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A Broad-line Quasar with Unexplained Extreme Velocity Offsets: Post-shock Outflow?

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Abstract

The quasar SDSS 0956 + 5128 exhibits three distinct velocity components with large offsets in emission: the systemic velocity of [O II], [O III], and [Ne III] narrow lines have redshift \( z = 0.714 \); the broad Mg II line is shifted by \(-1200 \text{ km s}^{-1}\) with respect to the narrow lines; the broad H\(\alpha\) and H\(\beta\) lines are at \(-4100 \text{ km s}^{-1}\). We present new Hubble Space Telescope spectra of Ly\(\alpha\) and C IV emission lines and high-resolution images of the quasar. The offsets of these lines are consistent with the velocity component of the Balmer emission, and the photometry in optical and near-infrared wavelengths does not show any signs of recent mergers in the host galaxy or irregularities in the location of the quasar. The data do not confirm predictions of the previous most likely hypotheses involving a special orientation and morphology of the quasar disk, such as in the recoiling black hole scenario, neither it is consistent with accretion disk winds. Instead, based on the cumulative evidence, we propose a new scenario, in which the broad-line region is in the state of outflow caused by a strong shock wave, with a supernova as a possible event for producing the shock ejecta.

Unified Astronomy Thesaurus concepts: Quasars (1319); Shocks (2086); Supernovae (1668)

1. Introduction

Although there initially appeared to be several subtypes of active galactic nuclei (AGN) and quasars (QSO) (Antonucci 1993), it has been believed for approximately three decades that nearly all observed AGN are consistent with being similar objects observed from different lines of sight (Lawrence & Elvis 1982; Antonucci & Miller 1985; Bailey et al. 1988; Miller et al. 1991; Urry & Padovani 1995; other references in Antonucci 1993). One consequence is that all quasar spectra exhibit the same set of significant spectral lines: (1) broad emission (or absorption) lines (BEL) including C IV, Ly\(\alpha\), H\(\alpha\), H\(\beta\), and Mg II, among others, with Doppler widths of \(-10^4 \text{ km s}^{-1}\) (Wills et al. 1993; Murray et al. 1995; Vanden Berk et al. 2001) that are normally virialized (Korista et al. 1995; Dietrich et al. 1998; Shapovalova et al. 2001); (2) narrow emission lines, including [O III]\(\lambda\lambda\) 4959,5007, [Ne II]\(\lambda\lambda\) 3869, and [O II]\(\lambda\lambda\) 3727, with widths of \(-500–1000 \text{ km s}^{-1}\); and (3) a wide range of possible narrow emission or absorption lines from the host galaxy, with widths of \(<500 \text{ km s}^{-1}\). These observations have led to a physical picture in which this emission originates, respectively, from a broad-line region (BLR) \(-\sim 1 \text{ pc}\) from the central supermassive black hole, a narrow-line region (NLR) \(-\sim 10^3 \text{ pc}\) away, and the remainder of the host galaxy, which might extend to \(-\sim 10^4–10^5 \text{ pc}\) out. Although inflows or outflows might skew the profiles of these lines (see Gaskell 1982; Eracleous et al. 1995; Strateva et al. 2003), they all emanate from objects in the same host galaxy, and thus are likely centered at the same Doppler velocity (equivalently, redshift) with respect to the observer.

However, a single quasar among the more than \(10^5\) quasars found in Sloan Digital Sky Survey (SDSS) appears to be entirely incompatible with this model. SDSS J095632.49 + 512823.92 (hereafter, SDSS 0956 + 5128) exhibits three distinct and non-typical features that, in combination, make this object unique (Steinhardt et al. 2012) (hereafter, S12).

At first, there are three significantly different velocity components, corresponding to \(z = 0.714, z = 0.707\), and \(z = 0.690\). The narrow-line emission of [O II], [O III], and [Ne III] provides the systemic redshift of the galaxy \(z = 0.714\). The blueshift of broad Balmer emission lines and Mg II from the host galaxy is \(-4100\) and \(-1200 \text{ km s}^{-1}\), respectively. It is not surprising on its own to observe three components. For example, such objects as I Zw 1 are known to exhibit more than two velocity systems with blueshifts from the systemic redshift (Laor et al. 1997; Vestergaard & Wilkes 2001). However, unlike such quasars, the broad emission lines in SDSS 0956 + 5128 are not double peaked or strongly skewed (as in the examples that were studied in detail in Eracleous et al. (1995, 2012) and Tsalmantza et al. (2011)). They are symmetric and completely offset and therefore appear to be consistent with some kind of physical offset of the BLR, such as an outflow.

Only a handful of objects studied in outflows have been observed with nearly as high offsets in H\(\beta\), H\(\alpha\), and Mg II. In fact, offsets of similar magnitude have been found more often in higher ionization lines, such as Si IV, C IV, or higher, and even so in the extreme tail of their offset distribution, as shown by Yu et al. (2021) in SDSS DR7 (Shen et al. 2011) and other quasar samples. The objects with symmetrically offset lines have been studied in connection with the recoiling black holes (BH; Bonning et al. 2007). In fact, no recoil candidates have
been identified with the BLR velocity as high as in the SDSS 0956 + 5128, which is almost twice the second highest offset (Chiaberge et al. 2017).

In addition, the broad Mg II line, which is typically found to be consistent with the systemic velocity (Hewett & Wild 2010; Shen et al. 2016), is offset by $-1200 \, \text{km} \, \text{s}^{-1}$ from the host lines, and thus by $+2900 \, \text{km} \, \text{s}^{-1}$ from Hα and Hβ. No other quasar spectra in the SDSS that have coverage of Balmer lines and Mg II are known to exhibit a strong velocity offset between these lines in the BLR, including the candidates for BH recoils (e.g., Bonning et al. 2007). Indeed, such an offset between Mg II and hydrogen lines, which have similar ionization potentials, should not be possible if both are emitted from nearby parts of the BLR.

It is worth noting that originally S12 reported that Hα and Hβ broad lines are asymmetric, while Mg II is symmetric, contrary to the claim that all lines are symmetric in this work. This is because there does not appear to be a strong asymmetry indicative of different velocity components in the Balmer lines. It may rather be attributed to the clumpy nature of the BLR. This is because there does not appear to be a strong asymmetry produced all of the observed features. The ideas included multiple objects along the line of sight, accretion disk winds, special morphological configurations, or a recoiling black hole.

To examine the applicability of different scenarios, additional observations of high-ionization lines, like C IV, are needed. Combining it with the high-resolution photometry of the central region allows a test of these hypotheses.

Here, new Hubble Space Telescope (HST) observations of C IV and Lyα lines and photometry of the central region of the host galaxy are presented and analyzed. Based on these data, we attempt to distinguish between the previously proposed mechanisms. As none of them appears to match these observations, a new mechanism is proposed to explain SDSS 0956 + 5128.

New HST measurements of the previously unobserved C IV and Lyα BELs in the UV spectrum (Section 2) and photometric observations of the host galaxy at high resolution (Section 3) are presented in the following sections. The broad UV lines are symmetric and appear to have the offset consistent with the Balmer lines. No irregularities are seen in the photometry of the central region of the galaxy. While the QSO is seen as spatially offset, it is within 3σ resolution. Section 4 reviews hypotheses that were previously proposed to explain SDSS 0956 + 5128, such as a combination of the recoiling BH scenario and a double-peaked emitter, and describes why it is a challenging problem. Instead, the cumulative evidence shows a peculiar velocity pattern of the BLR consistent with a strong shock outflow from the central region. Discussion of the observations and a new hypothesis along with final thoughts are presented in Section 5.

This work adopts a flat ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$ throughout.

2. HST Spectrum

The near-ultraviolet (NUV) spectrum of SDSS 0956 + 5128 was recorded with the Space Telescope Imaging Spectrograph (STIS) onboard the HST (Proposal 15872; Steinhardt et al. 2019). The first order G230L long-slit grating was used allowing for spatially resolved spectroscopy with 0.025 arcsec (~180 pc/arcsec) at $z = 0.7142$ and low to medium spectral resolution with $R \sim 500$–1010 (translates to 600–300 km s$^{-1}$ resolution at short to long wavelengths) in the NUV. The HST pipeline CALSTIS (Sohn 2019) used to reduce the spectrum allowed the detection of C IV and Lyα lines. The NUV spectrum allowed the detection of C IV and Lyα lines.

The background in the spectrum was fitted with the exponential function in linear wavelength assuming that the continuum is dominated by the quasar emission. The wavelength windows used for the fit (1290–1460, 1580–1810 Å) were expected to have little or no contamination from prominent line emission or Fe II,III pseudo-continuum described in Vestergaard & Wilkes (2001) and were similar to the clear quasar-continuum windows in Francis et al. (1991). The slope of the model continuum was used to validate the quasar nature of the spectrum. Calculated as $F_\alpha/F_\beta = (\nu_\beta/\nu_\alpha)^{\beta}$, it was found to be $\beta = -1.18 \pm 0.01$, which loosely agrees with the observed distribution of slopes of typical quasars, although in the redder part (Davis et al. 2007). The model was used for the calculation as a cross-check, as the observed spectrum did not cover the wavelengths normally used above 1850 Å.

The background-subtracted C IV and Lyα are shown in Figure 1. The systemic Lyα line is best fit with a Gaussian component at $z = 0.7135 \pm 0.0003$, at 2.3σ deviation from the systemic redshift measured in S12. The line profile is strongly asymmetric, with the most likely contribution from a blue-shifted broad Lyα component. This component is best fit at $z = 0.6909 \pm 0.0026$ with FWHM $\sim 11,511 \pm 1781 \, \text{km} \, \text{s}^{-1}$. This profile is consistent with the observations of Balmer lines in S12, where the narrow peaks are accompanied by the completely blueshifted broad emission. When considering other possible contributions to this blueshifted excess, Si III λ1265.5 and O V λ1218 lines coincide with the profile at $z = 0.707$ and $z = 0.690$, respectively (associated with two offsets identified in S12). However, neither the expected narrow width of these lines, nor the expected low flux can explain the strong broad excess that is best described by the broad Lyα emission.

Additionally, there appears to be a broad excess of flux in the red wing of the profile, which could not be caused by either Si III, O V, Fe II, or Si IV lines at any one of the involved redshifts. Including this component of the profile improves the fit. However, the widths and positions of the broad Lyα and the unknown component become less constrained, as reflected in their uncertainties (see Table 1). The small bump at rest wavelength 1240 Å suggests that the unknown broad component may be the offset N V emission. With this, the fit of the whole profile was produced with $\chi^2 = 0.77$, where the suspected broad N V line had FWHM $= 2907 \pm 2862 \, \text{km} \, \text{s}^{-1}$ at $z = 0.6914 \pm 0.0051$. There is, however, no distinct narrow N V λ1240 component. The offset of the broad Lyα and N V components is at 1.4 and 3.2σ levels, respectively.

The redshift of C IV is measured at $z = 0.6907 \pm 0.0008$ with $\chi^2 = 0.69$ per degree of freedom. Although due to low spectral resolution and spectral purity, the line appears to be strongly affected by the noise, it is above 4.2σ noise level. The
appear affected by strong emission or absorption features when resampled to the narrow NV line, which is unresolved in this spectrum. The spectrum is resampled to improve its signal-to-noise ratio.

Figure 1. Lyα λ1215 and C IV λ1549 spectrum profiles. Vertical dotted lines indicate the systemic redshift of line centroids. Lyα profile shows significant flux excess at ~2055 Å in the observed frame, fitted here as the offset broad Lyα emission. The excess of flux in the long-wavelength tail is suggested to arise from the offset NV broad emission, as there is a hint at the narrow NV λ1240 line, which is unresolved in this spectrum.

The excess of flux in the long-wavelength tail is suggested to arise from the offset NV line, which is unresolved in this spectrum. The spectrum is resampled to improve its signal-to-noise ratio.

As the left wing of the profile at 1490–1520 Å (rest frame) could be affected by the Fe II, Fe III, and Si II at 1531 Å emission at the systemic redshift (Vestergaard & Wilkes 2001), the width of the C IV fit was cross-checked by estimating the BH mass. The empirical mass estimator from Bonta et al. (2020) for single epoch measurements yields log(MBH/M⊙) = 8.80 ± 0.16, which is 1.0σ away from the Mg II-based estimate of log(MBH/M⊙) = 8.65 from S12. The relations based on the C IV line width are less well constrained than those made with the Hβ line mainly due to the lack of observations in the UV. The line shows significant flux excess at ~2055 Å in the observed frame, fitted here as the offset broad Lyα emission. The excess of flux in the long-wavelength tail is suggested to arise from the offset NV broad emission, as there is a hint at the narrow NV λ1240 line, which is unresolved in this spectrum. The spectrum is resampled to improve its signal-to-noise ratio.

Table 1

<table>
<thead>
<tr>
<th>Line</th>
<th>Component</th>
<th>Redshift</th>
<th>FWHM (km s⁻¹)</th>
<th>Offset (km s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N V λ1240?</td>
<td>BEL</td>
<td>0.6914 ± 0.0051</td>
<td>4917 ± 4840</td>
<td>−3996 ± 893</td>
</tr>
<tr>
<td>C IV λ1549</td>
<td>BEL</td>
<td>0.6907 ± 0.0008</td>
<td>12,491 ± 953</td>
<td>−4107 ± 143</td>
</tr>
<tr>
<td>Lyα λ1215</td>
<td>BEL</td>
<td>0.6909 ± 0.0026</td>
<td>11,511 ± 1781</td>
<td>−4079 ± 457</td>
</tr>
<tr>
<td>Hα λ6563</td>
<td>BEL</td>
<td>0.690</td>
<td>~7200</td>
<td>−4100</td>
</tr>
<tr>
<td>Hβ λ4861</td>
<td>BEL</td>
<td>0.690</td>
<td>~7200</td>
<td>−4100</td>
</tr>
<tr>
<td>Mg II λ2798</td>
<td>BEL</td>
<td>0.7071 ± 0.0006</td>
<td>12,800 ± 490</td>
<td>−1200</td>
</tr>
<tr>
<td>Lyα λ1215</td>
<td>NEL</td>
<td>0.7135 ± 0.0003</td>
<td>1978 ± 565</td>
<td>−123 ± 48</td>
</tr>
<tr>
<td>[O III] λ4959</td>
<td>NEL</td>
<td>0.714</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[O III] λ5007</td>
<td>NEL</td>
<td>0.714</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[O II] λ3727</td>
<td>NEL</td>
<td>0.714</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[Ne III] λ3881</td>
<td>NEL</td>
<td>0.714</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. The offsets are stated with respect to the systemic redshift (z = 0.7142) reported in S12.

As part of the same proposal (15872), the ACS/WFC camera of the HST was used to take six dithered images (~347 s each) in F606W and four (575 s each) in F850LP filters to produce the combined images with 2075 and 2300-second exposures, respectively. The individual exposures were aligned, background-subtracted, and drizzled by grizli pipeline (Brammer & Matharu 2021). The final products represent the combined mosaics of these dithered images for each filter.

3. HST Images
The reconstruction of the quasar emission was performed by using an effective PSF (ePSF) constructed with the photutils package (Bradley et al. 2020) and based on six foreground stars in the images utilized here. It is an empirical model based on the selection of stars in the images (Anderson & King 2000; Anderson 2016). It is produced by simply measuring the flux of stellar sources in the vicinity of the target at individual pixels and it represents a map of fractional flux produced by a point source given the optics and the detector sensitivity, i.e., the instrumental PSF scaled by the pixel sensitivity map. This method was shown to be more precise and numerically efficient than deconvolving the photometry and instrumental effects, assuming and then fitting an analytical function. The advantages are particularly justified, when only a single point source is investigated.

Figure 2 shows the residuals after fitting and subtracting the best-fit PSF from the images. The fit was performed using the 2D image, profile-fitting code IMFIT (Erwin 2015) with reduced $\chi^2 = 2.83$ for F606W and $\chi^2 = 1.36$ for F850LP images. With the pixel scale of 0.03 per pixel, the images allowed us to resolve the host structure around the AGN. The figure shows both the residuals in terms of the instrumental read errors and the residuals in units of Poisson $\sigma$ defined using the average of the counts in the observed and model images. These maps indicate that the residual host emission around the AGN is most significant in the F606W band (up to 5$\sigma$, Poisson), while the emission in F850LP (up to 2–3$\sigma$) is shallower and more extended outside of the central region than in F606W. This is roughly in agreement with the relative amount of flux of the model SED emission of the host galaxy at the respective wavelengths presented in S12.

The residuals in either filter do not indicate any disruption or deformation in the central structure of the apparently elliptical light profile, which would be expected from a recent galaxy merger. However, it was not possible to perform a detailed study of the host galaxy profile due to the overall shallow photometry. The cyan crosses indicate the best-fit centers of the quasar emission, which are misplaced from the center of the isophotal host emission by 1.1 (0.24 kpc) and 1.4 (0.31 kpc) pixels in F606W and F850LP, respectively. Given the resolution, the offset up to $\sim$1.5 (3$\sigma$) pixels is allowed, which makes the best-fit QSO location consistent with the center of the host emission.

4. Previously Proposed Explanations

There exist several mechanisms that are responsible for creating different distinct velocity components in BLRs of quasars. However, none of them appears to provide a full explanation for the observed features of SDSS 0956 + 5128. Those include outflows, quasar morphology and orientation or quasar motion with respect to its host that could correspond to one or both of the velocity components in SDSS 0956 + 5128. Specifically, S12 considered multiple objects along the line of sight, double-peaked emitter profile, and a recoiling black hole. Another considered mechanism is accretion disk winds that may be responsible for velocity profiles typically seen in most of the QSOs with outflows. This section describes how the previous and new evidence from SDSS 0956 + 5128 fits within these scenarios and shows that none of them are capable of explaining the observation completely.

4.1. Multiple Objects Along the Line of Sight

Perhaps the simplest explanation for multiple velocity components would be multiple objects along the same line of sight. However, this explanation cannot produce the broad lines observed in SDSS 0956 + 5128. There is a unique set of narrow lines, consistent in their redshift, and two velocity
components, represented by either broad Mg II or Balmer lines, but not both. With two objects along the line of sight, two sets of narrow lines would have to be present, even if there was a specific combination with a strong Mg II broad emission and very weak Balmer lines in one object and a very weak Mg II and strong Balmer emission in the other.

In addition, the narrow lines argue against this explanation. Narrow Balmer lines at the systemic velocity indicate that the central region of the presumed host galaxy is illuminated by the quasar. The broad Balmer lines are bluer than the host. Thus, if along the same line of sight, they would need to be in front of the host and unable to produce these features. Therefore, a scenario with three distinct components in the same system has to be considered: emission of the host ($z = 0.714$) in the NLR, Mg II ($z = 0.707$) and Balmer ($z = 0.690$) emission in the BLR.

### 4.2. Disk Winds

In the context of a single QSO system, one common mechanism thought to be responsible for outflows in the BLR is accretion disk winds (e.g., models by Murray et al. (1995) and Mathews & Blumenthal (1977)). In support of these models, Gaskell (1985) found evidence that BLR clouds could be radiatively accelerated. It was proposed and modeled that radiation pressure could be responsible for accelerating the gas clouds radially outward (Emmering et al. 1992; Everett 2005).

In such a scenario, the velocity of the outflow is highest for the high-ionization material of the BLR and decreases for species with lower ionization energies. Examples of such profiles can be seen in Meyer et al. (2019), Shen et al. (2016), Marziani et al. (2010), Marziani et al. (1996), and Brotherton et al. (1994). As the ionization potentials are correlated with the radial distances of emission lines, the lines like N V, C IV, and other high-ionization lines experience some of the largest relative velocities reaching several thousands of kilometers per second (Yu et al. 2021). The intermediate- to low-ionization emission, including hydrogen lines and Mg II, is typically seen accelerated to at most a few hundred kilometers per second. Often Hα, Hβ, and Mg II are consistent with the systemic velocity to within $\sim$200 km s$^{-1}$ (Hewett & Wild 2010; Shen et al. 2016).

Although such a negative velocity gradient could produce a difference in emission line velocities, the difference seen between the hydrogen lines and Mg II in SDSS 0956 + 5128 is too steep and too high for the lines of such similar ionization potentials. For instance, Meyer et al. (2019) show that the offset velocities of Mg II and other low-ionization lines are typically identical in spectroscopically observed SDSS quasars, with velocity shifts well within a few hundred kilometers per second at $z < 7$. Moreover, in the rare cases where Mg II blueshifts of $\sim$10$^5$ km s$^{-1}$ are reported, they are generally connected with other mechanisms (as in the recoiling black hole candidate, 3C 186, in Chiaberge et al. (2017)).

The similarity between ionization potentials of H/β and Mg II alone may not be indicative of their physical proximity, especially if the lines originate from fully and partially ionized regions and their emission is driven by different excitation mechanisms. However, the correlation between the radius of the species in the BLR and the accompanying continuum luminosity (at $\lambda = 5100 \AA$ and 3000 \AA) indicates that they are likely coming from the adjacent gas shells in the BLR. Figure 3 shows estimates with several of such empirical relations. They may not be applicable to all quasars, because they are based on different sample selections. However, any pair of radius estimates show that H/β and Mg II here are closely spaced and H/β is closer to the center on average.

Thus, if a negative velocity gradient is responsible for the extreme offsets of the hydrogen and Mg II lines in SDSS 0956 + 5128, there should be an even larger difference when Mg II is compared with high-ionization lines. For example, such a trend was found in the offsets of emission lines of I Zw 1 (Laor et al. 1997; Vestergaard & Wilkes 2001) and other quasars (Wilkes 1986; Espey et al. 1989; Corbin 1990). However, as shown in Section 2, this is inconsistent with the new HST observations presented in this work, especially with the C IV, possibly N V, and the hydrogen lines being symmetric and part of the same velocity system at $-4100$ km s$^{-1}$.

### 4.3. QSO Jets

Alternatively, QSO jets that provide a way of losing the angular momentum for the supermassive black hole (SMBH) can cause QSO outflows (Zheng et al. 1990). Even though the jets are highly collimated, they may cause outflows in the BLR assuming a high covering factor of the clouds. It was shown in Zheng et al. (1990) that double-peaked Balmer emission can be produced in such AGN models. However, this does not explain the symmetric single-peaked lines observed in SDSS 0956 + 5128.

### 4.4. Double-peaked Emitter

In another scenario, large line shifts of over 4000 km s$^{-1}$ observed in some galaxies can be described by models with non-axisymmetric accretion disks (Strateva et al. 2003): flattened, eccentric disks (or other forms of asymmetries) and a preferred inclination angle (Chen & Halpern 1989; Eracleous et al. 1995). The problem in this case is that BELs in such systems produce double or asymmetric profiles. S12 reported that the Balmer lines in SDSS 0956 + 5128 have asymmetric profiles, with a faint, broad component and that Mg II, in contrast, is symmetric. However, the asymmetry appeared only in one of three independent observations (S12).

If the model of a double-peaked emitter is allowed to have sufficiently many parameters, it is possible to produce a
reasonable fit to the spectrum in most cases. However, in this case, one double-peaked emitter is not able to explain scenarios in which different lines show different offsets. At least two eccentric emitter components are required to provide an explanation for the two offsets, but still not sufficient to produce a symmetric (non-double) Mg II, Lyα, and C IV (and possibly N V), unless these lines have double profiles with the second component being very weak.

4.5. Recoiling Black Hole

Finally, S12 suggested that SDSS 0956 + 5128 may be a recoiling BH in a post-merger galaxy, in which the BLR is a combination of eccentric and circular components. An SMBH resulting from coalescence of two smaller SMBHs can receive a kick in some direction, depending on the rotation properties of the system (Campanelli et al. 2007b; Loeb 2007; Schnittman & Buonanno 2007).

It was shown that such a BH can still exhibit symmetric BELs with the offset of over 1000 km s$^{-1}$ (Merritt et al. 2006; Loeb 2007). However, an offset of ~4000 km s$^{-1}$ would be difficult to produce. Some analytical and numerical considerations limit the maximum recoil velocity to ~4000 km s$^{-1}$ (Campanelli et al. 2007a, 2007b; Baker et al. 2008) or even lower (Healy et al. 2014), while others can reach up to ~5000 km s$^{-1}$ for special configurations (Lousto et al. 2012). In observations, one potential candidate is the object CID-42 (Civano et al. 2010, 2012; Blecha et al. 2013), with the offset of up to 1300 km s$^{-1}$ detected in the broad Balmer emission. Another candidate for an SMBH recoil with more BEL detections, 3C 186 Chiaberge et al. (2017), shows the highest known offset of ~2100 km s$^{-1}$, which is second only to SDSS 0956 + 5128 with the offset nearly twice as high (~4100 km s$^{-1}$). In addition, the spectroscopic velocity profile of 3C 186 appears to be constant with respect to the ionization potential of C IV, C III, and Lyα, as well as Mg II.

In SDSS 0956 + 5128, C IV (and possibly N V) and the hydrogen lines are consistent with this scenario; however, Mg II is not. Given the similarity of the ionization potentials of hydrogen and Mg II lines, it seems very unlikely that the Mg II region could be moving ~2900 km s$^{-1}$ slower than the rest of the recoiling BLR. One possibility is to assume that Mg II is consistent with the recoil scenario and that all of the BLR is offset by at least the offset of Mg II (~1200 km s$^{-1}$). Then even slightly higher ionization lines, including the hydrogen lines, could arise due to an eccentric emitter disk that introduces additional offset on top of the recoil and causes asymmetry of the Balmer lines. Therefore, in this scenario, the Balmer and Mg II emission must come from separate locations, with the latter being further out and the higher ionization lines, like C IV or N V, must also have the same asymmetry, as reported for the Balmer lines in S12.

In support of the idea of the recoiling BH, S12 showed using ground-based photometry that the peak of intensity in SDSS 0956 + 5128 was possibly offset from the center of light in the host galaxy, although the data had low resolution and systematic effects in PSF fitting were not ruled out. Additionally, photometric decomposition showed that the host is a dusty galaxy, which can be consistent with various states of galaxy evolution, including a possible post-merger. S12 showed that based on the timescale for the BLR to sustain emission after the quasar accretion was disrupted, the recoil could have occurred in the past 140 Myr. This could allow for the host galaxy to preserve the evidence of a recent merger on a less than dynamical time, detectable in the follow-up resolved observations.

However, the new evidence presented from HST does not hold any indications of a BH recoil that could result from a previous galaxy merger. It is shown in Section 3 that the QSO, fitted with a PSF, is spatially consistent with location of the isophotal center of the residual galaxy emission and no strong irregularities in the structure are seen that could result from a recent galaxy merger, although the photometry is not deep enough to accurately fit the host morphology. It remains possible that the strong signatures of the merger could have been erased to the point of being undetected at the given resolution. Nevertheless, new observations of the high-ionization line C IV and low-ionization Lyα appear to be consistent with the offset of the Balmer lines, they are symmetric (see Section 2). The symmetry is contrary to the expectation from the BH recoil hypothesis. It was also shown by S12 that the system lies on the standard $M_{\text{BH}}/M_{\text{bulge}}$ galaxy mass relation, with the virial mass of the SMBH of log$(M_{\text{vir}}/M_\odot) = 8.65$ (S12) lying close to the empirical relation in the plane of the galaxy luminosity and the black hole mass. Therefore, this does not provide any sharp indications that the SMBH does not belong to the host. In this context, the evidence suggests that the offsets in SDSS 0956 + 5128 do not appear to be caused by the motion of the quasar, but are rather intrinsic to the QSO.

In Section 5, we argue that the radial velocity profile in the BLR of SDSS 0956 + 5128 is reminiscent of the post-shock outflow and use the idea of star formation in the accretion disks (e.g., from Goodman & Tan 2004) to support this mechanism for causing strong outflows in the BLR of quasars.

5. Interpretation

The observations of SDSS 0956 + 5128 appear to be inconsistent with known physical mechanisms and suggest that an outflow with very distinct velocity signature is responsible.

The event that produced the outflow must have an origin at the BH or close to it. This appears to be the case, because the symmetry of the BELs suggests a spherically uniform outflow. Additionally, the whole BLR appears to be affected, where the radial velocity is constant across a large fraction of the BLR, between the high-ionization region and low-ionization hydrogen lines. Finally, there appears to be a drop-off of the outflow velocity starting from the location where Mg II is produced. Therefore, it may be safe to assume any origin of such event within the inner boundary of the BLR, with its effects limited to the BLR outskirts.

Clearly, some extreme physical conditions must be at play. The event has to be consistent with the outflow energetically and with the observed radial velocity profile, as indicated by the offsets of the broad lines and their expected radial distances. The upper limit on the time of the event can be placed by using the velocity of the outflow.

Below, a shock wave from an energetic explosion is postulated as a mechanism for causing an outflow. It is shown that this mechanism can be consistent with the observed features in SDSS 0956 + 5128. Then the plausibility of the extreme physical conditions due to a supernova explosion is considered, along with a discussion of whether stars can exist in close proximity of a SMBH and how they can appear there in the first place.
5.1. Post-shock Outflow

The velocity profile of the outflow as a function of radius in the BLR of SDSS 0956 + 5128 is strongly reminiscent of that of a "shocked" material (Taylor 1950), as it shown in this section. It is expected that the radial profile in terms of increasing radial distances is as follows: C IV, Lyα, Hβ, and Mg II, where Mg II must be at least as far out as the Balmer line emission. Based on the spectroscopic observations made in Section 2 here and in S12, the outflow velocity profile is constant at \( \Delta V \approx 4000 \) km \( s^{-1} \) starting at the location of the C IV line and extending out to the hydrogen lines. Then the radial velocity drops to \(-1200\) km \( s^{-1} \) at the location of Mg II. Assuming the velocities estimated from several spectra across an extended timeline are accurate, there would be only one explanation for different offset velocities of the Balmer lines and Mg II: the latter line must originate at larger radii due to its lower ionization energy. In this case, the overall velocity profile is characteristic of a post-shock outflow, such as the outflows in the interstellar medium (ISM) produced by supernova (SN) explosions.

Assuming a uniform density of the medium, the evolution of shocks can be described as a three-phase process that starts with a free expansion at high pressure relative to the surroundings, during which the mass of the medium swept up by the shock wave along the direction of travel is insignificant compared to the mass of the shock material itself. Thus, the energy and momentum of the wave are conserved and the kinetic energy \( E_k \) is:

\[
E_k = M_g V_g^2 / 2,
\]

where \( M_g \) and \( V_g \) are the mass and velocity of the ejecta.

As the shock shell expands in radius, it is opposed by a larger mass of the ambient medium. When the two masses become equal, the shock enters the Sedov–Taylor phase (Taylor 1950). There, the ejecta starts to lose its momentum, while the matter is too heated to irradiate, so the system remains adiabatic. At this stage, the expansion of the shock radius \( R_s \) with time \( t \) is found to depend entirely on the initial kinetic energy \( E_k \) and density of the medium \( \rho_0 \):

\[
R_s(t) \propto E_k^{1/5} \rho_0^{-1/5} t^{2/5}.
\]

Finally, as the temperature of the shock drops, C, N, and O ions start to recombine, helping to cool the shock material efficiently, which starts to lose its energy radiatively until the flow becomes subsonic and merges with the surrounding medium.

This evolution can be matched with the velocity components observed in SDSS 0956 + 5128, as illustrated by the velocity and distance profiles of a shock wave in Figure 4. In this interpretation, the velocities presented here sample the first two phases: C IV, Lyα, Hβ, and Hα represent the region in the free expansion phase, while Mg II is in the Sedov–Taylor region. Also, in the analysis above, the high-ionization N V line was possibly identified with the offset, placing it consistently with the lines in the first phase. This phase is sampled well with four or five lines probably spanning a significant fraction of the BLR radial profile. However, the second phase is only seen with one BEL (Mg II). Fortunately, there have been two observations of this line 7 yr apart to confirm the detection.

\[\text{N V is the line with the highest ionization potential in our sample, which places it closest to the SMBH.}\]
density as a function of radius, where the timescale goes as \( t \propto n_e^{-1/3} \) in the first phase and \( t \propto n_e^{-1/3} \) in the second.

Predicting the mass and type of the candidate supernova star is beyond the scope of this work, but it is possible to estimate an order of magnitude mass of the ejecta and their kinetic energy. The ejecta mass can be obtained by locating the boundary between the first two shock regions. This radial distance encloses the mass of the swept-up gas comparable to the mass of the shocked ejecta, as this is the approximate condition for termination of the first phase.

The boundary must lie between the hydrogen lines (e.g., \( \text{H}\beta \)) and Mg II, which are close spatially (see Figure 3), but correspond to different velocity components in the BLR. Assuming \( \text{H}\beta \) is at the boundary (as shown in the right panel of Figure 4), we can use the estimated radius of the boundary of 0.057 pc and the BLR density of \( n_e = 10^3 \text{ cm}^{-3} \) to estimate the ejecta mass. This produces \( M_{\text{ej}} \sim 2 \times 10^5 M_\odot \).

With the velocities of the BEL offsets in the first phase, the kinetic energy of the event is \( E_K = 5 \times 10^{55} \text{ erg} \). Here, it is assumed that most of this mass is contained in a thin shell at the radius of \( \text{H}\beta \). Therefore, the exploded star must have had an initial mass \( M_\star \geq M_{\text{ej}} \). Such objects have not been observed before, although theoretical considerations of instability growth in the accretion disks of quasars suggest a possibility for formation of stars with masses at least as high as \( 10^2 \sim 10^7 M_\odot \) (Goodman & Tan 2004).

5.2. Origin of Stars in AGN

If a stellar explosion produced the observed features in the spectrum of SDSS 0956 + 5128, how could a star appear in the vicinity of an SMBH in the first place? And how could it be nearly as massive as \( 2 \times 10^4 M_\odot \)? The star might be formed either in the proximity of the SMBH or in a host galaxy and then captured into the accretion disk. One way or another, it probably owes its large mass to the abundance of material in the accretion disk of an SMBH.

The growth of supermassive stars may stem from the capture of stars from the host galaxy. The closest galactic source of stars is the bulge that encircles the quasar. Stochastic encounters can result in significant changes of stellar velocities on a relaxation timescale that could lead to stars being deflected off their orbits. A “lucky” star brought to the central object with the mass \( 10^{8.6} M_\odot \) would not risk being disrupted due to tidal forces, unless it sinks into the black hole. The reason is the tidal radius of BHs with masses \( > 10^5 M_\odot \) becomes smaller than the Schwarzschild radius. In fact, sinking into the BH would be a more likely outcome, as otherwise reaching an exact stable orbit around the BH would require acquiring a very specific velocity making it very unlikely.

Following on the idea of disk–star interactions as a potential mechanism for removal of angular momentum from AGNs (Ostriker 1983), Syer et al. (1991) investigated a possibility for stars to be captured by the accretion disk for favorable inclinations of stellar orbits. This mechanism was characterized by shorter than the relaxation timescale for delivering stars into the disk. It could be possible as the growth of the gaseous disk and clouds would be expected to extend as far as to the edge of the influence of the BH for the stellar bulge. Stars would then be dragged down by the viscous forces to the stable circular orbit over time. If such stellar migration is real, then according to the predictions of Artymowicz et al. (1993), after the QSO acquires a disk and turns on, in the span of \( 10^8 \) yr, there can be as many as \( 10^4 \) captured stars. They would be dragged down the disk, enmassed by the disk material to as high as \( \sim 10^2 M_\odot \), and evolve on their respective main-sequence timescale leading to Type II SNe. For the case of SDSS 0956 + 5128, a single core-
collapse supernova with such initial mass would not be able to explain the observed BLR offsets. Although \(\sim 10^{-3} \text{--} 10^{-4}\) of such SNe simultaneously would, this could hardly be a plausible scenario. In addition, it was argued that the stars might more likely be destroyed by the release of energy for circularization of their orbit in the accretion disk, as a very limited set of conditions for entry must be met to stay bound (Goodman & Tan 2004).

On the other hand, Goodman & Tan (2004) considered in situ star formation and growth of massive stars. The main argument that stars can and possibly should form in BH accretion disks was that, starting from a distance of \(\sim 10^3 R_\text{S}\), where \(R_\text{S}\) is the Schwarzschild radius, the disks are dominated by self-gravity and are expected to fragment via local dynamical instability. Goodman & Tan (2004) considered fragmentation at the exact boundary, where the radiation pressure equals the gas pressure as, at this location, any fragments would be well separated and therefore likely to grow via accretion of the surrounding gas. The authors showed that given the strong accretion in the disk, the star is more likely to grow than to fragment.

The properties of the protostar would be defined by the instability. As mentioned previously, the initial overdensity masses could reach anywhere in the range \(10^3 \text{--} 10^5 M_\odot\), and are likely to grow by further accretion. The mass growth continues until the gap roughly of the size of the protostar’s Roche lobe is cleared in the accretion disk. Finally, the material in the Roche lobe would contract until the star reaches the main sequence. Such stars are likely to be supported by radiation pressure and experience significant mass loss, although the levels are not known for the very high masses over \(10^3 M_\odot\).

In the theoretical framework of Goodman & Tan (2004), the mass of a protostar in a disk of \(10^8 M_\odot\), SMBH is expected to be \(\sim 10^5 M_\odot\), if it forms at the edge of the low self-gravity of the disk. The likely outcome of the SNe of stars with mass \(>10^2 M_\odot\) is a complete collapse to a BH (Fryer et al. 2001), although an instability from \(e^+e^-\) pair production may occur that would convert all of the stellar mass to ejecta at explosion. Therefore the scenario in which a star with an initial mass \(10^4 M_\odot\) evolves into a less massive \(\sim 10^5 M_\odot\) star by mass loss and causes a pair-instability supernova that ejects all of the material in an explosion would be consistent with the observation in SDSS 0956 + 5128.

Following Goodman & Tan (2004), if the star is stable on the main sequence, it can be expected to migrate inward, preserving the disk gap, and reach the tidal radius in a time \((\sim 10^5 \text{ yr})\) shorter than the main-sequence time \((\sim 10^7 \text{ yr})\). It would be of particular interest here to know whether the star is expected to disintegrate once on the main sequence or if it survives for some parameters. Future numerical simulations of such processes would be of particular interest to answer these questions.

If star formation in accretion disks is common, how frequently would an SDSS 0956 + 5128-like event occur? Goodman & Tan (2004) estimate that, if star formation in a QSO happens at a rate of one per viscous time, then given the approximate number density of QSOs at redshifts \(0.5 < z < 1.5\), \(10^{-5}\) massive stars per QSO per year should form, for a total of a few stars per year in a survey the size of SDSS.

However, most of those stars will not produce an observable supernova. Goodman & Tan (2004) argued that sinking into the SMBH is the typical outcome. Fresh, hydrogen-rich material from the accretion disk can mix into the convective stellar core, so that the main-sequence lifetime becomes longer than the timescale for reaching the event horizon. Thus, their deaths would not be observable.

Perhaps if the accretion disk becomes sparse toward either near the Eddington luminosity or toward the end of a quasar’s lifetime, there might be just a high enough density to form a massive star, yet not enough additional material to sustain that star until it reaches the event horizon. The resulting supernovae might even provide a turnoff mechanism, so that quasars die with a bang rather than with a whimper. As SDSS 0956 + 5128 lies at \(z = 0.7\), below which relatively few quasars are observed, it is likely to turn off in the near future. It is therefore plausible to associate the extreme features of SDSS 0956 + 5128 with a short-lived turnoff mechanism. If such a process lasts for \(\sim 10^3 \text{--} 10^4 \text{ yr}\) (based on the timeline of the shock wave in Figure 4), finding one example in all of SDSS is plausible.

6. Discussion

It is argued here that none of the common and less so mechanisms, except for the shock wave, are likely to produce a spectroscopic signature observed in the BLR of SDSS 0956 + 5128. The scenarios that involve special morphology, alignment of multiple objects, or radiation output of the QSO or SMBH mergers each have at least one sharp inconsistency with the evidence (see Section 4). Instead, this work proposes the idea of shock waves to explain the observed spectroscopic offsets. The toy model requires the tuning of only the BLR density parameter to match the velocity offsets in SDSS 0956 + 5128, as well as the location of Mg II line.

To support or reject the idea of the supernova shock causing the outflow in the BLR, it is necessary to collect more observational evidence. Below is the list with a couple of possibilities.

1. Other offset lines? The shock mechanism predicts that there must be a continuum of velocity components in the second phase of the shocked BLR (see Section 5.1 and Figure 4), as opposed to only one that was observed. Although the most prominent BEL in the second phase (Mg II) was already observed, lower ionization lines in the NUV, like O i, Si II, or C II are not detected in the HST spectrum here. Instead, they could be targeted with higher signal-to-noise spectra. Additionally, the Fe Kα line in the X-rays would be expected to have the high-velocity offset of 4100 km s\(^{-1}\), as the other lines of that velocity component. Probably, the direction of the offset and the line symmetry would depend on the position relative to the potential SN explosion site in the accretion disk. If any of these lines are inconsistent with the prediction, this will rule out the hypothesis.

2. Traces of neutrinos and electromagnetic emission. From another perspective, SN shocks act as neutrino production sites, through pion decays as a result of proton–proton interactions. It was suggested that the diffuse neutrino background may be substantially contributed to by AGN stellar explosions (Zhu et al. 2021). In order to detect these events, it was shown (though for much less massive stars) that short bursts in the diffuse neutrino background and the ensuing lasting electromagnetic emission can be
used. Therefore, such a signature may be used to search for potential candidates for follow-up observations or for testing models of neutrino and electromagnetic emission produced by energetic stellar explosions.

After all, the shock hypothesis here is an analytical solution based on the simple assumptions of shock–medium interaction and lacks a more detailed insight. Therefore, numerical modeling of the involved processes would be required to test the idea more robustly. Below are the suggestions for possible experiments and predictions.

1. **Downstream velocity as function of time.** The BLR gas with different offsets starts mixing in the snowplow phase altering the velocity of the BLR outflow. If one can calculate the outflow velocity of every one of the observed emission lines as a function of time, it will be possible to predict the blueshift that the lines should have at a time of a possible future observation. It will also be possible to predict how the strength of the broad-line emission will change over time, as the emitting gas moves away from its ionization zone. Additionally, the density of the BLR assumed here corresponds to a rather conservative lower limit and it has a uniform radial profile, which can be tested by modeling the broad-line emission observed in SDSS 0956 + 5128.

2. **Numerical simulation of stars in a strong gravitational potential.** One of the main problems in the shock hypothesis is what caused it. The only possibility to create a shock wave of the required energy known to us is a potential supernova. If the outflow profile in SDSS 0956 + 5128 is a signature of an SN (see Section 5), then the mass of the ejecta is estimated to be \( \sim 10^4 M_\odot \) and the kinetic energy is \( E_k \sim 10^{53} \text{erg} \). It is unclear whether stars can be “safely” delivered to accretion disks of SMBHs and then grow to such extent by accretion, but there exist theoretical models that predict formation of such supernovae. If the two BN 0963 11p 1010 timescale wins, then it is possible that SNe are more frequent and could also play an important role in turning off QSOs.

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