Superluminous quasars and mesolensing

Alexander Raikov\textsuperscript{1,2}, Nikita Lovyagin\textsuperscript{3}, and Vladimir Yershov\textsuperscript{4}

\textsuperscript{1}Special Astrophysical Observatory, Russian Academy of Sciences  
Niznii Arkhyz, 369167 Russia  
\textsuperscript{2}Pulkovo Observatory  
65(1) Pulkovskoye shosse, St. Petersburg, 196140, Russia  
\textsuperscript{3}Saint Petersburg State University  
7-9 Universitetskaya emb., St. Petersburg, 199034, Russia  
\textsuperscript{4}Mullard Space Science Laboratory,  
Holmbury St.Mary, RH5 6NT, United Kingdom

Abstract

Observed magnitudes of many quasars with redshifts exceeding $z = 5$ correspond to luminosities $L_{\text{bol}} > 10^{14} L_\odot$. The standard mechanism of quasar energy release by accretion suggests that masses of superluminous quasars should exceed $10^{10} M_\odot$. On the other hand, the age of these objects in the standard cosmological model is below one billion years, which is too short to explain their formation in the early Universe. Many quasars are known to be gravitationally lensed; showing multiple images of the same object. In the case of remote quasars with no multiple images, it is still possible that they are also gravitationally lensed by foreground objects of intermediate masses, such as globular clusters or dwarf galaxies. Such mesolensing would result in essential amplification of quasar brightnesses, subject to geometrical configuration between the lens and the lensed object. Here we estimate the fraction of quasars whose brightness might have been amplified by gravitational lensing.

Keywords: quasars, luminosity function, gravitational lensing

To be published in Proc. conf. VAK-2021, August 23-28, 2021, Sternberg Astronomical Institute, Moscow

Since Arp (1987), it has been known that there is a statistically significant over-density of quasars within areas of the sky near foreground galaxies. One of the possible explanations for this phenomenon was suggested by Baryshev, Raikov & Yushchenco (1993, 1998) in terms of gravitational lensing of remote quasars by intermediate-mass objects ($10^6 - 10^7 M_\odot$) located in the vicinities of foreground galaxies. These could be globular clusters or satellite dwarf galaxies. Gravitational lensing by intermediate-mass objects (mesolensing) differs from microlensing (Linder & Schneider 1988) by much longer duration of the effect. It is also different from lensing by large-mass foreground objects which usually splits the lensed object image into multiple images, whereas mesolensing does not split images and only results in brightness amplification.
Figure 1: Left: redshift distribution of quasar luminosities from the LQAC-4 catalogue for the infrared band $J$; Right: fraction $r = (n_{\text{bright}} - n_{\text{faint}})/(n_{\text{bright}} + n_{\text{faint}})$ indicating the excess of bright quasars over the faint ones in the luminosity histograms for redshift slices within $0.1 < z < 2$ and with $\Delta z = 0.1$ for each slice (two examples of these histograms are shown in Fig. 2 for $z = 0.2$ and $z = 0.8$).

Then Raikov & Orlov (2016) suggested that the same mesolensing effect might be responsible for the brightness amplification of some superluminous quasars at high redshifts. The problem is that within the standard cosmological model some of them have luminosities $L_{\text{bol}} > 10^{14} L_\odot$. By assuming that quasar energy is emitted via the mechanism of accretion onto a supermassive blackhole, the corresponding mass of such a blackhole should exceed $10^{10} M_\odot$. On the other hand, the age of high-redshift objects (less than 0.7 Gyr) is too small to explain their formation in the early Universe.

In the last few years, the number of catalogued high-redshift quasars has dramatically increased (Flesch 2015; Gattano et al. 2018; Ross & Cross 2020; Flesch 2021), and so has the number of known superluminous quasars at high redshifts. In X-rays, the all-sky survey by the Spektr-RG (SRG) space observatory also produces a growing number of high-redshift quasars with X-ray luminosities exceeding $10^{46}$ erg/s and masses of their blackholes exceeding $10^9 M_\odot$ (Khorunzhev et al. 2021).

Most of the high-redshift superluminous quasars are seen as single sources, but we know (Baryshev & Bykhmastova 1997) that their brightnesses could be enhanced by mesolensing without splitting source images, provided that the mass profile in the gravitational lens is of the King-type (King 1962). There are numerous objects with such mass profiles in the vicinities of foreground galaxies, so one would expect a large fraction of quasars to be lensed.

This fraction can be estimated by exploring statistical properties of available quasar catalogues, the most convenient one being the large astrometric catalogue of quasars LQAC-4 (Gattano et al. 2018) because it includes absolute magnitudes for different wavelength bands.

We have converted these absolute magnitudes to bolometric luminosities by using the average spectral energy distribution of quasars published by Krawczyk et al. (2013). The left panel of Fig. 1 shows the redshift distribution of these luminosities based on the infrared band $J$ from LQAC-4. The infrared band $J$ is likely to be less affected by the observational selection effect than the other wavelength bands. However, even in this case, an observational selection effect takes place for redshifts $z > 3$, because one can see that for these redshifts the quasar luminosity-evolution stripe narrows at its low-luminosity fringe, as shown in Fig. 1 (left). By contrast, the width of this stripe...
at $0.5 < z < 2.0$ remains approximately constant, which indicates that the observational selection effect for low-redshift quasars is minimal or absent (indeed, one can expect that quasars, by being the brightest objects in the Universe, are all captured by modern telescopes at low redshifts).

We have built luminosity histograms for the quasar redshifts ranging from $z = 0.1$ to $z = 2.0$, using a redshift interval 0.1 and the same width for each redshift slice $\Delta z = 0.1$. By counting the number of bright and faint objects, $n_{\text{bright}}$ and $n_{\text{faint}}$, above and below the luminosity $L$ corresponding to the histogram maximum, we can estimate the asymmetry – the excess of the number of bright quasars over the faint ones, $r = (n_{\text{bright}} - n_{\text{faint}})/(n_{\text{bright}} + n_{\text{faint}})$, which gives the fraction of gravitationally lensed quasars, assuming that the natural luminosity distribution of quasars at each redshift slice must be symmetrical with respect to the average luminosity.

As we can see from the right panel of Fig.1, the number of gravitationally lensed quasars is growing with redshift, which is expected, as the number of foreground galaxies and their surrounding mesolenses (globular clusters) increases proportionally to the foreground volume. The negligibly small fraction of gravitationally lensed quasars at small redshifts reaches 80% at the redshift $z = 1.5$. Beyond this point, the linear growth of $r$ breaks down and the fraction of lensed quasars becomes underestimated, which is likely to be caused by the observational selection effect.

The calculations for $z > 2$ give us an underestimated fraction $r \approx 30\%$. We can thus conclude (with caution) that the fraction of gravitationally lensed quasars is, at least, 30%. However, our calculations suggest a more radical conclusion that practically all of the high-redshift quasars (say, for $z > 5$) are gravitationally lensed, and that for some of them the geometrical configuration between the lensed quasars, the gravitational lens and the observer is such that the lensed quasars appear as superluminous objects, with their luminosities amplified by a factor of hundreds to thousands.

Therefore, the masses of supermassive blackholes associated with these quasars
could actually be much smaller, which would resolve the conflict between the age of the Universe corresponding to the redshifts of superluminous quasars and the time needed for the formation of their supermassive blackholes.

The time scales of the quasar brightness variability due to their gravitational lensing on globular clusters can be from years to a few thousand years \cite{Baryshev & Bykhmastova 1997}, depending on the source-to-lens geometrical configurations. Some smaller-time-scale variability can be expected due to microlensing on individual stars belonging to globular clusters.

As an example, the superluminous X-ray quasar SRGE J170245.3+130104 at redshift \( z = 5.5 \) has reportedly reduced its brightness by half between the first and second all-sky surveys by the SRG space observatory \cite{Khorunzhev et al. 2021}. This might be caused by either internal change in the quasar accretion process or by the change in the quasar-to-lens geometrical configuration. In the latter case, one would expect some further reduction of its observed brightness during the next forthcoming all-sky surveys by the SRG.

Foreground objects acting as mesolenses are unlikely to be observed directly or spectrally by having luminosities much smaller than those of quasars. However, since the lensing effect is the same for all wavelengths, comparing light curves in different spectral bands could be regarded as an observational test for mesolensing.

**Acknowledgement.** This research has been partly supported by the St. Petersburg State University’s project # 73555239.

**References**

Arp H., 1987, Quasars, redshifts and controversies, Interstellar Media, Berkley

Baryshev Yu.V., Raikov A.A., Yushchenco A.V., 1993, in 31st Li`ege Intern. Astroph. Coll., 307

Baryshev Yu.V., Bukhmastova Yu.I. 1997, AZh, 74, 497

Yushchenco A.V., Baryshev Yu.V., Raikov A.A. 1998, Astron. Astrophys. Trans., 17, 9

Flesch E.W., 2015, PASA, 32, e010

Flesch E.W., 2021, e-Print: arXiv:2105.12985

Gattano C., Andrei A. H., Coelho B., et al., 2018, A&A, 614, A140

Khorunzhev G.A., Mecheryakov A.V., Medvedev P.S., et al., 2021, AZh Lett., 47, 155

King I.R., 1962, Aston.J, 67, 471

Krawczyk C.M., Richards G.T., Mehta S.S., et al., 2013, ApJS, 206, 4

Linder E.V. & Schneider P., 1988, A&A, 204, L8

Raikov A.A., Orlov V.V. 2016, Astrophys. Bull., 71, 129

Ross N.P., Cross N. J. G., 2020, MNRAS, 494, 789