The Astrophysical Journal, 697:288–292, 2009 May 20 doi:10.1088/0004-637X/697/1/288

SDSS J092712.65+294344.0: RECOILING BLACK HOLE OR A SUBPARSEC BINARY CANDIDATE?

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Received 2008 September 18; accepted 2009 March 4; published 2009 May 1

ABSTRACT

A search for recoiling supermassive black hole (SBH) candidates recently yielded the best candidate thus far, SDSS J092712.65+294344.0 reported by Komossa et al. Here we propose the alternative hypothesis that this object is an SBH binary. From the velocity shift imprinted in the emission-line spectrum we infer an orbital period of ∼190 years for a binary mass ratio of 0.1, a secondary black hole mass of 10^8 $M_\odot$, and assuming inclination and orbital phase angles of 45°. In this model the origin of the blueshifted narrow emission lines is naturally explained in the context of an accretion flow within the inner rim of the circumbinary disk. We attribute the blueshifted broad emission lines to gas associated with a disk around the accreting secondary black hole. We show that, within the uncertainties, this binary system can be long lived and thus, is not observed in a special moment in time. The orbital motion of the binary can potentially be observed with the VLBA if at least the secondary black hole is a radio emitter. In addition, for the parameters quoted above, the orbital motion will result in a ∼100 km s^{-1} velocity shift of the emission lines on a timescale of about a year, providing a direct observational test for the binary hypothesis.

Key words: black hole physics – galaxies: individual (SDSS J092712.65+294344.0) – galaxies: nuclei – quasars: emission lines

Online-only material: color figure

1. INTRODUCTION

The "mass loss" and gravitational rocket effect in the aftermath of the coalescence of a supermassive black hole binary (SBHB) can have profound effects on the properties of the nucleus of the host galaxy and give rise to unique observational signatures (Redmount & Rees 1989; Milosavljević & Phinney 2005; Loeb 2007; Shields & Bonning 2008; Lippai et al. 2008; Schnittman & Krolik 2008; Kocsis & Loeb 2008; Mohayaee et al. 2008; Devecchi et al. 2009; Blecha & Loeb 2008; Gualandris & Merritt 2008).

Since the emission of gravitational waves in the last stages of the merger is not symmetric in general, the product of the merger can receive a significant recoil velocity, up to a few × 100 km s^{-1} for low black hole spins or spin axes aligned with the orbital axis (Herrmann et al. 2007a, 2007b; Baker et al. 2006, 2007; González et al. 2007; Koppitz et al. 2007; Rezzolla et al. 2008). In the special case of maximally spinning, equal-mass supermassive black holes (SBHs) with their spin vectors in the orbital plane and directed opposite to each other, the recoil speed can be up to ∼4000 km s^{-1} (Campanelli et al. 2007b). The fraction of coalescences expected to produce a remnant recoiling at $V > 1000$ km s^{-1} is about 10%, assuming black hole spins of $cJ/GM^2 = 0.9$, mass ratio range of $0.1 < q < 1$, and arbitrary spin orientations (Schnittman & Buonanno 2007; Campanelli et al. 2007a; Baker et al. 2008).

Since the escape speed from most galaxies is less than 2000 km s^{-1} (Merritt et al. 2004), if high-velocity recoils are common, there should be many "empty nest" galaxies, without a central SBH. This is in contrast with the observation that almost all galaxies with bulges have a central SBH (for summary see Ferrarese & Ford 2005). However, if following a galactic merger the two SBHs find themselves in a gas-rich environment, gas accretion torques will act to align the spin axes with the orbital axis and thus, reduce the post-merger kick to a value well below the galactic escape speed. This effect is expected to increase the chance of retention of recoiling SBHs by their host galaxies (Bogdanović et al. 2007). Gas-poor mergers, on the other hand can lead to large recoil speeds that launch the final black hole out of the potential well of the host bulge or host galaxy.

Bonning et al. (2007) searched the Sloan Digital Sky Survey (SDSS) archive for merger products with large velocity offsets from their host galaxy. Among nearly 2600 objects, they found no convincing evidence for recoiling SBHs in quasars, placing an upper limit of 0.2% on the probability of kicks with projected speeds greater than 800 km s^{-1} and 0.04% on the probability of kicks with projected speeds greater than 2500 km s^{-1}. More recently, Komossa et al. (2008), hereafter KZL08, reported the discovery of one such candidate, an SBH receding from its host galaxy at a high projected speed of 2650 km s^{-1}. This detection has very important implications for the cosmological evolution of SBHs. However, it is also remarkable given the likelihood of high-velocity kicks and a narrow observational window (in cosmological terms) associated with this class of objects (Blecha & Loeb 2008). Combined with several observational curiosities, they call the recoil idea into question (see discussion in Section 3). Here we propose that the peculiar spectroscopic properties of SDSS J092712.65+294344.0 (Adelman-McCarthy et al. 2007) can be explained in the context of an SBHB model. In Section 2, we describe the proposed model, in Section 3, we discuss its physical basis, revisit the recoiling black hole model, and close by considering observational tests.

2. A SUPERMASSIVE BINARY BLACK HOLE MODEL FOR SDSS J092712.65+294344.0

SDSS J092712.65+294344.0 (hereafter J0927) exhibits an unusual optical emission-line spectrum that features two sets of lines offset by 2650 km s^{-1} relative to each other. The "redward" system consists of only narrow emission lines (r-NELs) with a full width at half maximum (FWHM) of about

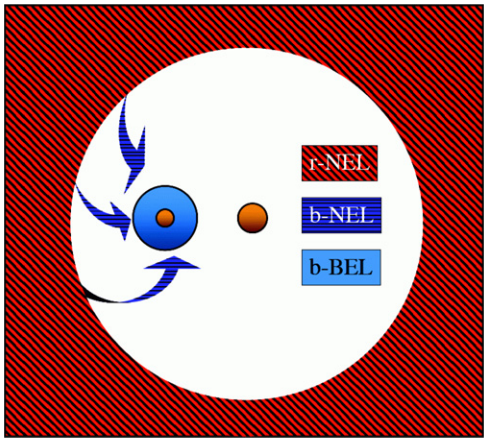

Figure 1. Illustration of the innermost region of a circumbinary disk after the binary has cleared a low density "hole" in the center (top view, not drawn to scale). In the context of the model proposed here, the r-NELs are associated with the circumbinary disk, b-BELs with the disk surrounding the less massive secondary SBH, and b-NELs with the accretion streams flowing from the inner edge of the circumbinary disk toward the disk of the secondary. Accretion occurs preferentially on the secondary SBH, rendering the primary quiescent or much fainter in comparison.

(A color version of this figure is available in the online journal.)

170 km s^{-1} at a redshift of $z = 0.713$; this was identified by KZL08, as the redshift of the galaxy that hosted the recoiling SBH at its birth. The "blueward" emission-line system comprises broad Balmer lines (b-BELs) and narrow, high-ionization forbidden lines (b-NELs) at a redshift of $z = 0.698$ (see Table 1 in KZL08, for the list of lines). In addition, the emission-line ratios of both the blueward and redward systems are consistent with photoionization by a hard ionizing continuum typical of an active galactic nucleus (AGN).

According to the recoiling SBH interpretation of KZL08, the b-BELs originate in the broad-line region (BLR) retained by the SBH. Because of their lower FWHM in comparison to b-BELs, the b-NELs were attributed to gas that is only marginally bound to the SBH. The FWHM of the b-NELs was explained in the context of an accretion disk that is expanding in the process of outward transport of angular momentum, the associated outflows, and the swept up interstellar matter (ISM). The r-NEL lines were attributed to the narrow-line region that remains bound to the host galaxy. The accreting SBH provides a source of ionizing radiation for the b-BELs and b-NELs, as well as for the r-NELs, albeit from a larger distance.

We find that, in the time that it takes the disk to expand to the extent needed to explain the width of the b-NELs, the AGN has traveled tens of kiloparsecs away from the host galaxy and thus, is not likely to power the r-NELs. Combined with the narrow observational window and specific configuration of the pre-coalescence binary, this presents a challenge for the recoiling SBH model (see Section 3.2 for more detailed discussion). Note, however, that the outflow origin of the b-NELs cannot be excluded based on the available data.

We make the alternative suggestion that the observed velocity shift represents the projected orbital velocity of a bound black hole pair. In this model, the emission lines of the blueward system (b-NELs and b-BELs) originate in gas associated with the less massive, secondary black hole, while the r-NELs originate in the ISM of the host galaxy (Figure 1). The accreting secondary SBH is the main source of ionizing radiation while the primary SBH is either quiescent or much fainter than the secondary (see the discussion in Section 3). From the observed X-ray luminosity of J0927 ($L_X = 5 \times 10^{44}$ erg s^{-1}; KZL08) we infer the bolometric luminosity of the secondary[3] and derive a lower limit on its mass of $M_2 \gtrsim 5 \times 10^7 M_\odot$, based on the Eddington limit. We interpret the observed velocity separation of the two emission-line systems as the projected velocity of the secondary relative to the center of mass. Assuming a circular orbit, the projected velocity of the secondary, u_2, is related to its orbital velocity, V_2, via $u_2 = V_2 \sin i \, \sin\phi = 2650$ km s^{-1}, where i is the inclination of the orbital axis of the binary relative to the line of sight, and ϕ is the orbital phase at the time of the observation ($\phi = 0$ corresponds to conjunction). We derive the following expressions for the binary separation and orbital period as

$$a \approx 0.16 \, \frac{M_{2,8}}{1+q} \left(\frac{0.1}{q}\right) \left(\frac{\sin i}{\sin 45^\circ} \, \frac{\sin\phi}{\sin 45^\circ}\right)^2 \text{ pc} , \qquad (1)$$

$$P \approx 190 \, \frac{M_{2,8}}{(1+q)^2} \left(\frac{0.1}{q}\right) \left(\frac{\sin i}{\sin 45^\circ} \, \frac{\sin\phi}{\sin 45^\circ}\right)^3 \text{ yr} . \qquad (2)$$

In the above expressions, $q \equiv M_2/M_1 \leqslant 1$ is the binary mass ratio, and $M_{2,8}$ is the mass of the secondary SBH in units of $10^8 \; M_\odot$. We refrain from using the AGN scaling relations based on the Hβ line width and the continuum luminosity (Kaspi et al. 2005) to estimate the size of the BLR. A scenario in which the size of the BLR is determined by the SBHB dynamics most likely does not represent a "typical" AGN and hence, these or similar relations may not hold. For example, the BLR around the secondary SBH can be truncated by the tidal forces from the primary. This would result in broader lines, compared to a typical AGN with a black hole of the same mass.

If the measured FWHM of the [O III] λ5007 lines is used as an indicator of the stellar velocity dispersion (Nelson 2000), the M–σ relation (Tremaine et al. 2002, for example) implies a mass for the primary SBH that is ~three orders of magnitude below what we adopt in our model. However, such a discrepancy is not unprecedented; there are specific examples of objects that exhibit comparably large discrepancies (Nelson & Whittle 1996). Moreover, if J0927 is a product of a recent merger the velocity dispersion of the narrow-line region gas may not be a good tracer of the stellar velocity dispersion.

3. DISCUSSION & CONCLUSIONS

3.1. The Physical Picture

The evolution of a binary orbit is determined by the relative efficiency of processes that can transport orbital angular momentum, such as stellar and gas dynamical processes and in later stages, the emission of gravitational radiation (Begelman et al. 1980). In the binary model considered here stellar processes are expected to be inefficient and to operate on timescales comparable to the Hubble time (Berczik et al. 2006; Sesana et al. 2007; Perets et al. 2007). A scenario in which large amounts of cold gas are present within the subparsec binary orbit is not favored in the context of current understanding of these systems (Armitage & Natarajan 2002; Milosavljević & Phinney 2005; MacFadyen & Milosavljević 2008). Feedback from the

[3] Using the average quasar spectral energy distributions of Elvis et al. (1994), we find that that the bolometric luminosity is related to the X-ray luminosity via $L_{\rm bol} \approx 14 \, L_X$. Here, the X-ray luminosity is measured in the 0.1–2.4 keV band observable by *ROSAT*.

AGN and binary torques are expected to efficiently heat and disperse the gas. As a consequence, the gaseous dynamical friction does not affect the orbital evolution of the binary in this phase. The gas outside of the SBHB orbit, in the circumbinary disk, can exert torques on the binary and Cuadra et al. (2009) found that only binaries with mass $\lesssim 10^7 M_\odot$ can coalesce within a Hubble time due to this effect (see also Hayasaki 2009), while more massive SBHBs, such as the one assumed here, evolve on longer timescales. If stellar and gas dynamical mechanisms for angular momentum transport are inefficient, the evolution of the subparsec binary orbit will be determined by the emission of gravitational radiation and the assumption of the circular orbit is justified. Note, however, that if high, near-Eddington mass accretion rates onto the binary are plausible, interactions with the circumbinary disk may drive the evolution of the orbital separation and eccentricity on a timescale ∼few × $t_{\rm visc} \approx 10^8$ yr, shorter than $t_{\rm gw}$ (where $t_{\rm visc}$ and $t_{\rm gw}$ are, respectively, the viscous timescale of the disk at the inner edge and the gravitational wave decay time). Realistically, $t_{\rm visc}$ will be longer because the structure of the disk and consequently, accretion rate will be affected by the presence of the binary. If so, the timescale given by $t_{\rm visc}$ can be considered a conservative lower limit on the life span of the binary and the assumption of circularity (or more precisely, moderate eccentricity) is still a plausible one. The timescale for orbital decay of the binary due to the emission of gravitational waves is

$$t_{\rm gw} \approx 1.4 \times 10^{10}\, \frac{M_{2,8}}{(1+q)^5} \left(\frac{0.1}{q}\right)^2 \left(\frac{\sin i}{\sin 45^\circ}\, \frac{\sin \phi}{\sin 45^\circ}\right)^8 \ {\rm yr}\,. \tag{3}$$

Since $t_{\rm gw}$ is a sensitive function of $\sin i$ and $\sin \phi$, it may be shorter than the Hubble time if we are observing the binary at low inclination or close to conjunction, or alternatively if the binary orbit has eccentricity $e > 0.1$.

We thus assume that the binary described here is surrounded by a circumbinary disk, as illustrated in Figure 1. As the binary orbit decays, the inner rim of the disk follows it inward until the timescale for orbital decay by gravitational radiation becomes shorter than the viscous timescale. In the model presented here, $t_{\rm gw} > t_{\rm visc}$, implying that the binary has not detached from the circumbinary disk and can still draw matter from it. Moreover, detailed calculations have shown that for small mass ratios ($q \lesssim 1/{\rm few}$) accretion occurs preferentially onto the lower-mass object which, as a consequence, will be more luminous and easier to detect (Artymowicz & Lubow 1996; Gould & Rix 2000). For example, Hayasaki et al. (2007) find a significant inversion of accretion rates, $\dot{M}_2/\dot{M}_1 = 3.25$ for a $q = 0.5$ binary. This effect is consistent with the picture proposed here that the single set of broad emission lines observed in J0927 is associated with the secondary SBH. On the other hand, a lower limit of $q > 0.01$ can be placed on the binary mass ratio, given our choice $M_2 = 10^8 M_\odot$ and the expected upper limit to black hole masses, $M_{\rm max} \sim 10^{10} M_\odot$ (Natarajan & Treister 2009).

In addition to simulations of SBHBs, the accretion flow between a circumbinary disk and the binary has been modeled in simulations of disks surrounding stellar, T Tauri binaries (Günther & Kley 2002; Günther et al. 2004). The dynamics of these two types of systems are, in fact, quite similar. In particular, a common result of the above simulations is that the accretion on individual binary members is mediated by one or more accretion streams, implying that these may arise as a general property of circumbinary accretion flows. The detailed structure and spectroscopic signatures of such flows are unknown, nevertheless, we propose the following simple picture for the system considered here. Because the gas in accretion streams flowing toward the secondary SBH has a nonzero angular momentum, it is expected to form a small accretion disk surrounding the secondary SBH prior to plunging into it. Given the uniform and monotonic orbital evolution of the binary, this may be a long lived and stable phenomenon, where the rate of accretion onto M_2 (i.e., the surface density of the disk surrounding the black hole) will be determined by the flow rate of matter in the gas streams. MacFadyen & Milosavljević (2008) found the flow rate in such a binary system to be of the order of 10% of the accretion rate onto a single black hole with a mass equal to that of the binary. Some of the gas in the flow is accreted by the black holes, while the rest develops eccentric orbits, may collide with the inner rim of the circumbinary disk and leave the binary system in form of the high-velocity outflows (Armitage & Natarajan 2002; MacFadyen & Milosavljević 2008). While the details of this process remain to be modeled, we suggest in the context of our proposed scenario that a negligibly small fraction of the gas will be accreted by the primary black hole, given the angular momentum "barrier" that the gas experiences. Consequently, an AGN associated with M_1 may either be faint or have short lived accretion phases. This implies that for the binary mass ratio of $q = 0.1$, the accretion rate onto the secondary is less than or equal to its Eddington limit ($\dot{M}_2 \lesssim \dot{M}_{\rm Edd,\,2}$). Thus, the necessary conditions to establish a long term accretion process on M_2 exist, though the realistic physical picture may be more complex due to radiative feedback from the AGN.

The accretion flow within the Roche lobe of the secondary would resemble the accretion flow onto a single SBH in an AGN, i.e., its optical spectroscopic signature will be that of an AGN, exhibiting a spectrum with a blue, featureless continuum and broad, permitted emission lines. This picture is consistent with the properties of the observed b-BELs—if the FWHM of these lines are interpreted to roughly represent the size of the emission region around the secondary, it follows that the size of this region is $\sim 0.1a$ (assuming $i = 45^\circ$). Using the Eggleton (1983) approximation we estimate the effective Roche lobe radius of the secondary to be $R_{L2}/a = 0.21$ for $q = 0.1$. Thus, the BLR is bound to the secondary SBH, consistent with the expectation that any gas beyond the Roche lobe of the secondary should be tidally truncated by the primary.

Binaries with moderate eccentricities and mass ratios that are not extreme are expected to truncate their circumbinary disks at an inner radius of about twice the binary semimajor axis, and hence, the streams from the circumbinary disk to the secondary will flow over a region of size comparable to that of the binary orbit. The stream properties will be intermediate between the physical properties of the secondary's BLR and the NLR of the host galaxy; Dotti et al. (2008), for example, estimate an *average* density in such a circumbinary region in the range (2–8) × $10^6\ {\rm cm}^{-3}$. Of course the density of the gas streams themselves will be higher but they will likely be surrounded by lower-density envelopes resulting from expansion or ablation of the gas due to illumination and heating by the accreting black hole. The gas in the streams will be photoionized by the AGN continuum and the resulting emission-line spectrum may have the following properties. (1) It will consist of permitted lines, as well as forbidden lines from the lower-density parts of the flow, such as the ionized skin of the streams. Due to proximity in velocity space, the lines from the stream should be shifted to approximately the velocity of the broad emission lines from the vicinity of the secondary. (2) The profiles of the lines from this stream will be narrower than the broad, permitted lines and asymmetric, since they trace the *emissivity weighted* distribution of the spatially confined stream of gas.[4] (3) The line shifts, and perhaps also the asymmetries will be variable over the orbital cycle of the binary. We propose that the b-NELs, with their variety of shifts and widths, originate in this part of the flow. Circumstantial evidence in support of the proposed picture is also provided by the relative intensities of the b-NEL and r-NEL lines. By comparing the relative line intensities reported by KZL08 with the photoionization models of Nagao et al. (2001, 2002) we find that the observed [Ne III]/[O II] ratios suggest a higher density (by 1–2 orders of magnitude) in the b-NLR compared with the r-NLR. Moreover, the [O III]/Hβ ratios suggest a higher ionization parameter in the former region by a factor of several, which is also reflected in the [Ne III]/[Ne V] ratio. These differences in density and ionization are consistent with our hypothesis that the r-NLR is associated with gas in the nucleus of the host galaxy while the b-NLR is associated with denser gas that is part of the accretion flow onto the secondary black hole. The above conclusions are subject to some uncertainty because the results of photoionization models are sensitive to a variety of input parameters, such as the spectral energy distribution of the ionizing continuum.

3.2. The Recoiling Black Hole Scenario Revisited

Let us consider the characteristic timescales relevant for the recoiling SBH model with the parameters adopted by KZL08. The time during which a recoiling SBH of mass $\sim 6 \times 10^8\, M_\odot$ appears as an AGN can in principle be close to 10^9 yr, if the mass of the accretion disk carried along by the SBH is comparable to its own mass (Loeb 2007). This cannot be the case in J0927, if its SBH charges away from the host galaxy at nearly the maximum speed predicted by numerical relativity. To accommodate a high-velocity kick, the mass of the disk should be small enough not to slow down the SBH, implying that $t_{\rm AGN} \ll 10^9$ yr. Indeed, Blecha & Loeb (2008) calculate that the mass of the gas disk carried by the recoiling SBH in J0927 is $\sim$2% of the SBH mass, which would be accreted in only $\sim 10^7$ yr, if the accretion rate is 0.1 of the Eddington limit.

If the FWHM of the [Ne III] line is indicative of the expansion of the accretion disk due to outward transport of angular momentum, as suggested in the context of the recoiling SBH model, then the final disk radius is $\sim$seven times larger than that immediately after the recoil. This factor is based on a comparison of the FWHM of the [Ne III] line (reported by KZL08) and the line of sight recoil velocity.[5] A disk expansion should be accompanied by a drop in surface density and an accretion rate reduction by a factor of $>7^2$ (assuming the same disk scale height before and after the expansion). Even if the initial luminosity of this system was close to the Eddington limit, it is now a factor of 100 lower, implying a minimum SBH mass of $\sim 5\times10^9\, M_\odot$, given the estimated bolometric luminosity. It also follows from conservation of angular momentum that in process of disk expansion a sizable portion of the disk mass will be accreted, $M_{\rm acc} \sim M_{\rm disk}/\sqrt{7}$. Given the SBH recoil velocity and the estimated accretion timescale of $\sim 10^7$ yr (Blecha & Loeb 2008), this implies that, by the time this fraction of disk mass is accreted, the receding AGN should be at least few tens of kiloparsecs away from the host galaxy. This poses a challenge for the recoiling SBH model given the requirement for the AGN to power the observed emission lines in both its own BLR and NLR and the NLR bound to the host galaxy. More specifically, the ionization parameter of the r-NLR should be considerably lower than what is observed (see our comparison with photoionization models in Section 3.1). We note that origin of the widths and shifts of the [Ne III] and other b-NELs in an outflow or the swept up ISM gas cannot be excluded. In such a scenario the geometry and velocity distribution of the line-emitting gas is likely to be very complex.

A detection of an AGN recoiling at nearly the maximum speed predicted by numerical relativity requires a combination of coincidences: (1) its recoil velocity vector must lie close to our line of sight; (2) the parameters of the pre-coalescence binary should have been such as to give a recoil speed close to the maximum; and (3) we should be observing the object in a relatively narrow time window after the recoil. This would also imply a larger population of systems at lower recoil speeds, which were not found by Bonning et al. (2007). Indeed, Dotti et al. (2008) calculate that SBHBs with parameters similar to those considered here can be $\sim$100 times intrinsically more common than the recoiling SBHs. A related question, then, is why have there been no more discoveries of SBHBs in the SDSS. The observational biases in the case of subparsec SBHBs are not understood due to uncertainties in the structure and properties of their nuclear regions. The Doppler shift signature may not be observable in all subparsec binaries. The majority of them may either be quiescent or they may exhibit a different signature that we still do not recognize, thus, making the expected (a posteriori) discovery rate for this class of objects difficult to evaluate.

3.3. Possible Observational Tests

The observational property of J0927 that presents the biggest challenge to any model are its two sets of narrow emission-lines. It seems that by coincidence the [O III] λ4959 line at $z = 0.713$ overlaps with the [O III] λ5007 line at $z = 0.698$. Moreover, the low signal-to-noise ratio (S/N) at the blue end of the original SDSS spectrum makes the line profiles difficult to characterize. New optical spectra with a higher S/N and spectral resolution are needed to characterize the line profiles and make better measurements of some line strengths (especially [Ne V]). Complementary near-IR spectra in the J band could show the profile of the Hα line and additional narrow, forbidden lines of important diagnostic value.

Spectroscopic monitoring on timescales of years to decades could provide the most direct test of the binary hypothesis. According to the SBHB model, the emission lines associated with the BLR of the secondary SBH (b-BELs) will shift at a rate of

$$\frac{du_2}{dt} \approx 88\,\frac{(1+q)^2}{M_{2,8}}\left(\frac{q}{0.1}\right)\left(\frac{\sin i}{\sin 45^\circ}\right)^{-3} \times \left(\frac{\sin\phi}{\sin 45^\circ}\right)^{-4}\left(\frac{\cos\phi}{\cos 45^\circ}\right)\,{\rm km\ s^{-1}\ yr^{-1}}\,. \quad (4)$$

Thus, at $\phi = 45^\circ$, the b-NELs would shift by $\sim$100 km s^{-1}

[4] The asymmetry may arise since in general case the stream geometry and velocity will not be symmetric with respect to the observer. While the exact profile shapes of these lines will depend on the photoionization effects (not considered here), these are not expected to give rise to symmetric line profiles, in general.

[5] Assuming that the recoil velocity and the FWHM of the [Ne III] line indicate the truncation radius of the disk before and after the expansion. Larger factors are expected if the radius of marginal self-gravity is considered instead to obtain the former value.

in about a year.[6] Spectroscopic and imaging observations at high angular resolution with the *Hubble Space Telescope* (*HST*) are necessary in order to measure the redshift of the host galaxy, determine whether its morphology shows signs of a recent merger, and provide a check against the possibility of projection of two otherwise unrelated AGNs along the line of sight. Also, in case of the recoiling SBH, *HST* may resolve an off-center AGN, depending on the orientation of the recoil velocity vector with respect to the line of sight. In the case of a binary scenario, if the two black holes (or at least the secondary) are radio emitters, their orbital motion may be detected with the VLBA. At the redshift of J0927, the orbital separation of the binary with parameters scaled as in Equation (1), translates to an angular separation on the sky of about $\sim 20\ \mu$as. This is comparable to the astrometric precision achieved with the VLBA and for a higher-mass binary may approach the expected spatial resolution of the *Square Kilometre Array*.

The confirmation of either model would be a major step toward understanding of subparsec binaries or recoiling SBHs. A binary holds great promise for revealing the physics of gas in the nuclear region and the accretion signatures in the pre-coalescence phase of its evolution. Discovery of a recoiling SBH, on the other hand, has important implications for understanding the demographics of SBHs and their cosmological spin evolution. Both scenarios have direct ramifications for the rate of SBHB coalescences and the exploration of the binary parameter space, of large importance for gravitational wave observatories such as the *Laser Interferometer Space Antenna*.

We thank Cole Miller for useful discussions, and Chris Reynolds, and Sean O'Neill for helpful comments. T.B. thanks the UMCP-Astronomy Center for Theory and Computation Prize Fellowship program for support.

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[6] However, note that there is a range of nonextreme parameter values for which the normalization factor in Equation (4) takes a lower value and consequently, the monitoring period may need to be longer.