J. Astrophys. Astr. (2010) **31,** 213–219

Could the Optical Transient SCP 06F6 be due to Microlensing?

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Received 2010 February 17; accepted 2010 September 28

Abstract. In this paper, we consider the mysterious optical transient SCP 06F6 displaying a symmetric light curve with a (half-time) duration of about 100 days. The projected location of the event falls close to the center of the galaxy cluster CL 1432.5 + 332.8 lying at the redshift $z = 1.112$. Guided by suggestive symmetry of the light curve and its similarity in two photometric bands, which is a typical signature of microlensing events, we discuss this possibility in several scenarios. As a consistency check we use the lens mass inferred from the event duration and the size of the source. The second check comes from a plausible assumption that since the event was highly magnified there was a perfect alignment at the maximum magnification.

A scenario where the lens and the source are located in our Galaxy is ruled out. There remain extragalactic scenarios in which the source is a broad absorption line quasar at redshift 2.7 (as might be suggested by transient's spectroscopy) and the lens could be a compact object associated either with the cluster or with quasar's host galaxy. They give reasonable results.

Even if the true nature of the transient eventually turns out different, the idea presented here is interesting from the perspective of cosmological microlensing studies.

Key words. Gravitational lensing—cosmology: miscellaneous.

1. Introduction

As reported in the original paper by Barbary *et al.* (2009), the SCP 06F6 transient was discovered on 25 February 2006 during the HST Cluster SN Survey. It was seen 35″ away from the center of a galaxy cluster CL 1432.5 + 332.8 located at the redshift $z_{\rm cl} = 1.112$ (Elston *et al.* 2006) and lasted about 200 days. Like other researchers, we will, however, refer to the half-time of the total duration, i.e., 100 days. This is especially convenient for our further discussion. Photometric observations performed by HST Advanced Camera for Survey (ACS) and Subaru FOCAS camera, revealed a symmetric light curve with brightness rising from below the detection level (ca. 27.5 mag) to about 21 mag at maximum; then decreasing again below 27 mag. The light curve was similar in two photometric bands i_{775} and z_{850}, details are described in Barbary *et al.* (2009). Spectroscopy performed by Subaru and Keck Observatory revealed red continuum with five broad absorption features centered at 4320, 4870, 5360, 5890 and 6330 Å, the middle three being the strongest. Lack of Lyman-alpha absorption features below 4500 Å, places a strong limit on the source redshift $z_s \leq 2.7$, had it been located at cosmological distance (Barbary *et al.* 2009).

Barbary *et al.* (2009) carefully examined the case of galactic origin of the transient involving spectroscopic arguments, photometric flux limitations and the lack of proper motion detection as possible constraints on the effective temperature and distance to the source. The conclusion was that it is hard to imagine any reasonable galactic scenario for the event. Comparing the SDSS spectral database, Barbary *et al.* (2009) found that broad absorption lines quasars (BAL QSOs) and Carbon White Dwarfs (DQp WDs) are spectroscopically the most similar to the transient, although there still remain unexplainable differences in the spectra. The overall conclusion was that the SCP 06F6 probably represents a new class of transients. Later on Gänsicke *et al.* (2009) matched the absorption lines of SCP 06F6 with carbon C_2 Swan bands template redshifted to $z = 0.143$ concluding that the transient defines a new class of slowly evolving supernova explosion producing carbon rich atmosphere. The most recent paper by Soker *et al.* (2010) develops this idea further discussing four other scenarios: tidal destruction of a CO white dwarf by intermediate mass black hole, Ia-like supernova inside a dense wind of carbon star, asteroid collision with a white dwarf and a core collapse supernova.

However, the light curve of the transient is strikingly similar to the microlensing event (Paczyński 1986). Barbary *et al.* (2009) discuss this as well concluding that unusually long duration of the event is hard to reconcile with microlensing. However, they do not give precise meaning to this statement. It is certainly true in classical, i.e., galactic setting such as typical to the former (MACHO, EROS) or ongoing (OGLE) microlensing experiments (Wambsganss 2006) as we will see later on. From the duration of the event one is able to deduce the likely magnitude of the lens mass which in such classical scenario turns out unrealistic.

The other argument against microlensing is the very-high minimal magnification of the event, estimated by Barbary *et al.* (2009) as $\mu \sim 120$. Even though it is much larger than usually encountered in known microlensing systems, it is not impossible in principle. Hence, it does not discard microlensing hypothesis by itself. It only means that the alignment in the lensing system should be very strong, i.e., the impact parameter u_0 should be very small. Such strong alignment would create opportunity that the finite size of the source manifested itself by subtle deviations from achromaticity of the light curve. Such discrete differences between i_{775} and z_{850} bands were indeed reported by Barbary *et al.* (2009) despite the light curve's appearance was generally the same in two photometric bands. We take this as a possible indication of finite source effect and use it as an additional constraint on the scenarios tested below.

Therefore, taking the suggestive light curve profile as a hint, and basing this on lens mass estimates together with (possible) bounds on the source size as checkpoints for consistency, we explore the microlensing hypothesis in several possible scenarios.

2. Microlensing: Background and some scenarios

Microlensing is the phenomenon of changing the brightness of a point-like source if a compact point-like massive object (the lens) crosses (due to projected proper motion effect) the line of sight to the source with an impact parameter less than the

Einstein ring radius ϑ_E of the lens (Paczyński 1986; Wambsganss 2006). Because the images resulting from such strong lensing event are unresolved, their combined brightness results in gradually increasing the brightness of the source till the closest encounter and then decreasing again in a symmetric way as the lens traverses the line of sight. The symmetry of a light curve is a signature of microlensing although the parallax effect can produce subtle asymmetry, which could be especially relevant for rather nearby systems. In principle, because the duration of the event (totally about 200 days) encompasses substantial fraction of the Earth orbital period, one should think of the parallax effect seriously. However, the light curve is too poorly sampled to allow for parallax effect fitting.

In classical (i.e., galactic) setting where the distances could be taken as Euclidean, the time scale for the microlensing t_E of a source lying at a distance D_s by a lens with mass M at the distance D_l moving with transverse velocity v_t (with respect to the source – observer line, at the lens plane) is set by the Einstein ring crossing time

$$t_E = \frac{\vartheta_E D_l}{v_t}, \tag{1}$$

where $\vartheta_E^2 = (4GM/c^2)(D_{ls}/D_l D_s)$. Taking into account that in Euclidean geometry $D_{ls} = D_s - D_l$, one can estimate the mass of the lens moving with relative transversal velocity v_t, responsible for the event of (half) duration t_E

$$M = \frac{v_t^2 c^2 t_E^2}{4G(1 - (D_l/D_s))D_l}. \tag{2}$$

In cosmological setting, i.e., when the point-like lens and the point-like source are extragalactic, lying at cosmological distances, one has to modify the formulae appropriately:

$$\left(\frac{t_E}{1 + z_l}\right)^2 = \frac{4GM}{c^2 v_t^2} \frac{D_{ls}^{\text{ang}} D_l^{\text{ang}}}{D_s^{\text{ang}}}. \tag{3}$$

The modification is two-fold. First, the observable time scale t_E should be rescaled by $1 + z_l$ factor due to cosmological time dilation. Since the Einstein ring angular radius is rescaled here to the lens plane, the effect (passage through the Einstein radius) occurs at the lens location. Second, instead of Euclidean distances one has to use angular diameter distances

$$D_{12}^{\text{ang}} := \frac{1}{1 + z_2} \frac{c}{H_0} \tilde{r}(z_1, z_2)$$

where $\tilde{r}(z_1, z_2) = \int_{z_1}^{z_2} (\mathrm{d}x/h(x))$ is the dimensionless (i.e., expressed as a fraction of the Hubble horizon) comoving distance in the given cosmological model, which we take to be the ΛCDM flat model with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. Consequently, the expansion rate (in units of H_0) is equal to $h(z) = \sqrt{\Omega_m (1 + z)^3 + \Omega_\Lambda}$. The Hubble constant H_0 is assumed to be $H_0 = 75\,\text{km s}^{-1}\,\text{Mpc}^{-1}$. In principle, whenever the velocities of the source v_s, the lens v_l and the observer v_{obs} (e.g., with respect to CMBR) are known, one should use the so called effective transverse velocity of the lensing system according to the formula derived in Kayser *et al.* (1986). Because we do not have such detailed knowledge in the cosmological scenario considered below, we assume that the above corrections are already accounted for in the assumed v_t value. Hence, the mass of the lens responsible for the (observable) microlensing time scale t_E reads:

$$M = \frac{c v_t^2 H_0 t_E^2}{4G(1+z_l)} \frac{\tilde{r}_s}{\tilde{r}_{ls}\tilde{r}_l}, \tag{4}$$

where v_t is the relative transversal velocity of the lens and relative dimensionless comoving distances in the system are: $\tilde{r}_s := \tilde{r}(0, z_s)$, $\tilde{r}_l := \tilde{r}(0, z_l)$ and $\tilde{r}_{ls} := \tilde{r}(z_l, z_s)$.

If the impact parameter u_0 (normalized to the Einstein radius) is comparable to the size of the source normalized to the Einstein radius $\rho_0 := r_*/r_E$ finite size effects show up. In the definition of ρ_0 it is convenient to take the linear size of the Einstein radius at the source plane, i.e., $r_E = \vartheta_E D_s$ because then r_* represents the physical linear size of the source. There are two important consequences of the finite size of the source. First is that maximal amplification gets lower (than in exactly point-source case with the same impact parameter) and second is that the light curve might display some chromatic effects (due to different brightness profiles at different wavelengths for an extended source). It is obvious that finite source size effects might be important for high magnification events. The SCP 06F6 transient (if due to microlensing) is exactly of this kind (magnification factor at least $\mu_0 = 120$). Therefore, besides the estimates of the lens mass we will use the inferred source size as an additional consistency check. Theory of finite size effects has been developed by Witt & Mao (1994). Because exact formulae are sophisticated and in our case magnification μ_0 is very high, we will assume that μ_0 corresponds to the maximum magnification when an extended source and the lens are perfectly aligned. In such case one has $\mu_0 = \left(\left(\sqrt{\rho_0^2 + 4}\right)/\rho_0\right)$ and consequently $\mu_0 = 120$ translates into an estimate for $\rho_0 = 0.017$. We discuss several possible microlensing scenarios below.

2.1 *Purely galactic scenario*

This is the one in which both the lens and the source belong to our Galaxy like in microlensing surveys such as MACHO, EROS or OGLE (see, Wambsganss 2006 for a detailed review). Strictly speaking, target sources for MACHO and EROS were in LMC/SMC and only in OGLE it was the galactic bulge, but it does not matter for our discussion.

This classical setting is the one where standard symmetric light curves were found in a number of cases (although with significantly lower magnifications). Probably it is also the one which the authors (Barbary *et al.* 2009, Gänsicke *et al.* 2008) discussing the nature of SCP 06F6 had primarily in mind while discarding the microlensing hypothesis. Taking $v_t = 200\,\mathrm{km\,s^{-1}}$, assuming that lens is at $D_l = 5\,\mathrm{kpc}$ and source is at $D_s = 10\,\mathrm{kpc}$ one gets the lens mass of $M = 6.5\,\mathrm{M}_\odot$. Varying the distances over reasonable admissible galactic scales (as well as reasonably changing the relative velocity) the conclusion is that the mass of the lens should range from 5 to $20\,\mathrm{M}_\odot$ which is implausible due to the fact that the lens should be point-like and really dark (i.e., unseen down to 27 mag). Even if one speculated of an extraordinary coincidence of having and isolated black hole as a lens, the finite source argument implies that the source should have the radius of about $r_* \sim 6 \times 10^2\,\mathrm{R}_\odot$ and be extremely dim, which is hard to imagine. Therefore, the conclusions of Barbary *et al.* (2009) and Gänsicke *et al.* (2008) are fully supported by the above estimates, in this case.

2.2 *Extragalactic source and galactic lens*

Another possibility can be that the source is a dim extragalactic object – a BAL quasar, for example, and the lens is a dark object belonging to our Galaxy. In this case, one should use equation (2) with a very good approximation: $D_s \gg D_l$, and assuming that transversal lens velocity is typical for galactic objects. Again the mass of the lens is significant – ranging from 1 to 20 $M_{\odot}$ depending on the lens distance and the relative velocity assumed. If $D_l = 5$ kpc and $v_t = 200\,\mathrm{km\,s^{-1}}$, then $M = 3.3\,M_{\odot}$. The masses are also quite big as for extremely dim lenses.

Concerning the size of the source: if it is located at $z_s = 2.7$ the estimate for ρ_0 gives $r_* = 9 \cdot 10^{17}$ cm (where the Einstein radius has been rescaled by angular diameter distance to the source). Even if the source is assumed to lie at the cluster distance with $z = 1.112$ or even closer, still the order of magnitude for r_* would be similar. This value is much higher than 10^{14} cm usually assumed (e.g., Mortonson *et al.* 2005) and observationally estimated for the quasar emission region (Wambsganss 2006 and references therein).

2.3 *Extragalactic source and the lens associated with the source*

It might be that the lens lies within the host galaxy of the source. Such scenarios have been for long contemplated in the context of quasar microlensing as a possible source of quasar variability (Hawkins & Taylor 1997; Hawkins 1998). The problem is that in such a case – similarly as in the standard quasar microlensing studies where microlenses are associated with lensing galaxies responsible for producing multiple macroimages of the quasar – one would expect not single isolated microlensing events but rather high magnification events (HME) form the source crossing the web of caustics produced by an ensemble of microlenses. It could happen, however, that the finite source size effects smoothed the HME in a way that it might resemble smooth, symmetric light curve similar to that predicted by single mass microlensing. Having this in mind we continue with the point-mass lens approximation. Even though the formulae we use would not be fully consistent with a smoothed out HME case, we nevertheless use them as a guidance for checking consistency of the idea.

In this scenario, $D_l = D_s$ and these two cancel in the formula (3). Assuming $v_t = 300\,\mathrm{km\,s^{-1}}$ (as typical velocity dispersion in elliptical galaxies) and $D_{ls} = 5$ kpc the inferred mass of the lens would be $0.54\,M_{\odot}$ which is typical mass of white dwarfs. With distances between lens and source are allowed to vary from 1 to 10 kpc, the mass would lie in the range from 2.7 to $0.3\,M_{\odot}$. If the source lies closer, i.e., at the cluster redshift $z_s = 1.112$, then the respective range is higher from 0.8 to $8\,M_{\odot}$. The source size would be of the order of $r_* = 1.2 \cdot 10^{12}$ cm which is somewhat (at least by an order of magnitude) smaller than 10^{13}–10^{15} cm usually estimated from observations (Gil-Merino *et al.* 2005; Wambsganss 2006; Fohlmeister *et al.* 2007; Eigenbrod *et al.* 2008).

2.4 *Purely extragalactic scenario*

At last one can imagine a scenario in which both the lens and the source are extragalactic. The projected location of the transient and lack of Lyman-alpha features suggest to start with the case where the lens is associated with the CL 1432.5 + 332.8 cluster (i.e., $z_l = 1.112$) and the source is a BAL quasar at $z_s = 2.7$ (upper limit from spectral considerations which also fairly represents the median source redshift in known quasar-galaxy strong lensing systems, Kochanek 2006). Taking the transversal velocity in the system as typical velocity dispersion in cluster's potential well $v_t = 1000\,\mathrm{km\ s^{-1}}$ the observed value of the transient's half-time duration $t_E = 100$ days gives the mass $M = 2.8 \times 10^{29}$ g $\approx 1.4 \times 10^{-4}\,M_\odot$. The inferred size of quasar emission region turns out to be $r_* = 6.7 \times 10^{12}$ cm which is near the right magnitude matching both expected and observationally derived values. If one allows the relative transversal velocity vary from 600 to 10,000 km s^{-1} the inferred lens mass would range form 10^{29} g $= 5. \times 10^{-5}\,M_\odot$ to 2.8×10^{31} g $= 1.4 \times 10^{-2}\,M_\odot$. The inferred sizes of quasar emission regions would range from 4×10^{12} to 6.7×10^{13} cm. The last case is perfectly compatible with estimates derived in quasar microlensing studies. It is quite a reasonable result. Despite very small lens mass, it is expected that the intra-cluster/intergalactic medium could be filled with free floating clumped material. The question is in which amount and with which mass distribution. Observational evidence for the existence of compact massive intergalactic objects would be important for the so called problem of missing baryons in clusters.

3. Conclusions

Guided by the suggestive symmetric appearance of the light curve of SCP 06F6 transient, which displayed only very slight (if at all significant) colour dependence, we asked whether the microlensing nature of this event is really ruled out or considered for several possible scenarios. From the duration of the event (and assumptions concerning relative transversal velocity) we estimated the lens mass. Because the event was extremely magnified, hence the impact parameter should be very small, we assumed that finite size effects should be taken into account. The estimated size of the source served as additional consistency check.

Whereas the cases of lenses (and source) located in our Galaxy are indeed unrealistic, the remaining case of microlensed extragalactic source (presumably BAL quasar) does not lead to major inconsistency with general knowledge. Microlensing due to a star in a host galaxy could in principle manifest itself as a smoothed out high magnification event (HME) due to caustic crossing. This case would lead to a prediction that another HME could occur in the future in the same place. In principle, it is a testable conjecture. However, the most likely magnification would be much lower than that of the transient. Having in mind that the source was extremely dim (below the survey's threshold), possible observational verification of such scenario would be very difficult.

Consistent estimates were found in the case when both the lens and the source were extragalactic. We examined only the case when the lens was associated with the cluster and the source lied farther away (actually at the largest admissible distance). Clumped free floating intergalactic materials like stars, planets, molecular cloudlets or (perhaps primordial) black holes potentially can serve as lenses (Wambsganss 2006). This expectation is consistent with baryonic matter budget in clusters, especially with the so called missing baryons problem.

The cosmological microlensing hypothesis although demands an unusual setting (the transient itself being unusual as well) which is more parsimonious than already proposed models of explosion in carbon-rich environment in the sense that it invokes known phenomenon (microlensing) and the lens population (intergalactic clumped matter) expected to exist. It does not, of course explain the source's spectrum, but in light of the data we have this and perhaps will remain a weak point of all the models (until next similar event).

Even though the proponents of alternative explanation for the transient might be on a right track the idea presented here can stimulate further work on cosmological microlensing and eventually open a new interesting field of research. One may imagine analyzing cluster SN survey data with techniques more suited for microlensing searches (typically lower magnifications) than for supernovae hunting. Besides there are about 120 strong lensing clusters discovered so far with Wen *et al.* (2008) reporting discovery of four new such systems. There are several examples of multiply imaged quasars (lensed by clusters) with very large image separation, for example, SDSS J1004+4112 system for which time delay between images have been measured (Fohlmeister *et al.* 2007). In such cases, differential studies of quasar's macroimages (in a manner similar to classical quasar microlensing) could provide information about compact intergalactic objects.

Acknowledgement

The work was supported by the Polish Ministry of Science Grant no. NN203 390034.

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