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The parameters of binary black hole system in PKS 1510-089*

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Observations of PKS 1510-089 indicate the existence of a deep flux minimum with a timescale of ~ 35 min and an interval of about 336 ± 14 d. A binary black hole system is proposed to be at the nucleus of this object. The secondary black hole orbits around the primary black hole. The minimum is caused by the periodic eclipse of the primary black hole by the secondary black hole. Based on the observations of PKS 1510-089, we estimate the parameters of the binary black hole system. The masses for the primary and secondary black holes are $1.37 \times 10^9 M_\odot$($M_\odot$ is the solar mass) and $1.37 \times 10^7 M_\odot$, and the major axis for this pair being about 0.1 parsec(pc).

Keywords: active galaxies, black hole, individual (PKS1510-089)
PACC: 9870J, 9760L, 9780

1. Introduction

Black holes are a very challenging topic in astronomy and physics.[1−6] Supermassive black hole binaries (SBHBs) were first proposed to exist in active galactic nuclei (AGN) in Ref.[7]. Since then, astronomers have often used it to explain the observed curved variability in active galaxies.[8−15]

PKS 1510-089 is a flat-spectrum radio quasar at a redshift of 0.361. The angle between its parsec-scale jet and the line of sight is only 0.05 rad. Its light curve is quite different from the ones of other blazars. Besides fast and small amplitude variations and irregular outbursts, some brightness minimum were also observed.[3,16] These minima have nearly the same timescale (~ 35 min) and intervals (336 ± 14d) , based on which, Ref.[3] argued that the minimum was a periodic phenomenon and proposed that there was an SBHB at the centre of PKS 1510-089. The secondary black hole (SBH) orbits around the primary black hole (PBH). The minimum is caused by the periodic eclipse of the primary black hole by the secondary black hole. Based on the observations of PKS 1510- 089, we can estimate the parameters for the binary black hole system.

Throughout this paper, we adopt a cosmology with deceleration factor $q_0 = 0.5$, cosmological constant $\Lambda = 0$ and hubble constant $H_0 = 75$ km·s^{-1}·Mpc^{-1}.

2. Calculations

Figure 1 gives a 2-D diagram of binary black hole system in PKS 1510-089.

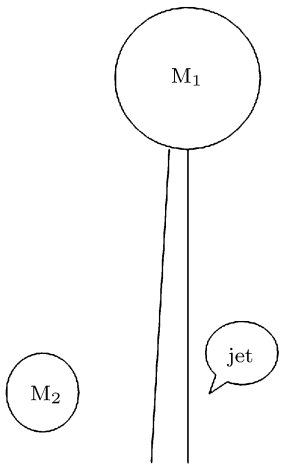


Fig.1. The supermassive black hole binary model of PKS 1510-089, M_1 is the primary black hole (PBH), M_2 is the secondary black hole (SBH).

Figure 2 shows how the brightness minimum occurs. When the SBH reaches A, it begins to cover part

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of jet, which causes the luminosity to drop off. The luminosity reaches the lowest value when the SBH moves to O_1, a is the semimajor axis of orbit of the SBH, we also take it as the distance between PBH and SBH, R_2 is the radius of SBH, $R_{\rm j}$ is the radius of jet.

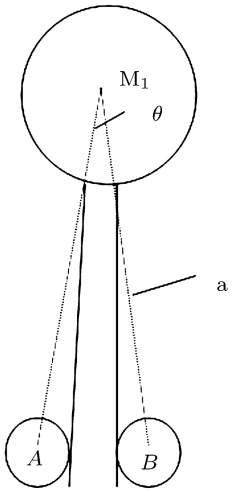


Fig.2. The occurrence of minimum when SBH moves from A to B.

According to Ref.[16], its magnitudes in the optical R band dropped from 16.62 ± 0.12 mag to 17.92 ± 0.15 mag in 16 min, and rose back to 16.57 ± 0.57 mag in 16 min. It is possible to calculate the ratio of S_1 to S_2 with these data.

$$\triangle m = -2.5 \times \lg\Big(\frac{S_1}{S_1 + S_2}\Big) = 1.3, \tag{1}$$

where $\triangle m$ is the variation in magnitude, S_1 is the area of uncovered section of the jet, and S_2 is the area of covered section of the jet, which is equal to the area of roundness with a radius of R_2. From the expression above, we can obtain $2S_1 \simeq S_2$. Figure 3 shows the extreme situation. The radius of SBH (R_2) may be much smaller than radius of jet ($R_{\rm j}$), but it cannot be too small. In the extreme situation, $S_2 = \pi R_2^2$, for $2S_1 \simeq S_2$, we have

$$2 \times (\pi R_{\rm j}^2 - \pi R_2^2) = \pi R_2^2. \tag{2}$$

From the above expression, we have $R_2 = \sqrt{2/3}\, R_{\rm j}$. We can see from Fig.3 that

$$\begin{aligned} AB &= 2\sqrt{(R_{\rm j} + R_2)^2 - (R_{\rm j} - R_2)^2} \\ &= 2\sqrt{4R_{\rm j}R_2} = 4.8R_2, \end{aligned} \tag{3}$$

where AB is the distance for the SBH to move from one end 'A' to another end 'B'. Let $AB = k \times R_2$, the k value should be always smaller than 4.8.

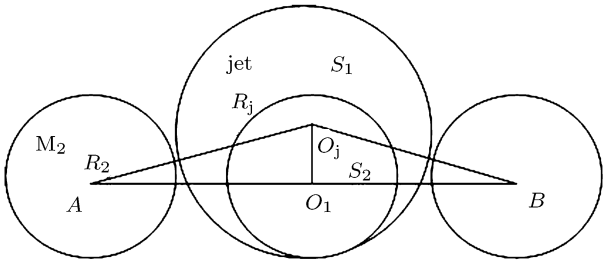


Fig.3. The extreme situation with the radius of SBH (R_2) being much smaller than the radius of jet ($R_{\rm j}$).

According to Refs.[3] and [16], it takes about 35 min for the SBH to move from A to B, and the interval is $\sim 336 \pm 14$ d, thus we obtain

$$a\theta_1 = a\frac{t \times 2\pi}{T} = |AB| = kR_2, \tag{4}$$

where θ_1 is the opened angle when the SBH moves from A to B, t is the timescale of brightness minimum, and T represents the interval, then

$$a = \frac{kR_2 \times T}{2\pi t}, \tag{5}$$

which can be written as

$$a = 3 \times 10^5 \times \frac{kM_2 \times T}{2\pi \times t \times M_\odot}\ \text{cm}. \tag{6}$$

M_2 is the mass of the SBH, let

$$\frac{M_1}{M_2} = q. \tag{7}$$

M_1 is the mass of the PBH. For the SBHB system, we have

$$G(M_1 + M_2) = \frac{4\pi^2 a^3}{T^2}, \tag{8}$$

$$M_1 + M_2 = \frac{4\pi^2 a^3}{GT^2}, \tag{9}$$

$$M_2(1 + q) = \frac{4\pi^2 a^3}{GT^2}. \tag{10}$$

Substituting the expression (6) into above equation, we can obtain

$$M_2(1 + q) = \frac{k^3 M_2^3}{1.9 \times 10^{13} \times M_\odot^2}. \tag{11}$$

From the expression above, we have

$$M_2 = 4.4 \times 10^6 \sqrt{\frac{1+q}{k^3}} M_\odot, \tag{12}$$

$$M_1 = qM_2 = 4.4q \times 10^6 \sqrt{\frac{1+q}{k^3}} M_\odot. \tag{13}$$

Substituting the expression (12) into the expression (6), yields

$$a = 3\times10^3\times\frac{kM_2\times T}{M_\odot 2\pi t} = 4.8\times10^{12}\times\sqrt{\frac{1+q}{k^3}}\,\mathrm{cm}. \quad (14)$$

Thus, the values of M_1, M_2 and a are dependent on k and q.

3. Gravitational lensing effect

According to Einstein's general relativity, the light will be deflected by a gravitating body,[17] and thus the apparent brightness of a background radiation source is amplified.[18] Both the deflection of light and the variation in apparent brightness of a radiation source by an external gravitational field, are collectively known as a gravitational lens. In our scenario, the gravitational lensing effect surely exists when the SBH crosses the jet, and may affect our results. This effect is taken into account in this section.

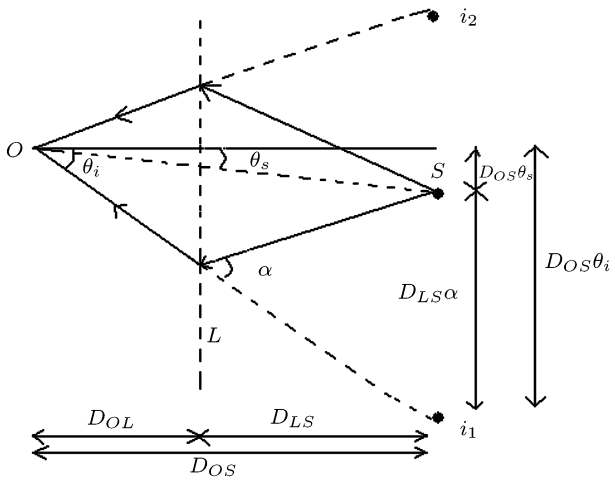


Fig.4. The geometry of gravitational lens where the source S is magnified by matter located at the plane L and produces two images i_1 and i_2 with respect to the observer O and all the deflection is assumed to take place at the plane of the lens.

The geometry of a gravitational lensing is shown in Fig.4.[19] The rays are assumed to propagate in straight lines to and from the lens plane, and are deflected instantaneously from the lens plane. α is the deflection angle. From the geometry of the diagram it follows that

$$\alpha D_{LS} + \theta_s D_{OS} = \theta_i D_{OS}. \quad (15)$$

The amplification is

$$\lambda = \Big(1 - \frac{D_{LS}D_{OL}}{D_{OS}}\frac{\alpha}{\theta_i D_{OS}}\Big)^{-1}, \quad (16)$$

where D_{LS} should be smaller than 0.1 pc,

$$D_{OL} = \frac{cZ + \frac{1}{2}(1 - q_0 cZ^2 + \cdots)}{H_0} = 1.57\times10^9 \text{ pc},$$

$D_{OS} = D_{OL} + D_{LS} < 1.57\times10^9 + 0.1$ pc $\approx D_{OL} = 1.57\times10^9$ pc. Substituting them into the expression above, we obtain

$$\lambda \le \Big(1 - 6.3\times10^{-11}\frac{\alpha}{\theta_i}\Big)^{-1}. \quad (17)$$

We can see from the above expression that the value of λ approaches 1. The magnification caused by the gravitational lensing effect is so subtle that we can ignore it reasonably.

4. Results

Supermassive black hole binaries play important roles in astrophysics, they were proposed to exist in many sources in order to explain the variability and the misalignments between the direction of radio jets and discs in active galaxies.[12,14,20,21]

Observation of OJ 287 shows periodic outbursts at intervals of 11.6 a. Reference [14] proposed that the period was caused by the SBHB existing in OJ 287's nucleus. The outbursts at 11.6 a intervals would be caused by the effect of the motion of the companion black hole's on the disc of the primary black hole. Indirect evidence has been used to derive the masses of the objects and the physical sizes of their orbit around one another. The masses are probably 5×10^9 $M_\odot$ and 2×10^7 $M_\odot$ for the two objects. The major axis for this pair is ~ 0.1 pc.

For PKS 1510-089, it was also proposed to harbour an SBH. The central black hole mass of $10^{9.130}$ solar mass was estimated by using the data given in Ref.[22]. This value can be considered as the total mass of the two black holes. Because it contains not only the black hole binary, but also other matters, this value may be a little bigger than the actual value. Take $M_1 + M_2 = 10^{9.130}M_\odot$, and we will have

$$M_1 + M_2 = 4.4(1+q)\times10^6\sqrt{\frac{1+q}{k^3}}M_\odot = 10^{9.130}M_\odot, \quad (18)$$

which follows

$$\frac{1+q}{k} = 45.5. \quad (19)$$

We know that k should be smaller than 4.8, then we obtain

$$q = k\times45.5 - 1 \le 217. \quad (20)$$

If the secondary black hole is comparable to the primary, the primary would rotate around their mass centre with a large amplitude, which leads up to a significant sinusoidal twist of jets. Such a twist was not detected by VLBI. So we have $M_2 \ll M_1$. According to Ref.[14], q of OJ 287 is ~ 200. If we take q as 100 in PKS 1510-089, then

$$k = \frac{1+q}{45.5} = 2.2. \tag{21}$$

Substituting it into the expressions (12), (13) and (14), we obtain

$$M_1 = 1.37 \times 10^9 M_\odot, \tag{22}$$

$$M_2 = 1.37 \times 10^7 M_\odot, \tag{23}$$

$$a = 2 \times 10^{16} \text{ cm}. \tag{24}$$

These black hole masses are only upper limits, but these values are quite similar to those in the OJ 287 system.[14] Therefore, there exists a binary black hole system in the centre of PKS 1510-089 with M_1 and M_2 being 1.37×10^9 $M_\odot$ and 1.37×10^7 $M_\odot$ respectively, and the major axis for this pair being ~ 0.1 pc.

5. Discussion

Binary black hole model is a prospective explanation for AGN's periodic variability. The SBHSs were first proposed by Begelman, Blandford *et al* in 1980.[7] At that time they were proposed to exist in many sources in order to explain the variability and the misalignments between the direction of radio jets and disks in active galaxies.[21] Strongest evidence for the existence of SBHB came from the observations of 3C66B[23] and NGC 6240.[20] Reference [23] indicates that the observation of an SBHB in the radio galaxy 3C66B for its core showed a definite elliptical motion with a period of 1 a. And the observation, performed with the ACIS-S detector on board the Chandra x-ray observatory, led to the discovery of two hard nuclei, coincident with the optical-IR nuclei of NGC 6240.[20]

In AGNs, the accretion disc and the jet co-exist, however, in the cases for OJ287, Mkn501, and 3C 273, the authors did not take into account the effect of the accretion disc or the jet of the SBH. They did not considered the interaction between the two jets either. On the one hand, taking them into account will make the problem very complex, and on the other hand, the angle between the SBH's jet and the line of sight may be very large, which makes it impossible to be observed. Then its effect on observation is so subtle that it can be ignored. In our scenario of PKS 1510-089, we do not consider the accretion disc or jet of SBH or the interaction between the two jets either. We will pay more attention to this problem in our future work.

In the expression (2), we use the radius of the SBH's event horizon to calculate the area. However, the event horizon casts a relatively large shadow with a apparent diameter of 10 gravitational radii, which is due to the bending of light by the black hole.[24] Representing R_2 in the expressions (2) and (3) with $10R_2$, we obtain $AB = 14R_2$. Substituting $k < 14$ into the expression (20), we obtain $q < 637$. It is still reasonable to assume $q = 100$ in this scenario.

6. Conclusion

We have estimated the parameters of the binary black hole system in PKS 1510-089 according to the observed periodic eclipse of the PBH by the SBH. Our conclusion show that the decline in luminosity is attributed to the effect of the SBH on the PBH's jet. We also take into account the magnification of luminosity that is due to the gravitational lensing effect. As a result we find that this effect is so small that it can be ignored reasonably. Based on the value of black holes' total mass in Ref.[22], we obtain results as follows:

$$M_1 = 1.37 \times 10^9 M_\odot, \tag{25}$$

$$M_2 = 1.37 \times 10^7 M_\odot, \tag{26}$$

$$a = 2 \times 10^{16} \text{ cm}. \tag{27}$$

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