1. INTRODUCTION

SDSSJ092712.65+294344.0 (hereafter “SDSSJ0927” in this paper) is an object whose spectrum was acquired by the Sloan Digital Sky Survey (SDSS) as part of its quasar sample. It was first given special attention by Komossa et al. (2008), who combed the SDSS quasar database for objects in which there was a substantial velocity offset between the [O iii]5007 line and the other emission lines. In this case, there is [O iii]5007 emission at the redshift of the broad line centroid (\(z = 0.698 \pm 0.001\)). Hereafter we will refer to this as the associated system. There is a second [O iii]5007 line shifted 2650 km s\(^{-1}\) to the red, at \(z = 0.713\) (hereafter the redshifted system). In fact, there are entire sets of narrow emission lines ([O iii]5007, H\(\beta\), [Ne iii]3869, [O i]3727, [Ne v]3426) at both redshifts, while broad lines (H\(\beta\), H\(\gamma\), [Mg ii]2800) are present only in the lower redshift associated system. Moreover, the narrow lines in the associated system all have substantially broader profiles (FWHM \(\approx\) 450–2000 km s\(^{-1}\)) than those in the redshifted system (FWHM \(\approx\) 170 km s\(^{-1}\)). No stellar lines can be detected in the SDSS spectrum, so there is as yet no measure of the redshift of the host galaxy. For reference, the SDSS spectrum is shown in Figure 1 with the key lines from both systems marked.

Recent numerical relativity calculations have shown that it is possible for a black hole merger to be sufficiently asymmetric that the new merged system moves relative to the original center of mass by as much as several thousand km s\(^{-1}\) when the spins of the original pair are properly aligned relative to the orbital angular momentum and each other (Baker et al. 2006; Campanelli et al. 2007; Gonzalez et al. 2007; Pollney et al. 2007). On this basis, Komossa et al. (2008) suggested that this is an example of exactly such an event: the redshifted narrow emission lines indicate the rest-frame of the host galaxy, while the associated emission lines, both broad and narrow, are attached to the black hole of the ejected quasar, which is moving through the host with a velocity along our line-of-sight of 2650 km s\(^{-1}\).

This suggestion was criticized by Bogdanovic et al. (2009) and Dotti et al. (2009), who argued that the data were more plausibly explained as arising from a black hole binary of separation \(\sim 0.1–0.3\) pc and mass ratio \(q \simeq 0.1–0.3\). In this picture, both black holes are surrounded by a circumbinary disk whose inner edge is a few times the orbital separation. The less massive black hole captures the majority of any gas traveling inward from the inner edge of the disk; accretion of this gas powers the quasar. Thus, the associated system would be attached to the lower-mass black hole, while the redshifted system would be affiliated with the more massive black hole. Both Dotti et al. (2009) and Bogdanovic et al. (2009) argued that this model is much more probable than the merger-recoil model. However, Dotti et al. (2009) estimated that the rate of production of such systems should be \(\sim 10^{-6}\) yr\(^{-1}\) within \(z \sim 1\), while Bogdanovic et al. (2009) argued that such a recoiling quasar would stay within the galaxy for \(\sim 10^7\) yr; in other words, there should be \(\sim 10\) at any given time within \(z \sim 1\). On the other hand, there is no guarantee that the merger product would carry enough accretion fuel to last for \(10^7\) yr. In addition, it seems somewhat implausible that a recoiling black hole would create a narrow emission-line system centered on its velocity. The gas emitting these lines would need to have had initial binding energy to the pre-merger black hole within \(\langle v_{\text{NLR}}/v_{\text{kick}} \rangle^2 \simeq 3\%\) of the critical binding energy at which matter stays bound to the merged black hole. Here \(v_{\text{NLR}}\) is the characteristic speed of the gas relative to the merger remnant and \(v_{\text{kick}}\) is the recoil speed.

Serious difficulties also exist for the binary model. The problem we find most disturbing is the tight kinematic relation between the broad emission line system and its associated narrow lines. In this model, the broad lines are made in more or less conventional fashion, even though the second, more massive black hole, is close enough that its gravity must influence the broad line gas — after all, its gravity is strong enough to force an orbital speed for the quasar black hole \(\geq 2650\) km s\(^{-1}\). The associated narrow lines are attributed to gas flowing between the circumbinary disk and the lower-mass black hole, and therefore traverse a region where, by construction, the characteristic orbital speed is \(\gtrsim 2000\) km s\(^{-1}\). It is hard to understand how, under these circumstances, the narrow lines could be centered on the velocity of the broad lines and have FWHMs as small as 450 km s\(^{-1}\). In addition, Dotti et al. (2009) estimated that the density of the associated narrow emission-line gas, if it occupies a thin disk filling the area within the edge of the circumbinary
is a moderate Type 2 Seyfert, while SDSSJ0927 contains a powerful quasar. Moreover, all the difficulties of the models proposed earlier (either the high-speed recoil or the binary black hole model) disappear viewed from this perspective: there is no problem with probabilities—we already know of another example in the nearby Universe. There is no problem with keeping the gas of the higher redshift system within a narrow range of velocities—it is confined within a galaxy while it travels through a region (the cluster now, not the vicinity of a binary black hole) with much higher orbital speeds. In addition, as we will show shortly, the directly derived properties of the emission-line gas are compatible with this model.

2. EMISSION-LINE ANALYSIS

The flux ratios of the associated narrow lines are very similar to those commonly found in active galactic nuclei (AGNs). According to Komossa et al. (2008), the lines Hβ, [O iii], and [O ii] have the relative strengths 1.0, 1.5, 6.7, 1.8, and 4.0 (Table 1), while in the “mean” narrow line system in a Seyfert or quasar, they would be 1.0, 3.2, 5.0, 1.4, and 1.2 (Krolik 1999). The greatest contrast is in the [Ne v]3426 line. We might therefore suppose that the physical conditions in this gas (ionization parameter, density, etc.) are very similar to what is generally found in other AGNs. In our new interpretation, this gas can therefore be found in its usual location, ~100–1000 pc from the black hole at the center of the galaxy.

The detailed character of this emission-line system is one place where the analogy with NGC 1275 may break down. The line emission at the systemic velocity in NGC 1275 is likely affected by a number of processes in addition to AGN photoionization (Johnstone & Fabian 1988; Sabra et al. 2000; Ferland et al. 2008) that may have their origin in special properties of the cluster environment. Some of these processes may also influence the narrow emission lines associated directly with the quasar SDSSJ0927. However, its luminosity is so much greater than that of the Seyfert galaxy NGC 1275 that the relative

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**Table 1**

| Line        | Associated System | Redshifted System | Mean Narrow-Line System |
|-------------|-------------------|-------------------|-------------------------|
| Hβ          | 1.0               | 1.0               | 1.0                     |
| [O ii]3727  | 1.5               | 2.6               | 3.2                     |
| [O ii]5007  | 6.7               | 10.1              | 5.0                     |
| [Ne iii]3869| 1.8               | 0.7               | 1.4                     |
| [Ne v]3426  | 4.0               | 0.3               | 1.2                     |

*Note.*

4 Normalized to Hβ.

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Since the submission of this paper, a paper by Shields et al. (2009) has appeared that presents new data and independent arguments that SDSSJ0927 is most likely to be a superposition of two systems rather than an ejected or binary black hole.
importance of these other processes may be smaller; perhaps that is why its line ratios so closely resemble those of a generic AGN.

The relative fluxes of the narrow lines in the redshifted system in SDSSJ0927 are also similar to the narrow emission-line regions in AGNs: 1.0, 2.6, 10.1, 0.7, and 0.3, where the lines are listed in the same order as before and also given in Table 1. In the model we favor, this emission would come from gas in the small galaxy that has fallen in from outer regions of the cluster, but is now close enough to the quasar that the gas is photoionized by the quasar continuum. The power source for the redshifted emission lines is different from the case of NGC 1275 where (owing to the relatively small ionizing luminosity of the AGN) the emitting gas in the infalling galaxy is photoionized by hot stars within the galaxy itself.

Without going into an extensive photoionization analysis, we can use the emission-lines in the redshifted system in SDSSJ0927 to see if its basic physical properties are consistent with our model. The flux ratio of the two members of the [O ii]3726,3729 doublet is $1 \pm 0.1$, implying an electron density $n_e \approx 300$ cm$^{-3}$ (Osterbrock & Ferland 2006). In our model this would be gas that, in the absence of a nearby quasar, would reside in cold H i clouds in the ISM of a normal galaxy. The emission measure inferred from the H$\beta$ luminosity is $1 \times 10^{67}$ cm$^3$ (we remeasured both the H$\beta$ and the continuum flux in the SDSS spectrum, and assume $H_0 = 70$ km s$^{-1}$Mpc$^{-1}$, $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$). The implied gas mass is then simply the emission measure divided by the mean density, so that $M_g \approx 2.5 \times 10^7 M_{\odot}$, an entirely plausible gas mass for the irradiated dense clouds in the hypothesized infalling galaxy.

We can estimate the distance from the quasi-stellar object to this infalling galaxy by using the emission line ratios to estimate the ionization parameter in the gas due to exposure to the quasar continuum: $r \approx [L_{\text{ion}}/(n_e \xi)]^{1/2}$, where $L_{\text{ion}}$ is the ionizing luminosity of the quasar, $r$ is the distance from the gas to the quasar, and $\xi \equiv L_{\text{ion}}/(n_e \xi)$ is the ionization parameter.

Assuming that $F_{\text{ion}}/\lambda F_{\lambda}(4000 \ \text{Å}) = 5$, we find that the quasar ionizing luminosity is $8 \times 10^{41}$ erg s$^{-1}$. The ionization parameter appropriate to the observed [O iii]5007/H$\beta$ ratio is $\xi \approx 0.05$ (Osterbrock & Ferland 2006), while we measure $n_e = 300$ cm$^{-3}$ (we caution, however, that the [Ne v] line indicates that there is a significant amount of gas in a higher ionization state, so a simple one-zone model may be somewhat misleading). The implied physical separation between the quasar and hypothesized infalling galaxy is then 8 kpc (similar to the transverse separation between the two systems seen in NGC 1275). If the typical column density of this gas is comparable to the column density of gas in a galactic disk, $N_H \sim 10^{21}$ cm$^{-2}$, it would be optically thick at the Lyman edge, so all the incident ionizing photons would be absorbed and reprocessed. The ratio of the ionizing luminosity from the quasar to the narrow H$\beta$ emission line implies that the irradiated gas would cover a solid angle of $\sim 0.2$ steradians, or an area of 12 kpc$^2$ for a separation of 8 kpc.

Thus, in all respects that we can measure from the existing data, the properties of the redshifted narrow emission-line system are fully compatible with our hypothesis that SDSSJ0927 is a higher redshift version of the NGC 1275 system: a galaxy falling into the deep potential well of a rich cluster of galaxies where it interacts with the host galaxy of an AGN.

3. TESTABLE PREDICTIONS

This model makes a number of predictions that can be readily tested by observations. First, if stellar absorption lines can be detected in this object’s spectrum, their centroid should be close to the bluer system’s velocity, and they might be doubled, with a separation $\approx 2600$ km s$^{-1}$. We recognize, however, that it is in general difficult to detect stellar absorption lines in quasar spectra because they are usually so strongly diluted by the quasar continuum. In addition, high-resolution optical imaging (e.g., using HST), should detect some extended light, perhaps exhibiting irregular structure due to the galaxy–galaxy interaction we suggest is occurring.

Secondly, there should be a rich cluster surrounding this object. The left panel of Figure 2 shows a color SDSS cutout 2' on a side, centered on SDSSJ0927. This corresponds to a physical size of $\sim 850 \times 850$ kpc at the redshift of the quasar. A number of faint red galaxies are visible, particularly to the southwest of the quasar. In the right-hand panel, we plot a histogram of photometric redshifts for galaxies in this field.

Figure 2. Left: SDSS color cutout of a 2' × 2' box around SDSSJ0927. The quasar is marked with a red box. Right: histogram of SDSS-derived photometric redshifts for all galaxies in the left panel within 1' radius of the quasar. The redshifts of the faint red galaxies to the southwest of the quasar are shown by shading in the histogram.
have a stellar mass $\simeq \log_{10} M_\odot$, and then smoothing with a Gaussian of radius 2 pixels ($1''$ FWHM). All nonblack pixels represent a significant detection of object flux, and the red circle indicates the size of the SDSS spectroscopic fiber.

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

Figure 3. Postage stamp $\chi^2$ image of the immediate environment around SDSSJ0927 produced by combining all five SDSS images (ugriz bands), and using redshifts derived from template fitting and made available in the Photoz table (Csabai et al. 2003). Typical quoted errors for the photometric redshifts are $\pm 0.05$. It is clear that in the region as a whole there is an overdensity of galaxies with redshifts slightly less than that of the quasar; the small shift is likely an artifact of the photo-$z$ template fitting, rather than a real difference between the quasar redshift and that of the galaxies in this concentration. Particularly noteworthy, nearly all the faint red galaxies noted in the SW quadrant of the image galaxies in this concentration. Further evidence in favor of both a galaxy cluster surrounding the position of the quasar. Perhaps the redshifted emission-line system is associated with the portion of this galaxy nearest to the quasar (inside the SDSS $3''$ fiber).

Fourth, a cluster whose potential is deep enough to produce an orbital speed of 2600 km s$^{-1}$ should be a bright X-ray source. Komossa et al. (2008) found two observations in the ROSAT archives and estimated the X-ray luminosity at $5 \times 10^{44}$ erg s$^{-1}$. Although an X-ray luminosity of this magnitude would be expected from a quasar having the observed optical luminosity, this luminosity would also be typical of rich clusters of galaxies. It is possible that the X-rays come from both sources.

If these observations had been pointed toward SDSSJ0927, the angular resolution of ROSAT (half-power width $\simeq 5''$) would have been great enough to clearly distinguish a point source from an extended source, as this half-power width translates to 36 kpc at $z = 0.7$. However, in both observations, SDSSJ0927 was near the edge of the field of view, so the resolution was somewhat degraded by imperfections in the ROSAT mirror. In addition, confidence in an observational estimate of this source’s angular extent is also undercut by the small number of counts detected: 70 in one observation, 47 in the other. Neither Chandra nor XMM-Newton observations of this field have been obtained so far.

4. CONCLUSIONS

We believe that, in contrast to more exotic interpretations involving binary black holes and black hole merger events, the most plausible interpretation of the SDSS quasar SDSSJ0927 is that it is a system much like NGC 1275: an AGN lying near the center of a rich cluster of galaxies, interacting with a smaller galaxy that has fallen toward it from farther out in the cluster. There is a very strong phenomenological resemblance between the two systems (the offset velocity is actually about 10% smaller in the SDSS object), and there are none of the physical conundrums that cause concern about the black hole binary interpretations.

Our arguments also suggest that the correct interpretation of double-peaked emission line profiles can be a subtle problem. Two well-separated peaks in a profile do demand two separate regions with dynamical coherence in which gas suitable for line emission is gathered. How that coherence is maintained is another matter: a pair of massive black holes could account for two deep gravitational potential minima, but so could two dense stellar clusters, or one black hole and one stellar cluster. For that matter, there can also be cases in which the gas concentrations are not due to gravity, but to jet working surfaces. Moreover, as we have pointed out, two separate line-emission regions do not necessarily require two separate sources of ionizing photons. The strongest evidence for two sources of ionizing photons is two spatially separated regions of continuum emission.

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