A Semi-automatic Search for Giant Radio Galaxy Candidates and their Radio-Optical Follow-up

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Abstract We present results of a search for giant radio galaxies (GRGs) with a projected largest linear size in excess of 1 Mpc. We designed a computational algorithm to identify contiguous emission regions, large and elongated enough to serve as GRG candidates, and applied it to the entire 1.4-GHz NRAO VLA Sky survey (NVSS). In a subsequent visual inspection of 1000 such regions we discovered 15 new GRGs, as well as many other candidate GRGs, some of them previously reported, for which no redshift was known. Our follow-up spectroscopy of 25 of the brighter hosts using two 2.1-m telescopes in Mexico, and four fainter hosts with the 10.4-m Gran Telescopio Canarias (GTC), yielded another 24 GRGs. We also obtained higher-resolution radio images with the Karl G. Jansky Very Large Array for GRG candidates with inconclusive radio structures in NVSS.

1 Introduction

Giant Radio Galaxies (GRGs) are defined in the literature as having extended radio emission over a (projected) largest linear size (LLS) >1 Mpc, using values of $H_0 = 50–100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Those are very rare objects. Indeed, from many ars...
cles published prior to our study (e.g., [9, 11, 15, 12]), homogenising the data to $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, we compiled a list of only 100 GRGs.

Statistical analyses of samples of GRGs [9, 10] suggest that their extreme sizes neither can be explained by a preferred orientation in the plane of the sky, nor by a location in less dense regions of the Universe, nor by more powerful jets feeding their lobes and thus reaching further out in intergalactic space. Instead, [10] argued that it is an exceptionally long-lasting radio activity in $\sim 10\%$ of FR II sources [8] that allows GRGs to develop. On the other hand, [13] found evidence for the lobes of GRGs to be oriented normal to the major axes of galaxy overdensities near the hosts. Thus, the reason why some radio galaxies become giants is still not fully understood, and larger samples of GRGs are desirable to clarify this issue.

Many new GRGs were recently discovered by us [2] from a visual inspection of large-area radio surveys and subsequent identification of the host, e.g., in NED [14] or the SDSS [1]. In order to increase our discovery rate we designed a computational algorithm that can be applied directly to radio survey images.

2 Automated Search in the NVSS Image Atlas

The NVSS at 1.4 GHz [6] currently provides the best combination of sensitivity to radio sources of large angular size ($\lesssim 16''$), low brightness ($1-\sigma \sim 0.45 \text{ mJy beam}^{-1}$), angular resolution (45''), and coverage ($\delta_{2000} > -40^\circ$ or 82\% of the sky). The NVSS image atlas contains 2326 images of $4^\circ \times 4^\circ$ with 1024$^2$ pixels of $15'' \times 15''$. To detect new GRGs in these images, we designed an algorithm to find contiguous emission regions, large and elongated enough to suggest the presence of a GRG. First, the images were binarized by setting all pixels above 3 times the noise level to 1, and all others to 0. Then we applied the closing procedure, which consists of two steps: 1) the erosion operator sets a pixel to zero if any of its 8 neighbors is zero; 2) the dilatation operator sets a pixel to 1 if any of its 8 neighbor pixels has value 1. Thus, closing provides an image cleaned from noise pixels. After that, we perform region growing, which selects only contiguous regions of pixels of value 1 that are larger than a minimum number of pixels. To avoid spurious detections, we also excluded from our search those regions with noise levels $\gtrsim 0.6 \text{ mJy beam}^{-1}$, e.g. near strong sources or close to the Galactic plane, as explained in [16]. Limiting the region size to at least 300 pixels or 18 arcmin$^2$ we obtained 1000 such regions. Since our regions were chosen to be contiguous, and many radio galaxies are known to show two or three separate, neighboring emission regions (core and lobes), we used visual inspection to detect these cases. To find the host galaxy, we overlaid NVSS contours with optical images from DSS [7] or SDSS [1]. When available, we used FIRST images [3] to look for faint ($\lesssim 2 \text{ mJy}$) radio cores between widely spaced radio lobes in NVSS. We found optical hosts for 160 candidates with redshifts in NED. Of these, 15 turned out to be previously unreported GRGs. For many of the remaining candidates, plus several of those found in [2], we retrieved photometric redshifts from SDSS [11] or [4, 5]. This allowed us to estimate
their linear sizes, and select the largest sources with sufficiently bright host galaxies for optical spectroscopy.

For many of our GRG candidates the angular resolution of NVSS is not sufficient to decide on the optical host galaxy, often because the lobes are far apart and no central compact source is detected that would indicate the host. For some of these we obtained Karl G. Jansky Very Large Array (VLA) observations at higher angular resolution and/or frequency.

3 Follow-up with Optical Spectroscopy and Radio Imaging

From the list of candidates for which an estimation of their linear size was possible, we selected those that could be larger than \(\sim 0.7\) Mpc. For the optically brighter hosts \((r < 16.5\) mag\) we obtained spectroscopy with two 2.1-m telescopes in northern Mexico: the Obs. Astronómico Nacional (OAN, San Pedro Mártir) during several runs in 2013 and 2014, and the Obs. Astrofísico G. Haro (OAGH, Cananea) in April 2014. Spectra of four fainter hosts \((r > 18\) mag\) were obtained with the OSIRIS instrument on the 10.4-m Gran Telescopio Canarias (GTC) in Spain.

With our spectroscopy at the 2.1-m telescopes we were able to confirm 18 GRGs with \(\text{LLS} > 1\) Mpc, and several more with smaller radio sizes. Of the four candidates observed with GTC, three have sizes of 1.2–1.5 Mpc, and one has \(\text{LLS} \sim 0.8\) Mpc.

For another 14 very extended sources, with either undetected radio core or uncertain radio structure, we obtained VLA observations in C-configuration at higher angular resolution than NVSS. Two of the most clear-cut results are shown in Fig. 1.

4 Conclusions

We developed and applied a semi-automatic method to find GRGs in the NVSS radio survey. Radio-optical overlays allowed us to find the host galaxy and redshift, resulting in 15 previously unreported GRGs. For another 29 candidates without known spectroscopic redshift, we obtained spectra with 2-m and 10-m class telescopes. Of these, we confirmed 24 new GRGs with sizes from 1.0 to 2.3 Mpc and several others of smaller size. So far, our project has uncovered 39 new GRGs.

Most of our spectroscopic redshifts fall within \(\pm 15\%\) of the photometric ones given in \([1,4,5]\). We also found many GRG candidates with \(|b| < 10^\circ\), for which the host galaxy is obvious, relatively bright, and little affected by Galactic extinction.

We also obtained new radio observations with the VLA of 14 GRG candidates, in order to find the radio nucleus or confirm the physical connection of the radio structure, and to estimate the dynamical ages of the lobes. Analysis of these data is in progress.

Our optical spectroscopy is ongoing at OAN and GTC during 2015. In our GTC observations we are aiming at spectroscopy of GRG candidates at \(z > 0.5\).
Fig. 1 Two of our VLA follow-up observations in grey-scale, with a noise of 0.1 mJy beam$^{-1}$. Contours are from NVSS, starting at 1.3 mJy beam$^{-1}$ (3$\sigma$). (a) J0047+5339: NVSS shows two amorphous lobes, with no obvious radio core. Our new VLA L-band (1–2 GHz) image with 21$''$ × 14$''$ ($\alpha \times \delta$) resolution reveals collimated structures in the lobes for the first time. We also detect a 0.8-mJy core of an R=16.3 mag host galaxy, for which we obtained a redshift of 0.146 at OAN. The source’s angular size of $\sim 16''$ implies an LLS of 2.3 Mpc. (b) J0157+0209: The NVSS image only shows diffuse emission and no radio core. Our new VLA S-band (2–4 GHz) image, with 7$''$ × 10$''$ ($\alpha \times \delta$) resolution, clearly detects a 1.8-mJy core, coincident with a host of $r'=17.8$ mag at $z = 0.2217$ [1]. The source’s angular size of 7' thus corresponds to an LLS of 1.4 Mpc.

and LLS $>$ 2.5 Mpc to probe the density and physical conditions of GRGs in the intermediate-redshift Universe.

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References

1. Alam S., Albareti F. D., Allende Prieto C., et al., 2015, [arXiv:1501.00963]
2. Andernach H., et al., 2012, [http://adsabs.harvard.edu/abs/2012sngi.confP...1A]
3. Becker R. H., et al., 1995, ApJ, 450, 559; [sundog.stsci.edu, third.ucllnl.org/cgi-bin/firstcutout]
4. Bilicki M., Jarrett T. H., Peacock J. A., et al., 2014, ApJS, 210, 9
5. Brescia M., Cavuoti S., Longo G., De Stefano V., 2014, A&A, 558, A126
6. Condon J.J., et al., 1998, AJ, 115, 1693; [http://www.cv.nrao.edu/nvss/]
7. Digitized Sky Survey, e.g., [http://archive.stsci.edu/cgi-bin/dss_form.html]
8. Fanaroff B., Riley J., 1974, MNRAS, 167, P31
9. Ishwara-Chandra C. H., Saikia D. J., 1999, MNRAS, 309, 100
10. Komberg B.V., Pashchenko I.N., 2009, Astronomy Reports, 53, 1086
11. Lara, L., Cotton W. D., Feretti L., et al., 2001, A&A, 370, 409
12. Machalski J., Jamrozy M., Zola S., Koziel D., 2006, A&A, 545, 85
13. Malarecki J. M., Jones D. H., Saripalli L., et al., 2015, MNRAS, in press; [arXiv:1502.03954]
14. NASA/IPAC Extragalactic Database (NED; [http://ned.ipac.caltech.edu])
15. Schoenmakers A.P., de Bruyn A.G., Röttgering H.J.A., van der Laan H., 2001, A&A, 374, 861
16. Silerio-Vázquez M., 2012, MSc thesis, CIMAT, Guanajuato, Mexico