Constraining Recoiling Velocities of Black Holes Ejected by Gravitational Radiation in Galaxy Mergers

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Abstract

Recent general relativistic simulations have shown that the coalescence of two spinning black holes (BH) can lead to recoiling speeds of the BH remnant of up to thousands of km/s as a result of the gravitational radiation emission. It is important that the accretion disc remains bound to ejected BH within the region where the gas orbital velocity is larger than the ejection speed. We considered the situation when the recoiling kick radius coincides with the radius of the broad line region (BLR). We show that in this situation the observed polarization data of accretion disk emission allow to determine the value of the recoil velocity. We present the estimates of the kick velocity for AGN with determined polarization data.

Keywords

supermassive black holes, active galactic nuclei, accretion disk, polarization;

1 Introduction

Mergers of spinning BHs can produce recoil velocities ("kicks") of the final merged BHs resulting from anisotropic gravitational radiation up to several thousands km/s [Loeb 2007; Shields and Bonning 2008; Komossa and Merritt 2008]. Gravitational wave (GW) recoil implies that the supermassive black hole (SMBH) spend a significant fraction of time off nucleus, at scales beyond that of the molecular obscurity torus. For example, according to [Batcheldor et al. 2010], isophotal analysis of M87, using data from the Advanced Camera for Surveys, reveals a projected displacement of 6.8±0.8 pc (~0''.1) between the nuclear point source (presented to be location of the SMBH) and the photo-center of the galaxy itself.

A recoiling SMBH in an active galactic nuclei (AGN) retains the inner part of its accretion disc. Bonning et al. (2007) and Komossa and Merritt (2008) have shown that the accretion disc will remain bound to the recoiling BH, inside the radius

$$R_k = \frac{GM_{BH}}{V_k^2} = 0.43 \left( \frac{M_{BH}}{10^8 M_\odot} \right) \left( \frac{V_k}{10^3 \text{km/s}} \right)^{-2} \text{pc}, \quad (1)$$

where $V_k$ is the recoiling velocity and $M_{BH}$ is the mass of a black hole.

According to Komossa and Merritt (2008) a large fraction of the broad line region (BLR) remains bound to the recoiling hole, which structure of the size of torus or larger will typically be left behind. It means that the upper radius of the accretion disk (i.e. $R_{BLR}$ in this situation) of the recoiling BH can coincide with $R_k$ and this fact allows for the ejected BH and disk to undergo a luminous phase for observations.

Bonning et al. (2007) have claimed that one of possible manifestation of a recoiling accretion disc is in QSO emission lines shifted in velocity from the host galaxy and they have underlined that few, if any, of these systems are likely candidates for recoiling BHs. They have examined broad line QSOs with observed $H_\beta$ and [OIII] from the SDSS which have broad emission lines substantially shifted relative to the narrow lines. In a result they placed upper limits on the incidence of recoiling SMBHs in QSOs from the SDSS.

Gravitational recoil kicks would have a variety of observational consequences. The kick velocity of remnant depends on the mass ration ($M_2/M_1 < 1$) and spin parameters ($a_1, a_2$) of the binary system, but not
the total mass of the system. For example, according to Bekenstein (1979), Fitchett (1983), González et al. (2007), the recoil velocity for a merger of non-spinning BHs is \( V_k \sim \eta^2 \), where \( \eta = M_1 M_2 / (M_1 + M_2)^2 \).

The power of gravitational waves (GW) is depend-

\[
M_{BH} = f \frac{R_{BLR} V_{BLR}^2}{G},
\]

where \( f \) is a virial coefficient (factor) that depends strongly on the geometry, velocity field and orientation of BLR, \( R_{BLR} \) is the radius of BLR and \( V_{BLR} \) is the velocity dispersion that is measured usually as the full width of the emission line at a half of height in the radiation spectrum, i.e. \( V_{BLR} = FWHM \). The BLR radius \( R_{BLR} \) is determined usually by the reverberation method, i.e. with time delay between continuum and emission line variations.

There are various approaches for determining the value of \( f \). Many authors used the value \( f \approx 1.0 \). Peterson and Wandel (1999) suggested the value \( f = 3/4 \). Onken et al. (2004) used the mean value of the virial coefficient as \( f = 1.4 \). McLure and Dunlop (2001) have shown that for a disc shaped BLR without a combination of a random isotropic components inclined at angle \( i \) to the observer line of sight the virial coefficient can be presented as:

\[
f = \frac{1}{4 \sin^2 i}.
\]

For a geometrically thin disc shape BLR, Eq. (2) and (3) transform into

\[
\sin i = \frac{1}{2} \left( \frac{R_{BLR}}{R_g} \right)^{1/2} \left( \frac{FWHM}{c} \right),
\]

where \( FWHM \) is the observed full width of the emission line. Vestergaard and Peterson (2006), Ho et al. (2008), Wang et al. (2009), Shen and Ho (2014), and \( R_g = GM_{BH}/c^2 \) is the gravitational radius.

The value of the inclination angle \( i \) can be determined from polarimetric observations. We have the results of the detailed numerical calculations of the degree of polarization \( P_1 (\mu = \cos i) \) for the radiation scattered in the optically thick plane parallel atmosphere. These calculations were made in the framework of the classical Chandrasekhar-Sobolev theory (Chandrasekhar 1950, Sobolev 1963).

2 Relation between polarization degree of emission lines and recoiling velocity of SMBH

We can obtain the constraints on the kick velocity value is one suggests that the next relation takes the form: \( R_k \approx R_{BLR} \). If this relation occurs then we obtain from (3) and (4):

\[
\sin i = 0.492 \alpha \left( \frac{FWHM}{V_k} \right), \quad \alpha = \frac{R_{BLR}}{R_k}.
\]
We shall consider the situation when the coefficient $\alpha \leq 1$. It means that our results of $V_k$ really present bounds on the kick velocity value. It is very important that the value of the inclination angle can be determined from polarimetric observations using the standard Chandrasekhar-Sobolev theory of multiple scattering of the radiation on free electrons and Rayleigh scattering on gas molecules and small dust particles. According to these classical works, the polarization degree of scattered radiation depends strongly on the inclination angle. For example, the scattered radiation has the maximum linear polarization $P_l = 11.7\%$ when the line of sight is perpendicular to the normal to the semi infinite atmosphere (Milne problem). Chandrasekhar (1950) and Sobolev (1963) presented the solution of so-called Milne problem that corresponds to multiple scattering of light in optically thick flattened atmosphere.

We used the theory of multiple scattering of polarized radiation and disc like model for the BLR and estimated the values of the virial factors and the mass values for SMBH in AGN (Piotrovich et al. 2015).

Now, using Eq. 3 is is possible to obtain the real relation between the degree of linear polarization and the recoil velocity $V_k$, of course, in the situation when $R_k \approx R_{BLR}$. At Fig. 1 it is presented the dependence of the polarization degree on the kick velocity according to Eq. (5) for the different values of FWHMs.

According to Lousto and Zlochower (2011) the recoil velocity of BHs with individual spin $\alpha = 1$ has the value $V_k = 4915.2$ km/s. For $FWHM = 5 \times 10^3$ km/s the polarization degree according to Eq. (6) is $P_l(H_\beta) = 0.624\%$. This value corresponds to the extreme kick velocity. This extreme case can only be realized by essentially particular fine tuned configuration of the individual black hole spin vectors.

3 Estimates of the kick velocity from the spectropolarimetric data of Smith et al. (2002) and Afanasiev et al. (2011)

For determining the kick velocity $V_k$ from Eq. (5) we used the polarimetric data that are presented in the spectropolarimetric atlas of Smith et al. (2002). They obtained the values of polarization degree and polarization angles for 36 Type 1 Seyfert galaxies. These data have been obtained in a result of different runs at the Anglo-Australian and William Hershel telescopes. From 36 objects presented in the atlas of Smith et al. (2002) for most of the observed objects there is a difference between the continuum and BLR emission values of the polarization degree, and the position angle. We suggest that this difference can be connected to the contribution of the kick velocity to the broad line structure according to Eq. (5). For estimates of FWHM values we used published data (Vestergaard and Peterson 2006; Ho et al. 2008; Wang et al. 2009; Feng et al. 2014). These data belong to the observed full width of the $H_\beta$ emission line, but the Smith et al. (2002) polarimetric data belong to $H_\alpha$ emission line. However existing relation between $H_\alpha$ and $H_\beta$ full width (Greene and Ho 2005) confirms the approximate equality between these widths:

$FWHM(H_\beta) = (1.07 \pm 0.07) \times 10^3 \left( \frac{FWHM(H_\alpha)}{10^3 km/s} \right)^{1.03 \pm 0.03}$ (6)

The results of our calculations of the SMBH kick velocities are presented at Table 1. Of course, these results can be considered as upper limits.

In our estimates of recoiling velocities we suggested $\alpha \leq 1$. It is interesting to compare the real value of $R_k$ from Eq. (1) with values of $R_{BLR}$ published in literature. For the value of $V_k$ which is presented in Eq. (1) we use the bound value of the kick velocity from our Table 1. The values of $R_{BLR}$, estimated by Greene et al. (2000); Shen and Loeb (2001); Bentz et al. (2012), correspond in the error limits to values of $R_k$ from Eq. (1).

For example, for Fairall 9 $R_{BLR} = 10^{16.89}$ cm, $R_k = 10^{16.8}$ cm, for I Zw 1 $R_{BLR} = 10^{17.4}$ cm, $R_k = 10^{17.5}$ cm, for Mrk 6 $R_{BLR} = 10^{16.3}$ cm, $R_k = 10^{16.4}$ cm, for MArk 279 $R_{BLR} = 10^{16.4}$ cm, $R_k = 10^{16.4}$ cm, for Mrk 509 $R_{BLR} = 10^{17.01}$ cm, $R_k = 10^{17.06}$ cm, for Mrk 335 $R_{BLR} = 10^{16.64}$ cm, $R_k = 10^{16.8}$ cm.
Table 1: Polarization of AGN radiation, Smith et al. (2002), Afanasiev et al. (2011) and bounds on kick velocity values (Eq. (5)).

| Objects | $P_1$ | FWHM | $V_k$ |
|---------|-------|------|-------|
| Akn 564 | 0.52 ± 0.02 | 865 | 772 |
| I Zw 1 | 0.67 ± 0.01 | 1117.4 | 959.9 |
| Mrk 290 | 0.90 ± 0.04 | 4270 ± 157 | 3160 |
| Fairall 51 | 5.19 ± 0.07 | 3079 | 1550 |
| NGC 3783 | 0.52 ± 0.02 | 3555 | 3242 |
| NGC 4051 | 0.55 ± 0.04 | 1034 | 925 |
| Mrk 509 | 0.85 ± 0.03 | 3423 | 2587 |
| Mrk 335 | 0.52 ± 0.02 | 1840 | 1695 |
| Mrk 6 | 0.90 ± 0.02 | 4512 ± 38 | 3343.3 |
| Mrk 304 | 0.72 ± 0.07 | 4532 | 3637 |
| Mrk 765 | 0.46 ± 0.07 | 1790 | 1718 |
| Mrk 871 | 0.65 ± 0.13 | 3688 | 3096 |
| Mrk 876 | 0.81 ± 0.04 | 5017 | 3843 |
| Mrk 915 | 0.47 ± 0.07 | 4560 ± 500 | 3864 |
| NGC 4593 | 0.57 ± 0.05 | 3769 | 3323 |
| NGC 6814 | 1.71 ± 0.07 | 4200 | 2548 |
| PG 0007+106 | 1.02 ± 0.38 | 5084.6 | 3605 |
| PG 0026+129 | 0.99 ± 0.28 | 2250 | 1611 |
| PG 0049+171 | 1.42 ± 0.31 | 5234.3 | 3411 |
| PG 0157+001 | 0.71 ± 0.28 | 2432 | 1965 |
| PG 0804+761 | 1.00 ± 0.38 | 3276 | 2326 |
| PG 0844+349 | 0.69 ± 0.10 | 2694 ± 58 | 2194 ± 47 |
| PG 0953+414 | 0.39 ± 0.12 | 3071 ± 27 | 2824 ± 28 |
| PG 1022+519 | 0.83 ± 0.30 | 1566.4 | 1364 |
| PG 1116+215 | 0.46 ± 0.10 | 2896.9 | 2794.6 |
| PG 2112+059 | 1.14 ± 0.22 | 3176.4 | 2173.6 |
| PG 2130+099 | 0.62 ± 0.15 | 1781 ± 5 | 1513 ± 4 |
| PG 2214+139 | 1.40 ± 0.16 | 4532 | 2903.3 |
| PG 2235+134 | 0.67 ± 0.23 | 1709.2 | 1411 |

Table 2: Polarization of AGN radiation and bounds on kick velocity values (Eq. (5)) for geometrically thick accretion flow, Smith et al. (2002), Afanasiev et al. (2011).

| Objects | $P_1$ | FWHM | $V_k$ |
|---------|-------|------|-------|
| Mrk 279 | 0.48 ± 0.04 | 5208 ± 95 | 2928 |
| Akn 120 | 0.40 ± 0.02 | 5536 ± 297 | 2768 |
| Fairall 9 | 0.40 ± 0.11 | 5618 ± 107 | 3786 |
| NGC 5548 | 0.69 ± 0.01 | 5822 | 3693 |
| PG 2209+184 | 0.83 ± 0.29 | 6487.3 | 3143 |

For AGNs, presented in the Table 1, the recoil velocities are essentially lower than the upper limit for recoil $\sim 5000$ km/s. For some other AGN, including Mrk 279, Akn 120, Fairall 9, NGC 5548 and PG 2209+184 polarimetric estimates with Eqs. (2) and (3) give the values above this upper limits. It appears that in the case of the geometrically thick disk-like structure of BLR the polarimetric data from Smith et al. (2002) and Afanasiev et al. (2011) provide the values extremely lower the largest recoil value.

According to Collin et al. (2006) and Decarli et al. (2011) the expression for the virial factor can be presented in the following form:

$$f = 0.25 \left[ \frac{(H/R)^2 + \sin^2 i}{R} \right], \quad V_{BLR} = FWHM,$$  

where $H/R$ is the aspect ratio, i.e. the ratio of the geometrical thickness of the BLR to this radius ($R = R_{BLR}$). As a result we obtain instead of (3) and (5) the following expressions

$$\sqrt{\left(\frac{H}{R}\right)^2 + \sin^2 i} = \left(\frac{FWHM}{2c}\right) \left(\frac{R_{BLR}}{R_g}\right)^{1/2}, \quad (8)$$

$$\sqrt{\left(\frac{H}{R}\right)^2 + \sin^2 i} = 0.492\alpha \left(\frac{FWHM}{V_k}\right). \quad (9)$$

The real value of the parameter $H/R$ can be obtained with (8) using the values of $\sin i$ from the polarimetric observations at the base of Chandrasekhar-Sobolev theory of the generation of polarization for multiple scattering in optically thick plane-parallel atmosphere.

The values of the recoil velocities for a number of AGN, calculating with (7) and (8) are presented in Table 2.

It should be noted that for the objects presented in the Table 1 the polarization degree data and corresponding values of $\sin i$ require the real geometrically thin BLR, i.e. $H/R \ll |\sin i|$.  

4 Discussion and conclusions

According to the basic result of our calculations presented at the Table 1 and Table 2 the kick velocity is smaller than the FWHM value. This result confirms the conclusion of Loeb (2007) that the accretion disc remains bound to the ejected BH within the region where the gas orbital velocity is larger than ejection speed.

The main problem is the fact that the remnant BH recoiling in any direction can exceed the escape velocity of galaxies. In this situation the recoil velocity must essentially exceed $\sim 2000$ km/s.

According to Loeb (2007) only the small fraction of quasars could be associated with an escaping BH. If the accreting disk remains bound to ejected BH, one can expect the radiation of this disk would be polarized. Our estimates of the recoiling velocities correspond to the
situation when $R_{BLR} \approx R_k$. But in many cases the situation is realized when $R_{BLR} < R_k$ and in these cases the values of $V_k$ will be considerably lower than obtained values. Therefore our results can be considered as bounds for the real velocity values.

Also it is important that according to Peterson (2007) and Komossa (2012) the region of the kick velocity ($R_k$ from Eq. (1)) is on the order of the size of the BLR of AGN.

Numerical relativistic simulations have produced recoil velocities $V_k \geq 10^3 \text{ km/s}$, even reaching $\sim 5 \times 10^3 \text{ km/s}$ for certain configurations of BH spins (Lena et al. 2014; Campanelli et al. 2007b; Lousto and Zlochower 2011; Lousto et al. 2012). Such velocities would cause large displacements of the coalesced SMBH from the center of galaxy or, in the extreme cases, eject it entirely from the host galaxy (Merritt et al. 2004; Volonteri et al. 2010). But recoils exceeding the escape velocity of the host galaxy are expected to be relatively rare. It is more important that coalesced SMBH will undergo damped oscillations that will prevent the real escape of the object from the host galaxy.

Merritt et al. (2009) and Gualandris and Merritt (2008) have shown that one of the key consequences of GW recoil is long lasting oscillations of the SMBH around the host galaxy core, implying that the SMBHs may spend as long as $10^6 \div 10^9$ years of the nucleus with an amplitude of parsecs or kiloparsecs. For example, N-body simulations have shown that the SMBH can oscillate within the bulge for $\sim 1$ Gyr before coming to rest (Gualandris and Merritt 2008).

Also it is important that recoiling BH trajectories strongly depend on the gas content of the host galaxy. Maximal BH displacements from the center may vary by up to an order of magnitude between gas rich and gas poor mergers.

The problem of oscillating of BH kicks in host galaxies is the extremely complex and deserves the special investigation. The base of our consideration is the suggestion that the radius of BLR coincides with the initial kick radius determined by Eq. (1) (Komossa and Merritt 2008). If even the intrinsic BH velocity oscillate, the initial BLR remains bound to the recoiling hole and therefore keeps the information on the initial recoiling velocity.

It should be mentioned that last investigations showed that the probability that a remnant BH recoils in any direction at a velocity exceeding $\sim 2000 \text{ km/s}$ (escape velocity of large elliptical galaxies) in only 0.03% (Lousto et al. 2012).

For all AGNs presented at our Table 1 and Table 2 the kick velocity appears smaller than the FWHM value though reach the values of thousands km/s. Of course, these values should be considered as the limit value. It is very important that our estimates confirm that a recoiling SMBH retained the inner part of its accretion disc and in many cases $R_k \approx R_{BLR}$.

Recently Robinson et al. (2010) have presented the results of spectropolarimetric observations of the quasar E1821+643 ($z = 0.297$). For this object the broad Balmer lines in total flux are redshifted by $\sim 10^3 \text{ km/s}$ relative to the narrow lines.

At first sight the quite large values of the recoiling velocity, presented at Table 1 can exceed the escape velocity of the host galaxy. But, according to Lousto et al. (2012), these events are expected to be relatively rare. More frequently the SMBH will undergo damped oscillations in the galaxy potential. N-body simulations (Gualandris and Merritt 2008) have shown that moderately large kicks, that can be sufficient to eject the SMBH from the core, result in long lived oscillations which damp on a timescale $\sim 1$ Gyr.

Systematic searches of large SDSS AGN samples have revealed $\sim 100$ objects that exhibit velocity shifts $> 10^3 \text{ km/s}$ between the broad and narrow lines (Bonning et al. 2007; Tsalmantza et al. 2011; Eracleous et al. 2012). We intend to arrange the special polarimetric programm of observations of these objects at the Russian BTA-6m telescope.

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