OBSERVATIONAL EVIDENCE FOR YOUNG RADIO GALAXIES IS TRIGGERED BY ACCRETION DISK INSTABILITY

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ABSTRACT

Bolometric luminosities and black hole (BH) masses are estimated by various methods for a sample of young radio galaxies with known ages. We find that the ages are positively correlated with the bolometric luminosities in these young radio galaxies. This positive correlation is consistent with the theoretical prediction based on the radiation pressure instability of accretion disks in Czerny et al. The ages of young radio galaxies are also found to be consistent with the theoretical durations of outbursts in BH mass and accretion rate (in Eddington unit) plane, where the outbursts are assumed to be triggered by the radiation pressure instabilities. Our results provide observational evidence for the radiation pressure instability, which causes limit-cycle behavior, as a physical mechanism that may be responsible for these short-lived young radio galaxies.

Key words: accretion, accretion disks – black hole physics – galaxies: active – instabilities – quasars: general

1. INTRODUCTION

Gigahertz-peaked spectrum (GPS; projected linear size \( D \lesssim 1 \) kpc) and compact steep-spectrum (CSS; projected linear size \( D \lesssim 20 \) kpc) radio sources constitute a large fraction (\( \sim 40\% \)) of the powerful radio source population. Their radio spectra are simple and convex with peaks close to 1 GHz and 100 MHz for GPS and CSS sources, respectively (see O’Dea 1998 for a review). Two basic models have been proposed to explain the CSS/GPS phenomena: (1) \textit{youth scenario}: the radio sources are compact because they are young, and the jets will expand into large-scale “classical” lobes during the course of their life (e.g., Fanti et al. 1995); (2) \textit{frustration scenario}: the radio emitting plasma is permanently confined to the region within the host galaxy by a cocoon of dense gas and dust for its entire life (e.g., van Breugel 1984). Both kinematic ages estimated from proper motions of hot spots (e.g., Giroletti & Polatidis 2009 and references therein) and radiative ages deduced by synchrotron theory based on the radio spectra of lobes (e.g., Murgia et al. 1999 and reference therein) provide values from \( \sim 10^3 \) to \( \sim 10^5 \) years, which strongly support the \textit{youth scenario}.

The duty cycle is one of key problems in understanding the evolution of active galactic nuclei (AGNs; e.g., Wang et al. 2009 and references therein). The extended radio emission in galaxies and quasars provides us with an opportunity to probe their history through the ages derived from the structural and spectral information of their radio lobes. Both the young compact symmetric object (CSO) with a much older extended relic emission (e.g., Owsianik et al. 1998) and the “double-double” radio source, which consists of a new lobe-pair near the core and a more distant faded lobe-pair (e.g., Lara et al. 1999; Schoenmakers et al. 2000), can be explained in terms of recurrent activity in their nuclei. These possibly re-born radio sources may be intermittent on timescales of \( \sim 10^4 \) to \( \sim 10^5 \) years (e.g., Reynolds & Begelman 1997).

A standard, geometrically thin accretion disk (SSD; Shakura & Sunyaev 1973) is known to be unstable in the innermost, radiation pressure dominated regions when accretion rate is high (e.g., Lightman & Eardley 1974). The thermally unstable inner region will possibly lead to the so-called limit-cycle behavior, which has been confirmed by numerical simulations of the time-dependent disk (e.g., Honma et al. 1991; Li et al. 2007). On the observational side, a perfect candidate of black hole (BH) X-ray binary GRS 1915+105 has been known to show the theoretically predicted limit-cyclic luminosity variations (e.g., Belloni et al. 1997, Nayakshin et al. 2000; Janiuk et al. 2002; Merloni & Nayakshin 2006). Czerny et al. (2009) found that the outburst durations are generally from \( \sim 10^2 \) to \( \sim 10^5 \) years for the BH mass \( M_{\text{BH}} = 10^7 \) to \( 10^{10} M_{\odot} \) and viscosity parameter \( \alpha = 0.02 \) to \( 0.2 \), which are roughly consistent with the observed ages of young radio galaxies, where the viscosity law with a geometric mean between the gas and the total pressure for scaling of the stress, i.e., \( T_\phi \propto (P_\text{gas}P_\text{tot})^{1/2} \), is adopted when modeling the time evolution of SSD under the radiation pressure instability. An important empirical correlation between the outburst duration, \( T_{\text{burst}} \), bolometric luminosity, \( L_{\text{bol}} \), and viscosity parameter, \( \alpha \), is given by Czerny et al. (2009):

\[
\log \left( \frac{T_{\text{burst}}}{\text{yr}} \right) \simeq 1.25 \log \left( \frac{L_{\text{bol}}}{\text{erg s}^{-1}} \right) + 0.38 \log \left( \frac{\alpha}{0.02} \right) - 53.6. \tag{1}
\]

Wu (2009) found that most young radio galaxies have relatively high accretion rates with average Eddington ratio \( \langle \log L_{\text{bol}}/L_{\text{Edd}} \rangle = -0.56 \) for a sample of 51 sources (32 CSS + 19 GPS), where \( L_{\text{Edd}} = 1.38 \times 10^{38} M_{\odot}/M_{\odot} \) is the Eddington luminosity. The accretion disk in these high Eddington ratio CSS/GPS sources may have suffered the radiation pressure instability, which provide a possibility of explaining their short-lived activities. In this Letter, we estimate the bolometric luminosities and BH masses for a sample of young radio galaxies with known ages. We then test whether the ages of young radio galaxies are consistent with the durations of outbursts or not, where the outbursts are assumed to be triggered by the radiation pressure instabilities of accretion disks (e.g., Czerny et al. 2009).

Throughout this paper, we assume the following cosmology: \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_0 = 0.3, \text{ and } \Omega_\Lambda = 0.7 \).

2. THE SAMPLE

We compile a sample of 37 young radio sources from the data available in the literature. The kinematic ages are selected mainly from Giroletti & Polatidis (2009) and references
### Table 1
The Data of Young Radio Sources

| Name          | Others | $z$  | Size kpc | Age (10$^3$ yr) | Method | Refs. | $L_{bol}$ (ergs s$^{-1}$) | $M_{BH}$ (log(M$_\odot$)) | Refs. | $L_{bol}/L_{Edd}$ log |
|---------------|--------|------|----------|-----------------|--------|------|----------------------------|--------------------------|------|------------------------|
| 0108+388      | ...    | 0.669| 0.023    | 0.40            | kin    | G09  | 44.20                      | L(O III)                 | L96  | 7.9                     | 21.6$^1$ | −0.82                |
| 0710+439      | ...    | 0.518| 0.088    | 0.93            | kin    | P03  | 45.75                      | L(Hα)                    | L96  | 8.4                     | 20.1$^1$ | −0.75                |
| 1031+567      | ...    | 0.450| 0.109    | 1.84            | kin    | T00  | 45.02                      | L(O III)                 | L96  | 8.1                     | 20.2$^1$ | −1.23                |
| 1358+626      | 4C 62.22 | 0.431| 0.160    | 2.4             | kin    | V06  | 45.10                      | L(O III)                 | L96  | 8.2                     | 19.3$^1$ | −1.27                |
| 1404+286      | OQ 208 | 0.077| 0.007    | 0.22            | kin    | L07  | 45.19                      | L(Hβ)                    | M03  | 8.7                     | 14.6$^1$ | −1.69                |
| 1934−638      | ...    | 0.183| 0.085    | 1.60            | kin    | G09  | 45.60                      | L(O III)                 | X99  | 8.5                     | 17.1$^1$ | −1.03                |
| 2021+614      | ...    | 0.227| 0.016    | 0.37            | kin    | T00  | 45.17                      | L(O III)                 | L96  | 8.9                     | 16.8$^1$ | −1.91                |
| 2352+495      | ...    | 0.238| 0.117    | 3.0             | kin    | P03  | 44.73                      | L(O III)                 | L96  | 8.4                     | 18.0$^1$ | −1.79                |
| J1111+1955    | ...    | 0.299| 0.070    | 1.62            | kin    | G05  | 45.11                      | L(O III)                 | P00  | 8.5                     | 18.4$^1$ | −1.48                |
| 0116+31       | 4C 31.04 | 0.060| 0.071    | 0.50            | kin    | G09  | 44.94                      | L(O III)                 | X99  | ...                     | ...          |...                    |
| 1718−649      | NGC 6328 | 0.014| 0.002    | 0.09            | kin    | G09  | 44.10                      | L(O III)                 | X99  | 8.4                     | 11.4$^2$ | −2.44                |
| 0316+413      | 3C 84  | 0.018| 0.015    | 0.24            | kin    | N09  | 44.60                      | L(O III)                 | H01  | 8.5                     | W02        | −2.04                |
| 1413+135      | ...    | 0.247| 0.031    | 0.13            | syn    | G05  | 44.14                      | Fitting                  | X06  | 8.0                     | 18.9$^1$ | −1.95                |
| 0035+227      | ...    | 0.096| 0.022    | 0.45            | syn    | G09  | 44.87                      | L(O III)                 | G04  | ...                     | ...          |...                    |

**Notes.**

* References for the radio sizes, the ages of these young radio sources, and the methods for deriving the ages.  
* References for the data used to derive the bolometric luminosities.  
* References for the BH masses and the apparent magnitude of the host galaxies in $R$–band used to estimate the BH masses in this work, of which (1) and (2) are selected from Snellen et al. (1996) and NED (NASA/IPAC Extragalactic Database; http://nedwww.ipac.caltech.edu) respectively.

**References.**

G09: Giroletti & Polatidis 2009; V06: Vink et al. 2006; G05: Gugliucci et al. 2005; N09: Nagai et al. 2009; M99: Murgia et al. 1999; F02: Fanti et al. 2002; A1: this work assuming the upper limit of light speed; A93: Akujor et al. 1993; K97: Katz-Stone & Rudnick 1997; A2: this work using the jet speed of 0.1c in An et al. 2004; T01: Tyulbashev & Chernikov 2001; T92: Taylor et al. 1992; K06: Krumen-Bajraszewa et al. 2006; L96: Lawrence et al. 1996; M03: Marziani et al. 2003; X99: Xu et al. 1999; P00: Peck et al. 2000; H01: Ho & Peng 2001; X06: Xie et al. 2006; G04: Goncalves & Serote 2004; H03: Hirata et al. 2003; W09: Wu 2009 and references therein; A00: Axon et al. 2000; W02: Woo & Urry 2002; Z03: Zakamska et al. 2003.

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therein), while the ages estimated from synchrotron cooling time mainly are taken from Murgia et al. (1999). We give the lower limits of kinematic age for four sources (0134+329, 0538+498, 1458+718, 2249+185) assuming the upper limit for the separation of hot spots to be the light speed $c$ in this work, since their radiative ages may be much shorter than the actual source ages in these jets or hot spots dominated sources (see Murgia et al. 1999 for more details). The kinematic age of CSS source 1328+307 (3C 286) is estimated in the present work from its projected linear size and jet propagation speed $\sim 0.1c$ (An et al. 2004). Several other individual sources with known ages are also selected from the literature. In total, our sample consists of 14 GPS and 23 CSS sources (see Table 1 for more details).

3. BOLOMETRIC LUMINOSITIES AND BH MASSES

The bolometric luminosity of AGNs is sometimes approximated from the optical luminosity, since the integration of spectral energy distribution (SED) is usually hampered by the lack of multi-wavelength observational data that spans many decades in wavelength. It is found that the bolometric luminosity is roughly nine times the optical luminosity, $L_{bol} = 9 L_{5100}$, where $L_{5100} = \lambda L_\lambda$ (5100 Å) (Kaspi et al. 2000). It should be noted that
the monochromatic optical luminosity cannot be used to derive the bolometric luminosity if the optical luminosity is contaminated by the jet emission in radio loud AGNs (e.g., BL Lacs) or obscured by the putative torus. The broad line emission is believed to be illuminated by the ionizing luminosity from the accretion disk, and, therefore, it can be used as a good indicator of thermal optical emission. We estimate the bolometric luminosities for nine sources from their broad line luminosities (e.g., Hβ, CIV) using the empirical correlations between the luminosities of different emission lines and bolometric luminosities derived from a sample of radio-quiet AGNs in Wu (2009). The bolometric luminosities of two sources fitted from their SEDs are selected directly (2342+821, 1458+718; Woo & Urry 2002). The bolometric luminosity of 1 source has been corrected for beaming effect is also included (1413+135, Xie et al. 2006). The bolometric luminosities of four optically Type 1 CSS sources are estimated from their optical luminosities with $L_{\text{bol}} = 9 L_{5100}$, since that, normally, the steep-spectrum sources do not suffer strong contamination from the Doppler-boosted emission of the jet due to the possible large inclination angles.

In the standard model, narrow emission lines (e.g., [O III]) are believed to be excited through photoionization by the UV continuum produced by the accretion disk (e.g., in radio-quiet AGNs). However, it is more complicated in young radio galaxies, since shocks caused by the interaction between the jet and interstellar medium (ISM) may also be important for the morphology, kinematics, and the excitation of narrow emission lines (e.g., Labiano et al. 2005; Holt et al. 2006). Moy & Rocca-Volmerange (2002) proposed that the shock ionization may be only important for sources with intermediate radio sizes ($2 \text{ kpc} < D < 150 \text{ kpc}$, e.g., CSS sources), while AGN photoionization is dominant in the most compact sources ($D < 2 \text{ kpc}$, e.g., CSS sources) and the extended sources with $D > 150 \text{ kpc}$. Moreover, the jet sizes in all GPS sources of our sample are less than 0.2 kpc (see Table 1), which are much less than the kpc-scale of narrow line regions. This also supports that the shock contribution to narrow lines from the jet-cloud interaction may be not important and, therefore, narrow line emission may still be a good indicator of central thermal emission in these GPS sources. To derive the bolometric luminosities for more sources, we investigate the relation between [O III] luminosities and bolometric luminosities for a sample of radio-quiet Type 1 AGNs, which include 20 Seyferts and 23 low red-shift QSOs. The Seyferts are selected from Kaspi et al. (2000), while the [O III] luminosities are chosen from Kraemer et al. (2004), and the QSOs are selected from Alonso-Herrero et al. (1997). To be consistent with other methods, we calculate the bolometric luminosities from $L_{\text{bol}} = 9 L_{5100}$ for these radio-quiet AGNs. The relation between the bolometric luminosities and [O III] luminosities is shown in Figure 1, and its linear regression is

$$\log L_{\text{bol}} = 0.95 \pm 0.08 \log L_{[\text{O III}]} + 5.39 \pm 3.17. \quad (2)$$

We find that bolometric correction factors, $L_{\text{bol}}/L_{[\text{O III}]}$, are about 2000 and 3000 for 20 Seyferts and 23 QSOs, respectively. The bolometric luminosities for 12 GPS and 9 CSS sources were calculated from [O III] luminosities derived from the relation between host galaxy absolute magnitude $M_K$ in the $R$ band and BH mass proposed by McLure et al. (2004),

$$\log_{10}(M_{\text{BH}}/M_\odot) = -0.5 M_K - 2.74. \quad (3)$$

4. RESULTS

We estimate the bolometric luminosities for 37 young radio sources by various methods. The relation between ages and bolometric luminosities for young radio galaxies is presented in Figure 2, where the bolometric luminosities of CSS sources calculated from [O III] luminosities are marked with extra open squares. We find that the ages are positively correlated with the bolometric luminosities in these young radio galaxies, which is consistent with the prediction of radiation pressure instability in accretion disks (Czerny et al. 2009). We plot the dashed lines corresponding to Equation (1) with viscosity parameters $\alpha = 10^{-4}$ and 1 in Figure 2. We find that most sources are located to the left of the line with $\alpha = 1$ ($L_{\text{bol}}-T_{\text{burst}}$), where the $\alpha = 1$ line gives an upper limit of the theoretical outburst duration. The relation between bolometric luminosity and half of the outburst duration with $\alpha = 0.1$ is also presented in Figure 2 ($L_{\text{bol}}-T_{\text{burst}}/2$, solid line), which is converted from Equation (1). We find that the real ages of sources in our sample are roughly consistent with the theoretical prediction of $T_{\text{burst}}/2$ with $\alpha \approx 0.1$, since that sources should have the real ages between 0 and $T_{\text{burst}}$
The triangles, squares, pentagons, and circles correspond to the age in bins of $[0-5 \times 10^2]$, $[5 \times 10^2-5 \times 10^3]$, $[5 \times 10^3-5 \times 10^4]$, and $[5 \times 10^4-5 \times 10^5]$ yr, respectively. The solid lines are the half of theoretical outburst durations predicted by the disk instability model with $\alpha = 0.1$, which are converted from the case of $\alpha = 0.2$ in Czerny et al. (2009, Figure 5) using the scaling relation of Equation (1).

(e.g., $0 < \text{age} < T_{\text{burst}}$), and, on average, the real ages should correspond to $T_{\text{burst}}/2$ with some dispersion around this value.

The BH masses are calculated from the luminosities of the host galaxy or collected from the literature. The Eddington ratios, $\dot{m} = L_{\text{bol}}/L_{\text{Edd}}$, were computed from the estimated bolometric luminosities and BH masses. We then compare the ages of young radio sources with the half of the outburst durations in the BH mass-accretion rate (in Eddington unit, $M_{\text{BH}}-\dot{m}$) plane where the outbursts are assumed to be triggered by the radiation pressure instabilities of accretion disks. To do so, we convert the contour map of $\alpha = 0.2$ in Czerny et al. (2009, Figure 5) to the case of $T_{\text{burst}}/2$ with $\alpha = 0.1$ using the scaling relation of Equation (1), since we find that most of the young radio sources can, on the average, be described by $\alpha \simeq 0.1$ in the $L_{\text{bol}}$–age relation. The ages of young radio sources are divided into four bins as $[0-5 \times 10^2]$, $[5 \times 10^2-5 \times 10^3]$, $[5 \times 10^3-5 \times 10^4]$, and $[5 \times 10^4-5 \times 10^5]$ yr according to the theoretical lines of $10^2$, $10^3$, $10^4$, and $10^5$ yr of Czerny et al. (2009), respectively.

The results are shown in Figure 3. We find that, on average, the ages of young radio sources are also roughly consistent with the half of outburst durations with $\alpha \simeq 0.1$ in the $M_{\text{BH}}-\dot{m}$ plane, even with substantial scatter. In particular, there are 12 sources in the bin of $[5 \times 10^3-5 \times 10^4]$ yr (red-pentagons), which coincide with the theoretical prediction of $10^4$ yr (red-solid line) very well.

5. SUMMARY AND DISCUSSION

We estimate bolometric luminosities and BH masses for a sample of young radio galaxies with known ages. We find a positive correlation between the ages and bolometric luminosities in these young radio sources (see Figure 2). This positive correlation is roughly consistent with the theoretical prediction based on the radiation pressure instability of accretion disks in Czerny et al. (2009). We find that the real ages of most sources are shorter than the upper limit of outburst duration with $\alpha = 1$, and, on average, correspond to the half of outburst durations with $\alpha \simeq 0.1$ (see Figure 2). We further compare the ages with the half of outburst durations in the $M_{\text{BH}}-\dot{m}$ plane, and find that the observational data are also roughly consistent with the theoretical prediction with $\alpha \simeq 0.1$ (see Figure 3). Therefore, our results provide observational evidence for the radiation pressure instability as a physical mechanism that may also be responsible for these short-lived young radio galaxies, beside the perfect application to the brightest Galactic X-ray binary GRS 1915+105.

The bolometric luminosities for young radio galaxies are estimated from their SED fittings, optical luminosities, broad line luminosities, or narrow line luminosities. In these methods, the most controversial one is that derived from the [O III] luminosity, due to the possible shock contribution caused by the jet–ISM interaction. However, the shock contribution may not be important in the GPS sources as suggested by the ionization diagnostics of different narrow emission lines (e.g., Moy & Rocca-Volmerange 2002). Wu (2009) also found that accretion activities may still play an important role in shaping the kinematics of [O III] narrow line in young radio galaxies. The bolometric luminosity calculated from [O III] luminosity is $\log L_{\text{bol}}([\text{O III}]) = 45.12$ for the GPS source 1404+286, which is consistent with that calculated from the broad line luminosity $\log L_{\text{bol}}([\text{H}\beta]) = 45.19$ very well, where the [O III] luminosity is selected from Marziani et al. (2003). This also supports the claim that the shock contribution to [O III] luminosity may not be important, and the [O III] luminosity can still be regarded as a good indicator of central thermal emission in these small radio-sized GPS sources. Labiano et al. (2005) found that the contribution to narrow line luminosity from the shocked gas is between 30% and 70% for the CSS source 3C 303.1, and this ratio is even lower in other two CSS sources (3C 67 and 3C 277.1), based on the ionization diagnostics of different narrow emission lines. Therefore, the bolometric luminosities of nine CSS sources calculated from the [O III] luminosities may not be overestimated too much, which will not change our main conclusion.

The limit-cycle behavior triggered by the radiation pressure instability of accretion disks provides a good explanation for the luminosity variations of X-ray binary GRS 1915+105 (e.g., Nayakshin et al. 2000; Janiuk et al. 2002; Merloni & Nayakshin 2006). Czerny et al. (2009) proposed that the young radio galaxies may have similar origins, and the unstable disk caused by radiation pressure may be the physical reason for their short-lived radio activities. We note that the unique limit-cycle variability appears only in the brightest X-ray binary GRS 1915+105 when it radiates at high luminosity (e.g., Belloni et al. 1997). Wu (2009) found that most of the young radio galaxies have relatively high Eddington ratios, and the accretion disk may also have suffered the radiation pressure instabilities in these young radio sources. We collect a sample of 37 young radio galaxies, and explore whether these young radio sources are consistent with the predictions of disk instability model in Czerny et al. (2009) or not. We test this in both the $L_{\text{bol}}$–age relation and the ages in the $M_{\text{BH}}-\dot{m}$ plane. We find that the real ages of most sources are, indeed, less than the upper limit of the theoretical outburst durations with $\alpha = 1$ (see Figure 2). The viscosity parameter, $\alpha$, should be larger than $10^{-4}$, since the real ages of most sources are longer than their predicted outburst durations (see Figure 2). We find that the real ages of these young radio sources are roughly consistent with the model predictions with $\alpha \simeq 0.1$, if we assume that the real ages, on average, should correspond to half of outburst durations (see Figure 2). The real ages of the young radio sources are also found...
to be consistent with the half of outburst durations with $\alpha \simeq 0.1$ in the $M_{\text{BH}}-\dot{m}$ plane (see Figure 3). It should be noted that there are still uncertainties in estimating BH masses, bolometric luminosities, and ages in these young radio galaxies. Moreover, the simplified disk model was used to derive Equation (1), where corona and jet are neglected (see Czerny et al. 2009 for more details). With all these uncertainties in mind, it seems that the observational data of young radio galaxies are in good agreement with the theoretical predictions of the disk instability model. We note that the disk instability model also predicts a complex behavior of the jet activities depending on the accretion rate and BH mass: (1) continuous jet at low accretion rate where the accretion disk is stable (e.g., $\dot{m} \lesssim 10^{-2}$, low luminosity AGN); (2) intermittent compact jet with short outburst duration ($\lesssim 10^5$ yr) at high accretion rate, where the disk is unstable and the jet is able to escape from the host galaxy and possibly grow to a large-scale radio source (e.g., FR I/FR II; see Czerny et al. 2009 for more details).

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