

CIRCUMNUCLEAR STAR-FORMING REGIONS IN EARLY TYPE SPIRAL GALAXIES: DYNAMICAL MASSES

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RESUMEN

Presentamos medidas de la dispersión de velocidades en 17 regiones de formación estelar circunucleares (CNSFRs) y los núcleos de tres galaxias espirales barradas: NGC 2903, NGC 3310 y NGC 3351 a partir de espectros de alta dispersión. Las dispersiones estelares han sido obtenidas de las líneas del triplete de CaII (CaT) a $\lambda\lambda$ 8494, 8542, 8662 Å, mientras que las dispersiones de velocidades del gas han sido medidas mediante ajustes gaussianos a las líneas de $H\beta$ λ 4861 Å y de [OIII] λ 5007 Å. Las CNSFRs, con tamaños de alrededor de 100 a 150 pc en diámetro, parecen estar compuestas por varios cúmulos estelares individuales con tamaños entre 1.5 y 6.2 pc medidos sobre imágenes del Telescopio Espacial Hubble (HST). Utilizando las dispersiones de velocidades estelares, hemos derivado las masas dinámicas para los complejos de formación estelar completos y para los cúmulos estelares individuales. Los valores de la dispersión de velocidades estelares están entre 31 y 73 km s⁻¹. Las masas dinámicas para las CNSFRs completas están entre 4.9×10^6 y $1.9 \times 10^8 M_{\odot}$ y entre 1.4×10^6 y $1.1 \times 10^7 M_{\odot}$ para los cúmulos estelares individuales. Hemos encontrado indicaciones de la presencia de dos componentes cinemáticas diferentes en el gas ionizado de las regiones. La componente estrecha proporcionada por el ajuste de dos-componentes gaussianas, parece tener un valor relativamente constante para todas las CNSFRs estudiadas, con los valores estimados muy próximos a 25 km s⁻¹. Esta componente estrecha podría identificarse con gas ionizado en un disco rotante, mientras que las estrellas y la fracción de gas (responsable de la componente ancha) relacionadas con las regiones de formación estelar, estarían mayormente soportadas por presión dinámica.

ABSTRACT

We present the measurements of gas and stellar velocity dispersions in 17 circumnuclear star-forming regions (CNSFRs) and the nuclei of three barred spiral galaxies: NGC 2903, NGC 3310 and NGC 3351 from high dispersion spectra. The stellar dispersions have been obtained from the CaII triplet (CaT) lines at $\lambda\lambda$ 8494, 8542, 8662 Å while the gas velocity dispersions have been measured by Gaussian fits to the $H\beta$ λ 4861 Å and to the [OIII] λ 5007 Å lines. The CNSFRs, with sizes of about 100 to 150 pc in diameter, are seen to be composed of several individual star clusters with sizes between 1.5 and 6.2 pc on *Hubble Space Telescope* (HST) images. Using the stellar velocity dispersions, we have derived dynamical masses for the entire star-forming complexes and for the individual star clusters. Values of the stellar velocity dispersions are between 31 and 73 km s⁻¹. Dynamical masses for the whole CNSFRs are between 4.9×10^6 and $1.9 \times 10^8 M_{\odot}$ and between 1.4×10^6 and $1.1 \times 10^7 M_{\odot}$ for the individual star clusters. We have found indications for the presence of two different kinematical components in the ionized gas of the regions. The narrow component of the two-component Gaussian fits seems to have a relatively constant value for all the studied CNSFRs, with estimated values close to 25 km s⁻¹. This narrow component could be identified with ionized gas in a rotating disc, while the stars and the fraction of the gas (responsible for the broad component) related to the star-forming regions would be mostly supported by dynamical pressure.

Key Words: HII regions — galaxies: kinematics and dynamics — galaxies: starburst — galaxies: star clusters: general

1. INTRODUCTION

Gas content, masses, bar structure, and dynamical environment can strongly influence the large-scale star formation rate (SFR) along the Hubble sequence (Kennicutt 1998). The variation of young stellar content and star formation activity is one of the most conspicuous characteristic along this sequence, and this variation in the young stellar popu-

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lation is part of the basis of the morphological classification made by Hubble (1926). The trend in SFRs and star formation histories along the Hubble sequence was confirmed from evolutionary synthesis models of galaxy colors by Tinsley (1968, 1972) and Searle et al. (1973). Later, the importance of the star formation bursting mode in the evolution of low-mass galaxies and interacting systems was studied by Bagnuolo (1976); Huchra (1977) and Larson & Tinsley (1978). Due to their different average SFR, the integrated spectra of galaxies vary considerably along the Hubble sequence.

The gas flows in disc of spiral galaxies can be strongly perturbed by the presence of bars, although the total disc SFR does not appear to be significantly affected by them (Kennicutt 1998). These perturbations of the gas flow trigger nuclear star formation in the bulges of some barred spiral galaxies. These structures around the nuclei of some spiral galaxies present higher than usual star formation rates and are frequently arranged in a ring pattern with a diameter of about 1 kpc. At optical wavelengths, these circumnuclear star-forming regions (CNSFRs) are easily observable rings. Although CNSFRs are very luminous, not much is known about their kinematics or dynamics for both the ionized gas and the stars. In fact, the most poorly known property of star forming clusters in galaxies is their mass.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Observations

High resolution blue and far-red spectra were acquired as part of an observing run in 2000. They were obtained simultaneously using the blue and red arms of the Intermediate dispersion Spectrograph and Imaging System (ISIS) on the 4.2-m William Herschel Telescope (WHT) of the Isaac Newton Group (ING) at the Roque de los Muchachos Observatory on the Spanish island of La Palma. The H2400B and R1200R gratings were used to cover the wavelength ranges from 4779 to 5199 Å ($\lambda_c = 4989$ Å) in the blue and from 8363 to 8763 Å ($\lambda_c = 8563$ Å) in the red with spectral dispersions of 0.21 and 0.39 Å per pixel, equivalent to a spectral resolution ($R = \lambda/\Delta\lambda$) of ~ 23800 and ~ 22000 , respectively, and providing a comparable velocity resolution of about 13 km s⁻¹. The CCD detectors EEV12 and TEK4 were used for the blue and red arms with a factor of 2 binning in both the “x” and “y” directions in the blue with spatial resolutions of 0.38 and 0.36 arcsec px⁻¹ for the blue and red configurations respectively. A slit width of 1 arcsec was used which, combined with the spectral dispersions,

yielded spectral resolutions of about 0.4 and 0.7 Å FWHM in the blue and the red, respectively, measured on the sky lines.

In the cases of NGC 2903 (Hägele et al. 2009) and NGC 3310 (Hägele et al. 2010) two different slit positions were chosen in each case to observe 4 and 8 CNSFRs, respectively, which we have labelled S1 and S2 for each galaxy. Besides, for NGC 3310 we observed the conspicuous Jumbo region. The name of this region, Jumbo, comes from the fact that it is 10 times more luminous than 30 Dor (Telesco & Gatlley 1984). For the third galaxy, NGC 3351 (Hägele et al. 2007), three different slit positions were chosen to observe 5 CNSFRs. In all cases one of the slits passes across the nucleus.

Several bias and sky flat field frames were taken at the beginning and the end of each night in both arms. In addition, two lamp flat field and one calibration lamp exposure per each telescope position were performed. The calibration lamp used was CuNe+CuAr.

We have also downloaded two astrometrically and photometrically calibrated broad-band images of the central part of each observed galaxy from the Multimission Archive at Space Telescope⁵. The images were taken through the F606W (wide V) and the F160W (H) filters with the Wide Field and Planetary Camera 2 (WFPC2; PC1) and the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) 2 (NIC2; for NGC 3310) and 3 (NIC3; for NGC 2903 and NGC 3351), both cameras on-board the HST. In the case of NGC 3310 we also downloaded the F658N narrow band image (equivalent to H α filter at the NGC 3310 redshift) taken with the Advanced Camera for Surveys (ACS) of the HST. All the measured sizes of the circumnuclear regions are defined using these high resolution images.

2.2. Data reduction

The data was processed and analyzed using IRAF⁶ routines in the usual manner. The procedure includes the removal of cosmic rays, bias subtraction, division by a normalized flat field and wavelength calibration. Wavelength fits were performed using 20–25 arc lines in the blue and 10–15 lines in the far-red by a polynomial of second to third order. These fits have been done at 50 and 60 locations along the slit in the blue and far-red, respectively,

⁵<http://archive.stsci.edu/hst/wfpc2>.

⁶IRAF: the Image Reduction and Analysis Facility is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation (NSF).

and they have yielded rms residuals between ~ 0.1 and ~ 0.2 px. We have not corrected the spectra for atmospheric extinction or performed any flux calibration, since our purpose was to measure radial velocities and velocity dispersions.

In addition to the galaxy frames, observations of 11 template velocity stars were made to provide good stellar reference frames in the same system as the galaxy spectra for the kinematic analysis in the far-red. They are late-type giant and supergiant stars which have strong CaT features.

3. SUMMARY AND CONCLUSIONS

We present the measurements of gas and stellar velocity dispersions in 17 circumnuclear star-forming regions (CNSFRs) and the nuclei of three barred spiral galaxies: NGC 2903 (Hägele et al. 2009), NGC 3310 (Hägele et al. 2010) and NGC 3351 (Hägele et al. 2007) from high dispersion spectra. The stellar dispersions have been obtained from the CaII triplet (CaT) lines at $\lambda\lambda$ 8494, 8542, 8662 Å that originates in the atmospheres of red giant and supergiant stars belonging to the underlying stellar population of the clusters, while the gas velocity dispersions have been measured by Gaussian fits to the H β λ 4861 Å and to the [OIII] λ 5007 Å lines.

The CNSFRs, with sizes of about 100 to 150 pc in diameter, are seen to be composed of several individual star clusters with sizes between 1.5 and 6.2 pc on *Hubble Space Telescope* (HST) images. Stellar velocity dispersions between 31 and 73 km s $^{-1}$ were obtained. For NGC 2903 and NGC 3351 these values are about 25 km s $^{-1}$ larger than those derived for the gas from the H β emission line using a single Gaussian fit. For NGC 3310 these values and those derived for the gas from the H β emission line using a single Gaussian fit are in relatively good agreement, with the former being slightly larger. However, the best Gaussian fits involved two different components for the gas: a “broad component” with a velocity dispersion similar to that measured for the stars for NGC 2903 and NGC 3351, and larger by about 20 km s $^{-1}$ for NGC 3310, and a “narrow component” with velocity dispersions lower than the stellar one by about 30 km s $^{-1}$. This “narrow component” seems to have a relatively constant value for all the CNSFRs studied in these three galaxies, with estimated values close to 25 km s $^{-1}$ for the two gas emission lines.

Values for the upper limits to the dynamical masses estimated from the stellar velocity dispersion using the virial theorem for the CNSFRs of NGC 2903 lie in the range between 6.4×10^7 and

$1.9 \times 10^8 M_{\odot}$ and is $1.1 \times 10^7 M_{\odot}$ for its nuclear region inside the inner 3.8 pc. In the case of NGC 3310 the masses lie in the range between 2.1×10^7 and $1.4 \times 10^8 M_{\odot}$ for the CNSFRs and for the nuclear region inside the inner 14.2 pc is $5.3 \times 10^7 M_{\odot}$. For NGC 3351 the dynamical masses lie in the range between 4.9×10^6 and $4.5 \times 10^7 M_{\odot}$ for the CNSFRs and is $3.5 \times 10^7 M_{\odot}$ for the nuclear region inside the inner 11.3 pc. Then, globally, the dynamical masses of the CNSFRs lie in the range between 4.9×10^6 and $1.9 \times 10^8 M_{\odot}$. Masses derived from the H β velocity dispersion under the assumption of a single component for the gas would have been underestimated by factors between approximately 2 to 4.

The derived masses for the individual clusters are between 1.4×10^6 and $1.1 \times 10^7 M_{\odot}$, between 1.8 and $7.1 \times 10^6 M_{\odot}$, and between 1.8 and $8.7 \times 10^6 M_{\odot}$ for NGC 2903, NGC 3310 and NGC 3351, respectively. Then, globally, the masses of these individual clusters vary between 1.4×10^6 and $1.1 \times 10^7 M_{\odot}$. These values are between 4.2 and 33 times the mass derived for the SSC A in NGC 1569 by Ho & Filippenko (1996) and larger than other kinematically derived SSC masses in irregular galaxies (McCrady et al. 2003; Larsen et al. 2004). It must be noted that we have measured the size of each knot (typically between 3 and 5 pc), but the stellar velocity dispersion corresponds to the integrated CNSFR wider area containing several knots. The use of these wider size scale velocity dispersion measurements to estimate the mass of each knot leads us to overestimate the mass of the individual clusters, and hence of each CNSFR. We cannot be sure though that we are actually measuring their velocity dispersion and thus prefer to say that our measurements of σ_* and hence dynamical masses constitute upper limits.

Masses of the ionizing stellar clusters (derived from their H α luminosities under the assumption that the regions are ionization bound and without taking into account any photon absorption by dust) for the regions of NGC 2903 vary between 3.3 and $4.9 \times 10^6 M_{\odot}$, and is 2.1×10^5 for its nucleus. The values derived in NGC 3310 vary between 8.7×10^5 and $2.1 \times 10^6 M_{\odot}$ for the star-forming regions, and 3.5×10^6 for the nucleus. For NGC 3351 they lie between 8.0×10^5 and $2.5 \times 10^6 M_{\odot}$ for the regions, and $6.0 \times 10^5 M_{\odot}$ for its nuclear region. Thus, the masses of the ionizing stellar cluster studied in these three galaxies vary between 8.0×10^5 and $4.9 \times 10^6 M_{\odot}$. Therefore, the ratio of the ionizing stellar population to the total dynamical mass is between 0.01 and 0.16. These values of the masses of the ionizing stellar clusters of the CNSFRs are comparable to that

derived by González-Delgado et al. (1995) for the circumnuclear region A in NGC 7714.

Derived masses for the ionized gas (also from their H α luminosities) vary between 6.1×10^4 and $1.3 \times 10^5 M_{\odot}$ for the regions and is $3 \times 10^3 M_{\odot}$ for the nucleus of NGC 2903; between 1.5 and $7.2 \times 10^5 M_{\odot}$ for the CNSFRs and $5 \times 10^3 M_{\odot}$ for the nucleus of NGC 3310; and between 7.0×10^3 and $8.7 \times 10^4 M_{\odot}$ for the CNSFRs of NGC 3351, and $2 \times 10^3 M_{\odot}$ for its nucleus. Globally, the masses of the ionized gas vary between 7.0×10^3 and $7.2 \times 10^5 M_{\odot}$ for the CNSFRs studied in these three galaxies. These values are also comparable to that derived by González-Delgado et al. (1995) for region A in NGC 7714.

We have found indications for the presence of two different kinematical components in the ionized gas of the regions. The narrow component of the two-component Gaussian fits seem to have a relatively constant value for all the studied CNSFRs, with estimated values close to 25 km s^{-1} . This narrow component could be identified with ionized gas in a rotating disc, while the stars and the fraction of the gas (responsible for the broad component) related to the star-forming regions would be mostly supported by dynamical pressure. To disentangle the origin of these two components it will be necessary to map these regions with higher spectral and spatial resolution and much better signal-to-noise ratio in particular for the O $^{2+}$ lines.

The observed stellar and [OIII] rotational velocities of NGC 2903 are in good agreement, while the H β measurements show shifts similar to those found between the narrow and the broad components. In the case of NGC 3310 the rotation curve shows a

typical S feature, with the presence of some perturbations, in particular near the location of the Jumbo region. For NGC 3351, the rotation velocities derived for both stars and gas are in reasonable agreement, although in some cases the gas shows a velocity slightly different from that of the stars. For the three galaxies, the rotation curve corresponding to the position going through the centre of the galaxy shows maximum and minimum values at the position of the circumnuclear ring.

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