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STUDIES OF RELATIVISTIC EFFECTS WITH RADIOASTRON SPACE MISSION

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SUMMARY: In the review we discuss possible studies of GR phenomena such as gravitational microlensing and shadow analysis with the forthcoming RadioAstron space mission. It is well-known that gravitational lensing is a powerful tool in the investigation of the distribution of matter, including that of dark matter (DM). Typical angular distances between images and typical time scales depend on the gravitational lens masses. For the microlensing, angular distances between images or typical astrometric shifts are about $10^{-5} - 10^{-6}$ as[1]. Such an angular resolution will be reached with the space–ground VLBI interferometer, Radioastron. The basic targets for microlensing searches should be bright point-like radio sources at cosmological distances. In this case, an analysis of their variability and a reliable determination of microlensing could lead to an estimation of their cosmological mass density. Moreover, one could not exclude the possibility that non-baryonic dark matter could also form microlenses if the corresponding optical depth were high enough. It is known that in gravitationally lensed systems, the probability (the optical depth) to observe microlensing is relatively high; therefore, for example, such gravitationally lensed objects, like CLASS gravitational lens B1600+434, appear the most suitable to detect astrometric microlensing, since features of photometric microlensing have been detected in these objects. However, to directly resolve these images and to directly detect the apparent motion of the knots, the Radioastron sensitivity would have to be improved, since the estimated flux density is below the sensitivity threshold, alternatively, they may be observed by increasing the integration time, assuming that a radio source has a typical core – jet structure and microlensing phenomena are caused by the superluminal apparent motions of knots. In the case of a confirmation (or a disproval) of claims about microlensing in gravitational lens systems, one can speculate about the microlens contribution to the gravitational lens mass. Astrometric microlensing due to Galactic Macho's action is not very important because of low optical depths and long typical time scales. Therefore, the launch of the space interferometer Radioastron will give excellent new facilities to investigate microlensing in the radio band, allowing the possibility not only to resolve microimages but also to observe astrometric microlensing. Shadows around supermassive black holes can be detected with the RadioAstron space interferometer.

Key words. Gravitational lensing – quasars: general – dark matter – Relativity

[1] In this paper as means arcsec.

1. RADIOASTRON

According to the schedule of the Russian Space Agency, the space radio telescope RadioAstron will be launched in 2007 (for an old description of the project, see Kardashev 1997). This space based, 10-meter radio telescope will be used for space – ground VLBI measurements. Observations will be made in four wavelength bands, corresponding to $\lambda = 1.35$ cm, $\lambda = 6.2$ cm, $\lambda = 18$ cm, $\lambda = 92$ cm.

It will not be the first attempt to build a telescope which is larger than the Earth. In 1997, Japan launched a HALCA satellite with 8 m radio telescope and as a result VLBI Space Observatory Programme (VSOP) began (Horiuchi et al. 2004). Since the apogee distance for the radiotelescope HALCA was 21,200 km, the apogee distance for RadioAstron should be about 350,000 km (or even 3.5×10^6 km see below), hence the fringe size for the shortest wavelength will be smaller than 1–10 μas. The minimum correlated flux for space-ground RadioAstron VLBI should be about 100 mJy for the 1.35 cm wavelength at the 8σ level (Kardashev 1997), therefore source fluxes should be higher than the threshold and about 24 mJy for the 6 cm wavelength.

An orbit for the spacecraft was chosen with a high apogee and with an orbital period around the Earth of about 9.5 days. The orbit evolves due to weak gravitational perturbations from the Moon and the Sun. The perigee is in a band from 10 to 70 thousand kilometers, the apogee is a band from 310 to 390 thousand kilometers. The basic orbit parameters will be the following: the orbital period, T will be 9.5 days, the semi-major axis, a, will be 189 000 km, the eccentricity, e will be 0.853, the perigee, H, will be 29 000 km.

A detailed calculation of the high-apogee evolving orbit can be performed once the exact time of launch is known.

After several years of observations, it would be possible to move the spacecraft to a much higher orbit (with apogee radius about 3.2×10^6 km), by an additional spacecraft maneuver, using the gravitational force of the Moon. In this case, it would be necessary to use 64-70 m antennas for the spacecraft control, synchronization and telemetry.[2]

Thus, as it was noted earlier, there are non-negligible chances to observe mirages (shadows) around the black hole at the Galactic Center and in nearby AGNs in the radio-band (or in the mm–band) using Radioastron (or Millimetron) facilities. Since a shadow size should be about 50 μas for the black hole in the Galactic Center and analyzing the shadow's size and shape one could evaluate the spin and charge of the black hole. For a detailed discussion, see (Zakharov et al. 2005a,b,c,d,e,f,g, 2006).

2. MICROLENSING FOR DISTANT QUASARS

Gravitational microlensing was predicted by Byalko (1969) and Paczynski (1986). For sources which are stars in Milky Way or Large Magellanic Cloud, monitored by MACHO, EROS and OGLE collaborations (Alcock et al. 1993, Aubourg et al. 1993, Udalski et al. 1994), they are given in a number of papers (see, for example, Zakharov 1997, Zakharov and Sazhin 1998, Kerins 2001, Griest 2002, Zakharov 2003, Zakharov 2004b, Zakharov 2006b). Moreover, microlensing for distant quasars was analyzed by Gott (1981) soon after the first gravitational lens discovery (Walsh et. al. 1979) and discovered (Irwin 1989) in gravitational lens systems, since the optical depth is highest for such systems.

For cosmological locations of gravitational lenses and stellar masses, typical angles between images are $\sim 10^{-6}$ as (Wambsganss 1990, 2001), or, more precisely,

$$\theta_E = \frac{R_E}{D_S} \approx 2.36 \times 10^{-6} {h_{65}}^{-1/2} \sqrt{\frac{M}{M_\odot}} \text{ as}, \qquad (1)$$

where R_E is the Einstein – Chwolson radius, D_S is an angular diameter distance between a source and an observer and $h_{65} = \dfrac{H_0}{(65 \text{ km}/(\text{c} \cdot \text{Mpc}))}$, where H_0 is the Hubble constant.

Theoretical studies of microlensing in gravitational lens systems started soon after the discovery of the first gravitational lens system (Chang 1979). Unfortunately, it is still not possible to resolve microimages. However, it may be possible to detect temporal variations of observed fluxes, or so called photometric microlensing.

In principle, the gravitational lens effect is achromatic, but sizes and locations for different spectral bands could be different and, if this is the case, we could observe the chromatic effect (Wambsganss and Paczynski 1991). This means that, sometimes, sources that demonstrate microlensing features in optical band, show no such features when observed in radio band and vice versa.

3. ASTROMETRIC MICROLENSING

Astrometric microlensing has been discussed in number of papers (Walker 1995, Miyamoto and Yoshii 1995, Sazhin 1996, Sazhin et al. 1998, Paczynski 1998, Boden et al. 1998, Tadros et al. 1998, Hon-

[2] `http://www.asc.rssi.ru/radioastron/`.

ma 2001, Honma and Kurayama 2002, Totani 2003, Inoue and Chiba 2003), but actually it is signature of the well-known bending of light by gravitational fields and, at the first time, the effect was discussed by Newton (1718). The first published derivation of the angle through which light was bent is by Soldner (1804) in the framework of Newtonian gravity. In the framework of general relativity, light bending was calculated by Einstein (1915) and his prediction was confirmed in 1919. Actually, such astrometric displacement of a distant image due to the bending of light by the gravitational field of a microlens is called astrometric microlensing and the effect could be detected by an optical astrometric mission like SIM (Space Interferometry Mission)[3], Gaia (Global Astrometric Interferometer for Astrophysics),[4] and radio projects like VERA (VLBI Exploration of Radio Astrometry) or RadioAstron.

3.1. Microlenses in our Galaxy

Let us first consider the basic definitions and relations. We consider a point-like lens. This means that the size of gravitating body is smaller than a typical scale for gravitational lensing. We will introduce the scale below. The distance between the source and observer is D_s, the distance between the gravitational lens and observer is D_d, and the distance between the gravitational lens and source is D_{ds}. Thus, we obtain the gravitational lens equation (Schneider et al. 1992)

$$\vec{\eta} = D_s\vec{\xi}/D_d - D_{ds}\vec{\Theta}(\vec{\xi}), \tag{2}$$

where the vectors $\vec{\eta}$, and $\vec{\xi}$ define coordinates in the source and lens planes respectively. The angle is determined by the relation

$$\vec{\Theta}(\vec{\xi}) = 4GM\vec{\xi}/c^2\xi^2. \tag{3}$$

If the right hand side of (3) is equal to zero, we obtain the conditions when the source, the lens and the observer are located along the same line ($\vec{\eta}$=0). The corresponding length, $\xi_0 = \sqrt{4GMD_dD_{ds}/(c^2D_s)}$, is called the Einstein – Chwolson radius. One can also calculate the Einstein – Chwolson angle, $\theta_0 = \xi_0/D_d$.

If we introduce the dimensionless variables,

$$\vec{x} = \vec{\xi}/\xi_0, \quad \vec{y} = D_S\vec{\eta}/(\xi_0 D_d), \quad \vec{\alpha} = \vec{\Theta}D_{ds}D_d/(D_s\xi_0), \tag{4}$$

the gravitational lens equation becomes

$$\vec{y} = \vec{x} - \vec{\alpha}(\vec{x}) \quad \text{or} \quad \vec{y} = \vec{x} - \vec{x}/x^2. \tag{5}$$

Solving this equation with respect to $\vec{x}$, we obtain

$$\vec{x^{\pm}} = \vec{y}[1/2 \pm \sqrt{1/4 + 1/y^2}]. \tag{6}$$

The distance between images is measured by

$$x^+ = y\left[\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{y^2}}\right], \quad x^- = y\left[-\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{y^2}}\right],$$

$$l = x^+ + x^- = 2y\sqrt{\frac{1}{4} + \frac{1}{y^2}}. \tag{7}$$

3.2. Typical time scales for astrometric microlensing in our Galaxy

Let us consider the asymptotic case for x^+ and $y \to \infty$. Then $x^+ \to y + \frac{1}{y}$, and the angular distance between the real image position and the image position in Einstein – Chwolson angles, reduces to $\Delta = x^+ - y \sim \frac{1}{y}$ (the angle describes an astrometric microlensing).

We now consider typical scales for lengths, time and angles. For the Galactic case, if a gravitational lens has mass $\sim M_\odot$ and is located at 10 kpc, then

$$\xi_0 := \left[\left(\frac{4GM}{c^2}\right)\left(\frac{D_d(D_s - D_d)}{D_s}\right)\right]^{1/2}$$
$$= 9.0\ \text{A.U.}\left(\frac{M}{M_\odot}\right)^{1/2}\left(\frac{D_d}{10\ \text{kpc}}\right)^{1/2}\left(1 - \frac{D_d}{D_s}\right)^{1/2}.$$

Thus, the Einstein – Chwolson angle is

$$\theta_0 := \left[\left(\frac{4GM}{c^2}\right)\left(\frac{D_s - D_d}{D_sD_d}\right)\right]^{1/2}$$
$$= 0.902\ \text{mas}\left(\frac{M}{M_\odot}\right)^{1/2}\left(\frac{10\ \text{kpc}}{D_d}\right)^{1/2}\left(1 - \frac{D_d}{D_s}\right)^{1/2}.$$

The distance between images is known to be $\sim 2\xi_0$ for small y, thus the angular distance is about few mas. Due to proper motion, we have

$$\dot{r} = \frac{V}{D_d} = 4.22\ \text{mas} \cdot \text{year}^{-1} \times \left(\frac{V}{200\ \text{km} \cdot \text{c}^{-1}}\right)\left(\frac{10\ \text{kpc}}{D_d}\right), \tag{8}$$

where V is a transverse velocity of the lens. Using the last two expressions, the typical time scale for microlensing, which is the time it takes for the source to cross Einstein-Chwolson radius due to proper motion (all distances can be considered on the celestial sphere) is:

$$t_0 := \frac{\theta_0}{\dot{r}} = 0.214\ \text{year}\left(\frac{M}{M_\odot}\right)^{1/2}\left(\frac{D_d}{10\ \text{kpc}}\right)^{1/2} \times$$
$$\times\left(1 - \frac{D_d}{D_s}\right)^{1/2}\left(\frac{200\ \text{km} \cdot \text{c}^{-1}}{V}\right). \tag{9}$$

[3] http://sim.jpl.nasa.gov

[4] http://sci.esa.int/gaia

The optical depth gives the probability that an arbitrary background star is located inside an Einstein – Chwolson ring in the celestial sphere.

We will now present rough estimates of the optical depth for astrometric microlensing using estimates for classic microlensing given by the MACHO and EROS collaborations, for $\tau_{\rm halo} \sim 1.\times 10^{-7}$. Since image displacement for classic microlensing is $\theta_{\rm class} \sim 1$ mas, then the optical depth with a displacement of $\theta_{\rm threshold} = 10$ μas and $\theta_{\rm threshold} = 1$ μas is given by the expression (Zakharov 2006a)

$$\tau_{\rm astromet} = \tau_{\rm halo} \left(\frac{\theta_{\rm class}}{\theta_{\rm threshold}} \right)^2 . \qquad (10)$$

Thus, for $\theta_{\rm threshold} = 10$ μas, the optical depth is about $\tau_{\rm astromet} \sim 1.\times 10^{-3}$, and for $\theta_{\rm threshold} = 1$ μas it is about $\tau_{\rm astromet} \sim 0.1$. Since, according to last estimates, $\tau_{\rm halo} = 1.2\times 10^{-7}$ (Alcock et al. 2000b, Griest 2002), the optical depth for classical microlensing toward Galactic bulge is about $\sim 3 \times 10^{-6}$ (Alcock et al. 2000a). Thus, the optical depth for astrometric microlensing is higher than that for classical microlensing.

We assume that the typical time scale for astrometric microlensing is double of the time it takes for an image position to change from $\theta_{\rm threshold}$ to the maximum displacement, $\theta_{\rm max}$. A typical maximum displacement is $\frac{\sqrt{2}}{2}\theta_{\rm threshold}$. Then, the typical time scale for astrometric microlensing is (one could use other definitions, but the difference associated with the definition is a factor of ~ 1)

$$t_{\rm astromet} = t_0 \frac{\theta_{\rm class}}{\theta_{\rm threshold}}. \qquad (11)$$

So, for $\theta_{\rm threshold} = 10$ μas, a typical time scale is about $t_{\rm astromet} \sim 20$ years and for $\theta_{\rm threshold} = 1$ μas it is about $t_{\rm astromet} \sim 200$ years.

4. MICROIMAGE RESOLVING FOR DISTANT QUASARS

4.1. Microlens locations

Microlenses could be located in the bulge or in the halo of a cosmological source, such as a galaxy or quasar, freely distributed at cosmological distances or located in our Galaxy.

Recent observations by the MACHO, EROS, OGLE collaborations (and their theoretical interpretations) showed that the optical depth for a galactic microlens is about $10^{-6} - 10^{-7}$ (Alcock et al. 2000a,b, Kerins 2001, Griest 2002). For a selected source, the probability of microlensing is very small and to observe an event would nominally require monitoring about 10^6 background sources, as for microlensing in our Galaxy. This is a challenging problem for radio astronomy because we do not have enough background point-like distant sources. However, the angular distance between images is about 10^{-3} as. Therefore, it may be possible to resolve point-like quasar images with the VLBI technique in radio bands. However, the sample of bright extragalactic sources is, unfortunately, too small to achieve this. There is also a possibility of resolving the stellar images in the IR band with modern optical telescopes (Delplancke 2001, Paczynski 2003).

It was shown that the optical depth for microlenses located in the halo or/and in the bulge of a quasar is low (Zakharov, Popovic, Jovanovic 2004). We shall not study this case as the optical depth is low and the angular distance between images is much shorter than the angular resolution for the RadioAstron interferometer.

4.2. Cosmological distribution for microlenses

Let us consider cosmologically distributed microlenses, as there is a hypothesis that variability of an essential fraction of distant quasars is caused by microlensing (Turner 1984, Fukugita and Turner 1991). If this is correct, one can say that the probability (the optical depth) is high in the radio band as well.

To evaluate the optical depth, we assume that the source is located at a distance with cosmological redshift z. Calculations for different parameters are already known (Zakharov, Popovic, Jovanovic 2004, 2005a,b). In these calculations, we used a point-like source approximation which means that as the result one will obtain an upper limit to the optical depth. In this case, the optical depth is (Turner 1984, Fukugita and Turner 1991)

$$\tau_L^p = \frac{3}{2} \frac{\Omega_L}{\lambda(z)} \int_0^z dw \frac{(1+w)^3 [\lambda(z) - \lambda(w)] \lambda(w)}{\sqrt{\Omega_0 (1+w)^3 + \Omega_\Lambda}}, \qquad (12)$$

where Ω_L is the compact lens density (in critical density units), Ω_0 is the matter density, Ω_Λ is a Λ-term density (or quintessence) and,

$$\lambda(z) = \int_0^z \frac{dw}{(1+w)^2 \sqrt{\Omega_0 (1+w)^3 + \Omega_\Lambda}}, \qquad (13)$$

is an affine parameter (in cH_0^{-1} units).

We use realistic cosmological parameters to evaluate integral (12). Observations of cosmological SNe Ia and the CMB anisotropy give $\Omega_\Lambda \approx 0.7$, and $\Omega_0 \approx 0.3$ (the so-called concordance model parameters). For example, recent observations of the WMAP team give for the best fit $\Omega_\Lambda \approx 0.73$, and $\Omega_0 \approx 0.27$ (Bennett et al. 2003, Spergel et al. 2003).

Thus, $\Omega_0 = 0.3$ and $\Omega_L = 0.05$ ($\Omega_L = 0.01$) could be adopted as realistic, if we assume that almost all baryonic matter forms microlenses ($\Omega_L = 0.05$), or that 20% of the baryonic matter forms microlenses ($\Omega_L = 0.01$)). However, for $z \sim 2.0$ the optical depth could be about $\sim 0.01 - 0.1$ (Zakharov, Popovic, Jovanovic 2004). If about 30% of non-baryonic dark matter forms cosmologically distributed objects with stellar masses (such as neutralino stars suggested in (Gurevich and Zybin 1995, Gurevich et al. 1996, 1997), $\Omega_L = 0.1$ could be adopted as realistic and in this case, the optical depth could be about ~ 0.1. Therefore, if 25% of baryonic matter forms cosmologically distributed microlenses one could say that Hawkins' hypothesis that microlensing causes variability for the essential fraction of all quasars should be ruled out, but if 30% of non-baryonic dark matter forms microlenses, about 10% of distant quasars should demonstrate these features.

4.3. Observed features of microlensing for quasars

Several years ago Hawkins (1993, 1996, 2002, 2003) put forward the idea that nearly all quasars are being microlensed. However, based on photometric observations of a sample of about 25,000 quasars, Vanden Berk et al (2004) claimed that the microlensing model was an unlikely explanation of variability.

Previous estimates show that if the Hawkins hypothesis is correct, Ω_L should be about 1 and that contradicts the data from observational cosmology. However, this hypothesis could be correct in part and, if observations indicate a value of Ω_L larger than 0.05, we could conclude that non-baryonic matter forms microlenses (they could be neutralino clouds or primordial black holes). If the Hawkins hypothesis is at least partially correct, an essential fraction of distant point-like sources should demonstrate features of microlensing since the optical depth could be evaluated using Eq. (12). In addition to microlensing there undoubted exist other causes of variabilities, and one could use various techniques to separate various types of variability (Koopmans and de Bruyn 2000, Koopmans et al. 2000b), since microlensing would have a different dependence of modulation indices in frequency than oscillations (scintillations). Resolving the microimages and measuring the centroid displacements for bright point-like sources in the radio band will be a critical test to prove (or rule out) the Hawkins hypothesis about microlensing for point-like sources at cosmological distances.

Candidate targets for VSOP or RadioAstron missions could be used to test the microlensing hypothesis for a distant quasar; sources have to have the following properties:
a) A source should demonstrate signatures of microlensing different from the typical features for scintillations on timescales < 3–5 years (5 years is the estimated duration of the RadioAstron mission);
b) A compact core for the source of size $\lesssim 40\ \mu$as and the flux density higher than RadioAstron thresholds ($\gtrsim 20$ mJy and $\gtrsim 100$ mJy at wavelengths of 6 cm and 1.35 cm, respectively).

If the Hawkins hypothesis is correct, an essential fraction of all point-like sources at cosmological distances should demonstrate signatures of photometric and, therefore, astrometric microlensing.

If, on the other hand, the Hawkins hypothesis is incorrect and cosmologically distributed microlenses give a small contribution to critical density, $\Omega_{\rm tot}$, one could still evaluate Ω_L from the observed rate of microlensed sources satisfying condition b), as the observed rate gives an estimate for the optical depth.

According to Horiuchi et al. (2004), about $14\% \pm 6\%$ of sources (from 344 ones) have core size $\lesssim 40\ \mu$as and the angle corresponds to the fringe size at the 6 cm wavelength. Such sources could be monitored photometrically and used in further analysis to determine the cause of variability. If the analysis indicate that microlensing is the likely cause of variability, the candidate could be selected as the preferable one to detect astrometrical microlensing features. But even in the case when a source demonstrates variability that should be explained by a cause other than microlensing, the source should be checked for image splitting and/or astrometric image displacement, since models for alternative explanations of variability may not be quite correct.

From theoretical point of view there is a possibility to detect microlensing for both core and bright knots. In this case the two situations will be characterized by different time scales.

5. MICROLENSING FOR GRAVITATIONAL LENSED SYSTEMS

A few years ago, Koopmans and de Bruyn (2000) and Koopmans et al. (2000) found the most realistic explanation of short-term variability of the gravitational lens CLASS B1600+434 at 5 GHz and 8.5 GHz (variabilities and possible explanations of the phenomena are discussed by Koopmans et al. (2003) and Winn (2004)). The authors considered different causes of variability such as scintillation due to scattering and microlensing. As a result, they concluded that microlensing phenomenon in the radio band was the best explanation for the observations. Flux densities changed from 58(48) mJy in March 1994, to 29 (24) mJy in August 1995, for the image A(B) (Koopmans et al. 1998). Another decrease, from 27(24) to 23(19) mJy, was found from February to October 1998 (Koopmans et al. 2000b, Koopmans and de Bruyn 2000). Strong variability was detected at 5 GHz, where the flux density was about 34–37 mJy in 1987 (Becker et al. 1991, Koopmans and de Bruyn 2000). However, it was about 45(37) mJy for image A(B) (Koopmans et al. 1998) and only 23 (18) mJy in June 1999 (Koopmans and de Bruyn 2000). Based on analysis of the variabilities, Koopmans and de Bruyn (2000) concluded that the variability is caused by superluminal motion of compact knots in the jet: VLBA and the 100-m Effelsberg telescope observations also found evidences for jet components in the CLASS gravitational lens B0128+437 (Biggs et al. 2004), but unfortunately their flux densities are too low to be observed by the RadioAstron interferometer.

The typical threshold for the RadioAstron interferometer sensitivity at 5 GHz is about 23 mJy, with an integration time of 300 s (Kardashev 1997). Therefore, in principle, such flux densities could be detected by the RadioAstron interferometer.

Treyer and Wambsganss (2004) concluded that, for photometric fluctuations ~ 0.5 mag, typical astrometric displacements should be about 20 – 40 μas. To evaluate photometric and astrometric microlensing, one could use numerical approaches and analytical asymptotical expansions near fold (Schneider and Weiss 1992a) and cusp singularities (Zakharov 1995, 1997a, Petters et al. 2001, Yonehara 2001). In principle, such a displacement could be observed by the Radioastron space-ground interferometer at 6 cm and 1.35 cm wavelengths, if flux densities for the object are high enough. For example, in the B1600+434 case, the flux density is suitable for the core (at least, at 6 cm wavelength), but if the superluminal motion of knots is responsible for microlensing, as Koopmans and de Bruyn (2000) claimed, the sensitivity of Radioastron should be improved by factor 10 at the 6 cm wavelength, to observe such a displacement of knots. At the 1.35 cm wavelength, the Radioastron flux density threshold is probably too high to allow detecting the displacement.

5.1. Typical time scales for microlensing

According to the standard model, typical timescales for radio microlensing could be much smaller than typical timescales in the optical band due to the effects of special relativity, various geometries and locations of radiating regions in these bands. For example, typical time scales in the optical band are determined by the transverse velocity ($v_{\rm trans}$), but in the radio-band timescales could be $\beta_{\rm trans}/v_{\rm trans}$ times smaller (Koopmans and de Bruyn 2000) (all velocities are expressed in units of c).

Typical time scales are determined by the ratio of typical sizes of caustics to the apparent velocity of the jet-component in the source plane (Blandford et al. 1977, Blandford and Konigl 1979, Koopmans and de Bruyn 2000). If the jet-component moves with a relativistic bulk velocity $\beta_{\rm bulk}$, then the apparent velocity is

$$\beta_{\rm app} = \frac{n \times (\beta_{\rm bulk} \times n)}{1-\beta_{\rm bulk}\cdot n} = \frac{\beta_{\rm bulk}\sin(\psi)}{1-|\beta_{\rm bulk}|\cos(\psi)}, \quad (14)$$

where ψ is the angle between the jet and the line of sight (Blandford et al. 1977, Blandford and Konigl 1979, Koopmans and de Bruyn 2000).

The apparent angular velocity of the jet component is

$$\frac{d\theta_{\rm s}}{dt} = \frac{\beta_{\rm app} c}{(1+z_{\rm s})D_{\rm s}} = \frac{1.2\cdot\beta_{\rm app}}{(1+z_{\rm s})}\frac{\rm Gpc}{D_{\rm s}}\frac{\mu{\rm as}}{\rm week}, \quad (15)$$

where $z_{\rm s}$ and $D_{\rm s}$ are the source redshift and the angular diameter distance to the stationary core, respectively. Using the estimate for observed source redshift $z_{\rm s}$, Fassnacht and Cohen (1998) and Koopmans and de Bruyn (2000) concluded that the angular velocity of B1600+434 should be

$$\frac{d\theta_{\rm s}}{dt} = 0.34\cdot\beta_{\rm app}\frac{\mu{\rm as}}{\rm week}, \quad (16)$$

for a flat Friedmann universe with $\Omega_{\rm m} = 1$ and $H_0 = 65$ km$\cdot$s^{-1}Mpc^{-1}. Based on observational data and simulations, Koopmans and de Bruyn (2000) also evaluated the typical size of knots in the jet, in the source plane for $2 < \Delta\theta_{\rm knot} < 5$ μas and an apparent velocity band of $9 < \Delta\theta_{\rm app} < 26$.[5] Therefore, apparent displacements for B1600+434 should be of the order of dozens of μas and the displacement could be measured with the RadioAstron interferometer at the 6 cm wavelength.

One could also evaluate linear size of knots through their angular diameter distances

$$\Delta\ l = \frac{c}{H_0}\frac{\Delta\theta_{\rm knot}\left[z_s-(1+q_0)z_s^2/2\right]}{1+z_s}, \quad (17)$$

where $q_0 = 1.3\cdot\Omega_m - 1 = -0.55$ (for a flat universe and $\Omega_m = 0.3$). Therefore, typical linear size of the knots should be $\Delta l \in (5\times10^{16}\ {\rm cm}, 14\times10^{16}\ {\rm cm})$.

Typical scales for microlensing are discussed for instance in recent papers by Treyer and Wambsganss (2004) and Zakharov (2006a). Usually locations of microlenses in gravitational macrolenses are discussed because of the optical depth for microlensing is high in comparison with other possible locations of gravitational microlenses. However, the cases for different microlens locations have been considered and, for example, galactic clusters or extragalactic dark haloes could have microlenses.

So, if we adopt the concordance cosmological model parameters ($\Omega_{\rm tot} = 1, \Omega_{\rm matter} = 0.3$, and $\Omega_\Lambda = 0.7$), typical length scales for microlensing are

$$R_E = \sqrt{2r_g\cdot\frac{D_sD_{ls}}{D_l}} \approx 3.4\cdot10^{16}\sqrt{\frac{M}{M_\odot}}h_{65}^{-0.5}{\rm cm}, \quad (18)$$

where "typical" microlens and sources redshifts are assumed to be $z_l = 0.5$, and $z_s = 2$ (Treyer and Wambsganss 2004) and $r_g = \dfrac{2GM}{c^2}$ is the Schwarzschild radius corresponding to microlens of mass M.

The corresponding angular scale is

$$\theta_0 = \frac{R_E}{D_s} \approx 2.36\cdot10^{-6}\sqrt{\frac{M}{M_\odot}}h_{65}^{-0.5}\ {\rm as}, \quad (19)$$

Using the length scale given by equation (18) and a velocity scale, say an apparent velocity $\beta_{\rm app}$,

[5]However, the explanation of variability due to superluminal motions in the jet and microlensing should probably be verified, because Patnaik and Kemball (2001) discussed observations which do not agree with this model (Koopmans and de Bruyn 2000).

one could calculate the standard time scale corresponding to crossing the Einstein – Chwolson radius

$$t_E = (1+z_l)\frac{R_E}{v_\perp} = \begin{cases} \approx 2\sqrt{\frac{M}{M_\odot}}\beta_{\rm app}{}^{-1}h_{65}^{-0.5} \text{ weeks} \\ \text{if } v_\perp = c\beta_{\rm app}; \\ \approx 27\sqrt{\frac{M}{M_\odot}}v_{600}{}^{-1}h_{65}^{-0.5} \text{ years} \\ \text{if } v_\perp \sim 600 \text{ km/s}, \end{cases}$$

where we assumed that the time scales are determined by an apparent velocity ($v_\perp = c\beta_{\rm app}$) or a typical transverse velocity $v_\perp \sim 600\ km/s$ ($v_{600} = v_\perp/(600 \text{ km/s})$) and the time scale t_E corresponds to the approximation of a point mass lens and a small source, in comparison with the Einstein – Chwolson radius. The approximation is probably correct and the time scale estimates could be used if microlenses are uniformly distributed at cosmological distances and actually one Einstein – Chwolson ring is located far enough from another (there are no intersections of Einstein – Chwolson cones at the celestial sphere). But the approximation fails if we use the microlens model for gravitationally lensed systems to explain the variability of image components.

If we use the simple caustic microlens model (such as the straight fold caustic model), there are two time scales, namely gravitational lens depends on "caustic size" and source radius R. If the source radius is larger than, or approximately equal to, the "caustic size" $r_{\rm caustic}$, (we use the approximation $\mu = \sqrt{\frac{r_{\rm caustic}}{y-y_c}}$ for the magnification near the caustic, where $y > y_c$ and y is a length in the perpendicular direction to the fold caustic), $R \gtrsim r_{\rm caustic}$, the relevant time scale is the "crossing caustic time", (Treyer and Wambsganss 2004)

$$\begin{aligned} t_{\rm cross} &= (1+z_l)\frac{R_{\rm source}}{v_\perp(D_s/D_l)} \\ &\approx 0.62\ R_{15}v_{600}^{-1}h_{65}^{-0.5} \text{ years} \\ &\approx 226\ R_{15}v_{600}^{-1}h_{65}^{-0.5} \text{ days}, \end{aligned} \quad (20)$$

where D_l and D_s correspond to $z_l = 0.5$ and $z_s = 2$ respectively and $R_{15} = R_{\rm source}/10^{15}$ cm.

However, if the source radius, $R_{\rm source}$, is much smaller than the "caustic size" $r_{\rm caustic}$, namely $R_{\rm source} << r_{\rm caustic}$, one could use the "caustic time", namely the time while the source is located in the area near the caustic, and the time scale corresponds to

$$\begin{aligned} t_{\rm caustic} &= (1+z_l)\frac{r_{\rm caustic}}{v_\perp(D_s/D_l)} \\ &\approx 0.62\ r_{15}v_{600}^{-1}h_{65}^{-0.5} \text{ years} \\ &\approx 226\ r_{15}v_{600}^{-1}h_{65}^{-0.5} \text{ days}, \end{aligned} \quad (21)$$

where $r_{15} = r_{\rm caustic}/10^{15}$ cm.

These time scales, $t_{\rm cross}$ and $t_{\rm caustic}$, could be of the order of days (or even hours), if $v_\perp$ is determined by the apparent motion of superluminal motion in the jet.

Thus, an estimate of $t_{\rm cross}$ could be used as a lower limit for typical time scales for the simple caustic microlens model, but since there are two length parameters in the problem and in general we do not know their values, we could not evaluate $R_{\rm source}$ only using the time scales of microlensing because the time scales could correspond to two different length scales. However, if we take into account the variation of amplitudes of luminosity, one could say that in general $t_{\rm cross}$ corresponds to smaller variation amplitudes than $t_{\rm caustic}$, because if the source square is large, there is a "smoothness" effect since only a small fraction of source square is located in the high amplification region near the caustic.

6. SHADOWS AROUND BLACK HOLES

Zakharov et al. (2005a) proposed to use VLBI technique to observe mirages around massive black holes and in particular, towards the black hole at Galactic Center. The boundaries of the shadows are black hole mirages. We use the length parameter $r_g = \frac{GM}{c^2} = 6\times10^{11}$ cm for the black hole at Sgr A^* and analytical approach to calculate shadow sizes, as explained in the text. By taking the distance of Sgr A^* to be $D_{\rm GC} = 8$ kpc, the length r_g corresponds to angular size $\sim 5\ \mu as$. Since the minimum arc size for the considered mirages is about at least 4 r_g, the standard RadioAstron resolution of about 8 μas is comparable with the required precision. In principle, it is possible to evaluate the black hole charge Q by observing the shadow size. The mirage size difference between the extreme charged black hole and Schwarzschild black hole case is about 30% (the mirage diameter for Schwarzschild black hole is about 10.4 and for the extreme charged black hole the diameter is equal to 8 or (in black hole mass units)) and typical angular sizes are about $\sim 52\ \mu as$ for the Schwarzschild and $\sim 40\ \mu as$ for the Reissner-Nordström black hole cases, respectively (Zakharov 1994, Zakharov et al. 2005a).

Therefore, for Sgr A^*, a charged black hole could be distinguished from Schwarzschild black hole with RadioAstron, at least if its charge is close to the maximum value. For stellar mass black holes, we need a much higher angular resolution to distinguish charged and uncharged black holes, since the typical shadow (mirage) angular sizes are about $2\times10^{-5}\mu as$, for galactic black holes. Clearly, this is too small to observe directly even in the future.

The angular resolution of the space RadioAstron interferometer will be high enough to resolve radio images around black holes.

In principle, measuring the mirage shapes, one could evaluate the black hole mass, inclination angle (i.e. the angle between the black hole spin axis and line of sight) and spin, if a distance toward the black hole is known. For example, for the black hole at the Galactic Center the mirage size is $\sim 52\ \mu as$ for the Schwarzschild case. In the case of a Kerr black hole (Zakharov et al. 2005a), the mirage is deformed depending on the black hole spin a and on the angle of the line of sight, but its size is almost the same. In the case of a Reissner-Nordström black hole its charge changes the size of the shadows up to 30% for the extreme charge case. Therefore, the charge of the black hole can be measured by observing the shadow size, if the other black hole parameters are known with sufficient precision. In general, one could say that measuring the mirage shape (in size) allows to evaluate all the black hole "hairs".

Few years ago the possibility of observing images of distant sources around black holes in the X-ray band by means of a X-ray interferometer was discussed by White (2000), Cash et al. (2000). Indeed, the aim of the MAXIM project is to realize a space based X-ray interferometer capable of observing with angular resolution as small as 0.1 μas.

In spite of the difficulties of measuring the shapes of shadow images, to look at black hole "faces" is an attractive challenge since the mirages outline the "faces" and correspond to fully general relativistic description of the region nearby the black hole horizon without any assumption about a specific model for astrophysical processes around black holes (of course, we assume that there are sources illuminating black hole surroundings). There is no doubt that the rapid improvement of observational facilities will enable to measure the mirage shapes using not only RadioAstron facilities but also other instruments and spectral bands, like the X-ray interferometer MAXIM, the RadioAstron mission or other space based interferometers in millimeter and sub-millimeter bands.

One could mention here that the Astro Space Centre of Lebedev Physics Institute proposed the Millimetron mission as a successor of the RadioAstron (the estimated year for a launch of the Millimetron mission is 2016). The cryogenic telescope will act at mm and sub-mm wavelength bands and the ground-space interferometer Millimetron–ALMA will have angular resolution about 10^{-9} as at 0.3 mm wavelength. In this case, the interferometer will provide a possibility of a clear reconstruction of the shadow shapes with the interferometer.

7. CONCLUSIONS

Firstly, one should point out that gravitationally lensed systems are the most promising objects to be used in a microlensing search. Astrometric microlensing could be detected in a gravitational lens system such as B1600+434, if the proper motion of source, lens and an observer are generated mostly by a superluminal motion of knots in the jet (superluminal motion in a jet was found with HALCA in the quasar PKS 1622-297 (Wajima 2005)). But in this case, based on flux density estimates (Koopmans and de Bruyn 2000), one could say that the sensitivity of the RadioAstron interferometer should be improved by a factor of 10.

Assuming there is microlensing of the core in the B1600+434 system for example, the astrometric microlensing should be about 20 – 40 μas (Treyer and Wambsganss, 2004). The RadioAstron interferometer will have enough sensitivity to detect such an astrometric displacement.

Secondly, in principle, microlensing of distant sources could be the only tool available for determination of the Ω_L using the microlensing event rate. To resolve Ω_L problem with the RadioAstron interferometer one should analyze variabilities of compact sources with a core size $\lesssim$ 40 μas and with high enough flux densities (about $\gtrsim$ 20 mJy at the 6 cm wavelength, and about $\gtrsim$ 100 mJy at the 1.35 cm wavelength) to fit the most reliable model for variabilities of the sources such as scintillations and microlensing. The fraction of the suitable extragalactic targets for the VSOP and RadioAstron missions is about 13% – 14% (Moellenbrock et al. 1996, Hirabayashi et al. 2000, Scott et al. 2004, Kovalev et al. 2005). If the analysis indicates that other explanations (such as scintillations) are more likely than microlensing, and future observations with the Radioastron interferometer show no astrometric microlensing features, one could conclude that the Hawkins hypothesis should be ruled out. However, if an essential fraction of variability could be fitted by microlensing, the sources should be adopted as the highest priority targets for future astrometric microlensing searches.

Therefore, one could say that astrometric microlensing (or direct image resolution with Radioastron interferometer) is the crucial test to confirm (or rule out) the microlens hypothesis for gravitationally lensed systems and for point-like distant objects.

Astrometric microlensing due to Macho's action in our Galaxy is not very important for observations with the space interferometer Radioastron, since event probabilities are low and typical time scales are longer than an estimated life-time of the Radioastron space mission.

We conclude that after the RadioAstron launch, we will have the first opportunity to detect microlensing directly. To make use of this opportunity, perspective targets need to be carefully evaluated in advance using both observational data and theoretical analysis. In the radio band, the number of point-like bright sources at cosmological distances and gravitationally lensed systems with point-like components demonstrating microlens signatures is not very high and the sources should be analyzed carefully in the search for candidates, for which the microlensing model fits the data better than alternative theories.

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ИСПИТИВАЊЕ РЕЛАТИВИСТИЧКИХ ЕФЕКАТА ПОМОЋУ СВЕМИРСКЕ МИСИЈЕ РАДИОАСТРОН

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Прегледни рад по позиву

У овом прегледном чланку дискутујемо могућа испитивања феномена опште теорије релативности (GR) као што су ефекти гравитационих микросочива и ефекти закривљења светлосних зрака у околини црне рупе помоћу наступајуће Радиоастрон свемирске мисије. Добро је познато да је ефекат гравитационих сочива моћан алат у истраживању расподеле материје, укључујући и тамну материју (DM). Типична угаона растојања између ликова и типичне временске скале зависе од маса гравитационих сочива. За микросочива, угаона растојања између ликова или типични астрометријски помаци износе око $10^{-5} - 10^{-6}$ лучних секунди. Таква угаона резолуција биће достигнута помоћу Радиоастрон свемирско-земаљског интерферометра са великом базом (VLBI). Основни циљеви потраге за микросочивима требало би да буду сјајни тачкасти радио извори на космолошким растојањима. У тим случајевима, анализа њихове променљивости и поуздано одређивање ефекта микросочива могли би довести до процене њихове космолошке густине. Осим тога, не може се искључити могућност да небарионска тамна материја такође формира микросочива под условом да је одговарајућа оптичка дебљина довољно велика. Познато је да је за системе под утицајем гравитационих сочива вероватноћа (оптичка дебљина) да се посматрају ефекти микросочива релативно висока, због чега такви објекти под утицајем гравитационих сочива, као што је например гравитационо сочиво CLASS B1600+434, изгледају најпогоднији за детектовање астрометријског ефекта микросочива, пошто су особине фотометријског ефекта микросочива већ детектоване код ових објеката. Међутим, да би се директно раздвојили ови ликови и да би се директно детектовало привидно кретање чворова, осетљивост Радиастрона би морала бити повећана пошто је процењена густина флукса испод прага осетљивости, а алтернативно, они би могли бити посматрани ако се повећа време интеграције, претпостављајући да радио извор има типично језгро – структуру са млазом и да су феномени микросочива проузроковани суперсветлим привидним кретањем чворова. У случају да се потврди (или оповргне) тврђење о ефектима микросочива у системима под утицајем гравитационих сочива, могуће је размишљати о доприносу масе микросочива укупној маси галаксије која игра улогу гравитационог сочива. Асиметрични ефекат микросочива услед дејства масивних објеката из халоа наше Галаксије (MACHO) није много важан због малих оптичких дебљина и дугих временских скала. Због тога ће лансирање свемирског интерферометра Радиоастрон обезбедити изванредна нова средства за изучавање ефекта гравитационих микросочива у радио домену, пружајући не само могућност раздвајања микроликова, већ такође и могућност да се посматрају астрометријски ефекти микросочива. Ефекти јаког гравитационог поља у околини супермасивних црних рупа могу бити детектовани помоћу Радиоастрон свемирског интерферометра.