

## IS J 133658.3–295105 A RADIO SOURCE AT $z \geq 1.0$ OR AT THE DISTANCE OF M 83?

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### ABSTRACT

We present Gemini optical imaging and spectroscopy of the radio source J 133658.3–295105. This source has been suggested to be the core of an FR II radio source with two detected lobes. J 133658.3–295105 and its lobes are aligned with the optical nucleus of M 83 and with three other radio sources at the M 83 bulge outer region. These radio sources are neither supernova remnants nor H II regions. This curious configuration prompted us to try to determine the distance to J 133658.3–295105. We detected H $\alpha$  emission redshifted by  $\approx 130 \text{ km s}^{-1}$  with respect to an M 83 H II region 2'5 east-southeast of the radio source. We do not detect other redshifted emission lines of an optical counterpart down to  $m_i = 22.2 \pm 0.8$ . Two different scenarios are proposed: the radio source is at  $z \geq 2.5$ , a much larger distance than the previously proposed lower limit  $z \geq 1.0$ , or the object was ejected by a gravitational recoil event from the M 83 nucleus. This nucleus is undergoing a strong dynamical evolution, judging from previous three-dimensional spectroscopy.

*Key words:* galaxies: active – galaxies: individual (M 83) – galaxies: kinematics and dynamics – galaxies: nuclei – galaxies: starburst

### 1. INTRODUCTION

The radio source J 133658.3–295105 (object 28 in Maddox et al. 2006 list) in M 83, is described as the core of an FR II radio source (Maddox et al. 2006; Soria & Wu 2003) whose radio lobes are objects 27 and 29 in the same list. The source presents characteristics of a radio galaxy or a quasar at a distance  $z \geq 1$ , as discussed by Soria & Wu (2003). These authors have found that at a distance  $d_L = 4.7 \text{ Gpc}$  ( $z = 1$ ,  $q_0 = 0.5$ ,  $H = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ), J 133658.3–295105  $L_{20 \text{ cm}}$  and  $L_{6 \text{ cm}}$  fit reasonably well with the expected FR II radio-source luminosities.

M 83 and NGC 5128 (Cen A) are the largest galaxies in one of the most active regions in the nearby sky, the Hydra-Centaurus group. Merger processes as well as Galactic inner build-up are evident in both galaxies. The radio source (RS) 28 appears projected at about  $60''$  from the nucleus of M 83 and the line joining RSs 27, 28, and 29 appears to emerge from the M 83 bulge as seen in Figure 1 (and Figure 1 of Maddox et al. 2006). This alignment was originally proposed by Cowan et al. (1994) to be a jet from the nucleus of M 83. Moreover, RSs 30, 32, and 36, and the M 83 optical nucleus (ON) itself appear to be strongly aligned with this structure, too (Figure 1, right). The whole structure covers  $\sim 100''$  on the sky. None of these radio sources are supernova remnants nor do they appear associated with H II regions (Maddox et al. 2006). RS 32 emits X-rays as a soft X-ray binary. RS 36 was also described as an X-ray binary with evidence for X-ray spectral evolution. The optical nucleus of M 83 is also a radio and X-ray source (Soria & Wu 2003).

These intriguing features encouraged us to try to determine more precisely the distance to RS 28. The complex structure of the central 300 pc of the bulge of M 83 suggests the possibility of it hosting a kick-off object, which has been theoretically predicted (Libeskind et al. 2006; Gualandris & Merrit 2007; Bonning et al. 2007), but not yet observed (Dottori et al. 2007).

Indeed, the condensation traditionally recognized as the M 83 ON (Figure 2c) is off-centered by  $4''$  ( $\sim 80 \text{ pc}$ )

to the northeast with respect to the center of the external K-band isophotes of the bulge (Jensen et al. 1981). At the bulge center, Thatte et al. (2000) have found the kinematic center (KC). More recently, Mast et al. (2006) demonstrated the existence of a third condensation (hidden nucleus, HN), also hidden at optical wavelengths,  $7''$  ( $\sim 140 \text{ pc}$ ) to the west-southwest of KC which seems to be a small galaxy being cannibalized (Díaz et al. 2006b). There is an arclet  $\approx 7''$  to the southwest of KC (Figure 2c) with more than twenty 30-Dor-like giant H II regions (Harris et al. 2001). Pa $\beta$  observed around KC and HN indicates the presence of regions that are actively forming stars (Díaz et al. 2006a).

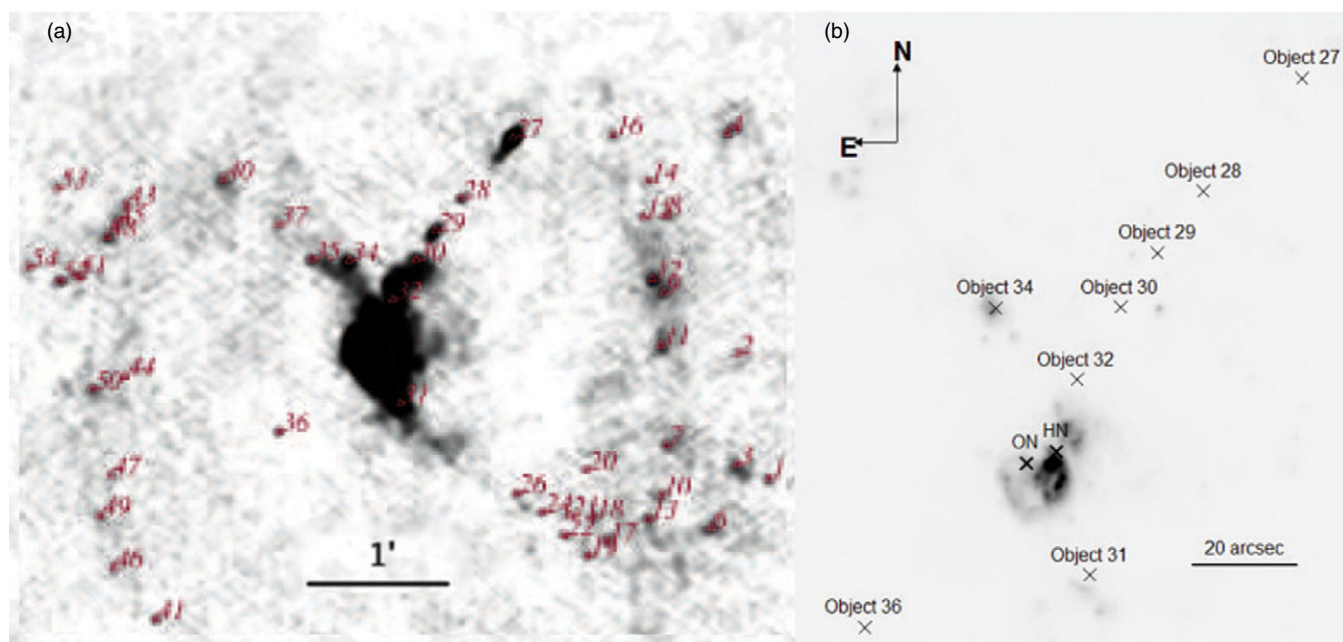
The derived mass of ON is  $\sim 4 \times 10^6 M_\odot$  (Elmegreen et al. 1998; Thatte et al. 2000). These authors proposed a similar mass for KC, while Dottori et al. (2007) determined a larger value of  $\approx 60 \times 10^6 M_\odot$ . HN has a mass of  $16 \times 10^6 M_\odot$  (Díaz et al. 2006a). The upper mass limits for the putative black holes (BHs) associated with ON, KC, and HN are  $0.2\text{--}1.0 \times 10^6 M_\odot$  (Dottori et al. 2007).

Numerical simulations show that ON, KC, HN, and the arclet of H II regions will merge, forming a single massive core in a few hundred Myr (Díaz et al. 2006b). Parallel to the merging process at the center of M 83, molecular clouds in the bar seem to be funneled inward (Elmegreen et al. 1998), guaranteeing central mass accretion in the future.

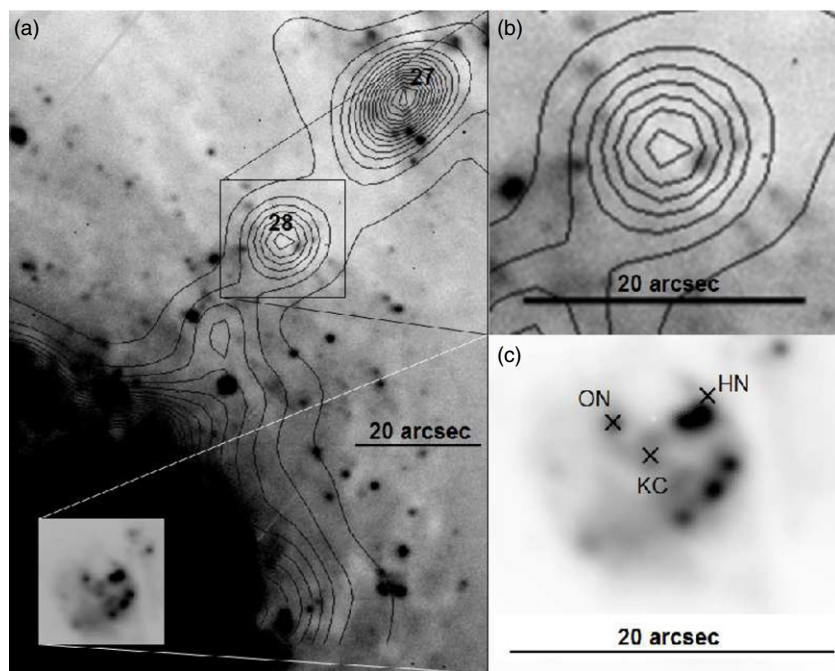
We discuss here the optical observations of the radio source J 133658.3–295105, taken to more precisely derive its distance and its nature.

### 2. OBSERVATIONS

In 2007 April, we obtained a 5 hr spectrum with the REOSC echelle spectrograph in a simple dispersion mode at the Complejo Astronómico El Leoncito (CASLEO) 2.2 m telescope, in Argentina. REOSC has a  $1024 \times 1024$  TEK CCD, with a  $24 \mu\text{m}$  pixel size. A  $1200 \text{ lines mm}^{-1}$  grating was used, covering the wavelength range from 6200 to  $6900 \text{ \AA}$  around



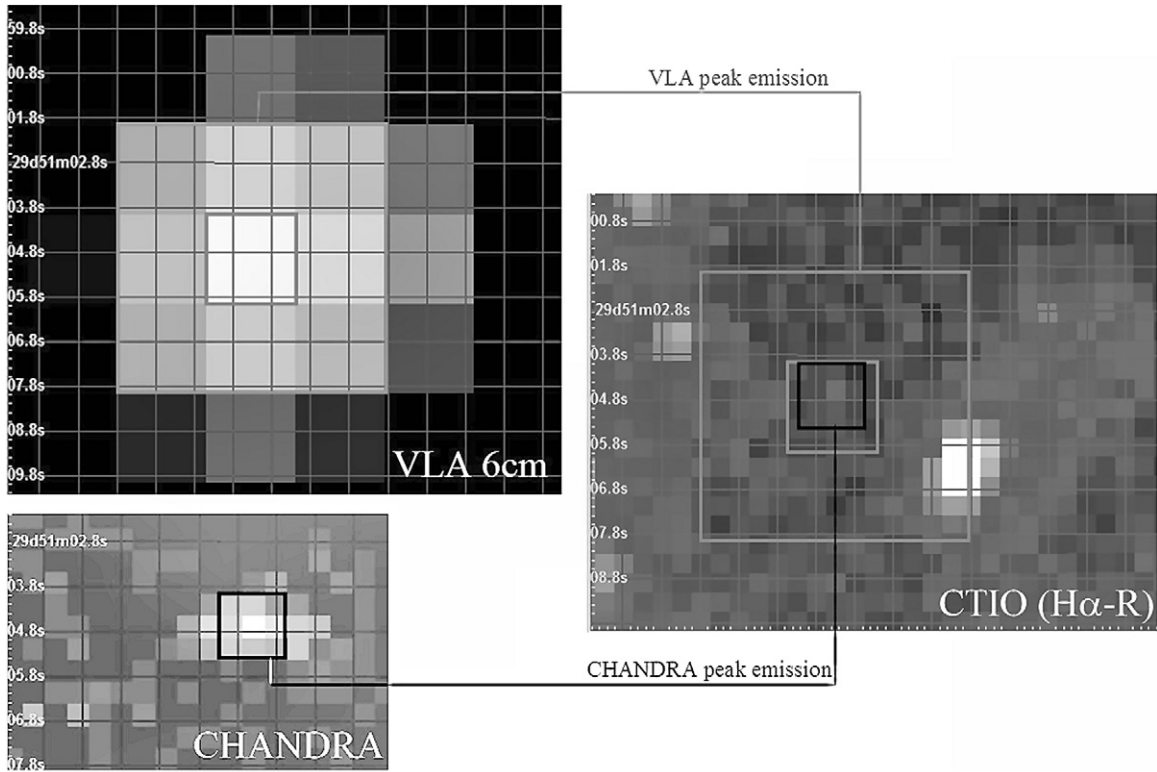
**Figure 1.** Left: Radiomap of M 83 6 cm emission, from Maddox et al. (2006). Right: detached line of radiosources, including the galaxy optical nucleus.



**Figure 2.** (a) GMOS 500 nm to 950 nm co-added image superimposed on the radioisophotes around RS 28. (b) Image blow-up around RS 28 showing that no optical counterpart is detected. (c) Blow-up of the bulge center in the co-added image showing the region complexity. The position of the optical nucleus (ON), kinematic center (KC) and hidden nucleus (HN) are denoted with crosses.

$H\alpha$ . The dispersion was  $32 \text{ \AA mm}^{-1}$ , the reciprocal dispersion  $0.76 \text{ \AA pix}^{-1}$ , the resolution  $2.5 \text{ \AA}$ , and the angular scale was  $1''.02 \text{ pix}^{-1}$ . The slit (at P.A. =  $152^\circ$ ) was positioned on an H II region  $2''.5$  to the east-southeast of RS 28. These  $2''$  seeing observations confirmed the nature of the H II region. On the basis of an accurate astrometric analysis of the source in different spectral domains, we planned the subsequent Gemini Multi Object Spectrographs-South (GMOS-S) observations. Figure 3 shows the astrometry and the H II region to the east-southeast of RS 28 on a ( $H\alpha - R$ ) Cerro Tololo Inter-American Observatory (CTIO) image.

RS 28 was observed by GMOS-S at GEMINI South in 2007 June (program GS-2007A-DD-17). We performed broad and narrow band imaging in the range 500 to 950 nm, centered at the position of the radio source emission peak with average seeing of  $0''.8$ . The observed bands and exposure times were  $g$ : 90 s;  $[O III]$ : 121 s;  $[O III]C$ : 121 s;  $H\alpha$ : 91.5 s;  $H\alpha C$ : 91.5 s;  $[S II]$ : 91.5 s;  $i$ : 60 s;  $CaT$ : 60 s; and  $z$ : 91.5 s. Spectroscopy in the spectral range 572–988 nm was performed with an effective exposure time of 3600 s and average seeing of  $0''.8$ . A  $1''.5$  long slit was positioned on RS 28 and oriented along the line of radio sources shown in Figure 1 (P.A. =  $140^\circ$ ).



**Figure 3.** Astrometry around RS 28 showing the relative spatial resolution of CTIO ( $H\alpha$ -R), 6 cm radio map, and *Chandra*'s X-ray map. The brightest knot in the CTIO ( $H\alpha$ -R) image is the  $H\text{II}$  region at  $2''.5$  east-southeast of RS 28.

### 3. WHERE IS RS 28?

Figure 2 shows the co-added image from the observed GMOS-S bands  $V$ ,  $[\text{O III}]$ ,  $[\text{O III}]C$ ,  $H\alpha$ ,  $H\alpha C$ ,  $[\text{S II}]$ ,  $z$ ,  $i$ , and CaT. We estimate that the detection limit at signal-to-noise ratio (S/N)  $\sim 3$  is  $m_i = 23.5 \pm 0.5$ . This is based on an average seeing of  $0''.8$  and takes into account the background noise from the M 83 disk.

It is expected that the disk of M 83 will dim background objects. Boissier et al. (2005) derive an azimuthal mean absorption  $A(FUV) = 2.0$  mag at R around 1 kpc, which translates into  $A(I) = 1.3$  mag (assuming  $A(FUV)/A(I) = 1.5$ ). Beckman et al. (1996) obtained, for three face-on galaxies, an inter-arm absorption 0.2–0.5 mag smaller than the azimuthal mean at 800 nm. That would lead to an absorption of the order of  $A(I) = 1.0 \pm 0.3$  mag for background objects at the projected position of RS 28 on the M 83 disk. These considerations lead us to estimate that our composed image could detect more than 80% of the broad- and narrow-line active galactic nuclei (AGNs) at  $1 \leq z \leq 3$  in the SEXSI sample (see Figure 6 in Eckart et al. 2006), irrespective of the redshift. The blow up of the composed GMOS image of the  $20''$  around RS 28 in Figure 2(b) does not show any sign of an associated optical source.

We have determined the detectability of RS 28 in our images using Cen A as an example. The radio source Cen A originates from the elliptical galaxy NGC 5128, which hosts a Seyfert 2 nucleus with a strong dust lane across its main body. Quasars with strong activity of star formation would present much dust and probably would suffer internal absorption as NGC 5128 does. The absolute brightness of NGC 5128 is  $M_B = -23.0$  mag at a luminosity distance 11 Mpc,  $(m - M) = 30.2$ . If Cen A was located at  $z \sim 1$ , NGC 5128 would shine at  $m_I =$

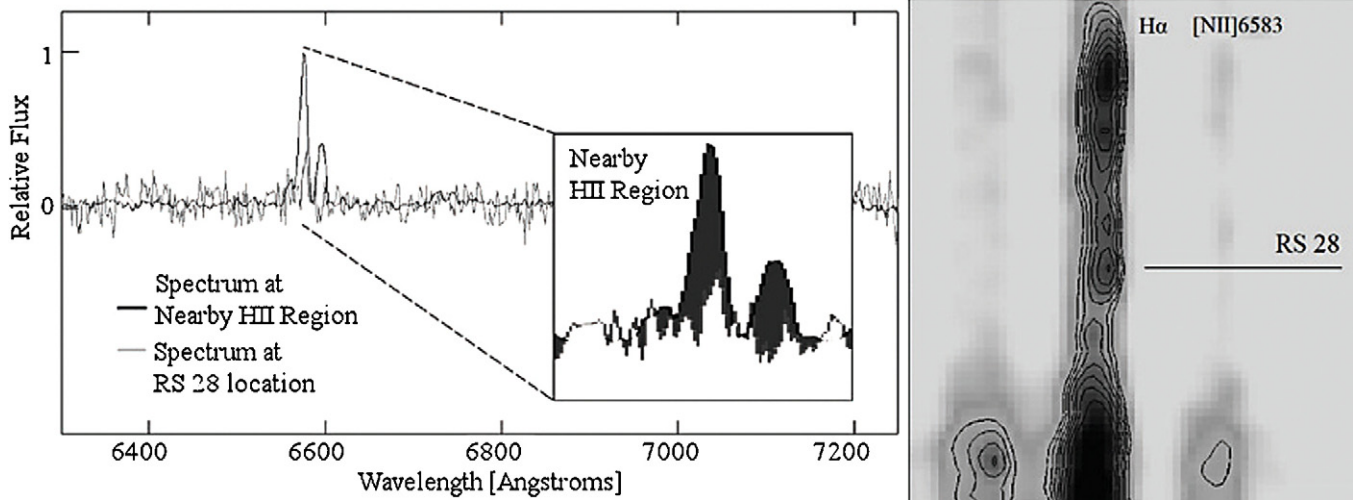
21.5 mag, or  $m_I = 23.1$  mag if located at  $z = 2$ . Therefore, if located somewhere in the redshift range  $1 \leq z \leq 2$ , a Cen A type galaxy would be detectable by our imagery. The angular distance between the maxima of Cen A radio lobes brightness is  $\sim 3^\circ$  (580 kpc), about twice the value quoted by Soria & Wu (2003) for RS 28 at  $z = 1$ . That relation is maintained if RS 28 is at larger  $z$ , since the angular size distance does not change significantly with  $z$ , for  $z \geq 1$ .

Our spectroscopy suggests that we should detect any distant background AGN-typical emission lines. In the co-added spectrum, the detection limit for the continuum of a giant elliptical galaxy at redshift 2 is  $m_i = 20.5 \pm 0.8$  (S/N  $\sim 3$ ), and it is  $m_i = 22.2 \pm 0.8$  for  $H\gamma$  detection in a QSO at  $1 < z < 2$ . Strong redshifted lines should fall into the spectral range covered by GMOS for  $1 \leq z \leq 2.5$ , as can be seen in the revised catalog of QSOs (Hewitt & Burbidge 1993). The most conspicuous emission lines and the corresponding  $z$  intervals are:  $[\text{O II}] \lambda 3727$  (0.34, 1.4);  $[\text{N V}] \lambda 3426$  (0.46, 1.77);  $[\text{Mg II}] \lambda 2798$  (0.8, 2.4);  $[\text{C III}] \lambda 1909$  (1.6, 3.9);  $[\text{He II}] \lambda 1640$  (2.1, 4.7);  $[\text{C IV}] \lambda 1549$  (2.2, 5.1);  $[\text{S IV}] \lambda 1402$  (2.6, 6.7); and  $[\text{Ne V}] \lambda 1240$  (3.4, 7.6). Our observational constraints set a limit of the order of  $z \approx 3$  for large radio galaxies.

We can get an idea of the expected S/N by looking at spectra obtained for broad- and narrow-line AGNs at different distances by the Keck observatory with exposure times of 1 to 2 hr (Eckart et al. 2006). For a similar exposure time (3600 s), we expect for GEMINI a S/N  $\approx 0.7$  times that of Keck. So, practically all lines, except for  $[\text{He II}]$  would be easily seen in our spectra. Therefore, from our optical spectroscopy, we can confidently say that if RS 28 is a high-redshift radio source, it should be at  $z \geq 2.5$ .

The RS 28 spectrum is compared in Figure 4 with that of a simultaneously observed, well-defined  $H\text{II}$  region located





**Figure 4.** Right: GEMINI+GMOS two-dimensional spectrum around RS 28. Left:  $I$  vs.  $\lambda$  shows the redshifted  $H\alpha$  at RS 28 with respect to that of the  $HII$  region located to the N.

on the arm to the north of RS 28. We see that  $H\alpha$  emission appears marginally at the RS 28 spectrum, redshifted with respect to that of the  $HII$  region. Radial velocities are respectively  $618 \pm 30 \text{ km s}^{-1}$  and  $522 \pm 12 \text{ km s}^{-1}$ . The  $HII$  region located to the east-southeast of RS 28 (Figure 3) is at  $V_r = 490 \pm 12 \text{ km s}^{-1}$ , based on our REOSC-CASLEO data. REOSC accuracy can be gaged by the nuclear spectrum taken on the same night and instrument configuration, which gives for the nucleus a  $V_r = 534 \pm 15 \text{ km s}^{-1}$ . The heliocentric velocity of M 83, from the NASA/IPAC Extragalactic Database (NED), is  $V_r = 513 \pm 5 \text{ km s}^{-1}$ . Two-dimensional CO observations (Sakamoto et al. 2004) provide for the nuclear region a value of  $V_{LSR} = 508 \pm 15 \text{ km s}^{-1}$  (error guess is from the position accuracy in Figure 3 of Sakamoto et al.). This value has to be added to the LSR velocity of approximately  $24 \text{ km s}^{-1}$  (obtained with Ed Murphy’s calculator in <http://fuse.pha.jhu.edu>) to compare with our measurement. We conclude that REOSC radial velocities are reliable within the errors.

The radial velocity of RS 28 is approximately  $130 \pm 40 \text{ km s}^{-1}$  larger than that of the close east-southeast  $HII$  region. The nucleus and the two  $HII$  regions show similar radial velocities because M 83 presents a small inclination of  $24^\circ$  with respect to the plane of the sky and the direction in discussion is at about  $130^\circ$  from the galaxy major axis and practically perpendicular to the bar (Figure 2) where noncircular motions are detected (Sakamoto et al. 2004). This result leads us to conclude that the  $H\alpha$  emission marginally detected at RS 28 is emitted by an object that does not take part of the disk kinematics, whose projected velocity in the radial direction is of the order of  $100 \text{ km s}^{-1}$ . These arguments point to a possible physical connection between RS 28 and M 83.

#### 4. FINAL REMARKS

Chance alignments do occur. A striking case is that of the two radio sources juxtaposed  $1'$  to the northeast and southwest of Scorpius (Sco) X-1, which for a long time were believed to be radio lobes of Sco X-1, until Fomalont & Geldzahler (1991) demonstrated by measuring Sco X-1 proper motion that they are unrelated background sources. On the one hand, deep optical imaging and spectroscopy on the location of the radio source RS 28 do not confirm the high-redshift nature of this

object, and on the other hand, GMOS/GEMINI-S spectroscopy marginally shows the presence of  $H\alpha$  in emission at a redshift similar to that of the galaxy but from a source kinematically well-differentiated from disk objects.

If its local character is confirmed, the FR II radio source RS 28 would have a total projected size  $\approx 0.5\text{--}1.0 \text{ kpc}$ . The possibility of RS 28 being ejected by a gravitational recoil, remnant of a previous M 83 nuclear merger, remains open. In that case, the driving engine within RS 28 that produced the ejecta RS 27 and RS 29 would be an accretion disk like those postulated for microquasars in the Galaxy and extragalactic radio sources. The reason why RS 27 and RS 29 sit along the apparent kick line remains unclear.

Physical properties of accreting BHs (temperature, ejecta size, etc) scale with some power of the BH mass (Mirabel & Rodríguez 1999). If ejecta size scales with the BH mass, a direct comparison with the microquasar 1E1740.7-2942 ( $M_{BH} \approx 10 M_\odot$ , size  $\approx 5 \text{ pc}$ ; Mirabel et al. 1992) leads to a mass for a RS 28 BH  $\sim 1000$  to  $2000 M_\odot$ . The characteristic blackbody temperature for Eddington-limit accretion (Rees 1984; Mirabel & Rodríguez 1999) should be  $T = 10^7 (M/M_\odot)^{-1/4}$  or about  $1/3$  to  $1/5$  of that of a Galactic microquasar.

X-ray and/or near-IR spectroscopic observations will be necessary to scan redshifts  $2.5 \leq z \leq 5.0$ , and also around  $z \sim 0$ , to unequivocally determine the distance to and the nature of J 133658.3–295105.

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