DISCOVERY OF THE DISTURBED RADIO MORPHOLOGY IN THE INTERACTING BINARY QUASAR FIRST J164311.3+315618

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\textbf{ABSTRACT}

We report the high-resolution radio observations and the subsequent analysis of the radio-loud compact steep spectrum quasar FIRST J164311.3+315618, one of the members of a binary system. The second component of the system is a radio-quiet active galactic nucleus. The projected separation of this pair is 2\textquoteright 3 (15 kpc); it is one of the smallest-known-separation binary quasars. The multi-band images of this binary system made with the Hubble Space Telescope show that the host galaxy of the radio-loud quasar is highly disturbed. The radio observations presented here were made with the Multi-Element Radio-Linked interferometer network (MERLIN) at 1.66 GHz and 5 GHz. We show that the radio morphology of FIRST J164311.3+315618 is complex on both frequencies and exhibits four components that indicate the intermittent activity with a possible rapid change of the jet direction and/or restarting of the jet due to the interaction with the companion. The radio components that are no longer powered by the jet can quickly fade away. We suggest that this makes the potential distortions of the radio structure short-lived phenomena. Our numerical simulations show that the influence of the companion can lead to prolonged current and future activities. FIRST J164311.3+315618 is an unusual and statistically very rare low redshift binary quasar wherein the first close encounter is probably just taking place.

\textbf{Key words:} black hole physics – galaxies: active – galaxies: evolution – galaxies: interactions

\textbf{Online-only material:} color figures

1. INTRODUCTION

It has been established that most galaxies host a supermassive black hole (Magorrian et al. 1998), and the next open issue is the mechanism that triggers gas accretion and nuclear activity. It is likely that active galactic nuclei can pass through subsequent stages of higher and lower activities. Intermittent behavior of this type can be caused by minor mergers or instabilities in the accretion flow. On long timescales, up to 10\textsuperscript{8} years, the merger activity is broadly considered as the cause of an enhanced accretion flow and the main provider of material for black hole growth (Barnes & Hernquist 1996; Volonteri et al. 2003; Di Matteo et al. 2005).

Close binary QSOs presumably represent a very early stage of a merger of galaxies. The merger will likely produce a supermassive binary black hole (Beigelman et al. 1980). Based on optical surveys, only about 0.1\% of all quasars observed have one or more nearby quasar companions at the same redshift (e.g., Kochanek et al. 1999; Hewett et al. 1995; Foreman et al. 2009). These may be gravitational lenses, true quasar pairs, or chance alignments. Arguments weighed after binary quasar classification are as follows: lack of a detectable lens, different quasar spectra, and/or properties such as the case in which one object is radio-quiet and the other is radio-loud. There is a growing number of identifications of physical pairs of quasars (Kochanek et al. 1999; Hennawi et al. 2010; Liu et al. 2010). Among them are the highest-known-redshift binary LBQS 0015+0239 at $z = 2.45$ (Impey et al. 2002), LBQS 1429−0053 (Faure et al. 2003) and UM 425 (Mathur & Williams 2003; Aldcroft & Green 2003) with similar optical spectra but a lack of a candidate-lensing system, and Q 2345+007 (Green et al. 2002) with different optical and X-ray spectra but no lens candidate found in the optical and X-ray bands. The smallest-known-separation binaries are LBQS 0103−2753 (Junkkarinen et al. 2001) with separation 0\textquoteright 3 and the very recently discovered SDSS J1536+0441 (Boroson & Lauer 2009; Decarli et al. 2009) with separation 1\textquoteright. While most of the binaries are O\textsuperscript{2} pairs (both quasars are radio-faint), there are four known O\textsuperscript{2}R systems (one quasar is radio-loud, and the other is radio-quiet), as follows: PKS 1145−071 (Djorgovski et al. 1987), MGC 2214+3550 (Munoz et al. 1998), Q1343+2640 (Crampton et al. 1988), and FIRST J164311.3+315618 (Brotherton et al. 1999), which is studied in the present paper. The existence of two images with extremely different flux ratios in the optical and the radio strongly favors the binary quasar classification.

Most of the binaries are high-redshift objects with separations of 3\textquoteright−10\textquoteright, which corresponds to distances of ~10−80 kpc (Mortlock at al. 1999). According to Junkkarinen et al. (2001) the observed 3\textquoteright−10\textquoteright binary QSOs mostly represent galaxy pairs undergoing the loop following the first close encounter. The still open question is whether or not the host galaxies of the binary quasars interact in the process of merging. If they do, we should observe morphological and kinematical distortions in these systems, and their characters should depend on the evolutionary stage of the pair. In the late phase of their encounter, we might expect a compact, morphologically highly disturbed system with a pair of active supermassive black holes at its center. The following binary supermassive black holes have been observed so far: NGC 6240 (Komossa et al. 2003), Arp 299 (Ballo et al. 2004), 0402+379 (Rodriguez et al. 2006), and COSMOS J100043.15+020637.2 (Comerford et al. 2009), as well as cluster members 3C75 (Owen et al. 1985) and J0321−455 (Klamer et al. 2004). Strong evidence for the interaction of the host galaxies of the binary active galactic nucleus (AGN) system SDSS J1254+0846 (separation 3\textquoteright 8) has been provided through the observed distortion of the optical light from one of the host galaxies, showing obvious tidal tails (Green et al. 2010). Here we report that the radio-loud/radio-quiet binary quasar system associated with the radio source FIRST J164311.3+315618 (hereafter FIRST J1643+3156) shows disturbed radio morphology.
possibly indicating that the two quasars are in the process of merging. The distortions of the host galaxy of the radio-loud quasar of this system have also been discovered (Martel et al. 2005).

The radio-loud/radio-quiet binary quasar associated with the radio source FIRST J1643+3156 has been classified by Brotherton et al. (1999) based on optical observations. It is a small separation, 2′.3 (15 kpc), quasi pair with redshift \( z = 0.586 \) and greatly discrepant optical and radio flux ratios (\( Q^2 R \) pairs). On this basis, the gravitational lens hypothesis has been ruled out (Brotherton et al. 1999). The radio-loud component of this pair is characterized by a strong, narrow emission line spectrum and X-ray emission. In the radio-quiet component the radio-loud source is redshifted relative to the radio-quiet one on the order of \( V = 300 \) km s\(^{-1}\) (Brotherton et al. 1999). The radio emission of the radio-quiet component is undetected. The radio-loud component of the binary quasar, FIRST J1643+3156, is a compact steep spectrum (CSS) radio source with spectral index \( \alpha \approx 0.82 \). It has a total flux density of \( S_{1.4\,\text{GHz}} = 112 \) mJy, which gives the moderate luminosity of \( L_{1.4\,\text{GHz}} = 26.20 \) W Hz\(^{-1}\).

In this paper, we present high-resolution radio observations of the radio-loud component of the binary system and the subsequent analysis. The observations were made with the Multi-Element Radio-Linked interferometer network (MERLIN) at 1.66 GHz and 5 GHz. The unusual complex morphology of FIRST J1643+3156 is discussed as the consequence of the quasars’ interaction and/or the restarting of the activity of the radio-loud component.

### 2. RADIO OBSERVATIONS

The binary quasar FIRST J1643+3156 belongs to the sample of 44 low-luminosity compact (LLC) objects we observed and analyzed in Kunert-Bajraszewska et al. (2010a). The snapshot 1.66 GHz and 5 GHz MERLIN observations of FIRST J1643+3156 were undertaken in 2007 and 2009. The target source and its associated phase reference source were observed for ~60 minutes including telescope drive times. The initial data reduction of raw MERLIN data was made using local d-programs and the AIPS-based PIPELINE procedure developed at Jodrell Bank Observatory (http://www.merlin.ac.uk/user_guide/). OQ208 was used as the point source or baseline calibrator and 3C 286 as the flux and polarization calibrator. Further cycles of phase self-calibration and imaging using the NRAO AIPS software were then used to produce the final total intensity (I) and polarization intensity (P) images. The polarization was detected only in component W2. The flux densities of the main components of the target source were then measured by fitting Gaussian models using AIPS task JMFIT (Table 2). The position of the optical counterpart of the target source is marked with a cross in the maps and was taken from the Sloan Digital Sky Survey (SDSS/DR7).

Throughout the paper, we assume a cosmology with \( H_0 = 71 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_M = 0.27 \), \( \Omega_L = 0.73 \).

### 3. RESULTS

The 1.66 GHz MERLIN radio image of FIRST J1643+3156 shows four components of the source (Figure 1[a]). The component indicated as C, the position of which is well correlated with the position of the optical counterpart, is a radio core. We have measured flux densities of the indicated components (Table 2) and calculated the spectral index for component C, which is \( \alpha_{\text{1.66 GHz}} \approx 0.6 \). However, this should be treated as an approximation since it is based on the snapshot observations, in which some flux can be missing. For this reason, we did not calculate spectral indices for the following weaker components: the radio lobes E, W1, and W2. However, in this case, the difference between the flux densities of the components at both frequencies is so large that we can assume they have steep spectra (Table 2). The lobe E is the weakest one in the 1.66 GHz image, and there is no trace of it in the 5 GHz image (Figure 1[b]). The 1.66 GHz MERLIN image shows that there is a connection between component C and the southwestern component W2. We suggest that this could be the most current jet direction and particle ejection. There is also an extended emission around the four compact components in the 1.66 GHz image. However, no extended emission and potential jet are visible in the 5 GHz image, and all three features detected in the 5 GHz image are very weak. W2 is also the only component showing polarization and only at the frequency of 1.66 GHz. Less than 1% of the total emission of W2 is polarized at 1.66 GHz. The polarization angle amounts to \(-59^\circ \pm 15^\circ\) (from north to east). The polarization vectors are often perpendicular to the jet direction, as in this case, suggesting that the component W2 is powered by the jet. However, the uncertainty of the polarization...
angle is large and, without more sensitive 5 GHz observations of FIRST J1643+3156, the interpretation should be treated as estimation.

Using the SDSS spectrum of FIRST J1643+3156, we have measured its emission linewidths and luminosities (Kunert-Bajraszewska & Labiano 2010). FIRST J1643+3156 has the largest [O iii] luminosity ($L_{[\text{O iii}]} = 1.1 \times 10^{43} \text{ erg s}^{-1}$) among the LLC objects we observed and was classified as a High Excitation Galaxy (HEG). Among the LLC objects that we consider as candidates for being in the short-lived radio object population, we found the following three binary systems: the two galaxy pairs (0854+210, 1506+354) and the quasar binary FIRST J1643+3156 (1641+320). Their morphologies are highly disrupted (Kunert-Bajraszewska et al. 2010a) and do not resemble typical CSS sources with symmetric double lobes.

3.1. Optical Imaging

FIRST J1643+3156 has been observed with the Wide Field Channel of the Advanced Camera for Surveys (ACS) of the Hubble Space Telescope (HST) and the results of the observations were presented by Martel et al. (2005). The images were made in 2005 in three filters: g (F475W), r (F625W), and I (F814W), and the exposure time of the observations was ~18 minutes in the g and r bands, and ~36 minutes in the I band. We have retrieved the data from the HST Archive and present the I-band image of FIRST J1643+3156 in Figure 2. As described by Martel et al. (2005), the host galaxy of the radio-loud quasar is highly disturbed, while the host galaxy of the radio-quiet source appears smooth and unperturbed. The following three

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{(a) The 1.66 GHz MERLIN radio image and (b) the 5 GHz MERLIN radio image. Contours increase by a factor of two, and the first contour level corresponds to $\approx 3\sigma$; vectors represent the polarized flux density. A cross indicates the position of an optical object found using the most actual version of SDSS. The shape of the beam is given in the bottom-left corner of each image.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{HST/ACS image of FIRST J1643+3156 in the F814W filter with an overlay of contours of the radio emission at 1.66 GHz. The two bright quasar nuclei are visible. The host galaxy of the radio-loud quasar is perturbed.}
\end{figure}
morphological features can be distinguished in the image of the host galaxy of the radio-loud quasar: a bright arc extending ~3 kpc west of the nucleus, a large diffuse knot located ~8 kpc to the south, and a group of filaments to the northeast of the nucleus. Distorted filaments are also observed between the radio-loud and radio-quiet quasars. We have made an overlay of the contours of the radio emission at 1.66 GHz on the optical image. We suggest that the bright arc on the optical image corresponds to the disturbed radio structure, which may indicate they are both effects of the quasars’ interaction.

4. DISCUSSION

FIRST J1643+3156 belongs to the population of CSS sources. CSS sources form a well-defined class of compact radio objects (≤20 kpc) and are considered younger progenitors of large radio-loud AGNs. This interpretation of the CSS class has now become part of a standard model (Fanti et al. 1995), and Readhead et al. (1996) have proposed an evolutionary scheme unifying the following three classes of radio-loud AGNs: gigahertz-peak spectrum (GPS) sources, CSS sources, and large-scale radio objects. The following two pieces of evidence definitely point toward GPS and large-scale radio objects. The following two pieces of evidence definitely point toward GPS and large-scale radio objects. The following two pieces of evidence definitely point toward GPS and large-scale radio objects. The following two pieces of evidence definitely point toward GPS and large-scale radio objects.

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The Radio Structure E–C–W1 could then be the sign of the radio-loud component does not have to be induced directly by interaction with the companion galactic core. It could be the intrinsic mechanism that made the quasar start its activity. The radio structure E–C–W1 could then be the sign of the radio-loud component does not have to be induced directly by interaction with the companion galactic core. It could be the intrinsic mechanism that made the quasar start its activity.

4.1. Intrinsic Activity Restart and Its Modulation by the Companion

The first scenario is based on the conclusion that if the radio activity timescale (~10^5 years) is much shorter than the tidal perturbation timescale (~10^7 years), the radio activity of the radio-loud component does not have to be induced directly by interaction with the companion galactic core. It could be the intrinsic mechanism that made the quasar start its activity. The radio structure E–C–W1 could then be the sign of the first period of activity, which was prematurely ceased by the instability of the accretion disk (Janiuk et al. 2002; Czerny et al. 2009). The model for the internal instability in the accretion disk is based on the radiation pressure dominance. This physical effect leads to the periodic outbursts of the disk luminosity, intermittent with the low-luminosity periods. The feature W2 is then interpreted as the subsequent activity phase, which could now be changed due to the interaction with the companion galaxy. We have performed such modeling (see Section 4.1.2 for the full description and plots) using the accretion disk instability cycle. To account for the influence of the companion galaxy, we changed the outer boundary condition in the evolutionary calculations. We assumed the accretion rate to be a periodic function of time, and this perturbation is given by the tidal interaction in the period ~10^7 years. The black hole mass was M_{BH} = 3 \times 10^8 M_{\odot}, as estimated for the radio-loud component (Shen et al. 2011). As a result, we obtained that the interaction with the companion quasar influences the modulation and overall evolution cycle of the primary quasar. It can dramatically change the activity pattern and lead to the prolonged, up to a few million years, activity outbursts.

Below, we present the results of the numerical modeling of the intermittent activity for the binary quasar.

4.1.1. Luminosity Outbursts of the Core of the Radio-loud Component

In Figure 3, we show an exemplary light curve that results from the accretion disk instability model. The model was described in detail with appropriate time-dependent equations and a numerical method in Janiuk et al. (2002).

The luminous core in our example exhibits regular outbursts for the external (mean) accretion rate of 14% of the Eddington rate. The duration of the outbursts and their separation depend on the black hole mass and viscosity parameter. In this case, the outburst cycle lasts about 2 \times 10^4 years.

In this model, we postulate that a large fraction of the disk power at outburst is transferred to the jet and provides a source for its kinetic energy, parameterized by the fraction \eta_jet in the range (0; 1). This jet fraction is dependent on time and radius via the local accretion rate, depending on both time and distance from the black hole:

\[ \eta_{\text{jet}} = 1 - \frac{1}{1 + A_{\text{jet}} m(r, t)^2}, \]  

with \(A_{\text{jet}}\) being a parameter of the model. The physical meaning of this parameterization is that at the Eddington accretion limit
there would be equipartition between the jet and disk radiation for \( A_{\text{jet}} = 1 \). We consider here the accretion rates well below the Eddington limit, and we adopt a moderate value of \( A_{\text{jet}} = 2.5 \). The disk–jet coupling results in reducing the outburst amplitudes in comparison to the models without the jets (Janiuk & Czerny 2011). This model is plausible for the radio-loud quasar and consistent with its observed luminosity.

4.1.2. Influence of the Companion Radio-quiet Quasar

To account for the influence of the companion galaxy, we change the outer boundary condition in the evolutionary calculations. The external accretion rate, instead of being a constant parameter, is a periodic function of time:

\[
\log \left( \frac{m_{\text{ext}}}{m_0} \right) = \sin \left( \frac{2\pi}{T_p} t \right),
\]

where \( T_p \) is a characteristic perturbation timescale. We assume that this perturbation is given by the tidal interaction and \( T_p \approx 10^7 \) years. The accretion rate is parameterized by \( m_0 = 0.014 \) and changes from \( 0.1 m_0 \) to \( 10 m_0 \), so that it never exceeds the Eddington limit during the perturbation cycle.

The modulation of the material supply rate to the outer disk edge results in periodic changes of the outburst pattern. Both the durations and amplitudes are affected.

In Figure 4, we show the modulated evolution of the unstable disk coupled with a jet. Note that Figure 4 shows a much longer timescale than Figure 3; the individual shorter timescale outbursts are marked as a shaded region. The adopted black hole mass was \( M = 3 \times 10^8 M_\odot \), the starting accretion rate \( m_0 = 0.014 \), and the jet parameter \( A_{\text{jet}} = 2.5 \). Now, the pattern of the long-term evolution is as follows: The largest external accretion rates result in a persistent outburst state of the disk, while the luminosity fluctuations occur at small accretion rates. This long persistent high state was not obtained in the simulations with a constant boundary condition and is an effect of the modulation. Moreover, it was not obtained in the models without the disk–jet coupling, and we instead had persistent quiescent states. Also, we note that the transition rates from the intermittent to the persistent state and vice versa are not equal—in the present simulation, the first transition occurs at \( m_1 = 0.08 \) and the second transition at \( m_2 = 0.02 \). This complex behavior results from the adopted jet cooling term, which depends nonlinearly on time and distance. In this way, the accretion disk plasma holds the “memory” of the past conditions as the information propagates inward in the disk in the viscous timescale, so that we obtain an effect of “hysteresis.”

In conclusion, the accretion rate modulation overimposed on the cyclic outbursts influences the source behavior on long timescales. This modulation is due to the companion galaxy tidal forces, which influence the rate of matter supply to the outer regions of the accretion disk. The transitions from the strong, periodically active behavior, through the “flickering,” and then to the persistent high state of the source may occur due to the companion interaction.

We may therefore be observing in the quasar FIRST J1643+3156 the active core that accretes near the transition rate from the intermittent to the persistent high state. We consider here a scenario in which the radio structure E–C–W1 is a sign of the past activity, and W2 is a current activity episode that can be prolonged up to a few million years due to the interaction with the companion quasar.

We emphasize here that the above numerical simulations give a novel result, and to our knowledge such hydrodynamical instability models with a time-dependent boundary condition have not been performed before. The details of the simulations also depend on the presence or absence of the jet or outflow from the disk and are intended to be discussed in a forthcoming paper.
The instability scenario discussed above explains the episodic activity of the radio source (Section 4.1.1) as well as the prolonged activity episodes due to the influence of the companion (Section 4.1.2). In this way, we account for the timescales appropriate for the observed source. However, because the geometry of the structures observed is also complex and the instability scenario itself is not able to predict geometrical changes (the non-colinearity of the observed structures), we discuss further possibilities below.

4.2. Geometry Changes Due to the Interaction with the Companion

The intermittent radio activity can be caused by an intrinsic mechanism. It also may be modulated or directly triggered by the interaction with the companion galaxy.

4.2.1. Precession

The observed complex radio structure of FIRST J1643+3156 could be caused by the accretion disk precession due to tidal forces induced by the companion in the binary system (Caproni et al. 2006). In this case, the precession due to the tidal interaction in a binary system will occur if the binary orbit is not coplanar with the accretion disk. Considering this scenario the disturbed radio morphology can be explained in the following way: The structure E–C–W1 is the first episode of the radio source activity and the first direction of the radio jet and particle ejection. Then, the precession causes the change in the accretion disk plane and the new jet direction of FIRST J1643+3156 is the southwestern one—the jet is fuelling the component W2. This precession scenario is therefore independent of but also complementary to the episodic activity scenario discussed above in Section 4.1, as it explains the lack of colinearity between the subsequent structures (to account simultaneously for both effects, i.e., the timescales and geometry changes, would require essentially 3D time-dependent global modeling of a non-axisymmetric unstable accretion disk, which is beyond the scope of the present work). The estimated age of the radio structure of FIRST J1643+3156 is on the order of $10^5$ years. The timescale of the decay of the components no longer powered by the jet (lobes E and W1?) is comparable with the timescale of its activity phase. However, during the first few periods of inactivity, the radio luminosity fades rapidly (Reynolds & Begelman 1997), making the potential distortions well visible only during a short period of time. The fading source structure is then characterized by weak emission detectable only in deep, low-frequency observations. It is possible then that the radio observations of FIRST J1643+3156 were made just in time to detect the distortions at lower 1.66 GHz frequency.

4.2.2. Jet–ISM Interaction

We also consider a scenario in which the radio activity of the FIRST J1643+3156 has been directly triggered by the interaction with the companion galaxy but in which its radio structure is a result of the jet interaction with the host galaxy environment. The 1.66 GHz image of FIRST J1643+3156 (Figure 1[a]) shows a diffuse radio emission around the radio-loud quasar, suggesting a very dense medium of the host galaxy of the source and indicating strong interactions. Simulations of colliding disk galaxies (Barnes & Hernquist 1996) tracked the evolution of both gas and stars in the merger during the subsequent orbital loops. The gas accumulates in the nucleus of each galaxy as the two orbit away from each other, but stronger perturbation of the incoming galaxies is visible only after the first pericentric passage. In such an environment, a black hole may undergo many fuelling events, and each event may completely disrupt and/or restart the jet. After each renewal, the jet may need to force its way through the changing nuclear environment anew. In the case of FIRST J1643+3156, the features W1 and W2 could be parts of the same jet. The jet is changing its orientation during propagation in the central regions of the host galaxy due to interactions with the dense environment. The feature E could then be the counter jet. The presence of strong [O II$\lambda$5007 in FIRST J1643+3156 (Brotherton et al. 1999; Kunert-Bajraszewska & Labiano 2010) suggests jet–interstellar medium (ISM) interactions. According to Labiano (2008), the expansion of the radio source through the host ISM could be triggering or enhancing the [O II$\lambda$5007 line emission through direct interaction. The presence of the cold accreting material could be responsible for even higher gas excitation, and consequently for higher [O II$\lambda$5007 line emission. Buttiglione et al. (2010) have discussed that the HEGs, such as the FIRST J1643+3156, are powered by accretion of cold gas probably provided by the merger with a gas-rich galaxy.

5. SUMMARY

FIRST J1643+3156 is an unusual and statistically very rare low redshift binary quasar. The radio morphology of FIRST J1643+3156 is complex on both frequencies and consists of four components, which indicates a rapid change of jet direction and/or restarting of the jet. The host galaxy of the radio-loud quasar is also highly disturbed, and we suggest that the first pericentric passage took place in this pair, igniting and/or changing the radio activity and morphology in the radio-loud component. We discussed the following possible scenarios that could explain such a complex radio morphology: (1) accretion disk instability, modulated by the interaction with the companion, (2) precession of the disk/jet due to the companion’s tidal forces, and (3) jet–cloud interactions.

New observations could test the evolution scenarios presented here. A more sensitive radio observation may allow us to trace the jet pattern and the change of its direction at both 1.66 GHz and 5 GHz frequencies. Infrared and X-ray observations could give us information about the intrinsic absorption and potential presence of the dense environment in FIRST J1643+3156.

Based on the analysis described above, we suggest that, regardless of the mechanism that caused the distortions of the radio structure visible in the binary system, they may be short-lived phenomena. The disturbed radio components that are no longer powered by the jet can quickly fade away. This makes the potential distortions detectable only during a short period of time and implies a low detection rate. To speculate on what could be the past and future history of the FIRST J1643+3156 binary system, we performed numerical simulations concerning the influence of the companion quasar on the activity of the radio-loud one. The results show that the ignited or subsequent activity phase can be prolonged up to a few million years and limits the occurrence of distorted radio structures, at least those caused by the internal instability in the accretion disk.

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