Chapter 36
A Search for Giant Radio Galaxy Candidates and Their Radio-Optical Follow-up

I. del C. Santiago-Bautista, C.A. Rodríguez-Rico, H. Andernach, R. Coziol, J.P. Torres-Papaqui, E.F. Jiménez Andrade, I. Plauchu-Frayn, and E. Momjian

Abstract We present results of a search for giant radio galaxies (GRGs) larger than 1 Mpc in projected size. We designed a computer 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) image atlas. Subsequent visual inspection of 1,000 such regions revealed 15 new GRGs, as well as many other candidate GRGs, some of them previously reported, for which no redshift was known. Our optical spectroscopy of 25 host galaxies with two 2.1-m telescopes in Mexico, and four others 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 some unconfirmed GRG candidates.

I. del C. Santiago-Bautista (✉) • C.A. Rodríguez-Rico • H. Andernach • R. Coziol • J.P. Torres-Papaqui
Deptartamento de Astronomía, DCNE, Universidad de Guanajuato, Guanajuato, Mexico
e-mail: isantiago@astro.ugto.mx; carlos@astro.ugto.mx; heinz@astro.ugto.mx; rcoziol@astro.ugto.mx; papaqui@astro.ugto.mx

E.F. Jiménez Andrade
Instituto Nacional de Astrofísica, Óptica y Electrónica, Tonantzintla, Pue., Mexico
e-mail: eric@inaoep.mx

I. Plauchu-Frayn
Instituto de Astronomía, UNAM, Ensenada, B.C., Mexico
e-mail: ilse@astrosen.unam.mx

E. Momjian
NRAO, Socorro, NM 87801, USA
e-mail: emomjian@nrao.edu

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36.1 Introduction

GRGs are usually defined as having radio emission extending over a (projected) largest linear size (LLS) >1 Mpc for $H_0 = 50$–$100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. GRGs are very rare. Indeed, in the literature prior to our study (e.g., [10, 12, 13, 16]), unifying the sizes with $H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, we found only ∼100 of these objects.

Statistical analyses of samples of GRGs [10, 11] 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, [11] argued that it is an exceptionally long-lasting radio activity in ∼10 % of FR II sources [9] that allows GRGs to develop. On the other hand, [14] found evidence for the lobes of GRGs to be oriented normal to the major axes of galaxy overdensities near the hosts. Nevertheless, the reason why some radio galaxies become giants is still not fully understood. Moreover, only ∼10 % of AGN are radio loud and a much smaller fraction still are GRGs. Determining how frequent GRGs really are can help to clarify why radio-loud AGNs are so rare in the first place. Thus, larger samples of GRGs are desirable to shed light on their origin.

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 [15] 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.

36.2 Search for GRGs in the NVSS Image Atlas

The NVSS at 1.4 GHz [7] currently provides the best combination of sensitivity to radio sources of large angular size ($\lesssim 16'$), low brightness (1-σ $\sim 0.45\,\mathrm{mJy\,beam^{-1}}$), angular resolution (45″), and coverage ($\delta_{2000} > -40°$ or 82 % of the sky). The NVSS image atlas contains 2,326 images of $4° \times 4°$ with pixels of $15'' \times 15''$. To detect new GRGs in the NVSS, 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 $\gtrsim 0.6\,\mathrm{mJy\,beam^{-1}}$, e.g. near strong sources or close to the Galactic plane, as explained in [17].

Limiting the region size to at least 18 arcmin^2 we obtained 1,000 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 [8] or SDSS [1]. When available, we used FIRST images [4] to look for faint ($\lesssim$2 mJy) radio cores between the radio lobes in NVSS. We found optical hosts for 160 candidates with redshifts in NED, of which 15 were previously unreported as GRGs. For many of the remaining candidates, plus several of those found in [2], we retrieved photometric redshifts from SDSS [1] or [5, 6]. This allowed us to estimate their linear sizes, and select the largest sources with sufficiently bright host galaxies for optical spectroscopy.

36.3 Follow-Up with Optical Spectroscopy and Radio Imaging

From the list of candidates with LLS $\gtrsim$ 0.7 Mpc, we obtained optical spectroscopy for hosts brighter than $\sim$16.5 mag, using two 2.1-m telescopes in northern Mexico: at Obs. Astronómico Nacional (OAN, San Pedro Mártir) during 2013 and 2014, and at Obs. Astrofísico G. Haro (OAGH, Cananea) in April 2014. The resulting redshifts confirmed 18 GRGs with LLS >1 Mpc, and several more with smaller radio sizes. Spectra of four fainter hosts ($r \gtrsim$ 18 mag) were obtained in 2014 with the OSIRIS instrument on the 10.4-m Gran Telescopio Canarias (GTC) in Spain. Three of these were found to have LLS = 1.2–1.5 Mpc, and the other had LLS $\sim$0.8 Mpc. The spectral activity types of the hosts observed here are as varied as we found them to be for a much larger sample we studied [3]. GRG hosts may be QSOs, Sy 1s or Sy 2s, LINERs, LLAGNs, or have no line emission, only that with increasing redshift the fraction of LLAGN decreases and the number of QSOs and Sy 1s increases.

For many of our GRG candidates the angular resolution of NVSS is not sufficient to reveal the optical host galaxy, often because the lobes are far apart and no central compact source is detected that would indicate the host. For 14 of these we obtained Karl G. Jansky Very Large Array (VLA) observations at higher angular resolution and/or frequency. Two of the most clear-cut results are shown in Fig. 36.1. Note that the core radio luminosity of the source with larger LLS is lower than that of the source with smaller LLS. These results agree with the absence of a correlation between core radio luminosity and LLS found in larger samples (see e.g. [10]).

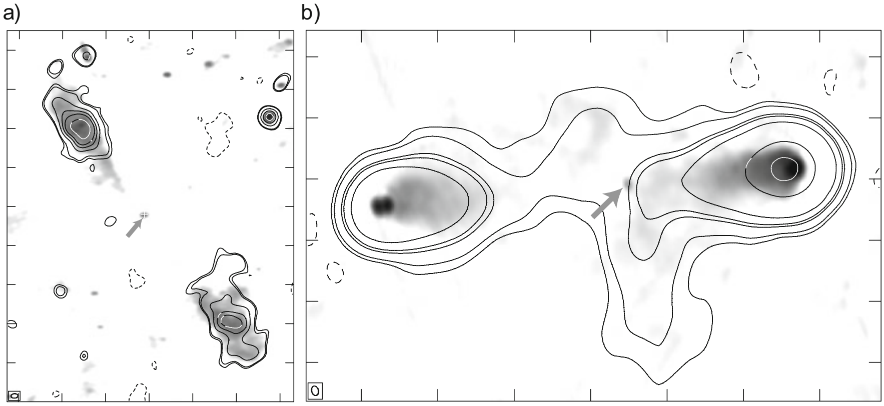

Fig. 36.1 Two of our VLA C-configuration images in grey-scale, with a noise of 0.1 mJy beam^{-1}. Contours are from NVSS, starting at 1.3 mJy beam^{-1} ($3\,\sigma$). (**a**) J0047+5339: NVSS shows two amorphous lobes, with no obvious radio core. Our new VLA L-band (1–2 GHz) image with $21'' \times 14''$ ($\alpha \times \delta$) resolution reveals collimated structures in the lobes for the first time. We also detect a 0.8-mJy core ($\log \mathrm{P}_{1.4} = 3.8 \times 10^{22}$ W Hz^{-1}) 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 $7'' \times 10''$ ($\alpha \times \delta$) resolution, clearly detects a 1.8-mJy core ($\log \mathrm{P}_{1.4} = 2.1 \times 10^{23}$ W Hz^{-1}), 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

36.4 Conclusions

Our new method to find GRGs in the NVSS radio survey, together with radio-optical overlays, led us to find the host galaxy and redshift for 15 previously unreported GRGs. We obtained new redshifts for another 29 candidates using 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 smaller ones. So far, our project has uncovered 39 new GRGs.

We also obtained new radio observations with the VLA of 14 GRG candidates, to better understand their radio structures, and to estimate the dynamical ages of the lobes. Analysis of these data is in progress.

With our GTC spectroscopy of GRG candidates with LLS $\gtrsim$ 2.5 Mpc at redshifts $z > 0.5$ we aim to probe the density and physical conditions of GRGs in the intermediate-redshift Universe. Among other goals, we wish to understand why the cosmological surface brightness dimming with a factor of $(1 + z)^4$ does not seem to prevent us from finding GRGs out to redshifts beyond unity.

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