THE SEARCH FOR POSSIBLE MESOSENSING OF COSMIC GAMMA-RAY BURSTS. DOUBLE AND TRIPLE BURSTS IN BATSE CATALOGUE

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The work is devoted to the search for possible effect of gravitational lensing on the objects like globular stellar clusters (mesolensing) on the lightcurves and spectra of large number of gamma-ray bursts from BATSE catalogue. The general properties and different types of such event were considered. As the result 11 possibly mesolensed gamma-ray bursts were found. The propeties of possible mesolenses are invesigated.

1 Introduction

The gravitational lensing event predicted by the General Theory of Relativity were discovered in 1979 [1] for the distant quasar, which image was duplicated by massive elliptical galaxy situated between quasar and observer. Since that time many lensed extragalactic objects (quasars, AGN) were found.

The last years of XX century the hypothesis of extragalactic origin of cosmic gamma-ray bursts [2] was confirmed (at least for sufficient part of gamma-ray bursts) by X-, optical and radio afterglows discovering (see [3] for example). But in this case we should observe the gravitational lensing effect for these objects too, as it was firstly reported in [4]. But a number of papers dedicated to the search of lensed gamma-ray bursts [5,6] had a negative result.

In this work we shall consider the so-called mesolensing event, when the role of gravitational lens is played by the body like globular stellar cluster in far galaxy or other body with mass about $10^6 M_\odot$. The probability of observation of such type of lensing can be quite large due to the sufficient total mass of such objects in the Universe [7,8], especially at large values of $z$ [9]. Mesolensing can be very often phenomenon for extragalactic sources, and possibility of very high amount of magnification of the image makes it one of possible explanation of observing correlation of quasars and nearby galaxies [10]. The primary goal of this work is to find gamma-ray bursts having the mesolensed properties.

2 Observational Properties of Mesolensed Gamma-Ray Bursts

The most simple case of gravitational lensing by a point mass, when the light deflecting angle is back proportional to the distance of light path from the lens, was considered many times [11]. The scheme of this phenomenon is shown on Fig.1a. In this case an observer $O$ will see two images of the source $S$ at different sides from the lens $L$. Angular distances of images from the lens $\theta_{1,2}$ will be equal to

$$\theta_{1,2} = \frac{\alpha}{2} \pm \sqrt{\left(\frac{\alpha}{2}\right)^2 + \theta_0^2}, \quad (1)$$

where $\alpha$ is the angle between source and lens directions and $\theta_0$ is angular Einstein radius defined by the
where $\theta$ is the mass of the lens. However, in the case of gamma-ray bursts we cannot resolve two different lensed images with separation about $1''$, but we can detect another effect related with difference of time of light propagation along trajectories 1 and 2. This effect appears for two reasons: geometrical difference of path lengths and relativistic time delay near the mass $L$ (Shapiro effect). This effects are adding to each other and finally burst signals by path 1 will reach the observer earlier than by path 2 and total time delay between moments of registration will be equal to

$$\Delta t = \frac{2GM(1 + z_L)}{c^3} \left[ \frac{\theta_1^2 - \theta_2^2}{\theta_0^2} + \ln \frac{\theta_1^2}{\theta_2^2} \right],$$

where $z_L$ is the lens redshift. In the case of gravitational lensing the gamma-ray burst will have two lightcurve components with similar profiles (differing only by a factor of constant) and similar spectra. Magnification of two images will be different and image 1 will be $K$ times brighter than image 2, and brightness ratio can be expressed by the formula

$$K = \frac{\theta_1^2}{\theta_2^2}.$$ 

Comparing the formulae (2) and (4) we obtain relation of two observational parameters $\Delta t$ and $K$:

$$\Delta t = \frac{2GM(1 + z_L)}{c^3} \left[ \frac{K - 1}{\sqrt{K}} + \ln K \right].$$

Here we can see that for given $\Delta t$ and $K$ from observations one may obtain mass $M$ if we can assume small $z_L$ and small size of the lens. We can also see that for $K > 1 \Delta t > 0$ and in the case of point mass lens bright image will be registered earlier than faint one.

As we can see from (3) time delay $\Delta t$ is proportional to the lens mass $M$ and type of lens will define type of lensing. In the case of macrolensing when the galaxy or galaxy cluster with mass about $10^{11} - 10^{13} M_\odot$ plays the role of lens the time delay will be equal to several months or years and in the same case we should register two different gamma-ray bursts from the one region on the sky. The search for this type of lensing was conducted in [5,6], but the result was negative.

In the case of microlensing on a singular star the time delay, vice versa, will be very small, about $10^{-5}$ sec and such duplication of burst lightcurve is very difficult to detect. Finally, in the case of mesolensing the amount of $\Delta t$ will be equal to several seconds what is comparable with the burst duration, and in this case we shall see one burst with duplication of its lightcurve on two similar (by a factor of constant) components with equal spectra.

But possible gravitational lens may be extended object with definite size and in this case formulae above will not be correct. To estimate the range of variability of point mass assumption we compare the external radius of globular cluster $r_t$ and spatial Einstein radius $\theta_0 L_{OL}$. This leads us to the limitation to the lens distance:

$$L_0 \geq \frac{r_t^2 c^2 L_{OS}}{4GM L_{LS}} \geq \frac{r_t^2 c^2}{4GM}.$$

If we take values $r_t = 30 pc$ and $M = 5 * 10^5 M_\odot$ that are typical for globular clusters [12], we shall obtain $L_0$ about $10^{10} pc$ which is comparable with the size of the Universe. This means that for all smaller distances of mesolenses we have to take into account their spatial mass distribution and light rays going inside of cluster. We shall call this case as “near mesolensing” and the case of point mass lens as “far mesolensing”.

The problem of mesolensing with account of inner structure of globular clusters was investigated in [13] and developed in [10]. The scheme of near mesolensing is shown on Fig.1b. The density distribution
for globular cluster is defined by a King law [14]:

\[
\rho(p) = \begin{cases} 
\rho_0 \left(1 + \frac{p^2}{r_c^2}\right)^{-\frac{3}{2}}, & p < r_t \\
0, & p \geq r_t
\end{cases}
\]

where \(p\) is the distance from the cluster center, \(\rho_0\) is the central density of the cluster and \(r_c\) is the core radius of the cluster. Following [13] and [10], we express the distances \(l\) (from ray path to the lens center), \(l_s\) (from lens center to the “source-observer” line), and \(r_t\) in the units of \(r_c\):

\[
x = \frac{l}{r_c}, y = \frac{l_s}{r_c}, x_t = \frac{r_t}{r_c}
\]

In this unit system the deflecting angle \(\delta\) will be expressed as

\[
\delta(l) = \frac{r_c}{F_L} \alpha(x),
\]

where \(F_L\) (lens focal distance) is determined as

\[
F_L = \frac{c^2}{8\pi G \rho_0 r_c},
\]
and function $\alpha(x)$ is following:

$$\alpha(x) = \ln (1 + x^2) - 4\sqrt{1 + x^2} - 1 + \frac{x}{x\sqrt{1 + x^2}}, x \leq x_t$$

$$\alpha(x) = \alpha(x_t) \frac{x_t}{x}, x > x_t.$$ (11)

The condition of registration of the light ray by observer may be written as

$$\alpha(x) = \frac{x - y}{g},$$ (12)

where the spatial parameter $g$ is defined by the formula

$$g = \frac{L_{OL}L_{LS}}{L_{OS}F_L}.$$ (13)

Given parameters $g, y$ and $x_t$, formulae (11) and (12) are building an equation for $x$, each solution $x_i$ of this equation will correspond to one source image an observer notices. The magnification of this image can be expressed by the formula

$$I_i = \left| \frac{x_i}{y} \frac{dx_i}{dy} \right|.$$ (14)

The time of registration of the $i$-image $t_i$ relatively to the time of light propagation through the center of cluster $t_0$ will be equal to

$$t_i - t_0 = \frac{8\pi G_0r_c^3}{c^3} (1 + z_L) T(x_i) = C_0T(x_i),$$ (15)

where the function $T(x)$ is expressed by the formula

$$T(x) = 2x\alpha(x) - 2\int_0^x \alpha(x') \, dx' - \frac{x^2}{g}.$$ (16)

Analysis of last formulae shows that at $g > 1$ there are two caustics. Axial caustic corresponds $y = 0$ and this case is the analog to the "Einstein Ring" for the point mass lensing, but now we shall have weak central image along with bright ring. There is also the conic caustic at $|y| = y_c(g, x_t)$, when two images merge to one and magnification of this image turns to infinity too. The conic caustic is clearly visible on Fig.2. Axial and conic caustics merge in the focal point of the lens.

The number of images is equal to one outside the conic caustic but rise up to three inside it ($|y| < y_c(g, x_t)$). Thus, in the case of near mesolensing of cosmic gamma-ray bursts we can see double or triple lightcurve, but all components should be similar (by the factor of constant) and have similar spectra again. Numerical analysis of formulae (13) and (14) shows that in most part of cases first (by the time of registration) component will be brightest as it took place in the point-mass lensing case, but now this rule can be broken, for example, near the conic caustic surface.

Far and near mesolensing properties discussed above shows that generally we should search for the double and triple gamma-ray bursts with any combinations of component brightness, but bursts with bright first lightcurve component will be more probable candidates to the mesolensed ones.

3 The search for possible mesolensed gamma-ray bursts

The search for possible mesolensed bursts were conducted amongst 1512 events registered by BATSE [15] during the whole CGRO work period from 1991 to 2000 and having MER format data with lightcurves
with resolution 16 and 64 ms and 16 channel spectra. At the first stage candidates with visually similar two or three lightcurve components were selected and approximate amounts of brightness ratio and time delay between them were estimated. At the second stage the similarity of these lightcurve components was tested by $\chi^2$-method with 0.003 significance level (this test is analogical to the $3\sigma$-test) and the values of brightness ratio and time delay were precisely calculated by best $\chi^2$-agreement method. Finally, third stage of the test was $\chi^2$-comparison of the 15 channel spectra of the components with the same significance level (channel 16 data with highest energy with maximum error was ignored). The method is similar to that developed in [16].

3.1 Double gamma-ray bursts

As the result of the search we have found 11 double gamma-ray bursts which two lightcurve components had satisfied all the statistical tests discussed above. Fig.3 shows lightcurves of all 11 candidates and Table 1 contains their parameters: burst name $NB$, BATSE trigger number $Tr$, burst galactic coordinates $l$ and $b$, their uncertainty $\Delta\epsilon$, brightness ratio of two components $K$ and time delay between their registration moments $\Delta t$. 6 of these candidates from 4 BATSE Catalogue [15], from GRB 930430B to GRB 960617B were firstly described in paper [17].

First of all we should emphasize on the fact that the brightest component appeared to be first one for all 11 candidates although, unlike [17], it was not required at the search procedure! This situation is difficult to imagine in the case of occasional similarity of two burst components and it sufficiently increases the probability of real mesolensing for even though some of these bursts.

Assuming the possible lens to be point mass with not so large $z_L$ we can estimate its mass by formula (5) for our 11 far mesolensed candidates. These values of mass are given in the last column of Table 1. For 6 described in [17] candidates these values of mass differ from noted in [17] due to taking Shapiro effect into account here. We can see that these values are suitable for globular clusters or objects described in [7–9]. We should also note that gamma-ray burst GRB 960617B is situated at 4° (about $2\Delta\epsilon$) from galaxy cluster AGC 1060 in Hydra.
Table 1: Double bursts parameters.

| Burst       | $T_R$ | $l$ | $b$ | $\Delta \varepsilon$ | $K$ | $\Delta t$ | $M$     |
|-------------|-------|-----|-----|------------------------|-----|------------|---------|
| 911006      | 871   | 266.7 | -65.5 | 3.4                     | 2.498 | 4.560     | $2.5 \times 10^5$ |
| 920113      | 1297  | 139.9 | +23.1 | 4.0                     | 1.447 | 4.544     | $6.2 \times 10^5$ |
| 920728      | 1729  | 76.6  | -15.4 | 4.4                     | 4.854 | 9.328     | $2.8 \times 10^5$ |
| 930430B     | 2322  | 65.2  | -56.9 | 1.7                     | 4.850 | 45.952    | $1.4 \times 10^6$ |
| 930602      | 2367  | 62.5  | +31.0 | 2.5                     | 8.986 | 9.696     | $2.0 \times 10^5$ |
| 931008C     | 2569  | 353.9 | -15.7 | 4.5                     | 1.571 | 7.744     | $8.7 \times 10^5$ |
| 960601      | 5483  | 119.8 | +2.1  | 3.9                     | 1.890 | 1.120     | $8.8 \times 10^4$ |
| 960615C     | 5499  | 330.2 | -29.7 | 7.5                     | 4.562 | 3.920     | $1.2 \times 10^5$ |
| 960617B     | 5504  | 273.2 | +24.5 | 2.2                     | 4.562 | 3.920     | $1.2 \times 10^5$ |
| 000126A     | 7968  | 111.8 | -26.3 | 4.5                     | 1.101 | 11.968    | $6.3 \times 10^6$ |
| 000407      | 8066  | 291.5 | -10.4 | 2.2                     | 2.119 | 1.952     | $1.3 \times 10^5$ |

3.2 Triple gamma-ray bursts

The procedure of statistic test for component similarity for triple bursts was the same as for double ones, best $\chi^2$-agreement method considered all three components data at once. As the result of these tests we had not found new candidates to mesolensed gamma-ray bursts, but third weak component was found and satisfied all similar tests for two double gamma-ray bursts listed above: GRB 911006 and GRB 930430B. As it can be seen on Fig.3, third weak component follows two others for first of these bursts and followed by them for second one. The parameters of relative brightness $j_i$ and time delays $t_i - t_{i-1}$ for these bursts are given in Table 2. Here parameters $j_i$ are normalized that brightness of the strongest component is equal to unity. These values for two brightest components slightly differ from that given in Table 1 for these two bursts due to third component taking into account in $\chi^2$-tests.

Table 2: Triple bursts parameters.

| GRB     | $j_1$ | $j_2$ | $j_3$ | $t_2 - t_1, sec$ | $t_3 - t_2, sec$ | $\Xi$ |
|---------|-------|-------|-------|------------------|------------------|-------|
| 911006  | 1.000 | 0.404 | 0.123 | 4.736            | 6.144            | 0.771 |
| 930430B | 0.221 | 1.000 | 0.191 | 17.088           | 45.952           | 0.372 |

Based on the values found we can try to calculate parameters of possible near mesolensing in equations (11) and (12), that is $g$, $y$ and $x_t$. Since we don’t know initial burst energy, brightness data for three components give us only two parameters for this task, for example, normalized brightness values for two weakest components $j_i$ given in table 2. Further, since we don’t know both $t_0$ and $C_0$ in equation (15), time arrival data give us just one parameter for lensing conditions calculation:

$$
\Xi = \frac{t_2 - t_1}{t_3 - t_2} = \frac{T(x_2) - T(x_1)}{T(x_3) - T(x_2)}.
$$

The value of this parameter for two triple gamma-ray bursts is shown in the last row of Table 2. Finally we have three independent parameters taken from the observations and may search three corresponding mesolensing parameters.

The search was conducted for values of $x_t$ from $\sqrt{10} = 3.16$ (that is lower than for any known globular cluster in our Galaxy [12]) to infinity, $g > 1$, $0 < |y| < y_c(g,x_t)$, where three lensed images are possible. This procedure was made for both gamma-ray bursts GRB 911006 and GRB 930430B and in both cases no corresponding lensing parameters were found.
This fact itself does not deny the possibility of near mesolensing of two triple gamma-ray bursts, since the lens density distribution may differ from predicted one by King law. Moreover, brightness of one or more components could be increased by microlensing effect at one singular star in a globular cluster, possibility of this effect being noticed in [10]. We may consider these two bursts to be the main candidates for near mesolensing, especially GRB 911006 with three components registered in decreasing order of intensity, which is most probable in the mesolensing case.

Here we should add that the same gamma-ray burst GRB 911006 was localized in thin annulus on the sky by triangulation measurements carried out by CGRO and “Ulysses” spacecraft [18] and bright (13") galaxy NGC 641 appeared to be situated in about 10' from this annulus near its closest point to the BATSE error box center. Although annulus half-width by $3\sigma$-level is, as paper [18] reports it two times less, about 5’.

4 Discussion and conclusion

In this work the possible gravitational mesolensing of cosmic gamma-ray bursts was considered. The results of the search for this type of lensing were more successful than that for macrolensing where no candidates were found. All double gamma-ray bursts with similar lightcurve and spectra of components had strong first and weak second pick on the lightcurve. It is this situation that is expected to be seen in the case of far mesolensing. The same picture is observed for one of two triple bursts found, GRB 911006. Taking into account the presence of bright galaxy close to its needle-type error box, we may call it the most interesting candidate considered in this paper.

Surely each of found double or triple bursts could have such lightcurve and spectral features due to the other, not related with gravitational lensing reasons. In connection with that the question of mesolensing probability is actual. This value will be very small if we assume total mass of mesolenses in the Universe.
to be such as observed in our Galaxy (about $10^{-3}$). But total mass of these objects may be sufficiently increased at large $z$ [9], the role of mesolenses can be played by the massive black holes, which number is expected to be very large [7,8]. We should also note that black hole will be displayed as far (point mass) mesolens independently of its distance, and this can be possible explanation of large number of double bursts with far mesolensing properties.

As in the case of macrolensing, the effect of mesolensing may occur only at extragalactic masses and observation of such event for gamma-ray bursts can be considered as very essential confirmation of extragalactic nature of these objects.

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