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GRAVITATIONAL MICROLENSES IN ACTIVE GALACTIC NUCLEI

L. Č. POPOVIĆ, P. JOVANOVIĆ, E. BON and M. S. DIMITRIJEVIĆ

Astronomical Observatory, Volgina 7, 11160 Belgrade, Serbia
E–mail lpopovic@aob.bg.ac.yu

Abstract. A short review of the gravitational microlensing phenomenology is given. The microlensing influence on radiation of QSOs is discussed. Taking into account recent determination of the Broad Line Region (BLR) size of AGN, we present our investigation of the importance of microlensing effect for spectral line shapes of AGN.

1. INTRODUCTION

The phenomenology of gravitational lenses effect, and introduction to this field has been given in several review papers and books (Schneider et al. 1992, Rafsdal and Surdej 1994, Fort and Mellier 1994, Zakharov 1996, Narayan and Bartelmann 1999, Paczyński 1996, Wambsganss 1999, Bartelmann and Schneider 1999, Mellier 1999, Claeskens and Surdej 2002). Consequently, we will no discuss here all aspects of the gravitational lenses in the universe, but we are going to present shortly the nature of the gravitational lensing effect in order to give the basic relations. The special attention we will pay to influence of gravitational microlensing on spectral line shapes.

The influence of microlensing effects on multiply imaged QSOs has been widely discussed (Ostriker and Vietri 1985; Kayser et al. 1986; Schneider and Weiss 1987; Nemiroff 1988; Irwin et al. 1989; Schneider and Wambsganss 1990; Yonehara et al. 1999; Mineshige and Yonehara 1999; Agol and Krolik 1999; Kraus et al. 1999; Belle and Lewis 2000; Popović et al. 2001ab, Abajas et al. 2002). It has been routinely assumed that only the continuum-emitting region of Active Galactic Nuclei (AGNs) is sufficiently compact to be affected by microlensing. However, recent results (e.g. Wandel et al. 1999, Kaspi et al. 2000) indicate that, also, Broad Line Regions (BLRs) of AGNs are smaller than was supposed before. Consequently, gravitational microlensing by stars in the lens galaxy can affect not only the continuum but also the broad emission lines of multiply imaged AGN (Popović et al. 2001ab, Abajas et al. 2002).

The aim of this paper is to give a short review of microlensing effect in AGNs, especially of the influence of microlensing effect on broad emission line shapes of AGN. In Section 2 we discus the gravitational lensing effect in general. In Section 3 we include microlensing effect in the case of different dynamics of emitting gas of

AGN and give the results of our investigation. In Section 4 conclusion is given. Some of the useful relations are given in Appendix (Section 5)

2. GRAVITATIONAL LENSING – PHENOMENOLOGY

Phenomelogy of multi-imaged celestial objects, well known as gravitational lens can be explained simply comparing this effect with atmospheric mirages. Since the light speed in a material medium is $v = c/n$ (where c is the light speed in vacuum, n is the refractive index), the light rays are bent when they travel into an inhomogeneous medium. Consequently in the lower atmospheric air layers with strong temperature or density gradients, the atmospheric mirages may be formed. On the other side, as a consequences of general relativity theory, space-time is curved by the gravitational potential ϕ, which depends on object mass, and in weak gravitational field approximation ($\phi/c << 1$) the equation of metric is (see e.g. Weinberg 1972)

$$ds^2 = -(1 + \frac{2\phi}{c^2})c^2dt^2 + (1 - \frac{2\phi}{c^2})(dx^2 + dy^2 + dz^2). \quad (1)$$

In the vicinity of the massive object, the light path is defined by null geodesic ($ds^2 = 0$). Moreover, taking into account that ($\phi/c << 1$), we can obtain for speed of light

$$v' \approx \frac{c}{1 - \frac{2\phi}{c^2}}, \quad (2)$$

and we can see that ϕ acts on the light speed as a medium with an effective refractive index n_ϕ as

$$n_\phi \approx 1 - \frac{2\phi}{c^2}. \quad (3)$$

Taking into account that a gradient in the Newtonian gravitational field exist in the vicinity of a massive object, the angular deflection of light trajectories $\vec{\alpha}$ will appear. Such deflected rays cause that an observer see the gravitational mirage of the source. The face of the mirage depends of mass of deflector, and the distances between the observer-source (D_{OS}), observer-lens (D_{OL}) and lens-source (D_{LS}).

Let us consider mass (M), so called deflector, at a distance D_{OD} from the observer and a point source S at a distance D_{OD} from the observer (see Fig. 1). The lens equation connects the source position, ($\vec{\theta_s}$) and the positions of the images ($\vec{\theta}$) seen by an observer (O), given the deflection angle $\vec{\alpha}$ produced by the gravitational lens (Fig 1). The lens equation can be written (see e.g. Zakharov 1996, Claeskens and Surdej 2002)

$$\vec{\theta_s} = \vec{\theta} - \frac{(D_{OS} - D_{OD})}{D_{OS}} \vec{\alpha}(D_{OD}\, \vec{\theta}). \quad (4)$$

To obtain the basic equations, let us consider two planes perpendicular to the line of sight, at the deflector and at the source distances, respectively. As seen by the observer (O), the deflector has angular coordinates (x_m, y_m) in the sky. Its projections in these two planes are in points A and A_s, with the corresponding linear coordinates

$$X_A = x_m D_{OD}, \qquad Y_A = y_m D_{OD}, \quad (5)$$

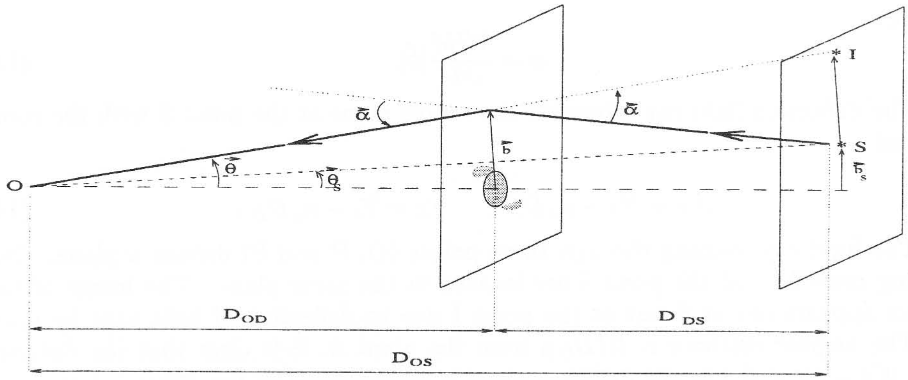

Fig. 1: The geometry of gravitational lensing: The observer, the lensing mass, and the source are located at the points O, M, and S, respectively. Light rays are deflected near the lensing mass by the angle α, and the image of the source appears to be located at the point I, not at S. The distances from the observer to the lens (deflector) and to the source are indicated as D_{OD} and D_{OS}, respectively.

$$X_{A_s} = x_m D_{OS}, \qquad Y_{A_s} = y_m D_{OS}. \tag{6}$$

Let the observer (O) look at the sky in the direction with angular coordinates (x, y). The line of sight intersects the deflector plane at point B which is defined by $\vec{b}$ and have coordinate

$$X_B = x D_{OD}, \qquad Y_B = y D_{OD}. \tag{7}$$

If there was no deflection of light by the massive object, the line of sight would intersect the source plane at point I with coordinates

$$X_I = x D_{OS}, \qquad Y_I = y D_{OS}. \tag{8}$$

The light ray passes the deflector at a distance

$$R = |\vec{b}| = \sqrt{(X_B - X_A)^2 + (Y_B - Y_A)^2}. \tag{9}$$

The light ray is deflected by the angle

$$\vec{\alpha} = \frac{4GM}{c^2}\vec{b}, \tag{10}$$

i.e. the angle has two components

$$\alpha_x = \alpha \frac{X_B - X_A}{R}, \tag{11}$$

$$\alpha_y = \alpha \frac{Y_B - Y_A}{R}, \tag{12}$$

where

$$\alpha = \frac{4GM}{c^2 b^2}|\vec{b}|. \tag{13}$$

The deflection light ray intersects the source plane at the point S with the coordinates

$$X_S = X_I - \alpha_x D_{DS}, \quad Y_S = Y_I - \alpha_y D_{DS}. \tag{14}$$

The light ray, passing through three points (O, B and S) defines a plane. The lensing mass M and the point I are located in the same plane. The image of the source appears not at S but at the point I due to deflection of light rays by mass M. The angular distance is R/D_{OD} from the point A. It is clear that the distance $|\vec{b}| + |\vec{b_s}| = (R + R_s)$ in the deflector plane is proportional to the distance between I and S in the source plane, and the latter can be calculated with Eq. (14). Including the Eqs. (11) and (12) in Eq (14) we obtain

$$R + R_s = \sqrt{(X_S - X_I)^2 + (Y_S - Y_I)^2}\frac{D_{OD}}{D_{OS}}, \tag{15}$$

$$R + R_s = \frac{4GM}{c^2 R^2}\frac{D_{DS} D_{OD}}{D_{OS}}, \tag{16}$$

This equation can be written as

$$R + R_s = \frac{R_E^2}{R},$$

where

$$R_E^2 = \frac{4GM}{c^2}\frac{D_{DS} D_{OD}}{D_{OS}} \tag{17}$$

is the Einstein Ring Radius (ERR). Eq. (16) has two solutions:

$$R_{\pm} = \frac{R_s^2 \pm \sqrt{R_s^2 + 4R_E^2}}{2}$$

This solution indicate two images of the source, located on the opposite side of the point A, at the angular distances R_+/D_{OD} and R_-/D_{OD}, respectively. Any of the lensing conserves surface brightness. The ratio of the image to source intensity, called amplification (A^m), is given by the ratio of their areas. This ratio can be calculated as (Pacyński 1996)

$$A_{\pm}^m = |\frac{R_{\pm} dR_{\pm}}{R_s dR_s}| = \frac{u^2 + 2}{2u\sqrt{u^2 + 4}} \pm \frac{1}{2}, \tag{18}$$

where distance between projected lens and source, expressed in ERR in source plane is

$$u = \frac{|\vec{b_s}|}{R_E}.$$

In the case of microlensing, it is not possible to see images of the source, but microlensing effect cause amplification of the source brightness. In this case the source amplification will be

$$A_+^m + A_-^m = \frac{u^2+2}{2u\sqrt{u^2+4}}. \tag{19}$$

On the other side, the chance of seeing a MLE is usually expressed in terms of the optical depth τ, which is probability that at any instant of time the source is covered by a deflector. The optical depth can be estimated computing the number of lenses within one ERR in line-of-sight. Let all lensing objects have identical mass $M_{\rm ml}$. We will divide the space between observer and source in a thin slabs, where one slab has thickness ΔD_{OD}. There is, on average one lens per surface area $\pi R^2 = \frac{M_{\rm ml}}{\rho \Delta D_{OD}}$, where ρ is the average mass density due to lenses in the volume $\pi\xi^2 \Delta D_{OS}$. The cross section of each lens is πR_E^2, where R_E is determined from Eq. (17).

The slab contribution to the optical depth is given as (Paczyński 1996)

$$\Delta\tau = \frac{\pi R_E^2}{\pi R^2} = [\frac{4\pi G\rho}{c^2}\frac{D_{DS}D_{OD}}{D_{OS}}]\Delta D_{OD}. \tag{20}$$

Taking that $\Delta D \to 0$, the total optical depth due to all lenses located in the part of spherical envelop can be calculated as

$$\tau = \frac{4\pi G}{c^2}\int_0^{D_s} \rho(D_{OD})\frac{D_{DS}D_{OD}}{D_{OS}} dD_{OD} \tag{21}$$

The solution of the integral in Eq. (21) depends on mass distribution of the deflectors, and several solution were performed (see e.g. Paczyński 1991, Kiraga and Paczyński 1994, Zakharov 1996).

As one can see from Eq. (21) the optical depth depends on the total mass in all lenses, but it is independent of the masses of individual lens. If the density of lenses is constant, we obtain

$$\tau = \frac{2\pi}{3}\frac{G\rho_{Av}}{c^2}D_{OS}^2$$

where ρ_{Av} is the averaged mass density of deflectors.

2. 1. CAUSTIC CROSSING

In most of cases we can not simply consider that microlensing is caused by an isolated compact object but we must take into account that the micro-deflector is located in an extended object (typically, the lens galaxy). In this case, when the size of the ERR of the microlens is larger than the size of the accretion disc, we can describe the microlensing in terms of the crossing of the disc by a straight fold caustic (Schneider et al. 1992). The amplification at a point close to the caustic is given by (Chang and Refsdal 1984),

$$A^m(X,Y) = A_0^m + \frac{K}{\sqrt{\kappa(\xi-\xi_c)}}\cdot H(\kappa(\xi-\xi_c)), \tag{22}$$

where A_0^m is the amplification outside the caustic, $K = A_0^m\beta\sqrt{\eta_0}$ is the caustic amplification factor, where β is constant of the order of unity (e.g. Witt et al. 1993). ξ is the distance perpendicular to the caustic and ξ_c is the minimum distance from the source center to the caustic. The more complex function of caustic can be found in Shalyapin et al. (2002).

Some other useful relations are given in the Appendix.

3. MICROLENSING INFLUENCE ON AGN RADIATION

3. 1. STANDARD MODEL OF AGN

The investigation of influence of microlensing on AGN radiation (in first order on QSO radiation) is important for our knowledge about structure of AGN emission region. To simplify the task, the papers devoted to this theme usually take in consideration two cases: a) the source is a point and lens has complex structure (see e.g. Shalyapin 2002); b) the source is complex and lens is point-like (see e.g. Yonehara et al. 1999, Agol and Krolik 1999). Very rarely consideration of complex structure of source and complex structure of lens is given (Popović et al. 2002a, 2003).

The geometry of emission line region in AGN is very complex. Narrow Line Region (NLR) is too large that microlensing can affect the light from this region, but Broad Line Region and continuum source is enough compact that this effect may play a role. As a standard model of AGN we can adopt that in the central part of emission line region a Black Hole exist. The innermost part radiate in the X-ray range (including the X-ray continuum and lines, e.g. Fe Kα line). The continuum emitting source of AGN is also compact (several light days), while the BLR lay between several light days and several tens of light days (Wandel et al. 1999, Kaspi et al. 2000). Taking into account the dimensions of the emitting region we will consider only microlensing of radiation coming from X-ray and optical part in continuum and in lines.

The geometry of emission region of AGN can be very complex, usually three geometries may be considered: spherical, biconical and cylindrical (Robinson 1995). It is interesting that one part of radiation coming from accretion disc (especially in X-ray, and also in some cases in UV and optical wavelength region, see e.g Eracleous and Halpern 1994, Popović 2001b), or from the region which has more complex structure (accretion disc + one more emission region, see e.g. Popović et al. 2001c)

3. 2. MICROLENSING OF AGN

Quasars are the first objects observed as gravitational lenses. The importance of gravitational microlensing by individual stars in a 'lensing galaxy' was first pointed out by Chang and Refsdal (1979). Till now, the investigation of this type of the microlensing has been performed by a number of authors (see e.g. Schneider et al. 1992, Zakharov 1996). When a QSO is lensed by a galaxy into multiple images, the probability that one of the stars belonging to the lens transit just in front of one of the microlensed QSO images is much higher. The microlensing can be used to analyze the structure of the emitting region in AGN. It was the accepted opinion that the microlensing preferentially amplifies the continuum emission region, coming from the central part ($\sim 10^{-4} - 10^{-3}$ pc), while the broad emission line (BEL) flux remains unchanged, because the dimension of BEL assumed to be around 1pc (e.g. Rees 1984, Claeskens and Surdej 2002).

The change in the continuum flux of quasars by stars or compact objects in intervening galaxies is now a well-established observational phenomenon. Several studies have attempted to resolve the structure of the region generating the optical and UV continuum by using the microlensing effect as a gravitational telescope (see Yonehara 1999).

Only extended objects of sizes comparable to or smaller than the Einstein radius associated with the gravitational lens will experience appreciable amplifications (e.g., Schneider et al. 1992). Thus, in the framework of the AGN standard model, in which the BLR is supposed to have a radius in the $0.1 - 1$ pc range, only massive deflectors could give rise to significant amplifications. However, recent results from the MACHO project indicate that the most likely microdeflector masses in the Galactic halo are within the range $0.15 - 0.9\ M_{\odot}$ (Alcock et al. 2000a). In the Galactic bulge the microdeflector masses are in good agreement with normal-mass stars (Alcock et al. 2000b). Estimates from the light curve of Q2237+0305 (Wyithe et al. 2000) are also in reasonable agreement with these values. Consequently, significant amplifications of the BEL would not be expected according to the standard model. This result has been pointed out by other authors (Nemiroff 1988, Schneider and Wambsganss 1990), even if they were somewhat optimistic concerning the distribution of the microlens mass adopted. However, recent studies indicate that the BLR size is smaller (from several light days to several tens of light days) than supposed in the standard model (Wandel et al. 1999, Kaspi et al. 2000). On the other side, analyzing the spectral line shape of Akn 120 and NGC 3516 Popović et al. (2001c, 2002b) found that the broad line shape can be fitted with two-component model, where significant contribution has emission of disc or disc-like region. They found that the radius of disc region is of the order of 1000 R_g. Taking into account that the mass of black hole in AGNs is somewhere about $10^8 M_{\odot}$, the dimension of this region is $\sim 10^{-3} - 10^{-2}$ pc. These investigations showed that the influence of microlensing on the broad emission lines should be revised, and consequently, recently in several papers this influence have been presented (Popović et al. 2001ab, Abajas et al. 2002, Popović et al. 2002a).

Moreover, the X-Rays of AGNs are generated in the innermost region of an accretion disc around a central super-massive Black Hole (BH). An emission line from iron Kα (Fe Kα) has been observed at 6-7 KeV in the vast majority of AGNs (see e.g. Nandra et al. 1997, Fabian et al. 2000). This line is probably produced in the very compact region near the BH of an AGN (Iwashawa et al. 1999, Nandra et al. 1999, Fabian et al. 2000) and can bring essential information about the plasma conditions and the space geometry around the BH. Thus it seems clear that the Fe Kα line can be strongly affected by microlensing and recent observations of two lens systems seem to support this idea (Oshima et al. 2002, Chartas et al. 2002). In following part of this paper we will present the investigation devoted to microlensing of broad line region and X-ray emitting region.

3. 3. THE MICROLENSING INFLUENCE ON THE BLR OF QSOS

In order to calculate the influence of microlensing to the broad emission lines of AGN, we started from the relation

$$F_{\lambda} = \int_V \varepsilon(x,y) I(x,y,\lambda) A^m(x,y) dV \tag{23}$$

where F_{λ} is the line flux, $\varepsilon(x,y)$ is the emissivity, $I(x,y,\lambda,\lambda_0)$ is the function of line intensity which also depends on geometry of line emitting region and velocity of emission gas. $A^m(x,y)$ is the amplification defined by Eq. (19) for point-like deflector and Eq. (22) for straight fold caustic. In this case the integration is in the plane of source, where $u = |\vec{b_s}(x, y)|/R_E$. The function of emissivity for BLR can be taken as

$$\varepsilon(r) = \varepsilon_0 \cdot r^q,$$

where q is the index of emissivity (e.g. in the case of disc emission $q = -3$, see e.g. Eracleous and Halpern 1994). The geometry and kinematics of emission gas determine the line intensity distribution through emission region. Very often the velocity of emission gas is assumed to be only function of distance from the central source (Robinson 1995)

$$v(r) = v_0 r^p$$

where p is the velocity index.

3. 4. MICROLENSING INFLUENCE ON X-RAY EMISSION

The influence of microlensing on X-ray radiation in continuum were considered in the papers of Yonehara et al. (1999). The influence on spectral line shape of Fe Kα line has been discussed in Chartas et al. (2002) and Popović et al. (2001b, 2002a).

In the standard configuration, microlensing affects one of the images of a lensed QSO and is produced by a star-sized object in the lens galaxy. An event of this type affecting the Fe Kα line has been reported in the quadruple imaged QSO J0414+0534 by Chartas et al. (2002). These authors observed a sudden increase in the iron line equivalent width from $\sim$ 190 eV to 900 eV only on image B of J0414+0534 proposing that it has been caused by a microlensing event. We can try to reproduce this enhancement with our models under the assumption of amplification by a straight fold caustic crossing. However the problem is highly unconstrained because both sets of variables, the one related to the microlensing (relative amplification, β, orientation of the caustic with respect to the rotation axis, direction of the caustic crossing, microlens mass) and the other related to the relativistic disc model (outer radius, emissivity, metric) should be considered to fit a unique number. Thus, we can do only an exploration of scenarios compatible with the result. In the first place we can fix the disc parameters adopted until now to study which values of the parameter β can reproduce the observed amplification in both metrics, Schwarzschild and Kerr. We have computed the maximum amplification for a caustic crossing along the accretion disc. The resulting amplifications indicate that there is a range of β values and microlens masses that can give rise to the observed amplification (see Table 1 and 2 in Popović et al. 2002a). For instance, for the value $\beta = 0.2$ (Chartas et al. 2002), a microlens of a solar mass can produce the observed enhancement. For $\beta = 1$, a low mass lens ($\sim$ 0.001 $M_\odot$) can also produce the required amplification.

Oshima et al. (2001) have also reported the presence of a strong (EW$\sim$ 960eV) emission Fe Kα line in the integrated spectra of the lensed QSO H 1413+117. Oshima et al. (2001) interpreted this results as produced by iron K$_\alpha$ emission arising from X-Ray re-processing in the broad absorption line region flow. Alternatively, we can assume that the individual spectra of the components (not available) are different, and that the excess emission in the iron line arises only from one of the components, like in the case of J0414+0534.

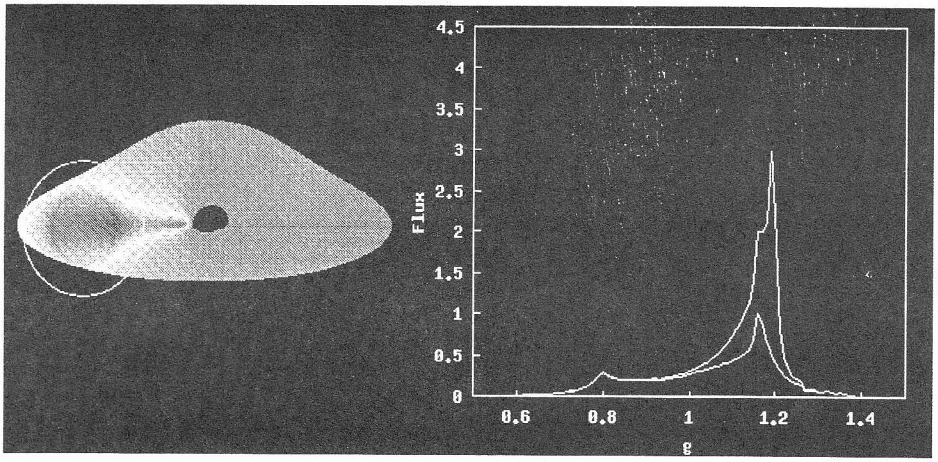

Fig. 2: *Left:* The point-like deflector crossing an accretion X-ray disc in Kerr metrics (illustration). *Right:* Corresponding amplification of Fe Kα line, bottom is unperturbed line (Popović et al. 2003)

Regardless of the true nature of the two events reported in J0414+0534 and H 1413+117, our analysis show that objects in a foreground galaxy with even relatively small masses can bring strong changes in the line flux. This fact indicates that changes in the Fe Kα line flux will be higher than in the UV and optical lines. Thus, the observation of the iron line in multi-imaged AGNs opens new possibilities to study the unresolved structure in QSOs and also the nature and distribution of compact objects in lens galaxies.

From this investigation one can conclude (see Popović et al. 2002a, 2003)

– Microlenses of very small projected Einstein radii ($\sim$ 10 R_g) can give rise to significant changes in the iron line profiles. The effects are two or three order of magnitude larger than the ones inferred for the UV and optical lines (Popović et al. 2001a). Off-centered microlenses would induce strong asymmetries in the observed line profiles.

– The effects of microlensing show differences in the Kerr and Schwarzschild metrics, the amplitude of the magnification being larger in the Kerr metric. The transit of a microlens along the rotation axis of the accretion disc would induce a strong amplification of the blue peak in the Schwarzschild metric when the microlens was centered in the approaching part. In the Kerr metric the amplification will be larger but will not affect so preferentially the blue part of the line. This difference could be interesting to probe the rotation of an accretion disc.

– Even objects of very small masses could produce observable microlensing in the iron Kα line of multiple imaged QSOs. We obtain that microlenses of 1 solar mass can explain the measured Fe Kα line excess in the J0414+0534 and H 1413+117 lens systems.

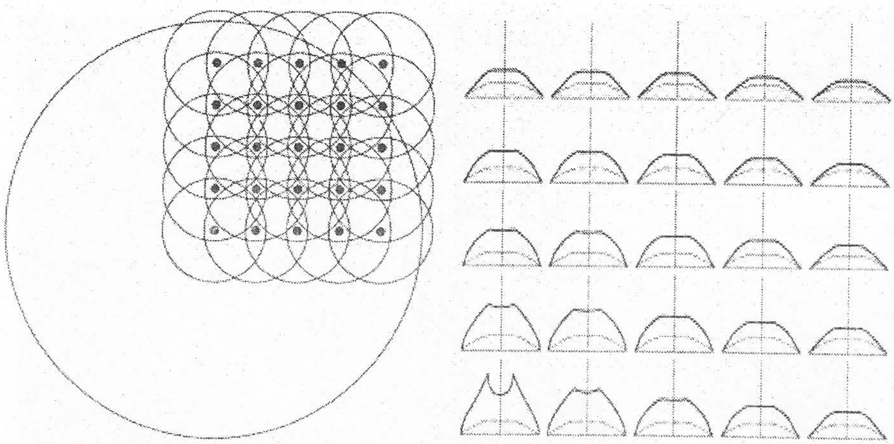

Fig. 3: *Left:* Grid of relative displacements between the microlens and the BLR. The large disc represents the BLR. The small discs correspond to the Einstein circle associated with the microlens, represented by a point. For each point (corresponding to a displacement of the microlens in the positive quadrant we compute an emission-line profile. *Right:* Spherical model with p=0.5, q=-1.5, and ERR is equivalent to dimension of BLR. On the x-axis we represent $x = v_{max}(\lambda - \lambda_0)/(c \cdot \lambda_0)$, which varies between -1 and 1. On the y-axis we represent the flux. The heavy solid line is the amplified line profile, and the lighter solid line is the unamplified line profile (Abajas et al. 2002).

3. 5. MICROLENS OF BLR; UV AND OPTICAL LINES

Here we will present some of the results concerning the microlensing influence on broad spectral line shapes. First, for different geometries the influence is given in Abajas et al. (2002), where the spherical, cylindric and biconical geometries of BLR were considered. Also, the influence in the case of Keplerian accretion disc was considered (Popović et al. 2001a)

From the investigation of the influence of microlensing on spectral line shapes of broad line from Broad Line Region we can conclude (see Abajas et al. 2002):

– The global amplification of the BEL induced by microlensing events could be relevant. It was identified a group of 10 gravitational lens systems (about 30% of the total sample) for which the microlensing effect could be observable, especially in high-ionization lines. In other gravitational lenses the microlensing amplifications would be much more modest.

– Even for relatively small microlenses corresponding to high values of the BLR radius/Einstein radius quotient, (BLR dimension are around 4 times larger than ERR), the effects produced by the differential amplification of the line profile (relative enhancement of different parts of the line profile, line asymmetries, displacement of the peak of the line, etc.) would be easily detectable except for highly symmetric velocity fields. The displacement of the peak of the line profile caused by microlensing is especially interesting, since it could otherwise induce inexplicable redshift differences between the different images in a gravitational lens system.

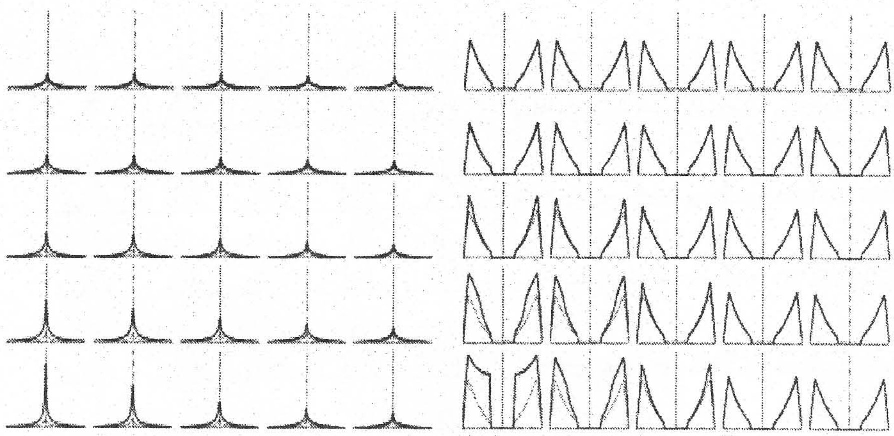

Fig. 4: *Left:* The same as in Fig. 3 (left), but for p=2, q=-1.5 *Right:* The same as at left, but for biconical model with i= 0, p=0.5, q=-1.5, and ERR is 1/4 of BLR dimension.

– The study of the changes between the BEL profiles corresponding to microlensed and non-microlensed images, or among the BEL profiles of lines with different ionization in a microlensed image, could be useful for probing current ideas about BLR size and stratification.

The influence of gravitational microlensing on the spectral line profiles originating from a relativistic accretion disc was considered in Popović et al. (2001a). Using the Chen et al. (1989) model for the disc, we show the noticeable changes that microlensing can induce in the line shape when the Einstein radius associated with the microlens is of a size comparable to that of the accretion disc. Of special interest is the relative enhancement between the blue and red peaks of the line when an off-center microlens affects the approaching and receding parts of the accretion disc asymmetrically (Popović et al. 2001a).

In an AGN formed by a super-massive binary in which the accretion disc is located around one of the super-massive companions (the primary), we discuss the possibility of microlensing by the secondary. In this case the ratio between the blue and red peaks of the line profile would depend on the orbital phase. We have also considered the more standard configuration of microlensing by a star-sized object in an intervening galaxy and find that microlensing may also be detected in the broad emission lines of multiply imaged QSOs. The changes observed in the line profile of Arp 102 B are taken as a reference for exploring both scenarios.

From this investigation one can conclude (Popović et al. 2001a):

– Gravitational microlensing can induce significant changes in the spectral line profiles generated by an accretion disc, even for relatively small values of the Einstein ring radius associated with the microlens (ERR$\simeq$ 40 R_g). Off-centered microlenses can induce relative enhancements of the blue and red peaks of the line profile, or even give rise to a central peak. These effects could be very strong when ERR is comparable to the disc dimension, $R_{out} - R_{in}$.

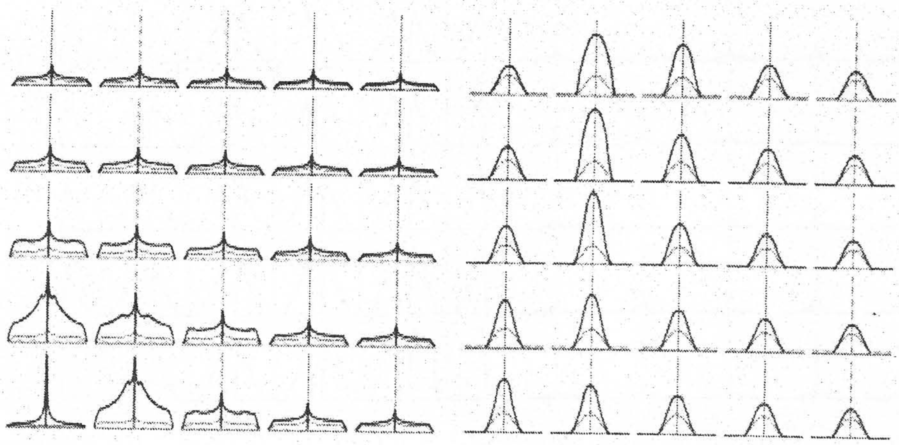

Fig. 5: *Left:* The same as in Fig. 4(right), but for i=0, p=2, q=-1.5, and REE is the same as BLR dimension. *Right:* The same as left, but for i=90, p=0.5, q=-1.5 (Abajas et al. 2002).

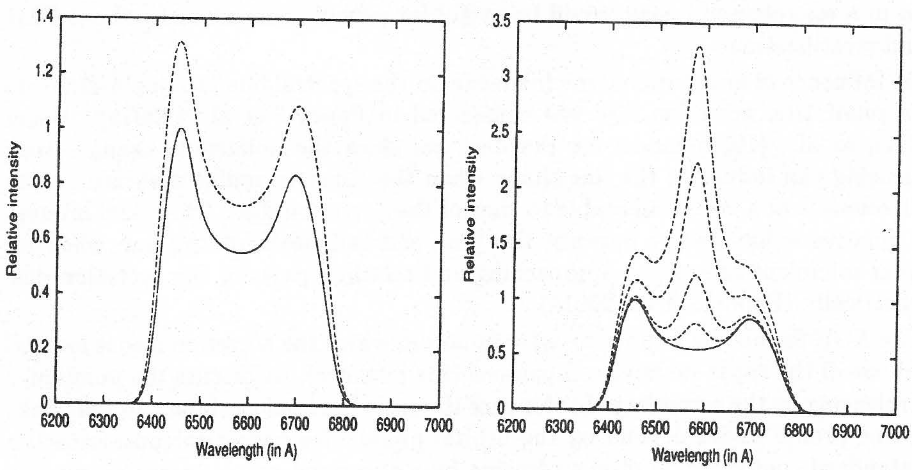

Fig. 6: *Left:* The H_α line profile calculated for a relativistic disc with parameters $i = 32°$, $R_{in} = 350\ R_g$, $R_{out} = 1000\ R_g$ and $\sigma/\lambda_0 = 850$ km s^{-1}. The profile deformed by gravitational microlensing is represented by the dashed line. The parameters of the gravitational microlens are: $\xi_0 = 0\ R_g$, ERR= 500 R_g and $\phi_0 = 90°$. The unperturbed profile is represented by the solid line. *Right:* The line profiles for different Einstein ring radii of the lenses ERR= 100 R_g, 200 R_g, 400 R_g and 600 R_g, respectively. The intensity of the central part is higher for higher ERR. The calculations were performed for $\xi_0 = 500\ R_g$ and $\phi_0 = 0°$ (Popović et al. 2001a).

– We found that a compact object of $\sim 1\ M_\odot$ in an intervening galaxy could give rise to effects easily detectable in the emission line profiles. That implies that, contrary to what has been assumed, not only the continuum but also the emission lines may be susceptible to microlensing in multiply imaged QSOs (in so far as the accretion disc model for Arp 102 B applies to a typical BLR).

– The transit of a microlens along the accretion disc can qualitatively reproduce the quasi-periodical variability of the ratio of red-to-blue peak intensities observed in the case of Arp 102 B in the 1990–1995 period.

In Popović et al. (2001a) two different physical scenarios that could reproduce the observed variability in Arp 102 B: i) microlensing by a super-massive companion ($M \approx 10^7\ M_\odot$) located at a distance of around 0.3 pc, and ii) microlensing by a compact object of a mass $\sim 1\ M_\odot$ in an intervening galaxy. The sinusoidal-like variation induced by microlensing does not extend beyond one period. It can be reproduced again after a long lapse of time (in the case of the super-massive companion) or randomly (in the case of the microdeflector in a intervening galaxy). This could be useful in distinguishing between microlensing and other different options that are strictly periodical, such as the model of an accretion disc with a hot spot.

4. Concluding remarks

The microlensing effect is widely investigated. Using this effect in the case of AGN we can investigate the structure of continuum source, as well as structure of line emitting region from X-ray to optical wavelength region. Recent investigation showed that this effect can be useful for mapping of very compact and kinematically complex continuum and line region in AGN.

5. Appendix

5. 1. SOME RELATION WHERE $D_{OD} \approx D_{OS}$

The size of the ERR projected on the source, R_E increases with the distance between the source and the microlens. For this reason, appreciable amplifications of the optical and UV Broad Emission Lines (i.e. R_E comparable or larger than the dimensions of the accretion disc) induced by a star-sized object are only possible if the microlens is far away from the source, in an intervening galaxy (typically the lens galaxy). In the optical and UV case, appreciable amplifications of the BELs from an object in the host galaxy of the AGN are possible only by a very massive object (Popović et al. 2001a). However, due to the comparatively tiny dimensions of the X-Ray line emission region, microlensing of a star-sized object in the host galaxy becomes a possibility.

In the case $D_{OD} \approx D_{OS}$ the distance, $D = D_{OL} = D_{OS} - D_{OL}$, between the microlens and the accretion disc is negligible with respect to the distance between the observer and the microlens, the expression for R_E (Eq. 17) can be approximated as

$$R_E \approx \sqrt{\frac{4GM_s}{c^2} \cdot D}, \qquad (A1).$$

From Eq. (A1) the mass of the microlens can be estimated as

$$M_s \approx \frac{R_E^2}{D} \cdot \frac{c^2}{4G} = 5.23 \cdot 10^{12} \cdot \frac{R_E^2}{D}\ M_\odot, \qquad (A2)$$

where R_E and D, are given in parsecs.

It is sometimes convinient to express Eq. (A1) in gravitational radii:

$$R'_E \approx \sqrt{\frac{4GM_{ml}}{c^2} \cdot D}, \qquad (A3)$$

where $R'_E = R_E \cdot R_g$, and from Eq. (A3) the mass of the microlens can be estimated as

$$M_{ml}[M_\odot] \approx \frac{R_E^2}{D} \cdot \frac{G}{4c^2} M_{BH}^2 = 1.19 \cdot 10^{-14} \cdot \frac{R_0^2}{D} M_{BH}^2, \qquad (A4)$$

where R_E is given in gravitational radii, D is given in parsecs and M_{BH} is given in solar masses.

5. 2. OPTICAL DEPTH FOR MICROLENSING OF HOST BULGE AND HALO STARS

The probability of seeing a MLE is usually expressed in terms of the optical depth τ. As far as the potential microdeflectors have an Einstein radius similar or larger than the radius of the disc, τ can be estimated as the fraction of the area in the source plane covered by the projected Einstein radii of the microlenses. Taking also into account that the distance between the accretion disc and the microlenses are negligible as compared with the distance between the observer and the microlenses

$$\tau \sim \frac{4\pi G}{c^2} \int_0^R \rho(r) r dr \qquad (A5),$$

where R is the radius of the bulge or halo.

To estimate the order of magnitude of τ we assume a constant mass density, thus

$$\tau \approx \frac{2\pi G}{c^2} \rho_o R^2. \qquad (A6)$$

Czerny et al. (2001) estimated that the total mass of the AGN bulges can reach values of $10^{12} M_{sun}$ and Schade et al. (2000) found typical values for the radius of the AGN bulges within the range 1–10 Kpc. Both results yield to a maximum optical depth from the bulge $\tau_b \sim 10^{-4}$. Using also favorable numbers for the galactic halo ($\rho \sim 0.01 M_{\rm sun}\ {\rm pc}^{-3}$, $R \sim 150$ Kpc) the optical depth could reach values of $\tau_h \sim 10^{-4}$. Adding both contributions a maximum optical depth of $\tau \sim 0.001$ would be expected in a favorable situation. A detailed computation of τ, in addition to include accurate density profiles, should include a cut in the lower limit of integration (r_{min}) to exclude from the integral the microdeflectors with Einstein radii smaller than the radius of the disc (although the approximation $r_{min} \sim 0$ used does not change significantly the order of magnitudes estimated for τ especially in the case of the halo).

5. 3. RELATION MASS OF DEFLECTOR *vs. CORRESPONDING REE*

Very often it is needed to calculate the masses of deflectors able to produce the visible amplification of the line. In this case it is convenient to express the REE in gravitational radii. As a rule, if the REE is with size of the order of emitting region, than we can expect that microlensing is present.

In a Friedmann universe for an observer at redshift z_i and a source at redshift z_j, the angular diameter distance is given by (Grogin and Narayan 1996)

$$D(z_i, z_j) = \frac{2c}{H_0} \frac{(1 - \Omega_0 - G_i G_j)(G_i - G_j)}{\Omega_0^2 (1 + z_i)(1 + z_j)^2}, \qquad (A7)$$

where H_0 is the Hubble constant, and we suppose that $H_0 = 50$ km s^{-1} Mpc^{-1}, $\Omega_0 = 1$. The factors G_{ij} are

$$G_{ij} = \sqrt{1 + \Omega_0 \cdot z_{ij}}. \qquad (A8)$$

As an example we will calculate this relation for MG J0414+0534, taking into account that $Z_{QSO} = 2.64$ and $Z_{lens} = 0.96$, we obtain $D_{0.0.96} = 1749$, $D_{0,2.64} = 1574$, and $D_{0.96,2.64} = 630$. Using the Eq. (17) for ERR we can calculate the ERR in deflector plane

$$r_E = \frac{R_E}{D_{OD}},$$

or

$$r_E = \sqrt{\frac{4GM_{ml}}{c^2} \cdot D'}$$

where

$$D' = \frac{D_{OS} D_{DS}}{D_{OD}}.$$

In our case $D' = 567$ Mpc and if we put the constants, we obtain

$$r_E = \frac{9.2 \cdot 10^{-2}}{M_8^{BH}} \sqrt{M_{ml} \cdot D'}$$

where mass of black hole is given in 10^8 solar masses, M_{ml} is given in solar mass, D in parsecs and r_E in gravitational radii. For the case MG J0414+0534 the relation between ERR and mass of lens is

$$r_E = 2.19 \cdot 10^3 \sqrt{M_{ml}},$$

and as we can see the object of mass of only 0.0001 $M_\odot$, has an ERR of about 50 R_g, and can produce significant amplification of Fe Kα line if we assume that the dimension of the region of formation of Fe Kα line is around 100 R$_g$ (Nandra et al. 1997).

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