specify the form of phase functions defining how the flux in a line received by a distant observer from an individual cloud depends on the cloud phase angle. These functions are important because the anisotropy of line emission, upon which a typical cloud emits mainly from the side illuminated by the ionizing source, represents a necessary condition for a time lag to occur in case of a spherically symmetric BLR, if one adopts the flare approximation (Shevchenko, 1984). Hereafter the time lag of the maximum of a line variation is implied. Assume that the surface of the cloud emits in a line orthotropically, and the dependence of the line luminosity of the surface element on the incident ionizing flux is described by the power law $l \propto f^s$. First let the cloud represent a flat "pancake" orthogonal to the direction to the ionizing source. Then the phase function has the form

$$j(\theta) \propto \cos\theta + |\cos\theta|, \tag{1}$$

where θ is the angle between the ionizing source and the observer as seen from the cloud. Consider next the case of a spherical cloud under the same assumptions. A close approximation to the phase function of a sphere, according to Shevchenko (1985b), is as follows

$$j_s(\theta) \propto (1+\cos\theta)\left(1+\frac{s}{2}\cos\theta\right), \tag{2}$$

valid on the interval $0 \leq s \leq 2$.

3. The time lag–parameter s relation

The simplest possible model of cloud distribution is the homogeneous one; it turns out to be very illuminating. Define $\alpha = \sigma n \equiv \text{const}$, where σ is the mean section of a typical cloud in the plane orthogonal to the ionizing source direction, and n is the number of clouds in a unit volume. The BLR radius in the homogeneous model is nothing but the radius of the illuminated domain, confined by cloud shadowing. This radius R is of order α^{-1}, hereafter we adopt $R \equiv \alpha^{-1}$. The general covering factor formally equals to unity, but due to large velocities of clouds the line photons may freely escape from the BLR. Formally this model is equivalent to a non-homogeneous one with no cloud shadowing (zero covering factor), but with an exponential cut-off in radial distribution of clouds.

According to Shevchenko (1985a, 1988), if there is a central cavity of radius R_0 in the homogeneous cloud aggregate, the time lags are described by the relation

$$\Delta t = \begin{cases} W(1-s)/\alpha c, & \text{if } 0 \leq s \leq 1 - 2\alpha R_0/W \\ 2R_0/c, & \text{if } s \geq 1 - 2\alpha R_0/W, \end{cases} \tag{3}$$

where W is a constant, which in case of phase functions (1) or (2) has corresponding values $W = 3.19$ or $W = 2$; c is the speed of light.

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Define a mean harmonic radius of the BLR in a line as $\langle R\rangle_h = \langle r^{-1}\rangle^{-1}$, where luminosity of a cloud in the line $L \propto r^{-2s}$ corrected for the local covering factor is used as a weight function. In the homogeneous model

$$\langle R\rangle_h = 2(1-s)/\alpha = 2(1-s)R, \tag{4}$$

where $0 \le s \le 1$ (Shevchenko, 1985a). Then $\Delta t = W\langle R\rangle_h/2c$, i.e. the time lag is directly proportional to the mean harmonic size. Differences in time lags are often taken as an evidence for a "stratification" of the BLR in multiple regions emitting in different lines. Eq. (4) clearly demonstrates that this stratification is irrelevant to matter distribution.

4. The amplitude–time lag relation

Define the amplitude of a flare in a line as the maximum relative increment of the observed flux: $\Delta A = \Delta F_{\max}/F$. In case of the model with a central cavity of radius R_0, if one adopts phase function (2), the ΔA dependence on s is as follows

$$\Delta A = \begin{cases} \frac{12(1-s)^{2(1-s)}e^{s-1}}{(s+6)\Gamma(3-2s,\chi)}c(s)((1+\Delta A_c)^s-1)\,d\tau, & \text{if } 0 \le s \le 1-\chi \\ \frac{3}{(s+6)(s-1)(2s-1)}\Big(\chi(2-s-\chi)+\frac{\chi^{3-2s}e^{-\chi}}{\Gamma(3-2s,\chi)} & \\ \times\Big(\chi - s + \frac{2(s^2-1)}{\chi}\Big)\Big)((1+\Delta A_c)^s-1)\,d\tau, & \text{if } 1-\chi \le s < 1-d\tau, \end{cases} \tag{5}$$

where $\Delta A_c = \Delta F_c/F_c$ is the fractional amplitude of the flare in the ionizing continuum, $d\tau = \alpha c\,dt/2 = c\,dt/2R$ is the duration of the continuum flare measured in light-crossing times of the BLR; $0.95 < c(s) \le 1$ for $0 \le s \le 1$; $\chi = \alpha R_0 = R_0/R$ is the radius of the cavity measured in units of the characteristic radius of the BLR. On the reason that the duration of the ionizing flare fixes the time resolution of time lags, Eq. (5) is applicable if $s < 1 - d\tau$.

Eqs (3) and (5) parametrically define the amplitude–time lag dependence. It is generally in accordance with observational data, presented by Cherepashchuk and Lyutyj (1973), Antonucci and Cohen (1983), Ulrich et al. (1984), Peterson (1993), as the amplitudes in lines are predicted to be much smaller than that in the continuum, and are expected to decrease with the time lag value.

For realistic values of $d\tau > 0.1$ (accordingly $s < 0.9$) the homogeneous model and the model with a cavity for even high values of χ (say, equal to 0.5) differ very slightly, by some percents, in the predicted amplitudes. Therefore one can hardly expect that any information on the amplitudes solely can say much about radial structure of the BLR. The "ΔA–Δt" diagram is much more informative in this respect. According to Eq. (3), if the cavity exists, the lags smaller than some value constant for all lines emitted anisotropically cannot be observed, and therefore the diagram is strongly sensitive to deviations in radial structure.

The ratio of amplitudes predicted for phase functions (1) and (2) in the homogeneous model, according to Shevchenko (1988), is confined between 0.72 and 0.88

for allowed values of s, i.e. the amplitudes are slightly affected by the choice of the phase function. The time lags are again better indicators, as they differ by 1.6 times (see Eq. (3)). Therefore the "ΔA–Δt" dependence can still be used to discern between various forms of phase functions.

The amplitude in a line for the BLR in a general standard model (described in Section (2)) in the flare approximation can be represented as

$$\Delta A = f(s)\, \Delta A_{qs}\, c\, dt/D, \tag{6}$$

where function $f(s)$ is shaped by the BLR geometrical structure as well as the form of cloud phase functions, and normally depends on s weakly and is of order of unity; $\Delta A_{qs} = (1+\Delta A_c)^s - 1$ is the amplitude corresponding to the quasistationary state, for which the continuum variations are much longer in duration than the light-crossing time of the BLR; D is the diameter of the BLR. Thus the amplitudes in lines are determined mainly by the amplitude and duration of the flare in the continuum and by the size of the BLR, and therefore can be used to estimate them.

The amplitudes of line variations in the flare approximation are less than in the quasistationary case by factor $c\, dt/D$. This marked difference indicates that the values of the parameter s cannot be derived by means of application of the quasistationary law to rapid events, whether the procedure of displacement of a line light curve on the value of the time lag is utilized or not. Application of this law is self-consistent on the time scale of slow variability, i.e., according to Lyutyj (1977), on the time scale of years.

5. Conclusions

Consideration of the amplitude–time lag dependence may often be helpful on the reason that, along the amplitude axis, it is strongly sensitive to the parameters of the continuum flare as well as to the size of the BLR, and, along the time lag axis, it is affected by the BLR geometrical structure and the form of phase functions of the BLR clouds. Therefore this diagram can provide basic information on the allowed BLR models before the detailed modelling of light curves is accomplished.

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