Gravitational microlensing: two aspects for the analysis

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The paper is dedicated to investigation of the microlensing phenomenon, which is an important constituent in studying and interpreting transient events in gravitationally lensed quasars. Microlensing events contain valuable information about the masses and velocities of compact objects populating the lensing galaxies, and allow us to measure the angular dimensions of remote quasars with a resolution unachievable with any other methods. In the present paper we describe an analytical method that allows accounting for the effect on the observed brightness of quasar macroimages of the microlens position along the quasar-lens-observer line of sight. On the other hand, microlensing may be a disturbing factor in solving some problems, in which case it must be investigated to be properly eliminated. One such case was discussed in the paper and it was shown how it can be done adequately. A simple way to eliminate the microlensing constituent from the light curves of the lensed quasar images with the aim to obtain the unbiased estimates of the time delays in gravitationally lensed quasars was described.

1 Introduction

The major part of matter in the Universe is presently believed to be either invisible or dark. Studying the composition and spatial distribution of dark matter is therefore most important for understanding the structure and evolution of the Universe dominated by dark matter and dark energy. Since the hidden mass practically does not radiate, it can be identified only in gravitational interaction with other objects consisted both of the dark and usual (luminous) matter. Theoretic analysis of the gravitational lensing phenomenon and observations of images of the remote quasars produced by the action of gravitational fields of the foreground galaxies provide most valuable clues for studying the properties of the dark matter and its distribution at different spatial scales in the Universe (Metcalf & Madau, 2001; Mellier & Meylan, 2004).

The microlensing effect is created by gravitational fields of small compact objects (Alcock et al., 1997; Sutherland et al., 1995). In order to estimate the mass distribution of microlenses, it is necessary to take into account the large-scale distributions of the surrounding fields of the gravitations of galaxies or their clusters in addition to the local characteristics of microlenses. At studying the microlensing effect in an environment with several spatial scales of inhomogeneities, one can expect results useful for interpreting observational data when solving the inverse problem of reconstructing the macro- and microlensing parameters of the whole mass from observations of the microlensing events.

The images of remote quasars seen though the gravitational fields of foreground galaxies are known to undergo various distortions, depending on their mutual locations and specific spatial distribution of the gravitational fields of galaxies. In some cases multiple images of the same quasar may arise instead of an actual image of the source quasar, - the phenomenon is called then a strong lensing, and an observer may see two or four images (macroimages) of the same quasar. Considering the fact that the light from such macroimages passes different paths to the observer, undergoing the influence of the gravitational field of microlenses, the fluctuations of quasar brightness seen in different macroimages will be registered shifted in time. The measurements of such time delays between the quasar brightness variations observed in its macroimages are of great interest. One of the applications of the obtained estimates is the definition of the Hubble constant (Refsdal, 1964).

Determination of the Hubble constant from measurements of the time delays puts quite high requirements for the accuracy of measuring the values of time delay, namely, it should be about 1 percent (Kochanek & Schechter, 2004). However, recent observations provide significantly less accuracy. Such a situation is associated with a number of known objective factors, among them microlensing events caused by motions of objects populating the lensing galaxy near the quasar-macroimage-observer light paths affect the accuracy of the time delays measurements most of all. In particular, in the case of an extended source variable microlensing will differently magnify different parts of the source in each quasar image, thus differently distorting the shapes and amplitudes of the light curves of macroimages (Barkana, 1997). The detailed theoretic analysis of the peculiarities of gravitational focusing of time-variable and extended sources can be found in the work (Minakov et al., 2001).

In this paper, an approach to analyze the microlensing events produced by the gravitational fields with several spatial scales of inhomogeneities is briefly described. Also, a case is considered, when microlensing is a disturbing factor needed to be properly accounted and mitigated: a simple and transparent procedure for decreasing the effects of microlensing on determinations of the time delays in gravitationally lensed quasars is described.

2 Analysis of the microlensing effects in the environment with several spatial scales of inhomogeneities

In studying the radiation propagation in the space, a situation arises when the medium inhomogeneities have several spatial scales. One of the examples is the focusing of quasar radiation in the gravitational field of a massive galaxy inside of which microlenses are located. The combined influence of the gravitational fields of microlenses and macrolen-galaxy on the source radiation can be taken into account in the approximation of a thin phase screen by introduction two independent phase correctors. One of them is connected with a microlens and the second one with the macrolens combined into one plane (Minakov, 1993). In this approximation, the influence of the gravitational field of the global structure on the local radiation focusing in the gravitational field of microlenses is not taken into account. The proposed method which is called a generalized method of phase screen (GMPS) offers a solution for the case where two screens are not combined into one plane, but are spaced a certain distance. The detailed description of the proposed method is given in the paper (Berdina et al., 2011).

The main idea of the GMPS lies in the fact that it allows obtaining the desired characteristics by transferring solutions sequentially from one screen to another, in the case when the wave propagates in a space filled with an environment (gravitational field in our case). GMPS is obtained on the basis of an analysis of Sobolev formula (Sobolev, 1966). The basic algorithm for obtaining the Sobolev formula is the analog of the derivation of the well-known Green formula. Similar approximations and transformations are used (Minakov & Tyrnov, 2003). Except for one significant and important difference - the Green formula considers the propagation of a wave in a vacuum, while the Sobolev method solves the problem of wave propagation in an environment with a given refractive index.

The analysis of radiation focusing in the gravitational field of the galaxy with a microlens was carried out in two stages. At first, solution in form of the analytical expressions for the intensity distribution in macroimages and the amplification factor was obtained for the case when the microlens was located between a source and a galaxy mass centre. And after that, another case was considered, when the microlens is placed between a galaxy centre and an observer, - also with a solution in the analytical form (Berdina et al., 2011).

On the basis of the GMPS, the results of the analysis of gravitational focusing were visualized by plotting intensity contours of images and numerical analysis of the behavior of the magnification factor of image brightness as a function of the microlens location (Berdina et al., 2012). It was shown that the value of the magnification factor depends on the position of the microlens along the propagation path. As the microlens approaches the observer plane, the magnification factor increases. This circumstance is confirmed by the character of the change in the structure of the intensity contours of the images. The microlens has the greatest influence in the case when it is located between the center of the galaxy mass and the observer. The change in the magnification factor in the microlens motion within the thickness of the galaxy is small, however, it may affect the evaluation of the characteristics of the gravitational lens system, such as the mass of the microlens, the mass of the galaxy, the angular size of the quasar, and the velocity.

3 The disturbing influence of microlensing on determination of the time delays

One of the most serious problems in time delay determination is due to microlensing events, which distort the intrinsic quasar light curves differently in different quasar images. The choice of a method to eliminate, or at least to mitigate the effect of microlensing in each specific case depends on characteristics of the quasar intrinsic variability and the variability caused by microlensing, in particular, on relationship between the typical amplitudes and time scales of both processes. Our approach described in details in the article (Tsvetkova et al., 2016), is applicable in the case of slow microlensing, that is for the events with the characteristic time scales larger that those of the quasar intrinsic variability. In short, the method utilizes some useful properties of representing the data of observations by the orthogonal polynomials. In our case, the system of Legendre polynomials turned out to be the best one in the sense of computational stability.

Representation of the observed light curves by the orthogonal polynomials allows, in particular, any term of the polynomial approximating a particular light curve to be eliminated or added again without a necessity to recalculate the rest of the expansion coefficients. It is just this property of the functions approximation that indicates the way to release the light curves from the component of variability resulted from microlensing events. In the case of slow microlensing, the lower terms of the series are excluded (up to the 2nd order, if necessary) from the series representing the approximations of the light curves of each macroimage. It should be noted that by mitigating in this way the observed light curves from the possible contribution from microlensing events, we also eliminate the average levels and linear trends in the constituent of the light curves inherent in the intrinsic quasar brightness variations. These low-order terms can be returned any time, restoring thereby the average level for each component and, if necessary, can be used to represent differential microlensing without any additional computations.

Further analysis consists in calculating the cross-correlation functions for the pairs of light curves of the components represented by their approximations. To eliminate the edge effects in calculation of cross-correlation functions, a procedure is used which is analogous to calculating a locally normalized discrete correlation function (LNDCF). A detailed description of the application of this procedure can be found in the article (Lehar et al., 1992). Then, a time shift at which the cross-correlation function reaches its maximum was assumed as an estimate of the time delay for each given pair of macroimages.

The time delays determined with the use of this method for gravitationally lensed quasars PG 1115+080, HE 0435-112 and QSO 2307+0305, (Tsvetkova et al., 2016; Berdina & Tsvetkova, 2017) are well consistent with the previous estimates and demonstrate good accuracy.

4 Conclusion

The microlensing phenomenon was considered in its two aspects, with one of them referring to the mathematic description of the process of light propagation with the aim to determine the physical parameters of the propagation environment, while the other one refers to the case, when microlensing is a disturbing factor needed to be adequately mitigated.

The proposed method for analyzing the gravitational focusing of the source radiation in the gravitational fields with different spatial scales lead to analytical expressions for the amplification factor of source brightness that in an explicit form depends on the position of the microlens in the galaxy. The advantage of the method is that it allows to obtain the required field characteristics, in the case when the wave propagates in a space filled with the medium.

The uniqueness of the proposed method for decreasing the effects of microlensing on determination of the time delays in gravitationally lensed quasars is in applying the fundamental properties of the approximation of functions in the form of series expansions in orthogonal polynomials. Such approach provides the best approximation to the observed light curves and affords an objective procedure, independent of the researcher's actions for mitigating the effect of microlensing events on the estimates of the time delays. The calculation of the cross-correlation function for the light curves represented by the corresponding approximating functions supplies its smoothness and guarantees the absence of random false maxima.

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