

A Hubble Space Telescope/NICMOS view of the prototypical giant HII region NGC604 in M33

Rodolfo H. Barbá · Jesús Maíz Apellániz ·
Enrique Pérez · Mónica Rubio · Alberto Bolatto ·
Cecilia Fariña · Guillermo Bosch · Nolan R. Walborn

Received: 30 January 2008 / Accepted: 2 April 2008 / Published online: 30 September 2009
© Springer Science+Business Media B.V. 2009

R.H. Barbá and G. Bosch are Members of the Carrera del Investigador Científico CONICET, Argentina and J. Maíz Apellániz is Ramón y Cajal Fellow.

Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

R.H. Barbá (✉)
Departamento de Física, Universidad de La Serena, Benavente
980, La Serena, Chile
e-mail: rbarba@xeneize.df.uls.cl

R.H. Barbá
ICATE-CONICET, San Juan, Argentina

J. Maíz Apellániz · E. Pérez
Instituto de Astrofísica de Andalucía-CSIC, Camino bajo
de Huétor 50, Granada, Spain

M. Rubio
Departamento de Astronomía, Universidad de Chile, Santiago,
Chile

A. Bolatto
Department of Astronomy and Laboratory for Millimeter-Wave
Astronomy, University of Maryland, College Park, MD 20742,
USA

A. Bolatto
Department of Astronomy and Radio Astronomy Laboratory,
University of California, Berkeley, CA 94720, USA

C. Fariña · G. Bosch
Facultad de Ciencias Astronómicas y Geofísicas, Universidad
Nacional de La Plata, La Plata, Argentina

C. Fariña · G. Bosch
Instituto de Astrofísica La Plata, CONICET, La Plata, Argentina

Abstract We present the first high-spatial-resolution near-infrared (NIR) imaging of NGC604, obtained with the NICMOS camera onboard the *Hubble Space Telescope (HST)*. These NICMOS broad-band images reveal new NIR point sources, clusters, and diffuse structures. We find an excellent spatial correlation between the 8.4 GHz radio continuum and the 2.2 μm nebular emission. Moreover, massive young stellar object candidates appear aligned with these radio peaks, reinforcing the idea that those areas are star-forming regions. Three different scaled OB associations are recognized in the NICMOS images. The brightest NIR sources in our images have properties that suggest that they are red supergiant stars, of which one was previously known. This preliminary analysis of the NICMOS images shows the complexity of the stellar content of the NGC604 nebula.

Keywords Galaxies: starburst · HII regions · ISM: individual (NGC604) · Messier 33 · Stars: red supergiants · Stars: early-type · Stars: formation

1 Motivation for a detailed study of NGC604

Giant HII regions (GHRs) are among the most luminous objects that can be individually identified in very distant galaxies. In these regions, star formation occurs at extremely high rates, hence they are also known as starburst regions. Given the young age and large number of massive stars in GHRs, some of them are still found embedded in their dusty parental molecular clouds. The morphology of these regions

N.R. Walborn
Space Telescope Science Institute, 3700 San Martin Drive,
Baltimore, MD 21218, USA

changes quite rapidly during the first few million years after the first generation of massive stars is born. Excellent images showing these evolutionary morphologies are those of the HII regions in the irregular galaxy NGC4214 (Maíz Apellániz 2000; MacKenty et al. 2000).

The natural extensions to larger scales are the starburst galaxies which can be observed at cosmological distances and, therefore, used as astrophysical signposts to trace the star-formation history of the Universe. However, due to their large distances, we must rely only on their major global properties, such as the behavior of the strong recombination lines originating in ionized nebulae. To improve our knowledge of these objects in distant galaxies, it is necessary to study resolved nearby examples. 30 Doradus in the Large Magellanic Cloud and NGC604 in M33 are the two largest GHRs in the Local Group (LG), so they are the prime candidates for such a study.

NGC604 is located at a distance of 840 kpc (Freedman et al. 2001). At such a distance, $1''$ is equivalent to 4 pc and consequently the capabilities of the *Hubble Space Telescope* (*HST*) are essential to study the region with high spatial resolution. NGC604 is powered by a massive young cluster without a central core that contains over 200 O and WR stars (Maíz Apellániz 2001 and references therein). This GHR is the best nearby example of a scaled OB association (SOBA), as defined by Maíz Apellániz (2001), a more extended type of object than 30 Dor, which is a Super Star Cluster (SSC). The combination of similarities and differences between these objects makes the combined analysis of both 30 Doradus and NGC604 a necessary step for the creation of a template for the understanding of distant starbursts.

In this contribution we describe the observations obtained and our general objectives, and we present a preliminary analysis of the new *HST*/NICMOS images.

2 Observations

We are dedicating much observational effort to a thorough multi-wavelength study of NGC604, from the far ultraviolet (FUV) to the near infrared with additional high-resolution millimetric observations, combining existing with new data. The new *HST* data are divided into three sets: (i) slitless objective-prism FUV spectroscopy obtained using ACS/SBC, (ii) multi-filter (six broad bands and two narrow bands) near ultraviolet (NUV) to optical imaging obtained using ACS/HRC, and (iii) NICMOS/NIC2 broadband imaging. These data sets were obtained as part of *HST* proposals GO-10419 and GO-10722. The existing data include STIS-NUV objective-prism spectroscopy and photometry obtained as part of *HST* program GO-9096, as well as archival *HST*/WFPC2 imaging. Additional observations were obtained using Gemini North/NIRI in three

broad-band and three narrow-band NIR filters, and with the Combined Array for Research in Millimeter-wave Astronomy (CARMA) in multi-configurations C, D, and E, to observe the CO(1 \rightarrow 0) transition with a velocity resolution of 3 km s^{-1} , and a beam size ranging from $3''$ – $5''$.

The main goals of this project are to obtain spectral classifications for about 200 stars, measuring their spectral energy distributions (SEDs) from 130 nm to $2.2 \mu\text{m}$, to identify embedded very young stellar populations hidden inside dust clouds, to measure the extinction law and its possible variations as a function of the environmental conditions, and to analyze the relationship between the hot stars and the surrounding gas. The combination of all data will allow us to obtain the most complete and detailed extinction-corrected Hertzsprung–Russell diagram of a resolved SOBA. The SEDs obtained will be analyzed with CHORIZOS (Maíz Apellániz 2004) as the primary code.

3 A NICMOS view of NGC604

Six *HST* orbits were allocated to observe six selected fields in and near NGC604 with the NICMOS camera-2 (NIC2), using the broad-band filters F110W, F160W and F205W (similar to the *J*, *H*, and *K* passbands, respectively). Figure 1 shows the observed fields on a K_s -band image extracted from 2MASS. A $37'' \times 32''$ (~ 140 pc) area centered on the core of NGC604 was observed in four tiles using a dithering strategy. An adjacent field to the south of the core, centered on a bright NIR source was also observed. In addition, sky frames were obtained in a nearby ($1' \equiv 240$ pc distant) field for background subtraction and to take into account the stellar population of the M33 disk in the subsequent photometric analysis.

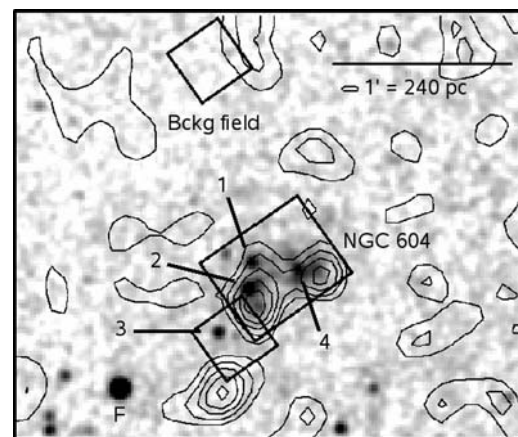


Fig. 1 2MASS K_s -band image of the region of NGC604. Infrared (IR) sources labeled 1, 2, 3, and 4 are associated directly with the molecular clouds (contours, adapted from Engargiola et al. 2003). Fields observed with the *HST*/NICMOS camera-2 are marked by rectangles. North is up and East to the left. The point source labeled 'F' is a Galactic foreground star

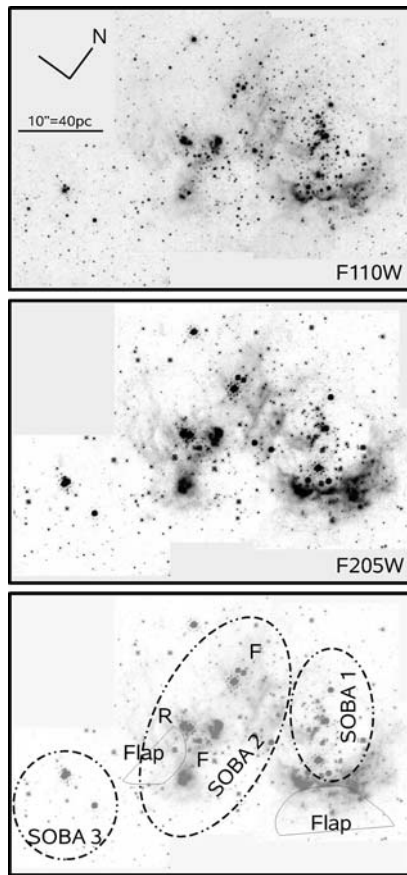


Fig. 2 *HST/NICMOS F110W (top panel) and F205W (middle panel) mosaics of NGC604. The bottom panel is an explanatory diagram for some structures discussed in the text. SOBAs labeled 1, 2, and 3 are the main SOBA, the secondary and the third SOBA located to the south, respectively. The 'F' label indicates the optically visible gaseous filaments. Flaps are areas with high optical extinction. 'R' refers to the red supergiant star discovered by Terlevich et al. (1996)*

Molecular clouds associated with NGC604 have been detected in CO by Engargiola et al. (2003 and references therein). The 2MASS K_s -band image (Fig. 1) shows a concentration of point-like sources in the core of NGC604, some of them surrounded by an extended halo. In contrast, the 'background' field seems devoid of such bright sources. The 2MASS IR sources are associated directly with the molecular clouds. This morphological relationship between IR sources and molecular clouds resembles that of the 30 Dor Nebula.

The new NICMOS broad-band imaging of NGC604 reveals new IR point sources, clusters and diffuse structures, improving the spatial resolution of the 2MASS data by more than an order of magnitude. Figure 2 shows the F110W and F205W mosaics of five NIC2 fields in the area observed of NGC604. The variety of observed structures is striking. The two optically detected SOBAs (main and secondary) are easy to discern. They are encircled by ellipses in Fig. 2 (see Maíz Apellániz et al. 2004 for a detailed explanation of the

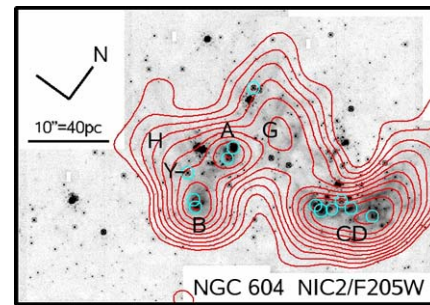


Fig. 3 *Contour diagram of the 8.4 GHz radio continuum (adapted from Churchwell and Goss 1999) superposed on the F205W NIC2 image. Labels indicate the radio continuum structures (see Maíz Apellániz et al. 2004 for an explanation). Circles mark the position of the massive young stellar object candidates*

optical structures). An additional SOBA affected by higher extinction is present to the south (labeled as 'SOBA 3'). The two cavities associated with the SOBAs are defined. Cavity A (associated with the main SOBA) is limited by a bright rim to the south. This rim is brighter in the F205W compared to the F110W filter, indicating that it is affected by a high extinction. The extended nebular emission to the southwest in the F205W image is coincident with the structure labeled as 'flap' by Maíz Apellániz et al. (2004), an (optical) obscuration area which is a dusty screen associated with the molecular cloud in that region. This main CO cloud lies on the southern edge of the bright nebular rim. Churchwell and Goss (1999) and Maíz Apellániz et al. (2004) have analyzed the extinction in NGC604 using radio continuum, $H\alpha$, and $H\beta$ images. They found a very good correlation between the CO emission and the total optical extinction, which indicates that the dust is associated with molecular gas. Some of the HII gas is located behind large-optical-depth well-defined dust 'flaps' that make it invisible in the optical. Figure 3 shows the 8.4 GHz radio continuum contours (from Churchwell and Goss 1999) superimposed on the F205W image. Again, the correlation between radio and 2.2 μm emission seems to be very good. The radio peaks C and D are superposed on the southwest NIR nebular emission. The radio peaks A and B are coincident with nebular knots. Peak A is one of the brightest $H\alpha$ structures (see Maíz Apellániz et al. 2004), and the same happens in the NIR. Gemini/NIRI images (not shown) demonstrate that most of such emission is produced in the warm gas as Brackett γ emission lines. A very interesting result is the remarkable spatial correlation between the massive young stellar object candidates and the radio peaks, which suggests that those areas are prime candidates for massive star-forming regions.

4 NICMOS photometry

Point-spread function photometry was performed on the NIC2 mosaics and the 'background' field. In total, we have

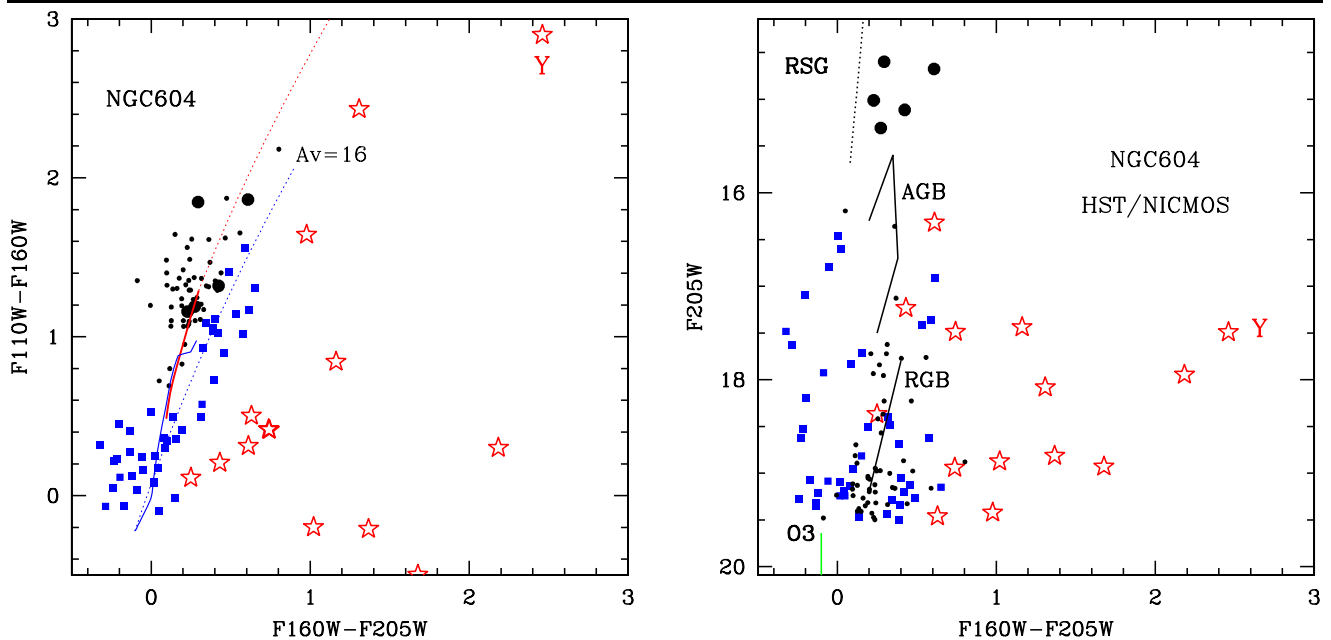


Fig. 4 NIC2 color-color (left) and color-magnitude (right) diagrams. This plot includes all sources with $m_{F205W} < 19.5$ mag. Color-color diagram: the main-sequence locus and the cool-giant branch are indicated as *solid lines*; reddening tracks for $A_V = 16$ mag are also plotted. Color-magnitude diagram: the red supergiant star locus is indicated as

a *dotted line* in the upper part of the diagram; the asymptotic giant branch and red giant branch are also plotted as *solid lines*. Symbols: ‘*stars*’ are massive young stellar object candidates; ‘*squares*’ are hot stars; ‘*dots*’ are mostly red-giant stars; and ‘*black circles*’ are red supergiant stars

more than 600 detections in the three filters with photometric errors of less than 0.3 mag. The photometric sensitivity is about 21.9 mag in the F205W filter, corresponding to an unreddened early B-type star at the distance of M33. Figure 4 shows the color-color and color-magnitude diagrams for all sources brighter than $m_{F205W} = 19.5$ mag (O3V star at M33). We decided to preserve our data in the NICMOS photometric system to avoid additional problems with color transformations to ground-based photometric systems. Main-sequence and red-giant stellar loci are plotted as continuous lines in the color-color diagram of Fig. 4. They were synthesized using CHORIZOS, Kurucz atmosphere models, and NIC2 filter transmission curves. Reddening vectors ($A_V = 16$ mag) for an early-type star and a red giant were derived in the same way, adopting a normal reddening law. In the color-color diagram one can discern three main populations of objects: (i) *blue, hot* stars with small or moderate reddening close to the main-sequence locus and along the reddening track; (ii) *red* stars at the red-giant locus; and (iii) a population of stars with IR excess to the right of the early-type star reddening vector.

The distribution of sources in the color-magnitude diagram shows that the *blue* sources (group i) correspond mostly to luminous hot stars associated with SOBAs (massive stars). Meanwhile, stars in the group (iii) are mostly massive young stellar object (MYSO) candidates and/or extreme emission-line objects. Objects in group (ii) are stars

belonging to the red-giant branch, and they are more or less smoothly distributed across the mosaic. The brightest objects in the field are five stars in group (ii). Their positions in the color-magnitude diagram suggest that they are red supergiant (RSG) stars. In fact, one of them has been identified spectroscopically as such by Terlevich et al. (1996). This star is a close companion to a compact massive cluster and two WR star candidates (WR11 and WR7; see Drissen et al. 1993 and Maíz Apellániz et al. 2004). The other four red supergiant star candidates are also located very close (a few arcsec) to *bona fide* WR stars, WR candidates or massive hot stars. The spatial coincidence observed between the RSG stars and the early-type objects addresses the question as to whether they belong to the same stellar generation or if they simply represent a superposition of different populations, as is the case for 30 Dor. In the latter GHR, Walborn and Blades (1997) proposed the coeval existence of five distinct populations, nicely distinguished by age and distribution. Likewise, this issue indicates the complexity of the stellar content in a GHR.

Among the MYSO candidates, a particular source deserves special consideration, owing to its large NIR colors. This object, labeled as ‘Y’ in Figs. 3 and 4, is barely detectable in the F110W image. Its NIR photometric properties are very similar to those of the MYSO in 30 Dor (Rubio et al. 1998; Brandner et al. 2001), indicating a high luminosity. The source Y is located in a region of very large extinction, close ($2''$) to a filled HII region (radio peak B) and the

molecular cloud core. Thus, this area has all the necessary ingredients to be a star-forming region.

5 Summary

In this contribution we have presented the first high-spatial-resolution NIR images of NGC604, obtained with the NIC2 camera onboard *HST*. These new NICMOS broad-band images reveal new NIR point sources, clusters and diffuse structures. We find an excellent spatial correlation between 8.4 GHz radio continuum and 2.2 μm nebular emission. We also find that MYSO candidates appear aligned with those radio-peak structures, reinforcing the idea that those areas are star-forming regions. Three different SOBAs can be recognized in the new NICMOS images. moreover, the brightest NIR sources in our images show properties that suggest the presence of RSG stars.

This preliminary analysis of the NICMOS images shows the extreme complexity of the stellar content in the NGC604 nebula.

Acknowledgements RHB would like to thank the Scientific Organizing Committee for the invitation to participate in the meeting and the Instituto de Astrofísica de Andalucía staff and Director for the warm hospitality during his visit to the Institute. We would like to thank Greg Engargiola and Ed Churchwell for giving us access to

their data. Support for this work was provided by FONDECYT Project No. 1050052 and DIULS 08102 (RHB), by the Chilean *Center for Astrophysics* FONDAP No. 10510003 (MR), and by the Spanish Ministerio de Educación y Ciencia (JMA and EP) through the Ramón y Cajal program and grants AYA2004-02703 and AYA2007-64712, which are co-financed with FEDER funds.

References

- Brandner, W., Grebel, E.K., Barbá, R.H., Walborn, N.R., Moneti, A.: *Astron. J.* **122**, 858 (2001)
- Churchwell, E., Goss, M.: *Astrophys. J.* **514**, 188 (1999)
- Drissen, L., Moffat, A.F.J., Shara, M.M.: *Astron. J.* **105**, 1400 (1993)
- Engargiola, G., Plambeck, R.L., Rosolowsky, E., Blitz, L.: *Astrophys. J. Suppl. Ser.* **149**, 343 (2003)
- Freedman, W.L., et al.: *Astrophys. J.* **553**, 47 (2001)
- MacKenty, J., Maíz Apellániz, J., Pickens, C., Norman, C., Walborn, N.R.: *Astron. J.* **120**, 3007 (2000)
- Maíz Apellániz, J.: *Publ. Astron. Soc. Pac.* **112**, 1138 (2000)
- Maíz Apellániz, J.: *Astrophys. J.* **563**, 151 (2001)
- Maíz Apellániz, J.: *Publ. Astron. Soc. Pac.* **116**, 859 (2004)
- Maíz Apellániz, J., Pérez, E., Mas-Hesse, J.M.: *Astron. J.* **128**, 1196 (2004)
- Rubio, M., Barbá, R.H., Walborn, N.R., Probst, R.G., García, J., Roth, M.R.: *Astron. J.* **116**, 1708 (1998)
- Terlevich, E., Díaz, A.I., Terlevich, R., González Delgado, R.M., Pérez, E., García-Vargas, M.L.: *Mon. Not. R. Astron. Soc.* **279**, 1219 (1996)
- Walborn, N.R., Blades, C.: *Astrophys. J. Suppl. Ser.* **112**, 457 (1997)