4.8. Gravitational lenses

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If the light rays from a distant source (e.g., a quasar) pass close to a massive body (e.g., a galaxy) in their propagation to the observer, a gravitational mirage arises: the observer may see either a ring, or an arc, or two or four images of the same source. This is a phenomenon of gravitational lensing, which is one of the predictions of the general relativity theory. It can arise at different spatial scales, from microlensing of stars by compact bodies populating our Galaxy (galactic microlensing) to gravitational lensing of quasars by foreground galaxies (strong lensing) or by remote galaxy clusters (weak lensing). The gravitational lensing phenomenon is presently believed to be a powerful tool to solving a number of fundamental problems of the contemporary astrophysics and cosmology, with the problem of dark matter being the most important one. According to the current conception, a contribution of the dark matter into the cosmological density is large enough, but its composition, properties, and distribution in the Universe remains to be unknown.

Because of gravitational focusing, distant quasars are observed split into two or more images. If some of the lensed images are observed through the densely populated regions of lensing galaxies, microlensing events can be observed, which occur in passing microlenses (planets, stars and stellar-like bodies) near the line of sight. Microlensing light curves contain extremely valuable information about masses and velocities of microlenses which cause these events, as well as about spatial structure of quasars' emitting regions with a resolution unachievable to other methods.

One more important astrophysical application of investigation of gravitationally lensed quasars (GLQ) should be noted. While propagating through the lensing galaxy along different paths corresponding to different lensed images, the light rays from the source quasar come to the observer with different time delays. Knowing of the time delays between the quasar intrinsic brightness variations provides an independent way to estimate the most important cosmological parameters of the Universe, such as the Hubble constant and deceleration parameter.

As a rule, GLQs are faint and extremely compact objects with a rather complicated spatial structure: for the majority of GLQs, two or four lensed quasar images and an image of a lensing galaxy are situated within a very small sky area, up to 2″ or even less. This makes high demands on the initial image quality and needs complicated algorithms of photometric image processing. Thus, such objects could attract a keen interest of researchers who have accumulated a great experience in developing methods of high resolution imaging for astronomy, namely speckle interferometry of red giants, binary and multiple stars, speckle imaging, and applications of the developed methods to processing images of asteroids and major planets (Dudinov V., Kuzmenkov S., Tsvetkova V., Konichek V., Pluzhnik Ye., Vakulik V., Zheleznyak A.).

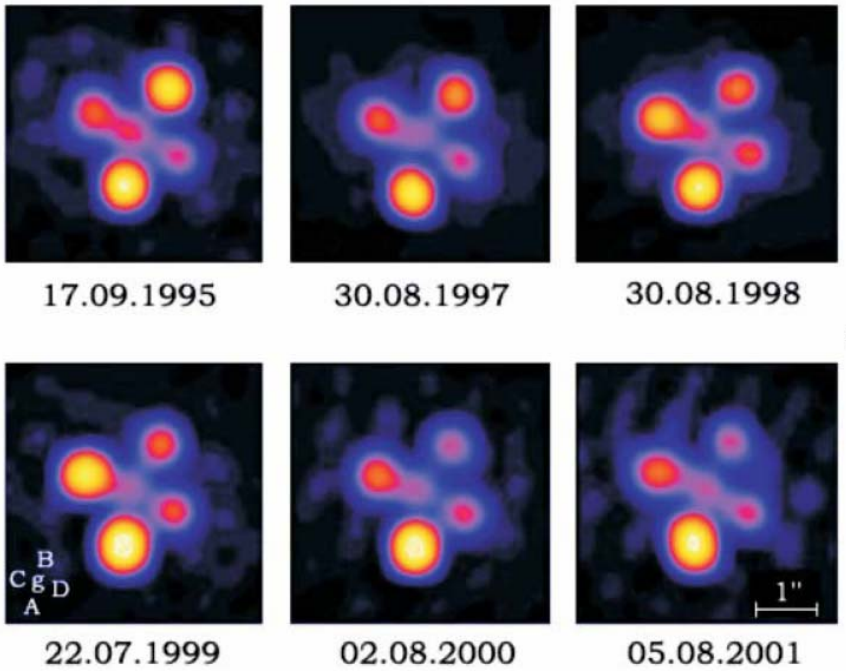

Figure 34. Images of gravitationally lensed quasar Q2237+0305 (Einstein Cross), obtained in VRI filters July 22, 1999 with the 1.5 m telescope at Maidanak observatory

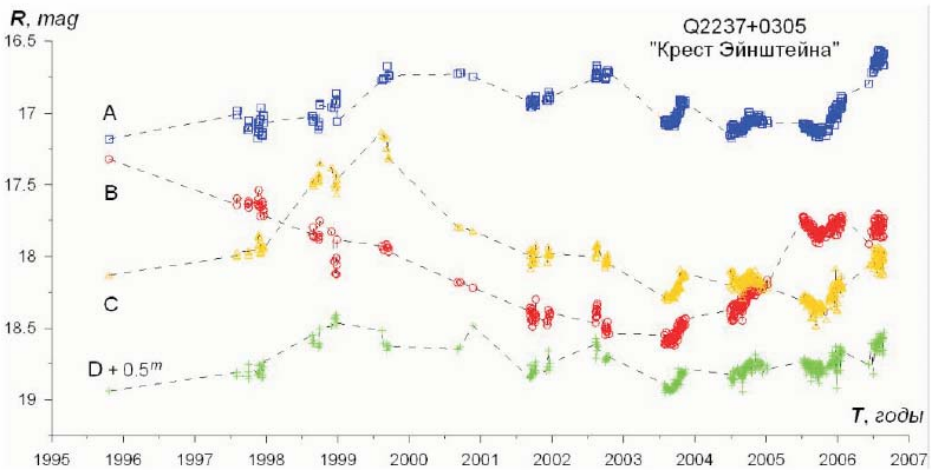

Figure 35. Results of photometry of the quasar Q2237+0305 (Einstein Cross), obtained in 1995-2006 years in filter R with the 1.5 m telescope at Maidanak Observatory (see Fig. 34)

Regular observations of GLQs with the 1.5-m telescope of the Maidanak Observatory (Central Asia) were started by workers of our Institute in 1997. The telescope with the diffraction quality optics, a modern CCD light detector, extremely good seeing conditions, and a large number of cloudless nights have made it possible to obtain a huge amount of superb observational data on a number of GLQs, with an emphasis on the Q2237+0305, Q0957+561, SDSS0909+532 and SBS 1520+530 systems.

During 2003-2007, the results of the long-term observations of these systems with the Maidanak telescope were being summarized. In particular:

1. For Q2237+0305, the Einstein Cross (see Fig. 34), a significant positive correlation between the variations of color indices and magnitudes of the lensed quasar images has been discovered, in the sense that the images tend to become bluer as their brightness increases. This microlensing-induced phenomenon, which has never been investigated earlier, is of a great diagnostic importance both for study of quasar spatial structure and for examining the physical state of the matter emitting by various quasar regions. The results allowed us to propose a new two-component model of the quasar Q2237 spatial structure consisting of a compact central source surrounded by an outer extended feature, with the central source contributing from 20% to 10% in the spectral bands from V to R, respectively. The quasar central source dimensions were estimated to be about $2{\cdot}10^{15}$ cm, provided that the transverse velocity is 5000 km/s, (V. Vakulik, V. Dudinov, V. Konichek, A. Zheleznyak, I. Sinelnikov).

The time delays between the quasar brightness variations seen in the lensed images of Q2237+0305 were estimated for the first time for this system in the optical wavelengths. The upper limits for time delays of B, C and D components with respect to A of order of three days were obtained. This has become possible thanks to observations of June-October, 2003, when the quasar intrinsic brightness variations revealed themselves in fact for the first time since the system discovery in 1985. Figure 35 presents results of photometry of the quasar Q2237+0305 (Einstein Cross) carried out in 1995-2006 years in filter R with the 1.5 m telescope at Maidanak Observatory (the component A – D are shown in Fig. 34). Figure 36 shows comparison of our photometric data for the quasar Q2237+0305 and data obtained in the frame of the programe OGLE III, revealing good resemblance.

2. For SDSS 0909+532, the first successful time delay measurement has been made for this system with the use of the joint observations at the 1.5-m telescopes in Maidanak and Calar Alto observatories (A. Zheleznyak, in collaboration with Ullán A. Goicoechea L. from the Calar Alto Observatory).

3. For Q0957+561, interpretation of the data obtained together with the Harvard-Smithsonian Center for Astrophysics (USA) in the framework of the international Quasar Observing Consortium (QuOC) program was fulfilled (W. Colley, R. Schild, V. Dudinov, A. Zheleznyak). The program permitted us to obtain a new more exact estimate of the time delay between the quasar brightness fluctuations seen in the two lensed images (417.09±0.07 days). Also, extremely short-time microlensing brightness variations (several days) of very small amplitudes, 0.04^m-0.05^m, caused seemingly by planetary

mass objects have been revealed and successfully interpreted by a new physical model of the quasar (V. Vakulik, in collaboration with R. Schild from the Harvard-Smithsonian Center for Astrophysics).

4. For SBS 1520+530, new accurate estimates of the R and I stellar magnitudes of the lensing galaxy have been obtained, with the R estimate being taken for the first time for this object (A. Zheleznyak, A. Sergeyev). A numerical simulation allowed estimating the mass of the lensing galaxy and a parameter, describing the mass distribution, which are in a good agreement with the system geometry and the observed relative magnification factor. Both the mass obtained and the measured (H-R) color index indicates that the lensing galaxy is a spiral one. The analysis of light curves in the V, R, and I bands covering the time period from 2001 to 2006 allowed us to confirm the time delay value measured previously and to detect microlensing brightness variations, which allowed us to obtain the first estimate of the source size for this system (~10^{15} cm).