Quasars with a Kick – Black Hole Recoil in Quasars

G. A. Shields\textsuperscript{2}, E. W. Bonning \textsuperscript{3}, and S. Salviander \textsuperscript{2}

ABSTRACT

Mergers of spinning black holes can give recoil velocities from gravitational radiation up to several thousand km s\textsuperscript{−1}. A recoiling supermassive black hole in an AGN can retain the inner part of its accretion disk, providing fuel for continuing AGN activity. Using AGN in the Sloan Digital Sky Survey (SDSS) that show velocity shifts of the broad emission lines relative to the narrow lines, we place upper limits on the incidence of high velocity recoils in AGN. Brief but powerful flares in soft X-rays may occur when bound material falls back into the moving accretion disk.

Subject headings: galaxies: active — quasars: general — black hole physics

1. Introduction

Recent numerical simulations of binary black hole mergers by a number of groups show large recoil velocities or “kicks” resulting from anisotropic emission of gravitational radiation [see, e.g., Campanelli et al. (2007) for a summary and references]. These results show a maximum kick for spins anti-aligned and perpendicular to the orbital angular momentum, reaching 2500 km s\textsuperscript{−1} for spin $a_* = 0.8$ (González et al. 2007; Tichy & Marronetti 2007). Campanelli et al. (2007) predict a maximum recoil velocity of 4000 km s\textsuperscript{−1} for equal mass black holes with maximal spin. For a binary supermassive black hole ($\sim 10^8 M_\odot$) formed during a galactic merger (Begelman et al. 1980), the kick may displace the black hole from the galactic nucleus or eject it entirely (Merritt et al. 2004, and references therein).

If an accretion disk is present, the inner part will remain bound to the black hole, fueling AGN activity as the black hole leaves the galactic nucleus. For a merger taking place in an AGN, the accretion disk fueling the AGN will remain bound to the recoiling black hole inside the radius $R_b = 10^{18.1} M_8/v_{1000}^2$ cm where the orbital velocity equals $v_{\text{kick}}$. Here, $M_8 = M_{\text{BH}}/10^8 M_\odot$ and $v_{1000} = v_{\text{kick}}/1000$ km s\textsuperscript{−1}. For an $\alpha$-disk (Shakura & Sunyaev 1973; Frank et al. 2002), the disk mass $M_b$ that remains bound is

$$M_b = (10^{8.0} M_\odot) \alpha^{-4/5} M_8^{3/2} M_0^{7/10} v_{1000}^{-5/2}$$

where $M_0$ is the accretion rate in solar masses per year (Loeb 2007; Bonning et al. 2007), subject to $M_{\text{disk}} < M_{\text{BH}}$ for stability. Until the disk is depleted, the post-merger accretion rate will resemble the pre-merger accretion rate, giving a disk consumption time $t_d \approx$
\[ \frac{M_b}{\dot{M}_0} \approx (10^8 \text{ yr}) \alpha^{-4/5} M_8^{3/2} \dot{M}_0^{-3/10} v_{1000}^{-5/2} \]

Thus a recoiling AGN could shine for a time comparable with estimates of the total AGN lifetime. Here we discuss two observational manifestations of black hole recoils in AGN, involving Doppler shifts of the emission lines and energy released by infall into the disk following the recoil.

2. Shifted emission lines

The broad emission-line region (BLR) of AGN corresponds to material that remains bound to the black hole, whereas the narrow lines arise from gas in the potential of the host galaxy that will not follow the recoiling black hole (Merritt et al. 2006). Therefore, the broad lines will appear shifted with respect to the galaxy systemic redshift as expressed by the narrow emission lines. We have carried out a search for candidate kicked QSOs using spectra from the Sloan Digital Sky Survey Data Release 5 (DR5). We used objects spectroscopically identified as QSOs by SDSS having 0.1 < z < 0.81 such that Hβ and [O III] λ5007 were both measurable. The lines were measured as in Salviander et al. (2007), involving subtraction of Fe II and narrow Hβ, and a Gauss-Hermite fit to the line profiles with asymmetry parameter \( h_3 \) and kurtosis parameter \( h_4 \). Our final data set consists of 2598 objects. This reflects the various quality cuts of Salviander et al. (2007) plus elimination of objects with strongly asymmetrical Hβ giving \( h_3 \) greater than 0.1 in absolute value. The displacement of the broad Hβ line peak with respect to the peak of [O III] was calculated as \( \Delta v_{\text{H} \beta} = c(z_{\text{H} \beta} - z_{\text{O III}})/(1 + z_{\text{O III}}) \) and analogously for Mg II. For details see Bonning et al. (2007).

The distribution of \( \Delta v_{\text{H} \beta} \) has a mean displacement of +100 km s\(^{-1}\) and a FWHM of 500 km s\(^{-1}\). The distribution of \( \Delta v_{\text{Mg}} \) has a similar FWHM and mean displacement of ~150 km s\(^{-1}\). In our data set of 2598 objects, the fractions \( f_i \) having \( \Delta v_{\text{H} \beta} \) greater than a given value are: \( f_{500} = 0.04, f_{800} = 0.007, f_{1000} = 0.0035, f_{1500} = 0.0012, f_{2000} = 0.0008, \) and \( f_{2500} = 0.0004. \) However, we regard these values as upper limits on the number of true recoils: (1) Mg II typically has a smaller shift than Hβ, such that \( \Delta v_{\text{Mg}} \approx 0.6 \Delta v_{\text{H} \beta} \). For recoils, one expects similar shifts for all broad lines. (2) The largest shifts occur only for objects with large Hβ FWHM, a correlation not expected for recoils. (3) The high \( \Delta v_{\text{H} \beta} \) objects generally have normal narrow line intensities and [Ne v] profiles wider than the lower ionization lines, consistent with a normal NLR with a central ionizing source. (4) Some high \( \Delta v_{\text{H} \beta} \) objects show a characteristic asymmetry involving a suppression of the flux on one side of the line, suggesting complications in the BLR.

Among the 501 objects having measured velocities for both Hβ and Mg II, there are no objects with \( \Delta v_{\text{Mg}} > 800 \text{ km s}^{-1} \) for which \( \Delta v_{\text{H} \beta} \) and \( \Delta v_{\text{Mg}} \) agree within expectation. This suggests \( f_{800} < 0.002, \) a tighter limit than above.

For mergers of two black holes with spin \( a_* = 0.9 \) and a range of mass ratio \( q \equiv m_2/m_1 > 0.2, \) Schnittman & Buonanno (2007) estimate theoretical values \( f_i^{500} = 0.31 \) and \( f_i^{1000} = 0.079. \) Convolving with random kick inclinations, we find the predicted line-of-sight fractions to be \( f_i^{500} = 0.18 \) and \( f_i^{1000} = 0.054. \) Our observational results give upper limits on \( f_i \) substantially lower than these predictions. However, a number of factors may contribute to the low observed incidence of recoil shifts. (1) A thorough exploration of parameter space for mergers is needed using full numerical relativity simulations (Campanelli et al. 2007). (2) The distribution of spin parameters \( a_* \) for supermassive black holes remains uncertain, as does the expected distribution of

\[^{1}\text{The SDSS website is http://www.sdss.org}\]
merger parameters (mass ratio, spin orientations). For example, Bogdanović et al. (2007) argue that gas accretion will align the spins with the orbital angular momentum vector, resulting in small kicks. (3) The likelihood of black hole mergers early in the luminous phase of an AGN is uncertain. (4) The observed shift velocity may be substantially reduced by dynamical effects including the inertia of the bound disk and the stars that remain bound to the recoiling hole, as well as the slowing of the black hole by the gravitational potential of the galaxy and by dynamical friction over the luminous life of the wandering AGN (Merritt et al. 2004; Madau & Quataert 2004).

These dynamical effects are less severe for large kick velocities. For our sample, the median value of $M_{\text{BH}}$, derived from the H$\beta$ line width (Salviander et al. 2007) is $10^{7.9} M_\odot$, with $L/L_{\text{Ed}} \approx 10^{-0.8}$, and $M_0 = 10^{-0.5}$. Here we have assumed $L = 0.1 M c^2$ and $L_{\text{bol}} = 9 \nu L_\nu (5100)$ (Kaspi et al. 2000). For this configuration, the bound disk mass is $M_0 \approx (10^{7.4} M_\odot) v_{1000}^{-5/2}$. The momentum of the recoiling black hole will be shared by the mass of the bound disk traveling with it, giving $v = v_{\text{kick}} M_{\text{BH}} / (M_{\text{BH}} + M_0)$. However, for $v_{\text{kick}} > 1500$ km s$^{-1}$ this does not seriously slow the hole. The typical $M_{\text{BH}}$ for our sample corresponds to $\sigma_* \approx 175$ km s$^{-1}$ by the $M_{\text{BH}} - \sigma_*$ relationship of Tremaine et al. (2002). A recoil at $v_{\text{kick}} = 2000$ km s$^{-1}$ gives $M_0 = 0.07 M_{\text{BH}}$, which slows the hole to 1900 km s$^{-1}$. The disk consumption time $t_d$ is about 17 million years. We have estimated the slowing of the hole in a simple model for the host galaxy resembling the isothermal sphere model of Madau & Quataert (2004). The hole reaches a radius of roughly 30 kpc while slowing to $\sim 1500$ km s$^{-1}$ during the luminous phase. (For this high velocity, dynamical friction is minor during $t_d$.) Most of the luminous phase is spent close to this velocity, and half of the objects will have a line-of-sight velocity component above 800 km s$^{-1}$ for random orientations.

If the AGN in our sample have a typical lifetime of 50 million years, whereas the life of objects with $v_{\text{kick}} > 2000$ km s$^{-1}$ is about 17 million years, then the fraction of AGN with an observed shift over 800 km s$^{-1}$ will be $f_{800} \approx (0.5)(17/50)f_{2000}^2$, where $f_{2000}$ is the intrinsic fraction of recoils over 2000 km s$^{-1}$. This may be compared with our observed limit of less than 0.2% for shifts over 800 km s$^{-1}$, implying that $f_{2000}^2 < 1.2\%$. This example suggests that the statistics of velocity shifts have potential to give useful constraints on high velocity recoil events.

3. Recoil flares

Marginally bound material will lag behind the recoiling hole and then fall back into the disk with velocity $\sim v_{\text{kick}}$. In the frame of the moving hole, the bound disk material has excess energy $E_{\text{flare}} = (1/2) M_8 v_{\text{kick}}^2$ compared to material in circular orbit with the pre-kick angular momentum. The energy associated with the mass given by Eq. 1 is

$$E_{\text{flare}} = (10^{57.3} \text{ erg}) \alpha_{-1}^{-4/5} M_8^{3/2} M_0^{7/10} v_{1000}^{-1/2}.$$ (2)

If this energy is dissipated on the dynamical timescale

$$t_{\text{flare}} = \frac{R_h}{v_{\text{kick}}} = (420 \text{ yr}) M_8 v_{1000}^{-3}$$ (3)

by shocks as the material falls back, the power associated with this “recoil flare” is

$$L_{\text{flare}} = (10^{47.2} \text{ erg s}^{-1}) \alpha_{-1}^{-4/5} M_8^{1/2} M_0^{7/10} v_{1000}^{5/2}.$$ (4)

The post-shock temperature will be

$$T_{\text{shock}} = (10^{6.9} \text{ K})(v_{1000})^2 = (0.7 \text{ keV}) v_{1000}^2$$ (5)

(Osterbrock & Ferland 2006). The flare may substantially exceed the luminosity of the
QSO in its active phase as well as the Eddington limit, raising the possibility of radiation driven outflows.

The shocks will emit soft X-rays, but absorption by the infalling material will be severe. Consider a QSO with $M_{\text{BH}} = 10^8 \, M_\odot$ accreting at $10^{-0.5} \, M_\odot \, \text{yr}^{-1}$ (giving $L/L_{\text{Ed}} \approx 10^{-0.9}$) before the final black hole in-spiral. For a kick velocity of 1000 km s$^{-1}$, the bound disk has mass $10^{7.7} \, M_\odot$, radius $R_b = 10^{18.1} \, \text{cm}$, and surface density $\Sigma \approx 10^{4.2} \, \text{g cm}^{-2}$. This corresponds to an electron scattering optical depth (if ionized) $\tau_e \approx 10^{5.8}$. The optical depth due to photoelectric absorption by H, He, and heavy elements will be large. The density of the infalling material is $N = 10^{8.9}$ atoms per cubic centimeter. For a rough estimate of the spectrum of the cooling shocked gas, we computed a coronal equilibrium model using version 07.02.00 of the photoionization code CLOUDY, most recently described by Ferland et al. (1998). We used $T = 10^7 \, \text{K}$, $N = 10^{10.6} \, \text{cm}^{-3}$, and solar abundances. The cooling time is $\sim 10^{-3.1} \, \text{yr}$, with much of the total cooling in the form of thermal bremsstrahlung. There are many strong emission lines, including lines of Fe XVII to Fe XX at 12 to 15 Å, each with several percent of the total energy. The thickness of the cooling zone will be $\sim 10^{11.8} \, \text{cm}$, small compared with $R_b$.

The X-ray luminosity will photoionize the infalling material approaching the shock. The local energy flux in the X-ray flare is $F_{\text{flare}} \approx 10^{9.8} \, \text{erg s}^{-1} \, \text{cm}^{-2}$, giving an ionizing photon flux of $\phi_i \approx 10^{19.4} \, \text{cm}^{-2}$. We have computed photoionization models with CLOUDY for this precursor zone. We used a thermal bremsstrahlung ionizing spectrum at $10^7 \, \text{K}$ with flux $10^{10} \, \text{erg s}^{-1} \, \text{cm}^{-2}$, a gas density $N = 10^{10} \, \text{cm}^{-3}$, and a cutoff column density $10^{24} \, \text{cm}^{-2}$. The photoionized depth in this pre-shock flow is $\sim 10^{13.5} \, \text{cm}$, again narrow compared to $R_b$. The high ionization parameter ($U = 10^{-0.9}$) and hard ionizing spectrum give strong ultraviolet emission lines of highly ionized species. The Ly$\alpha$ line has an emergent flux of 8% of the incident flux, 28 times the flux of H$\beta$. Other line intensities include $I(\lambda)/I(\text{Ly} \alpha) = 1.5$ for O VI $\lambda 1035$ and 0.8 for C IV $\lambda 1549$. The high density suppresses forbidden line emission. The line widths will be $\sim v_{\text{kick}}$. Any surrounding dusty torus (Antonucci & Miller 1985) will in turn reprocess much of this energy into infrared radiation from dust.

The number of recoil flares currently observable involves the rate of mergers, the probability of kicks of various velocities, and the flare duration at a given velocity. Let $dN/dt$ be the merger rate per year of observer time in some range of $M_{\text{BH}}$ and redshift $z$. Roughly, the number of kicks currently observable is $N_{\text{flare}} \approx (dN/dt) \left( t_{\text{flare}}(1+z) \right) f_{\text{v}}$, where $f_{\text{v}}$ is as above. Haehnelt (1994) derived the black hole merger rate from the QSO luminosity function. For $M_{\text{BH}}$ between $10^7$ and $10^8 \, M_\odot$, Haehnelt finds 0.016 events per year of observer time for $z < 3$, giving roughly 6, 0.2 flares in play for $v_{\text{kick}} > 500$, 1000 km s$^{-1}$, respectively. Uncertainties include the flare duration, the number of obscured QSOs, and Haehnelt’s assumed $L/L_{\text{Ed}}$ and QSO lifetime.

For a $10^8 \, M_\odot$ hole in a QSO shining at $0.3L_{\text{Ed}}$ at $z = 2$, the received flux from the flare is $\sim 10^{-11.7} \, \text{erg s}^{-1} \, \text{cm}^{-2}$ for $v_{1000} = 1$. The observed spectrum will be softened by the redshift, but a considerable fraction of the radiation should still be received at photon energies above 0.2 keV. At $10^{-11.7} \, \text{erg s}^{-1} \, \text{cm}^{-2}$, Hasinger, Miyaji, & Schmidt (2005) find $\sim 0.2$ soft X-ray sources per square degree, so that the recoil flares would need to be identified from among roughy $10^4$ other sources of similar flux.

Recoil flares may provide a unique opportunity to detect high velocity recoils in AGN. Detailed simulations of the gas dynamics and
emitted spectrum are needed to help identify these rare events.

We thank Ski Antonucci, Omer Blaes, Richard Matzner, Meg Urry, and Marta Volonteri for helpful discussions and communications. EWB is supported by Marie Curie Incoming European Fellowship contract MIF1-CT-2005-008762 within the 6th European Community Framework Programme.

REFERENCES

Antonucci, R. R. J., & Miller, J. S. 1985, ApJ, 297, 621

Begelman, M. C., Blandford, R. D., & Rees, M. J. 1980, Nature, 287, 307

Bogdanović, T., Reynolds, C. S., & Miller, M. C. 2007, ApJ, 661, L147

Bonning, E. W., Shields, G. A., & Salviander, S. 2007, ApJ, in press, arXiv:astro-ph/0705.4263

Campanelli, M., Lousto, C., Zlochower, Y., & Merritt, D. 2007, Phys. Rev. Lett., 98, 231102

Ferland, G. J., Korista, K. T., Verner, D. A., Ferguson, J. W., Kingdon, J. B., & Verner, E. M. 1998, PASP, 110, 761

Frank, J., King, A., & Raine, D. J. 2002, Accretion Power in Astrophysics: Third Edition (Cambridge University Press)

González, J. A., Hannam, M., Sperhake, U., Brügmann, B., & Husa, S. 2007, Physical Review Letters, 98, 231101

Haehnelt, M. G. 1994, MNRAS, 269, 199

Hasinger, G., Miyaji, T., & Schmidt, M. 2005, A&A, 441, 417

Kaspi, S., Smith, P. S., Netzer, H., Maoz, D., Jannuzi, B. T., & Giveon, U. 2000, ApJ, 533, 631

Loeb, A. 2007, arXiv:astro-ph/0703722

Madau, P. & Quataert, E. 2004, ApJ, 606, L17

Merritt, D., Milosavljević, M., Favata, M., Hughes, S. A., & Holz, D. E. 2004, ApJ, 607, L9

Merritt, D., Storchi-Bergmann, T., Robinson, A., Batcheldor, D., Axon, D., & Cid Fernandes, R. 2006, MNRAS, 367, 1746

Osterbrock, D. E., & Ferland 2006, ‘Astrophysics of Gaseous Nebulae and Active Galactic Nuclei,’ 2nd ed., University Science Books

Salviander, S., Shields, G. A., Gebhardt, K., & Bonning, E. W. 2007, ApJ, 662, 131

Schnittman, J. D., & Buonanno, A. 2007, ApJ, 662, L63

Shakura, N. I. & Sunyaev, R. A. 1973, A&A, 24, 337

Tichy, W. & Marronetti, P. 2007, arXiv:gr-qc/0703075

Tremaine, S., et al. 2002, ApJ, 574, 740