The TOOT00 Redshift Survey of Radio Sources

ELENI VARDOULAKI1, STEVE RAWLINGS1, GARY J. HILL2, STEVE CROFT3, KATE BRAND4, JULIA RILEY5, CHRIS WILLOTT6

1 Astrophysics, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK
2 University of Texas at Austin, 1 University Station, C1402, Austin, TX 78712, USA
3 Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory L-413, 7000, East Avenue, Livermore, CA 94550
4 National Optical Astronomy Observatory, Tuscon, AZ 85726-6732
5 Cavendish Astrophysics, Department of Physics, Madingley Road, Cambridge, CB3 OHE
6 Herzberg Institute of Astrophysics, National Research Council, 5071 West Saanich RD, Victoria, BC V9E 2E7, Canada

Received; accepted; published online

Abstract. We present first results from the study of the TOOT00 region consisting of 47 radio sources brighter than 100 mJy at 151 MHz. We have 81% spectroscopic redshift completeness. From the $K - z$ diagram we deduce that the host galaxies are similar to $\sim 3 L^*$ passively evolved elliptical galaxies and thus estimate the redshifts of the 9 sources without a secure spectroscopic redshift yielding a median redshift of 1.287. Above the RLF break we have a quasar fraction $f_q \sim 0.3$ although the quasars appear reddened; below the RLF break $f_q \to 0$ if we exclude flat-spectrum radio sources. We present a histogram of the number of TOOT00 radio sources versus their redshift which looks broadly like the Willott et al. (2001) prediction for TOOT, although the observed ratio of high to low redshift objects is somewhat lower than the prediction.

Key words: galaxies: active – galaxies: evolution – galaxies: formation – galaxies: luminosity function

©0000 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

1. Introduction

In search of a better way to determine the evolution of the radio-source population and to study the Radio Luminosity Function (RLF) many researchers have defined different redshift surveys using various samples at decreasing flux density limits (for example, the 3CRR, 6CE and 7CRS surveys). The first comprehensive study of the RLF was carried out by Dunlop and Peacock (1990) who used several complete samples selected at 2.7 GHz with flux density limits between 2.0 and 0.1 Jy. For samples selected at low frequency the benchmark bright survey is the 3CRR survey (Laing, Riley & Longair 1983). Various fainter surveys have followed, but the most complete in spectroscopic redshifts so far are the 6CE (Rawlings et al. 2001) and 7CRS samples (Willott et al. 2002).

The first demonstration of the need for a complete sample with a lower flux density limit than the 3CRR, 6CE and 7CRS samples was made by Willott et al. (2001), who argued that in order to determine the RLF at higher redshifts a new redshift survey based on a large ($\sim 1000$ source) sample about five times fainter than the 7CRS was needed. This was the scientific basis for the TexOx-1000 (TOOT) survey (Hill & Rawlings 2003), which aims to measure redshifts for $\sim 1000$ sources from the 7C survey with a flux density limit of 100 mJy at 151 MHz. TOOT was designed to trace radio sources that lie at the break in the RLF at reasonably high redshift. This makes TOOT the first survey able to study the sources responsible for the bulk of the radio luminosity density of the universe at high redshift (Hill & Rawlings 2003). The goal is to estimate the amount of energy injected in the intracluster medium (ICM) by radio sources and investigate how the radio-source population contributes to the entropy budget of the Universe (Rawlings 2003). The entropy budget of the Universe determines the structure and evolution of the intracluster medium (ICM) and records the thermodynamic history of the gas in clusters (Voit 2004). Furthermore, $\sim 10\%$ of the thermal energy in cluster baryons may originate from radio sources (e.g. Rawlings 2000); the study of radio sources by TOOT may help to explain the ‘excess’ entropy inferred in the central regions of clusters (Ponman et al. 1999).

The TOOT survey will also probe the existence of a redshift cut-off (e.g. Willott et al. 2001) for high radio luminos-
ity sources at $z > 2$, and allow us to carry out studies of various radio source properties which have up to now been dogged by small number statistics. This is particularly important because TOOT probes radio sources near the RLF break which are typical radio sources in the same luminosity-weighted way that an $L^*$ galaxy is typical of normal galaxies. It is also important to investigate whether the low-luminosity population evolves at all (e.g. Clewley & Jarvis 2005).

According to Faranoff & Riley (1974) there are two classes of radio sources, FRI and FRII, where above
\[ \log_{10}(L_{151 \text{MHz}}/\text{WHz}^{-1} \text{sr}^{-1}) = 25.5 \]
lie the FRIIs and below that the FRIs. More recent classification agrees with a dual-population model where the less radio-luminous population is composed of FRIs and FRIIs with weak/absent emission lines, and the more radio-luminous population of strong-line FRII radio galaxies and quasars, where the division is at
\[ \log_{10}(L_{151 \text{MHz}}/\text{WHz}^{-1} \text{sr}^{-1}) = 26.5 \]
(Willott et al. 2001) corresponding to the RLF break.

In this paper we present the scientific results derived from a preliminary study of one of the TOOT regions using optical, near-infrared and radio data. All the data will be presented elsewhere (Vardoulaki et al. in prep).

We use the convention for all spectral indices, $\alpha$, that flux density $S_\nu \propto \nu^{-\alpha}$, where $\nu$ is the observing frequency. We assume throughout a low-density, $\Lambda$-dominated Universe in which $H_0 = 70 \text{ km s}^{-1}\text{Mpc}^{-1}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

2. The TOOT00 region

The TOOT survey consists of several regions (Hill & Rawlings 2003), but here we consider TOOT00 only, studying 47 radio sources with flux densities above 100 mJy at 151 MHz. TOOT00 covers 1.42 deg$^2$ around RA = 00$^\text{h}$ 14$^\text{m}$, DEC = +35$^\circ$ 38′ (J2000.0). Optical spectroscopy was performed using the ISIS spectrograph on the William Herschel Telescope (WHT)$^1$, and the HET$^2$-Marcario Low Resolution Spectrograph (Hill et al. 1998). We have reliable spectroscopic redshifts for 81% of the sample, typically from narrow emission lines, with median redshift $z_{\text{med}} = 0.968$. For those objects with no spectroscopic redshift, typically because their optical spectra were completely blank, estimates were made based on the $K - z$ relation from Willott et al. (2003); the validity of this procedure is discussed in Sec. 3. With the addition of these estimated redshifts the median redshift for TOOT00 rises to 1.287; this is a slightly higher value than those found for the 6CE and 7CRS samples for both of which $z_{\text{med}} \sim 1.1$ (Rawlings, Eales & Lacy 2001 and Willott et al. 2002 respectively). Most of these spectra were taken at the WHT in August 2000, typically using the technique of ‘blind’ spectroscopy (Rawlings, Eales & Warren 1990) in which the radio data were used to determine the position and orientation of the spectroscopic slit. The near-infrared images were typically taken after spectroscopy and were used to estimate the redshifts of the TOOT00 radio sources without spectroscopic redshifts.

For all the TOOT00 objects we have optical spectra from either the WHT or the HET, radio maps from the VLA (A and B configurations) and near-infrared data from either UKIRT or the Oxford-Dartmouth Thirty Degree (ODT) Survey (MacDonald et al. 2004). For some of them we obtained multi-colour optical images from the ODT survey $K$-band magnitudes are measured from near-infrared images for 3, 4, 5, 8 and 9 arcsec diameter apertures, but the 4-arcsec aperture value is used in the $K - z$ diagram of Fig. 1.

For the TOOT00 radio sources we adopt the radio structure classification from Owen & Laing (1989). We use our VLA data to classify objects as Classical Double (CD), Twin Jet (TJ) and Fat Double (FD) radio sources: CDs correspond to FRIs, TJs to FRIIs and FDs to FRII division objects. The radio spectral indices $\alpha_{151\text{MHz}}^{1.4\text{GHz}}$ are calculated using the 1.4 GHz (NRAO/VLA Sky Survey - NVSS) and 151 MHz (7C) flux densities for the TOOT00 sources. The radio luminosity at rest-frame 151 MHz $L_{151\text{MHz}}$ is calculated using the flux densities of the TOOT00 objects at 151 MHz, their redshifts and their values of $\alpha_{151\text{MHz}}^{1.4\text{GHz}}$.

3. Scientific results

The $K - z$ diagram for the TOOT00 objects with spectroscopic redshifts are plotted in Fig. 1. There is a good agree-

---

1. The WHT is operated by the Isaac Newton Group of Telescopes (ING), at the Roque de Los Muchachos Observatory in La Palma, Spain.

2. The Marcario Low Resolution Spectrograph is a joint project of the Hobby - Eberly Telescope partnership and the Instituto de Astronomia de la Universidad Nacional Autonoma de Mexico. The Hobby - Eberly Telescope is operated by McDonald Observatory on behalf of The University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universitaet Muenchen, and Georg-August-Universitaet Goettingen.
The median spectral index for the TOOT00 radio sources is 

\[ \alpha = 0.5 \]

broad emission lines to the total number of them (Willott et al. 2003), filled symbols for quasars and empty ones for galaxies. The over-plotted lines give the flux density limits at 151 MHz of the 6CE, 7CRS and TOOT00 samples, which are 2 Jy (Rawlings, Eales & Lacy 2001), 500 mJy (Willott et al. 2002) and 100 mJy (Hill & Rawlings 2003) respectively.

For all 47 TOOT00 objects we plot the 151-MHz radio luminosity, \( L_{151\text{MHz}} \), versus redshift \( z \) diagram for TOOT00. We use square symbols for TOOT00 sources with spectroscopic \( z \), diamonds for the ones with estimated photometric \( z \) from the \( K - z \) relation (Willott et al. 2003), filled symbols for quasars and empty ones for galaxies. The over-plotted lines give the flux density limits at 151 MHz of the 6CE, 7CRS and TOOT00 samples, which are 2 Jy (Rawlings, Eales & Lacy 2001), 500 mJy (Willott et al. 2002) and 100 mJy (Hill & Rawlings 2003) respectively.

In Fig. 3 we plot the radio luminosity against the spectral index. We take the division between flat and steep spectrum radio sources to be at a spectral index \( \alpha = 0.5 \). Then 3 of the 47 TOOT00 radio sources are flat spectrum objects. The median spectral index for the TOOT00 radio sources is \( \alpha = 0.90 \), which tells us that the TOOT00 sources are typically steep-spectrum sources. Above the RLF break the quasar fraction, which is defined as the ratio of objects with broad emission lines to the total number of them (Willott et al. 2000), is \( f_q \sim 0.3 \). The spectra of these quasars (Vardoulaki et al. in prep) indicate they are all reddened, in the sense that the \( \text{Ly}_\alpha \) emission line is narrow, and broad \( (\geq 2000\text{km}\text{s}^{-1}) \) bases are seen only on lines like \( \text{CIV} 1549 \), implying the existence of an obscured nucleus (although spectropolarimetry would be needed to disentangle scattered and transmitted light). Below the RLF break \( f_q \to 0 \) if quasars close to either the RLF boundary or the flat/steep spectrum division are excluded. Bearing in mind the statistical uncertainty our results are in agreement with Willott et al. (2000), who found that above the break \( f_q \sim 0.4 \) and below the break \( f_q \sim 0 \).

In our sample, CDs and FDs typically look similar in the B-Array radio maps from the VLA (Vardoulaki et al. in prep) but the FDs show no compact hotspots in the high-resolution maps and most of the integrated flux is clearly in diffuse structures (e.g. Fig. 4).

The histogram of the number of TOOT00 objects versus redshift is shown in Fig. 5. The two TOOT00 objects above \( z = 4 \) have their redshifts estimated from the \( K - z \) relation of Willott et al. (2003) and given the scatter in that relation may not, in reality, be at such high redshifts. The overplotted Gaussians approximate the result of the Willott et al. (2001) prediction for TOOT. The prediction considers radio sources in two sub-populations, one dominant below the RLF break and one above the break. This prediction has two maxima, at \( z \sim 0.8 \) and 2.2, but predicts more sources in the higher redshift population than is observed. In crude terms it appears that there is slightly less ICM heating at high redshift due to radio sources than predicted by Rawlings (2000) using extrapolations of the RLF similar to those presented in Willott.
In TOOT00 there is a clear correlation between than the TOOT00 region in hand (Hill & Rawlings 2003).

There is a good agreement with the $K-z$ relation from Willott et al. (2001). We defer full discussion of this, as well as subtleties like spatial clustering yielding narrow features in $N(z)$, to a future paper.

4. Conclusions

The TOOT00 region defines the basic properties of radio sources around the RLF break at redshift $\sim 1-3$. In order to improve the statistics, there is a $\sim$10-times larger sample than the TOOT00 region in hand (Hill & Rawlings 2003). In TOOT00 there is a clear correlation between $K$ magnitude and redshift $z$, and a good agreement with the $K-z$ relation from Willott et al. (2003). We are confident of using this relation to estimate rough redshifts for the TOOT00 objects with no secure spectroscopic redshifts. The host galaxies of the TOOT00 radio sources are similar to those at 6CE and 7CRS sources, i.e. $\sim 3 \ L^{*}$ passively evolved elliptical galaxies that formed at high redshift. The TOOT00 radio sources are divided into two populations at the RLF break (see also Grimes et al. 2004): population-2 lies above the RLF break with $f_{\text{q}} \sim 0.3$ that basically consists of quasars (sometimes lightly reddened) and high-excitation narrow-line radio galaxies; population-1 lies below the RLF break and consists of few quasars ($f_{\text{q}} \rightarrow 0$) being dominated by low-excitation radio galaxies.

The big remaining question is whether the population-1 objects have any hidden quasar activity. We know that all TOOT objects have central engines producing jets but it is an open question whether jets of low power require significant accretion and hence optical quasar activity. In order to investigate this we have to study population-1 radio sources with Spitzer. Probably the most effective way of doing this is to study radio source samples in regions such as the Spitzer First Look Region (Condon et al. 2003) rather than target regions like TOOT with Spitzer.

Acknowledgements. EV and SR would like to thank the organisers of the conference: Montse, Rosa, Enrique and Jose Luis for their kind hospitality. EV would also like to thank the Ministerio de Educació y Ciencia for financial support for this conference. SR is grateful to the UK PPARC for a Senior Research Fellowship. The work of SC was performed in part under the auspices of USDOE by UCLLNL under contract W-7405-Eng-48.

References

Clewley, L., Jarvis, M. J.: 2005, MNRAS, 352, 909
Condon, J. J., Cotton, W. D., Yin, Q. F., Shupe, D. L., Storrie-Lombardi, L. J., Helou, G., Soifer, B. T., Werner, M. W.: 2003, AJ, 125, 2411
Dunlop, J. S., Peacock, J. A.: 1990, MNRAS, 247, 19
Faranoff, B. L., Riley, J. M.: 1974, MNRAS, 167, 31
Grimes, J. A., Rawlings, S., Willott, C. G.: 2004, MNRAS, 349, 503
Hill, G. J., Nicklas, H. E., MacQueen, P. J., Tejada, C., Cobos Dueñas, F. J., Mitsch, W.: 1998, Proc SPIE, 3355, 37
Hill, G., Rawlings, S.: 2003, NewAR, 47, 373
Laing, R. A., Riley, J. M., Longair, M. S.: 1983, MNRAS, 204, 151
MacDonald, E. C., Allen, P., Dalton, G., Moustakas, L. A., Heymans, C., Edmondson, E., Blake, C., Clewley, L., Hammell, M. C., Olding, E., and 5 coauthors: 2004, MNRAS, 52, 1255
Owen, F. N., Laing, R. A.: 1989, MNRAS, 238, 357
Pomran, T. J., Cannon, D. B., Saunders, R.: 1993, MNRAS, 263, 425
Rawlings, S.: 2000, ASP Conference Series, Vol. 199
Rawlings, S.: 2003, NewAR, 47, 397
Rawlings, S., Eales, S., Lacy, M.: 2001, MNRAS, 322, 523
Rawlings, S., Eales, S., Warren, S.: 1990, MNRAS, 243, 14
Voit, M. G.: 2004, astro-ph/0410173
Willott, C. J., Rawlings, S., Blundell, K. M., Lacy, M.: 2000, MNRAS, 316, 449
Willott, C. J., Rawlings, S., Blundell, K. M., Lacy, M., Eales, S. A.: 2001, MNRAS, 322, 536
Willott, C. J., Rawlings, S., Blundell, K. M., Lacy, M., Hill, G. J., Scott, S. E.: 2002, MNRAS, 335, 1120
Willott, C. J., Rawlings, S., Jarvis, M. J., Blundell, K. M.: 2003, MNRAS, 339, 173