Estimating black hole masses in young radio sources using CFHT spectroscopy

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The correlation between black hole masses and stellar velocity dispersions provides an efficient method to determine the masses of black holes in active galaxies. We obtained optical spectra of a Compact-Steep-Spectrum (CSS) galaxy 4C +29.70, using the Canada-France-Hawaii Telescope (CFHT) equipped with OSIS, in August 6, 2003. Several stellar absorption features, such as Mg I (5175 Å), Ca E band (5269 Å) and Na D (5890 Å), were detected in the spectra. The stellar velocity dispersion, σ, of the host galaxy, measured from absorption features is $\approx 250 \text{ km s}^{-1}$. If 4C +29.70 follows the $M_{\text{BH}} - \sigma$ relation established for nearby galaxies, then its central black hole has a mass of $\approx 3.3 \times 10^8 M_{\odot}$. In combination with the black hole masses of seven GPS galaxies in Snellen et al. (2003), we find that the average black hole mass of these eight young radio sources is smaller than that of the Bettoni et al. (2003) sample of extended radio galaxies. This may indicate that young radio sources are likely at the early evolutionary stage of radio galaxies, at which the central black holes may still undergo rapid growth. However, this needs further investigations.

1 Introduction

Gigahertz-Peaked-Spectrum (GPS: projected linear size $D < 1 \text{ kpc}$) and the more extended Compact-Steep-Spectrum (CSS: $D < 15 \text{ kpc}$) sources make up $\sim 40\%$ of radio-loud AGNs, yet their nature is not fully understood (see, e.g., O'Dea 1998, and references therein). There are two main theories to describe these compact sources: the ‘frustration’ scenario (van Breugel 1984), and the ‘youth’ scenario (Fanti et al. 1995). In the ‘frustration’ scenario, the source is enshrouded by a gas and dust cocoon so dense that its radio jets cannot escape nuclear confinement – which frustrates radio source growth. Alternatively, the youth scenario attributes compactness to evolution – if we observe it young, the radio jet will not have expanded much, and will still be relatively small. In this scenario, the GPS & CSS sources represent the earliest stages in the radio-loud AGN life cycle, before they expand into the large-scale ‘classical’ doubles. This is the currently preferred theory, which is supported by estimated dynamical ages for GPS sources of $t_{\text{dyn}} \sim 10^2 - 10^3 \text{ yrs}$ (e.g. Owsianik, Conway & Politis 1998; Tschager et al. 2000), and by radio spectral ages for the larger CSS sources of $t_{\text{sp}} < 10^4 \text{ yrs}$ (Murgia et al. 1999). These compact AGNs are then young radio sources, either emerging for the ‘first time’, or recently ‘born again’.

There is much evidence suggesting that a significant fraction of radio-loud AGNs exhibit radio activity which is very likely triggered by mergers of two or more galaxies, at least one of which is gas-rich (Heckman et al. 1986). Many compact radio source counterparts show optical features attributed to mergers (e.g. double nuclei, tidal tails, arcs, and distorted isophotes), implying that these sources are observed shortly after merging (Stanghellini et al. 1993), before the system has settled back down. All activity-inducing processes clearly involve injecting large amounts of gas and dust into the nuclear regions – at least initially, the radio source will be in a dense and dusty environment, with a huge reservoir of material poised to feed the central massive black hole (MBH) at high accretion rates.

According to AGN unification models, GPS & CSS radio sources are expected to harbor an obscured quasar (Fanti et al. 2000). In the past, there have been strong indications that jet power is proportional to AGN bolometric luminosity (e.g. Baum & Heckman 1989; Rawlings & Saunders 1991; Falcke et al. 1995). As GPS & CSS sources are powerful radio-loud AGNs, we may expect them to appear as optically bright quasars when their jet axes are viewed close to the line of sight. Yu & Tremaine (2002) proposed that the growth of high-mass MBHs comes mainly from accretion during the optically bright QSO phases. While the ‘classical’ radio doubles have already been growing over long times, GPS & CSS sources are more likely to be in the early stages of accretion and radio-loud activity, with the central
MBH still undergoing rapid growth. Since these compact sources are believed to evolve into the ‘classical’ extended ones, it is important to compare the \( M_{\text{BH}} \)-distribution in young radio sources with that of their larger descendants (e.g. Bettoni et al. 2003), in order to constrain the proposed ‘youth’ scenario, as well as the nature of accretion in compact radio sources. Such a comparison may also yield clues on the radio activity in these sources, e.g. ‘first time’ activity vs. ‘born again’ scenarios, as the \( M_{\text{BH}} \) values should be significantly larger in the latter case.

A key advance in estimating the central MBH masses (\( M_{\text{BH}} \)) within galactic bulges was the discovery of the \( M_{\text{BH}} - \sigma \) relation, a tight correlation between the MBH mass and the galactic bulge stellar velocity dispersion \( \sigma \) (Ferrarese & Merritt 2000; Gebhardt et al. 2000a; Tremaine et al. 2002). This relation provides an important consistency check against masses determined from reverberation mapping of Seyfert nuclei (Nelson 2000; Gebhardt et al. 2000b; Ferrarese et al. 2001). The tightness of the correlation over a wide range of galaxy types, both elliptical and spiral, means that \( M_{\text{BH}} \) can be estimated simply by measuring \( \sigma \) of the AGN host galaxy bulge; recently, MBH masses were estimated using this relation for a large sample of low- \( z \) radio galaxies (Bettoni et al. 2003).

The optical light from GPS & CSS radio sources, with optical identification and known galaxy morphologies, is thought to be dominated by old stellar populations (e.g., Snellen et al. 1999), making them suitable for measuring the velocity dispersion, \( \sigma \), of the host galaxy. By measuring \( \sigma \) from the stellar absorption lines in the host galaxies, we may then estimate the MBH mass using the \( M_{\text{BH}} - \sigma \) relation. Here we present the optical spectrum of a CSS source 4C +29.70, observed with the Canada-France-Hawaii Telescope (CFHT). By measuring the central stellar velocity dispersion \( \sigma \) of the host galaxy from the stellar absorption lines, we estimated the black hole mass using the \( M_{\text{BH}} - \sigma \) relation established for nearby galaxies.

2 OBSERVATIONS AND REDUCTIONS

Observations were obtained in 2003 August 6, using the 3.6m Canada-France-Hawaii Telescope, equipped with the Optionally Stabilized Imager and Spectrometer (OSIS). Spectra were secured using the O600 grism to cover the spectra region 4900A–7100 A, at 0.57Å pixel\(^{-1}\) dispersion. This allows us to measure the absorption lines of Mg I (5175Å), Ca E band (5269Å), and Na D (5890Å), and other absorption line blends from the host galaxy. A 0'58 wide slit, with a position angle of 90°, was used for all the observations. Initially, we planned to observe a sample of 27 GPS/CSS galaxies, however, we only succeeded to observe one CSS source 4C +29.70 due to poor weather during observing run. The total exposure time for 4C +29.70 was 30 minutes.

The chosen grism, combined with the slit, yields a spectral resolution for a velocity dispersion measurement of \( \sim 60 \) km s\(^{-1}\), which is adequate for the expected range of \( \sigma \).

Fig. 1 Rest frame spectrum of the CSS source 4C +29.70 (z=0.13069). The spectrum has been continuum-normalized to unity. The spectrum has been smoothed with a boxcar function of 3 pixels in order to slightly improve the S/N for the sake of the presentation. Various absorption features, such as Mg I (5175Å), Ca E band (5269Å), and Na D (5890Å), along with emission lines of [O III] 4959, 5007Å, and H\(\beta\), are marked. The horizontal axis is wavelength in Å, in the rest frame.

During the observations, the seeing ranged between 0'8 and 1'0. The targets were centered into the slit, and then the one-dimensional spectrum was extracted from an aperture of 2'5 diameter. Standard data reduction was applied to the spectra using the tasks available in the IRAF package. This procedure includes the bias subtraction, flat-fielding, wavelength calibration using an exposure of a He-Ne-Ar lamp, and extraction of one-dimensional spectra. We took two spectra and combined them in order to remove cosmic-ray hits and other occasional spurious signals in the detector. The continuum-normalized spectrum of 4C +29.70 is displayed in the rest-frame in Fig. 1. Several stellar absorption features are clearly visible in this spectrum, which include Mg I (5175Å), Ca E band (5269Å), and Na D (5890Å). Strong emission lines of [O III] 4959, 5007 Å are also detected in 4C +29.70, but H\(\beta\) is only marginally detected.

The stellar velocity dispersion \( \sigma \) was determined using the cross-correlation method (e.g. Tonry & Davis 1979) implemented in the IRAF RV package. In Fig. 1 the spec-

\footnote{IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.}
3 RESULTS AND DISCUSSIONS

4C +29.70 is a CSS source of intermediate strength, selected from the 408-MHz Bologna B2.1 catalogue (Saikia et al. 2002). Its redshift is $z = 0.13069$, corresponding to a distance of 476 Mpc ($H_0 = 75 \text{ km s}^{-1} \text{Mpc}^{-1}$ and $q_0 = 0.5$). It was observed in snapshot mode with the Very Large Array (VLA) A-array at 4835 MHz on 1985 February 10 (Saikia et al. 2002). The radio structure is highly asymmetric and double, and the total flux density is 263 mJy (Saikia et al. 2002). The largest angular size (LAS) of this source is 1.2 arcsec, corresponding to a projected linear size of 2.45 kpc. The spectral index $\alpha$, between 327 MHz and 5 GHz, is about 0.7 ($I_\nu \propto \nu^{-\alpha}$). 4C +29.70 was optically identified as a galaxy.

To determine $M_{\text{BH}}$ from the velocity dispersion, we use the fit of the $M_{\text{BH}} - \sigma$ relation from Tremaine et al. (2002), which is given by:

$$\log \left( \frac{M_{\text{BH}}}{M_\odot} \right) = (8.13 \pm 0.06) + (4.02 \pm 0.32) \log \left( \frac{\sigma}{200 \text{ km s}^{-1}} \right). \quad (1)$$

This relation was derived using a carefully culled sample of the best-quality black hole mass measurements, and a fitting technique that properly accounts for uncertainties in both $M_{\text{BH}}$ and $\sigma$.

The measurements used to calibrate the above relation were the luminosity-weighted velocity dispersion $\sigma_e$, measured in a slit aperture of length $2r_e$. However, our value of $\sigma$ does not exactly correspond to this aperture size. Velocity dispersions can be corrected to a standard aperture size using the relations given by Jørgensen, Franx & Kjærgaard (1995), but the corrections depend on the effective radii, which are not known accurately for 4C +29.70. Rather than apply an uncertain correction to the measured velocity dispersion, we choose to use our measured dispersion directly to estimate $M_{\text{BH}}$. As shown by Gebhardt et al. (2000a), the value of $\sigma$ measured from slit apertures of different length differ from $\sigma_e$ by less than 10% for typical, nearby elliptical galaxies.

Using the result of $\sigma \approx 250 \text{ km s}^{-1}$ in conjunction with the $M_{\text{BH}} - \sigma$ relation, we estimate a black hole mass of $\approx 3.3 \times 10^8 M_\odot$ for 4C +29.70. Recently, MBH masses were estimated using either the $M_{\text{BH}} - \sigma$ relation, or the black hole mass - bulge luminosity relation, for a large sample of low-$z$ radio galaxies (Bettoni et al. 2003). They found the black hole masses to range from $5 \times 10^7$ to $6 \times 10^9 M_\odot$, with an average $\langle \log (M_{\text{BH}}/M_\odot) \rangle \sim 8.9 \pm 0.4$. To compare the black hole masses of young radio sources to those of extended radio galaxies, we tentatively combine the black hole masses of several GPS galaxies estimated in Snellen et al. (2003) with our measurements. The average value of black hole masses of these eight young radio sources is $\langle \log (M_{\text{BH}}/M_\odot) \rangle = 8.1 \pm 0.4$. This value is apparently smaller than that of Bettoni sample. This may indicate that the young radio sources are likely at the early evolutionary stage of radio galaxies, at which the central black holes may still undergo rapid growth. To evolve into the extended radio galaxies in $\sim 10^7 - 10^8$ yr, averagely they must accrete at near (or even super-) Eddington luminosity, i.e. $\sim 3M_\odot \text{yr}^{-1}$ for a $10^{8.1} M_\odot$ black hole, from which the star formation rate of several hundred $M_\odot \text{yr}^{-1}$ is roughly expected (Wu & Cao 2006). According to the bolometric cor-

Fig. 2. Spectra of 4C +29.70 ($z=0.13069$) and the template star HD 224060. The spectral regions are adopted in the cross-correlation method to estimate the stellar velocity dispersion. The spectra have been continuum-normalized to unity. The spectrum of 4C +29.70 has been shifted vertically by 1.0 unit to avoid overlap. The object spectrum has been smoothed with a boxcar function of 3 pixels in order to slightly improve the S/N for the sake of the presentation. Various absorption features, Mg I (5175 Å), and Ca E band (5269 Å) are marked. The horizontal axis is wavelength in Å, in the rest frame.
rection of Hopkins et al. (2007), the hard X-ray luminosity of \( \sim 10^{44} \text{ erg s}^{-1} \) is then expected, which is consistent with the typical value of GPS galaxies (e.g. Guainazzi et al. 2006). However, the expected MFIR luminosity \( \sim 10^{45} \text{ erg s}^{-1} \) (Hopkins et al. 2007; Satyapal et al. 2005) are somehow larger than the observations (e.g. Heckman et al. 1994; Fanti et al. 2000). Nevertheless, our conclusion can not be firmly drawn at present stage due to the small sample size. Alternatively, young radio source can be ‘born again’ sources. The detection of quasar remnants in nearby galaxies, in the form of inactive massive BHs, conclusively demonstrates that the cosmic evolution of AGN activity must be episodic (Richstone et al. 1998). The duty cycle for accretion may be quite short, so that any individual massive BH is likely to have been activated (and deactivated) many times since it was formed. If this scenario is true, young radio sources may host black holes with masses comparable to those of extended radio galaxies.

Apart from the masses of central black hole, the nature of accretion in young radio sources can help us understand the evolution of radio galaxies. For a given supermassive black hole, the full life cycle of a radio galaxy is believed to be: GPS \( \rightarrow \) CSS \( \rightarrow \) FR II \( \rightarrow \) FR I (Marecki et al. 2003). In the unification scheme, FR II and FR I radio galaxies are unified with FSRQs and BL Lacs, respectively (Urry & Padovani 1995). For the population of blazars (i.e. FSRQs and BL Lacs), their accretion rate is believed to decrease along the evolutionary sequence FSRQs \( \rightarrow \) BL Lacs (Wang, Ho & Staubert 2003), in which FSRQs are rich in gas and therefore are characterized by large accretion rates, while BL Lac objects represent evolved sources depleted of gas, with faint nuclear emission and low-power jets (Cavaliere & D’Elia 2002; Böttcher & Dermer 2002). When viewed at large angles to our line of sight, the sequence becomes: FR II \( \rightarrow \) FR I, where FR II sources have higher accretion rates compared to FR I ones. Ghisellini & Celotti (2001) recently suggested that the dividing line between FR II and FR I corresponds to a transition in the accretion mode, from a SS disk (FR II) to an optically thin ADAF (FR I) one. If we fit GPS/CSS sources into this evolutionary sequence, their accretion rates are then expected to be relatively high.

In conclusion, we estimated the black hole mass for 4C +29.70, a CSS source, as a first step of our project to constrain the evolutionary scenario of radio galaxies through systematically comparing the black hole masses between young radio sources and extended radio galaxies. In combination with the black hole masses of seven GPS galaxies, we find that the average black hole mass of young radio sources are smaller than that of extended radio galaxies. This may indicate that the young radio sources are likely at the early evolutionary stage of radio galaxies, at which the central black holes may still undergo rapid growth. However, this result should be re-investigated with a large and complete sample, of which the comparison with the well constructed sample of extended radio galaxies is required as well. This is our ongoing project.

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