

# An independent determination of the local Hubble constant

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## ABSTRACT

The relationship between the integrated H  $\beta$  line luminosity and the velocity dispersion of the ionized gas of H II galaxies and giant H II regions represents an exciting standard candle that presently can be used up to redshifts  $z \sim 4$ . Locally it is used to obtain precise measurements of the Hubble constant by combining the slope of the relation obtained from nearby ( $z \leq 0.2$ ) H II galaxies with the zero-point determined from giant H II regions belonging to an ‘anchor sample’ of galaxies for which accurate redshift-independent distance moduli are available. We present new data for 36 giant H II regions in 13 galaxies of the anchor sample that includes the megamaser galaxy NGC 4258. Our data are the result of the first 4 yr of observation of our primary sample of 130 giant H II regions in 73 galaxies with Cepheid determined distances. Our best estimate of the Hubble parameter is  $71.0 \pm 2.8(\text{random}) \pm 2.1(\text{systematic}) \text{ km s}^{-1} \text{ Mpc}^{-1}$ . This result is the product of an independent approach and, although at present less precise than the latest SNIa results, it is amenable to substantial improvement.

**Key words:** H II regions – galaxies: star formation – distance scale – cosmology: observations.

## 1 INTRODUCTION

In the past two decades, a combination of different distance indicators (Cepheids, SNIa, surface brightness fluctuations, etc.; see Freedman & Madore 2010) has been used to vastly improve the accuracy in the determination of the Hubble constant  $H_0$ . The *HubbleSpaceTelescope* (HST) Key Project and Carnegie Hubble Program (Freedman et al. 2001, 2012), among others, have obtained an accuracy of 3 per cent on the measurement of  $H_0$  reporting values of  $73.8 \pm 2.4$  and  $74.3 \pm 2.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . Subsequently Humphreys et al. (2013), using the megamaser galaxy NGC 4258 (for which very precise ‘geometric’ distance measurements are available), reported  $72.7 \pm 2.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

On the other hand, *Planck* observations of the Cosmic Microwave Background (CMB) combined with a flat  $\Lambda$ CDM cosmology derived a value of  $H_0 = 67.3 \pm 1.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (Planck Collaboration XVI 2014) that indicates a  $2.5\sigma$  tension with the direct estimate

reported by Riess et al. (2011), suggesting the possible need of new physics to solve the problem.

Efstathiou (2014) re-examined the Cepheids analysis of Riess et al. (2011) and found  $H_0 = 72.5 \pm 2.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ; while using as the central calibrator the NGC 4258 megamaser and the SNIa data base, he obtained a value of  $H_0 = 70.6 \pm 2.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , concluding that there is no evidence for a need to postulate new physics. Riess et al. (2016) addressed Efstathiou (2014) result, suggesting that a change in the colour selection of the Cepheids removes the difference in the  $H_0$  values. The new results from SNIa (Riess et al. 2016) of  $H_0 = 73.24 \pm 1.74 \text{ km s}^{-1} \text{ Mpc}^{-1}$  have reinstated the ‘tension, now at the  $3.1\sigma$  level with the value obtained by Planck Collaboration XIII (2016) of  $H_0 = 67.8 \pm 0.9 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

This ‘tension has prompted us to explore using new and improved data, our local estimate of  $H_0$  based on the standard candle provided by the correlation that exists in H II galaxies (HIIGs) and giant H II regions (GHIIRs) between the turbulent emission line velocity dispersion ( $\sigma$ ) of the Balmer lines and its integrated luminosity (Terlevich & Melnick 1981; Melnick et al. 1987; Melnick, Terlevich & Moles 1988; Chávez et al. 2012).

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HIIGs are compact and massive systems experiencing luminous bursts of star formation generated by the formation of young super stellar clusters (SSCs) with a high luminosity per unit mass and with properties similar, if not identical, to GHIIRs. The potential of GHIIRs as distance indicators was originally realized from the existence of a correlation between the GHIIR diameter and the parent galaxy luminosity (Sérsic 1960; Sandage 1962); see also Kennicutt (1979). A different approach was proposed by Melnick (1977, 1978), who found that the turbulent width of the nebular emission lines is correlated with the GHIIR diameters.

Terlevich & Melnick (1981) (hereinafter TM81) found a tight correlation between the turbulent emission lines velocity dispersion and their integrated luminosity: the  $L - \sigma$  relation. This correlation, valid for HIIGs and GHIIRs, links a distance-dependent parameter, the integrated  $H\beta$  line luminosity, with a parameter that is independent of distance, the velocity dispersion of the ionized gas, therefore defining a redshift-independent distance estimator.

The  $L - \sigma$  relation represents a rather interesting distance indicator that with present instrumentation can be utilized out to  $z \sim 4$  (Melnick, Terlevich & Terlevich 2000; Siegel et al. 2005; Plionis et al. 2011; Terlevich et al. 2015; Chávez et al. 2016).

Chávez et al. (2012) confirmed that the  $L - \sigma$  relation does provide a reliable independent method to measure the Hubble constant. To determine the value of the local Hubble constant, the  $L - \sigma$  relation for HIIGs is anchored to a sample of GHIIRs in nearby galaxies having accurate distances determined using primary distance indicators.

Although the scatter of the  $L - \sigma$  distance indicator is about a factor of 2 larger than the one based on SNIa (Chávez et al. 2014), this is partially compensated by the larger number of local calibrators available for the  $L - \sigma$  method, i.e. galaxies with distance determination independent of redshift, compared to those available for SNIa, plus the fact that the number of GHIIRs per galaxy is usually more than 1, thus reducing the uncertainty per anchor galaxy.

A fundamental problem with the determination of the Hubble constant using SNIa is related to the low expected rate of SNIa inside the 30 Mpc reach of the HST for accurate Cepheid studies (Riess et al. 2016). The present sample of SNIa in galaxies with accurate distance estimates is 19 and it would not substantially increase over the remaining lifetime of the HST, given that their average rate is only about one SNIa per year (Riess et al. 2016). On the other hand, the number of anchor galaxies with GHIIRs and accurate Cepheid distances is presently 73 in our primary sample, with a total of 130 GHIIRs. Moreover, GHIIRs in special galaxies like the LMC, the SMC and NGC 4258 with very accurate redshift-independent distance determinations are also included in our sample of anchor galaxies.

The  $L - \sigma$  distance indicator assumes a linear relation between the logarithm of the  $H\beta$  emission-line luminosity  $L(H\beta)$  (proportional to the number of ionizing photons) and the logarithm of the width of the emission lines  $\sigma$ , proportional to the total mass of the system. Although there is a solid framework for understanding the underlying physics of the  $L - \sigma$  relation (Chávez et al. 2014), it remains empirical in the sense that we are not yet able to predict accurately the coefficients of the relation starting from basic principles.

Thus, the application of the  $L - \sigma$  relation as a distance estimator requires care when determining the slope of the relation, especially because standard least-squares techniques are usually not adequate for data with observational errors in the independent coordinate. Additionally, a good understanding of the random and systematic errors of the data is needed. For example, Chávez et al. (2014) found

that the size of the system, albeit difficult to measure, is a strong second parameter that reduces the scatter of the  $L - \sigma$  relation by about 40 per cent.

We also know that in very young starburst clusters, capable of ionizing the surrounding gas, the intensity of the emission lines fades rapidly as the massive stars evolve, while the velocity dispersions remain roughly constant for much longer, which may introduce a systematic effect as discussed by Melnick et al. (2017).

Furthermore, both the presence of dust, ubiquitous in young star-forming regions, and the possible escape of Lyman continuum photons may also introduce systematic effects that are difficult to remove. Potential systematic effects regarding the line profiles are the broad wings associated with the stellar winds of the most massive stars and the presence of multiple cores inside the spectrograph aperture. Systematic effects are also the main limitation for the SNIa distance estimator so an important sub-product of our technique is to provide a comparative method to study the systematics of both empirical methods.

The paper is organized as follows. In Section 2, we describe our new GHIIR data for the ‘anchor sample’. In Section 3, we present the corrections to the observed fluxes due to extinction and underlying absorption and Section 4 deals with evolutionary corrections. Section 5 discusses distances and luminosities. In Section 6, we present our method for determining  $H_0$ . Section 7 is a detailed study of the systematic errors that may affect the application of the  $L - \sigma$  relation to measure distances and to determine  $H_0$ . Section 8 presents a comparison with previous results for  $H_0$  in particular those from SNIa and the Planck collaboration. The conclusions are given in Section 9.

## 2 THE DATA

The use of the  $L - \sigma$  relation as a distance indicator and as a tool to derive the Hubble constant requires accurate determination of both the luminosity and the FWHM or velocity dispersion of the emission lines in GHIIRs and HIIGs. In this section we discuss the observations and the quality of the obtained data in our new sample of GHIIRs in nearby galaxies.

### 2.1 The new anchor sample

To improve the early work on GHIIRs and to obtain a fiducial anchor sample, we started in 2012 a long-term project to acquire integrated  $H\beta$  fluxes and velocity dispersions of a new sample of 130 GHIIRs in 73 galaxies for which accurate distances have been determined using primary distance indicators. Here we present the results of the observations of 36 GHIIRs hosted by 13 such nearby galaxies representing about 1/4th of our primary sample of GHIIRs.

Much of the variance in the value of  $H_0$  is related to the choice of distance to the galaxies in the anchor sample, which in turn is intimately linked to the choice of calibration of the Cepheids period-luminosity (PL) relation. A thorough discussion of this aspect can be found in Riess et al. (2016).

#### 2.1.1 Adopted distances

The Cepheid distances to our sample galaxies were obtained from NASA/IPAC Extragalactic Database.<sup>1</sup> Our adopted distance for

<sup>1</sup> This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

**Table 1.** Adopted distance moduli for the new anchor sample.

Object	Distance modulus (mag)	Distance (Mpc)	Reference
IC10	$24.22 \pm 0.13$	$0.70 \pm 0.04$	1
M101	$29.15 \pm 0.10$	$6.76 \pm 0.32$	2, 3, 4, 5, 6, 7, 8
M33	$24.58 \pm 0.10$	$0.82 \pm 0.03$	2, 3, 4, 5, 6, 9, 10, 11, 12, 13
M81	$27.80 \pm 0.10$	$3.63 \pm 0.17$	2, 3, 4, 6, 14, 15, 16
MRK116	$31.35 \pm 0.22$	$18.62 \pm 1.98$	17, 18, 19
N2366	$27.63 \pm 0.14$	$3.36 \pm 0.22$	20
N2403	$27.49 \pm 0.23$	$3.15 \pm 0.35$	3, 4, 21, 22
N4258	$29.37 \pm 0.06$	$7.48 \pm 0.03$	2, 3, 4, 5, 11, 15, 16, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33 <sup>a</sup>
N4395	$28.22 \pm 0.12$	$4.41 \pm 0.25$	34
N0925	$29.80 \pm 0.10$	$9.12 \pm 0.43$	2, 3, 4, 5, 16
N2541	$30.35 \pm 0.12$	$11.75 \pm 0.67$	2, 3, 4, 5, 16
N3319	$30.65 \pm 0.14$	$13.49 \pm 0.90$	2, 3, 4, 5, 16
N3198	$30.75 \pm 0.13$	$14.13 \pm 0.87$	2, 3, 4, 5, 16

Notes. 1: Sakai, Madore & Freedman (1999); 2: Paturel et al. (2002); 3: Saha et al. (2006); 4: Freedman et al. (2001); 5: Willick & Batra (2001); 6: Sakai et al. (2004); 7: Shappee & Stanek (2011); 8: Mager, Madore & Freedman (2013); 9: Lee et al. (2002); 10: Scowcroft et al. (2009); 11: An, Terndrup & Pinsonneault (2007); 12: Bhardwaj et al. (2016); 13: Gieren et al. (2013); 14: McCommas et al. (2009); 15: Gerke et al. (2011); 16: Kanbur et al. (2003); 17: Fiorentino et al. (2010); 18: Aloisi et al. (2007); 19: Marconi et al. (2010); 20: Ferrarese et al. (2000); 21: Madore & Freedman (1991); 22: Freedman & Madore (1988); 23: Hoffmann & Macri (2015); 24: van Leeuwen et al. (2007); 25: Di Benedetto (2013); 26: Macri et al. (2006); 27: Efsthathiou (2014); 28: Ngeow et al. (2003); 29: Fausnaugh et al. (2015); 30: Mager, Madore & Freedman (2008); 31: Caputo, Marconi & Musella (2002); 32: Newman et al. (2001); 33: Maoz et al. (1999); 34: Thim et al. (2004).

<sup>a</sup>The geometric maser distance for NGC 4258 is  $7.60 \pm 0.32$  Mpc (Humphreys et al. 2013).

each galaxy is the average value provided by the references in Table 1, weighted by the reciprocal of the quoted distance modulus error. We only considered distances based on CCD photometry, that have been obtained, almost entirely, from determinations published more recently than the year 2000. Where necessary, the published distance moduli were adapted using as a reference an LMC value of  $(m - M)_{\text{LMC}} = 18.50$ .

In addition to the references in Table 1, we provide the following specific comments:

(1) From the *HST* Key Project team papers we only used the result published by Freedman et al. (2001), adopting their metallicity-corrected distance values.

(2) From Kanbur et al. (2003) we adopted the metallicity-corrected distances obtained from the LMC Cepheid PL relation.

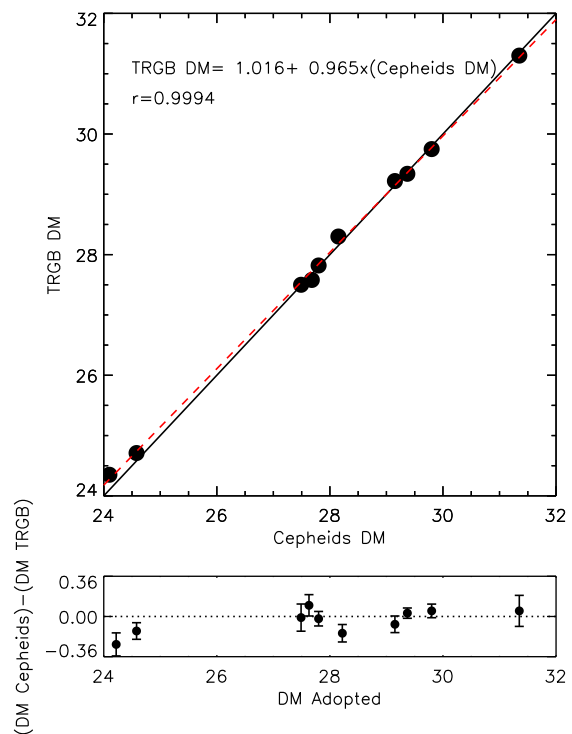
(3) In the case of Paturel et al. (2002), where they used the period-luminosity relation for Galactic Cepheids with HIPPARCOS distances, we used their adopted distance moduli, given in their Table 4 (Column 8).

We note that only one Cepheid distance was available for the galaxies IC 10, NGC 2366 and NGC 4395; for these three galaxies the adopted distance is the average of the Cepheid value and the mean of the Tip of the Red Giant Branch (TRGB) values. For MRK116 (I Zw 18), the distance values reported in the literature rely on theoretical models, because of the very low metallicity of this system ( $1/40\text{th } Z_{\odot}$ ), which prevents the use of empirical Period–Luminosity relations.

The distances obtained from the TRGB provided an important sanity check. The good agreement between the two sources of distance is shown in Fig. 1.

### 2.1.2 The GHIIR sample

In this section we present the results of the observations of 36 GHIIRs hosted by 13 nearby galaxies with redshift-independent distances. The targets are listed in Table 2 and a journal of observa-



**Figure 1.** Comparison of the distance moduli for our anchor sample obtained using the TRGB or the Cepheids PL relation. The solid line is the 1-to-1 relation and the red dashed line is the fit to the points,  $r$  is the correlation coefficient. The inset shows the coefficients of the fit. The residuals are shown in the bottom panel against the adopted distance moduli from Table 1.

tions is given in Table 3. Table 4 presents the relevant data for the new sample that we use in this paper to determine the zero-point of the  $L - \sigma$  relation and thus to derive the value of the Hubble constant.

**Table 2.** Regions observed.

Index	GHIIR	$\alpha$ (J2000)	$\delta$ (J2000)
1	IC 10-111	00 20 27.0	+59 17 29
2	IC 10-C01	00 20 17.0	+59 18 34
3	M101-NGC 5447	14 02 28.0	+54 16 33
4	M101-NGC 5455	14 03 01.2	+54 14 29
5	M101-NGC 5461	14 03 41.0	+54 19 02
6	M101-NGC 5462	14 03 53.1	+54 22 06
7	M101-NGC 5471	14 04 28.6	+54 23 53
8	M33-NGC 588	01 32 45.9	+30 38 51
9	M33-NGC 592	01 33 11.7	+30 38 42
10	M33-NGC 595	01 33 33.8	+30 41 30
11	M33-NGC 604	01 34 33.2	+30 47 06
12	M81-HK268	09 55 52.8	+68 59 03
13	M81-HK652	09 54 57.0	+69 08 48
14	MRK 116	09 34 02.0	+55 14 28
15	NGC 2366-HK110	07 28 30.1	+69 11 37
16	NGC 2366-HK54	07 28 46.6	+69 11 27
17	NGC 2366-HK72	07 28 43.0	+69 11 23
18	NGC 2366	07 28 54.6	+69 12 57
19	NGC 2403-VS24	07 36 45.5	+65 37 01
20	NGC 2403-VS3	07 36 20.0	+65 37 04
21	NGC 2403-VS44	07 37 07.0	+65 36 39
22	NGC 925-120	02 27 01.6	+33 34 28
23	NGC 925-128	02 26 58.6	+33 34 40
24	NGC 925-42	02 27 21.6	+33 33 31
25	NGC 4258-RC01	12 18 55.3	+47 16 46
26	NGC 4258-RC02	12 19 01.4	+47 15 25
27	NGC 4395-NGC 4399	12 25 42.9	+33 30 57
28	NGC 4395-NGC 4400	12 25 56.0	+33 30 54
29	NGC 4395-NGC 4401	12 25 57.6	+33 31 42
30	NGC 2541-A	08 14 47.6	+49 03 59
31	NGC 2541-B	08 14 37.3	+49 02 59
32	NGC 2541-C	08 14 37.2	+49 03 53
33	NGC 3319-A	10 39 03.9	+41 39 41
34	NGC 3319-B	10 39 00.3	+41 40 08
35	NGC 3319-C	10 39 17.7	+41 42 07
36	NGC 3198-A	10 19 46.1	+45 31 03

As in our previous work, further selection conditions are as follows:

(i) a lower limit for the equivalent width,  $EW(H\beta) > 50 \text{ \AA}$  to exclude highly evolved regions, diminish contamination by an underlying older stellar population (cf. Melnick et al. 2000) and avoid objects with a high rate of escape of ionizing photons, plus

(ii) an upper limit to the Balmer line widths,  $\log \sigma < 1.8 \text{ km s}^{-1}$  to minimize the possibility of including systems supported by rotation or with multiple young ionizing clusters, as discussed in Melnick et al. (1988).

### 2.1.3 Low-resolution spectrophotometry

We obtained the integrated emission-line fluxes from wide slit low-resolution spectrophotometry. When necessary, we converted the fluxes of  $H\beta$  to  $H\alpha$  using the theoretical ratio for case B recombination.

The low-resolution spectroscopy, used for measuring the emission lines flux, was obtained using similar Boller & Chivens Cassegrain spectrographs at two 2.1-m telescopes with similar configurations in long-slit mode. The telescopes are located at the Observatorio Astronómico Nacional (OAN-SPM) in San Pedro Mártir (Baja California) and at the Observatorio Astrofísico Guillermo Haro (OAGH) in Cananea (Sonora), both situated in northern México. The observations at OAGH were performed using a  $150 \text{ gr mm}^{-1}$

grating with a blaze angle of  $3^\circ 25'$  centred at  $\lambda \sim 5000 \text{ \AA}$  and a slit-width of 9 arcsec. The data from OAN were obtained using a  $400 \text{ gr mm}^{-1}$  grating with a blaze angle of  $6^\circ 30'$ , the grating was centred at  $\lambda \sim 5850 \text{ \AA}$  and the slit-width was 13 arcsec. At least three spectrophotometric standard stars were observed each night, and at least one GHIIR was repeated every night in order to concatenate the different observing runs. The objects were observed at small zenith distances. All nights reported here were photometric; the seeing in most nights varied between 1.1 and 1.4 arcsec.

The spectra were reduced using the standard procedure in IRAF.<sup>2</sup> The spectrophotometric standard stars observed were Feige 110, G191-B2B, BD+28, G158-100, Hz4, Feige 34, Feige 66 and BD+33. A typical low-resolution spectrum obtained at OAN-SPM is shown as an example in Fig. 2.

### 2.1.4 Comparison with previous work

We have compared our wide aperture spectrophotometry with published aperture photometry from Melnick et al. (1987), Kennicutt (1984) and Bosch, Terlevich & Terlevich (2002) hereinafter M87, K84, B02, respectively, for the giant  $H\text{II}$  regions NGC 588, NGC 592, NGC 595 and NGC 604 in M33 and NGC 5447, NGC 5461, NGC 5462 and NGC 5471 in M101.

K84 obtained photoelectric  $H\alpha$  photometry using single-channel photometers on the Kitt Peak 0.9m, CTIO 0.6m and the Manastash Ridge 0.8m telescopes with  $20 \text{ \AA}$  FWHM interference filters for line and continuum. The observations were performed through apertures large enough to include the outer edge of the  $H\text{II}$  region. As K84 provides no estimate of the extinction, we have assumed negligible extinction at  $H\alpha$  and transformed K84 fluxes to  $H\beta$  scaling them by the theoretical Balmer decrement (2.86).

Observations by M87 were made with the 1.52-m telescope of the Observatorio Astronómico Nacional at Calar Alto, Spain, using  $100 \text{ \AA}$  FWHM interference filters to define the line and continuum photometric bands. M87 used an RCA C31034 Ga-As photomultiplier and at least three concentric apertures, of which the biggest was always larger than the halo of the  $H\text{II}$  region. With these apertures, a curve of growth was constructed to estimate the contamination by diffuse emission in the host galaxy and the total emission line flux.

B02 measured the total fluxes of  $H\beta$  and  $H\alpha$  emission lines from CCD narrow-band images obtained at the 1.0-m Jacobus Kapteyn Telescope at the Observatorio del Roque de los Muchachos in the Canary Islands. The GHIIRs and the flux standard stars were observed using four narrow-band filters (FWHM  $\sim 50 \text{ \AA}$ ) centred at  $H\beta$  and  $H\alpha$  and their adjacent continua. B02  $H\beta$  fluxes are not as reliable as their  $H\alpha$  ones (see the original paper), so we have compared our photometry with B02  $H\alpha$  fluxes scaled by the theoretical Balmer decrement.

Fig. 3 shows the comparison of our photometry with that of K84 (top left), M87 (top right) and B02 (bottom left); using the same symbols, all are plotted together in the bottom right panel.

Regarding the comparison of our fluxes with those from K84, except for NGC 592 in M33 there is a reasonable agreement inside  $\pm 0.25 \text{ dex}$ .

The comparison of the  $H\beta$  fluxes shows a  $\pm 0.2 \text{ dex}$  concordance with M87 except for NGC 592 in M33 and NGC 5447 in M101. These regions are known to have multiple ‘knots’ so the discrepancy could be related to differences in the pointing. The case for NGC

<sup>2</sup> IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

**Table 3.** Journal of observations.

INDEX	Low-resolution spectroscopy						High-resolution spectroscopy					
	OAN-2.1m-B&C			OAGH-2.1m-B&C			OAN-2.1m-MEZCAL			OAGH-2.1m-CanHiS		
	Exp. time (s)	Number of Exp.	Date	Exp. time (s)	Number of Exp.	Date	Exp. time (s)	Number of Exp.	Date	Exp. time (s)	Number of Exp.	Date
1	360	4	Oct 13, 2012				900	3	Sep 23, 2013			
2	360	4	Oct 13, 2012							1200	3	Oct 11, 2013
3				900	4	Apr 14, 2013				1200	3	Mar 21, 2015
4				900	3	Apr 15, 2013				1500	3	Mar 22, 2015
5				900	3	Apr 13, 2013				1200	3	Mar 21, 2015
6				600	3	Apr 11, 2013				1800	3	Mar 22, 2015
7				900	3	Apr 11, 2013	1200	3	Mar 23, 2014	900	3	Mar 21, 2015
8	360	4	Oct 13, 2012	600	3	Nov 13, 2012	1200	3	Sep 25, 2013	1500	3	Oct 9, 2013
9	360	4	Oct 12, 2012	600	3	Nov 13, 2012				1200	2	Oct 15, 2014
10	360	4	Oct 12, 2012	300	5	Nov 13, 2012	600	3	Sep 25, 2013	900	2	Oct 17, 2014
11	360	4	Oct 14, 2012	900	2	Nov 12, 2012	1200	3	Aug 27, 2013	900	2	Oct 17, 2014
12				1200	3	Apr 11, 2013	900	3	Mar 20, 2014	1600	3	Mar 29, 2014
13				1200	3	Apr 13, 2013	1800	2	Mar 15, 2015			
14				900	3	Apr 11, 2013				1200	3	Mar 26, 2015
15	360	4	Oct 13, 2012							1200	2	Mar 23, 2015
16	360	4	Oct 13, 2012				1800	2	Mar 12, 2015	1200	3	Mar 23, 2015
17	360	4	Oct 13, 2012				900	2	Mar 13, 2015	1800	3	Mar 23, 2015
18	300	3	Oct 12, 2012	600	3	Nov 14, 2012	2400	2	Mar 12, 2015			
19	360	4	Oct 14, 2012	900	3	Nov 14, 2012				900	3	Oct 17, 2014
20	360	4	Oct 14, 2012	420	4	Nov 13, 2012				1000	3	Oct 12, 2013
21	360	4	Oct 14, 2012	600	3	Nov 14, 2012				1200	3	Oct 10, 2013
22	360	4	Oct 12, 2012	1200	3	Nov 14, 2012	1200	3	Sep 26, 2013			
23	480	5	Oct 12, 2012	1200	3	Nov 14, 2012	1200	3	Sep 24, 2013			
24	360	4	Oct 12, 2012	900	4	Nov 14, 2012	1200	3	Sep 24, 2013	1200	3	Oct 10, 2013
25				1200	3	Apr 15, 2013	1800	3	Mar 21, 2014			
26				1200	3	Apr 15, 2013	1200	3	Mar 22, 2014	1800	4	Mar 23, 2015
27				1200	3	Apr 16, 2013	1200	2	Mar 15, 2015			
28				1200	3	Apr 16, 2013	1200	4	Mar 30, 2014			
29				1500	3	Apr 12, 2013	1800	2	Mar 15, 2015			
30				900	3	Mar 13, 2016	1800	3	Mar 1, 2016			
31				900	3	Mar 13, 2016	1200	3	Feb 27, 2016	1500	3	Mar 10, 2016
32				900	3	Mar 13, 2016				1800	3	Mar 12, 2016
33				1200	3	Mar 15, 2016	1800	3	Feb 27, 2016			
34				1200	3	Mar 15, 2016	1800	3	Feb 27, 2016			
35				1200	3	Mar 16, 2016	1800	3	Feb 27, 2016			
36				1200	4	Mar 14, 2016	1800	3	Feb 29, 2016			

5447 is reinforced by the fact that also the emission line width observed by M87 in this GHIIR shows a discrepancy with our value. In both parameters, emission line flux and line width M87 show lower values than our present observations.

It is important to note that for NGC 592 the average between K84 and M87 measurement differs only 0.05 dex from our measurement. The comparison with B02 shows slightly higher scatter.

We can conclude that the comparison illustrated in Fig. 3 shows no systematic trends with the data from the literature and illustrates the difficulty in performing integrated photometry in extended H II regions.

### 2.1.5 High-resolution spectroscopy

Given that typical values of the velocity dispersion of GHIIRs are in the region of 10–30 km s<sup>-1</sup> high-resolution spectrographs are needed to accurately measure their emission line widths. To this end high-resolution spectra were obtained using Echelle spectrographs at the observatories OAN and OAGH.

At the OAN we used the Manchester Echelle spectrometer (Meaburn et al. 2003, MEZCAL) a long-slit nebular Echelle high-resolution spectrograph built to obtain spatially resolved profiles of

individual emission lines from faint extended sources. MEZCAL operates in the wavelength range 3900–9000 Å with a spectral resolving power  $\mathcal{R} \sim 100\,000$ . This Echelle spectrograph has no cross-disperser so it isolates single orders using interference filters. We used a 90 Å bandwidth filter to isolate the 87th order containing the H  $\alpha$  and [N II] nebular emission lines with  $\lambda_c = 6575$  Å. The observations were performed with a 70  $\mu$ m (0.95 arcsec) slit corresponding to a velocity resolution of  $\sigma_{\text{inst}} = 6.0$  km s<sup>-1</sup>. Two pixel binning was applied in both the spatial and spectral directions.

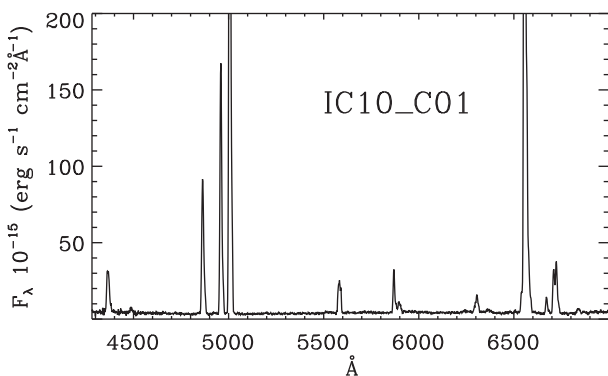
The Cananea High-Resolution Spectrograph (CanHiS) is a high spatial and very high spectral resolution Echelle spectrograph  $\mathcal{R} \sim 140\,000$  at the 2.1 m telescope at OAGH. Like MEZCAL, CanHiS utilizes medium-band interference filters to isolate individual orders (Hunten et al. 1991). We used the filter centred in H  $\alpha$ ,  $\lambda_c = 6563$  Å, covering a bandwidth of 90 Å. The observations were performed with a slit width of 50.7  $\mu$ m (0.45 arcsec) resulting in a velocity resolution  $\sigma_{\text{inst}} = 3.0$  km s<sup>-1</sup>.

Not having a cross disperser, both MEZCAL and CanHiS are very efficient instruments.

The data were reduced using standard IRAF tasks. The wavelength calibration and the instrumental resolutions were obtained

**Table 4.** New anchor sample of giant H II regions. Luminosities are corrected using Gordon et al. (2003) extinction law.

Name	Flux (H $\beta$ ) ( $10^{-14}$ erg s $^{-1}$ cm $^{-2}$ )	EW (H $\beta$ ) Å	$A_V$	$Q \times 100$	FWHM(H $\alpha$ ) Å	log $L$ (H $\beta$ ) (erg s $^{-1}$ )	log $\sigma$ (H $\alpha$ ) (km s $^{-1}$ )
IC10-111	5297 ± 626	118 ± 7.4	0.057 ± 0.053	0.182	1.048 ± 0.030	39.52 ± 0.08	1.180 ± 0.013
IC10-C01	3297 ± 380	221 ± 11.0	0.013 ± 0.078	0.000	0.817 ± 0.015	39.29 ± 0.08	1.114 ± 0.012
M101-NGC 5447	169 ± 8.3	169 ± 3.8	1.490 ± 0.113	0.022	1.433 ± 0.018	40.68 ± 0.07	1.414 ± 0.023
M101-NGC 5455	73.5 ± 6.6	112 ± 6.5	0.443 ± 0.075	0.007	1.353 ± 0.021	39.82 ± 0.07	1.369 ± 0.021
M101-NGC 5461	82.2 ± 9.8	135 ± 1.7	0.464 ± 0.063	0.087	1.120 ± 0.021	39.88 ± 0.07	1.295 ± 0.018
M101-NGC 5462	29.2 ± 1.5	180 ± 4.4	0.908 ± 0.070	1.828	1.130 ± 0.012	39.65 ± 0.06	1.304 ± 0.018
M101-NGC 5471	98.0 ± 11.	256 ± 0.7	0.371 ± 0.072	0.027	1.268 ± 0.014	39.91 ± 0.07	1.302 ± 0.018
M33-NGC 588	271 ± 24.	75 ± 0.8	0.513 ± 0.184	0.012	0.876 ± 0.012	38.59 ± 0.11	1.105 ± 0.011
M33-NGC 592	173 ± 15.	50 ± 0.4	0.261 ± 0.149	14.62	0.797 ± 0.017	38.34 ± 0.09	1.010 ± 0.010
M33-NGC 595	652 ± 74.	68 ± 0.5	0.549 ± 0.137	11.65	0.868 ± 0.013	39.15 ± 0.09	1.245 ± 0.016
M33-NGC 604	1508 ± 141.	95 ± 1.0	0.266 ± 0.136	0.007	1.132 ± 0.013	39.22 ± 0.09	1.269 ± 0.017
M81-HK268	33.0 ± 3.0	64 ± 4.7	0.973 ± 0.245	0.199	0.877 ± 0.021	39.19 ± 0.13	1.130 ± 0.012
M81-HK652	188.3 ± 25.	67 ± 1.8	1.004 ± 0.247	0.181	1.113 ± 0.018	39.96 ± 0.15	1.275 ± 0.017
MRK116	16.4 ± 1.2	88 ± 2.5	0.011 ± 0.259	15.28	1.205 ± 0.036	39.91 ± 0.16	1.307 ± 0.018
NGC 2366-HK110	22.0 ± 3.9	114 ± 7.56	0.011 ± 0.273	0.013	0.748 ± 0.018	38.48 ± 0.17	0.968 ± 0.008
NGC 2366-HK54	127 ± 14.	215 ± 3.1	0.589 ± 0.073	0.061	0.970 ± 0.022	39.27 ± 0.08	1.177 ± 0.014
NGC 2366-HK72	184 ± 16.	265 ± 7.7	0.014 ± 0.072	0.080	0.953 ± 0.019	39.40 ± 0.08	1.196 ± 0.014
NGC 2366	164 ± 15.	84 ± 7.2	0.016 ± 0.090	0.064	0.929 ± 0.054	39.35 ± 0.08	1.202 ± 0.014
NGC 2403-VS24	55.3 ± 6.6	149 ± 3.9	0.421 ± 0.159	0.100	0.960 ± 0.013	39.02 ± 0.13	1.176 ± 0.014
NGC 2403-VS3	75.7 ± 8.7	87 ± 0.9	0.442 ± 0.030	0.000	1.105 ± 0.021	39.17 ± 0.11	1.234 ± 0.015
NGC 2403-VS44	46.2 ± 6.7	125 ± 1.2	1.375 ± 0.062	0.002	1.234 ± 0.011	39.40 ± 0.12	1.291 ± 0.018
NGC 925-120	2.1 ± 0.5	102 ± 4.4	0.631 ± 0.127	3.289	0.950 ± 0.048	38.63 ± 0.12	1.030 ± 0.010
NGC 925-128	8.0 ± 1.0	118 ± 4.0	0.012 ± 0.058	0.001	0.964 ± 0.035	38.91 ± 0.08	1.178 ± 0.013
NGC 925-42	3.8 ± 0.8	116 ± 3.7	0.011 ± 0.015	0.011	0.901 ± 0.017	38.58 ± 0.11	1.126 ± 0.012
NGC 4258-RC01	35.0 ± 4.3	98 ± 6.6	0.679 ± 0.254	2.437	0.913 ± 0.046	39.71 ± 0.13	1.210 ± 0.015
NGC 4258-RC02	147 ± 32.	69 ± 0.7	0.295 ± 0.096	0.591	1.218 ± 0.032	40.14 ± 0.11	1.329 ± 0.019
NGC 4395-NGC 4399	9.8 ± 2.5	47 ± 6.0	0.327 ± 0.089	2.053	0.879 ± 0.025	38.52 ± 0.13	1.101 ± 0.012
NGC 4395-NGC 4400	147. ± 41.	82 ± 1.0	0.014 ± 0.060	7.096	1.061 ± 0.045	39.62 ± 0.13	1.297 ± 0.018
NGC 4395-NGC 4401	11.1 ± 1.9	73 ± 1.9	0.019 ± 0.043	0.115	0.785 ± 0.045	38.42 ± 0.09	1.022 ± 0.010
NGC 2541-A	7.1 ± 0.5	94 ± 14.0	0.001 ± 0.111	0.329	0.860 ± 0.009	39.25 ± 0.07	1.225 ± 0.034
NGC 2541-B	15.5 ± 0.1	98 ± 10.0	0.002 ± 0.080	0.015	0.980 ± 0.015	39.42 ± 0.06	1.243 ± 0.054
NGC 2541-C	13.9 ± 0.1	73 ± 6.7	0.001 ± 0.030	0.278	0.940 ± 0.017	39.50 ± 0.05	1.261 ± 0.062
NGC 3319-A	21.6 ± 0.1	114 ± 4.7	0.396 ± 0.221	0.329	1.090 ± 0.090	39.93 ± 0.13	1.326 ± 0.030
NGC 3319-B	17.5 ± 0.1	80 ± 4.9	0.000 ± 0.106	0.153	0.990 ± 0.031	39.66 ± 0.08	1.286 ± 0.011
NGC 3319-C	3.9 ± 0.2	123 ± 17.0	1.440 ± 0.251	0.132	0.910 ± 0.085	39.68 ± 0.26	1.221 ± 0.070
NGC 3198-A	15.0 ± 1.2	90 ± 11.0	0.015 ± 0.141	0.327	0.950 ± 0.077	39.73 ± 0.09	1.238 ± 0.028


**Figure 2.** IC10 C01 low-resolution spectrum obtained at OAN-SPM.

using an internal U-Ne lamp in CanHis, and a Th-Ar lamp for MEZCAL.

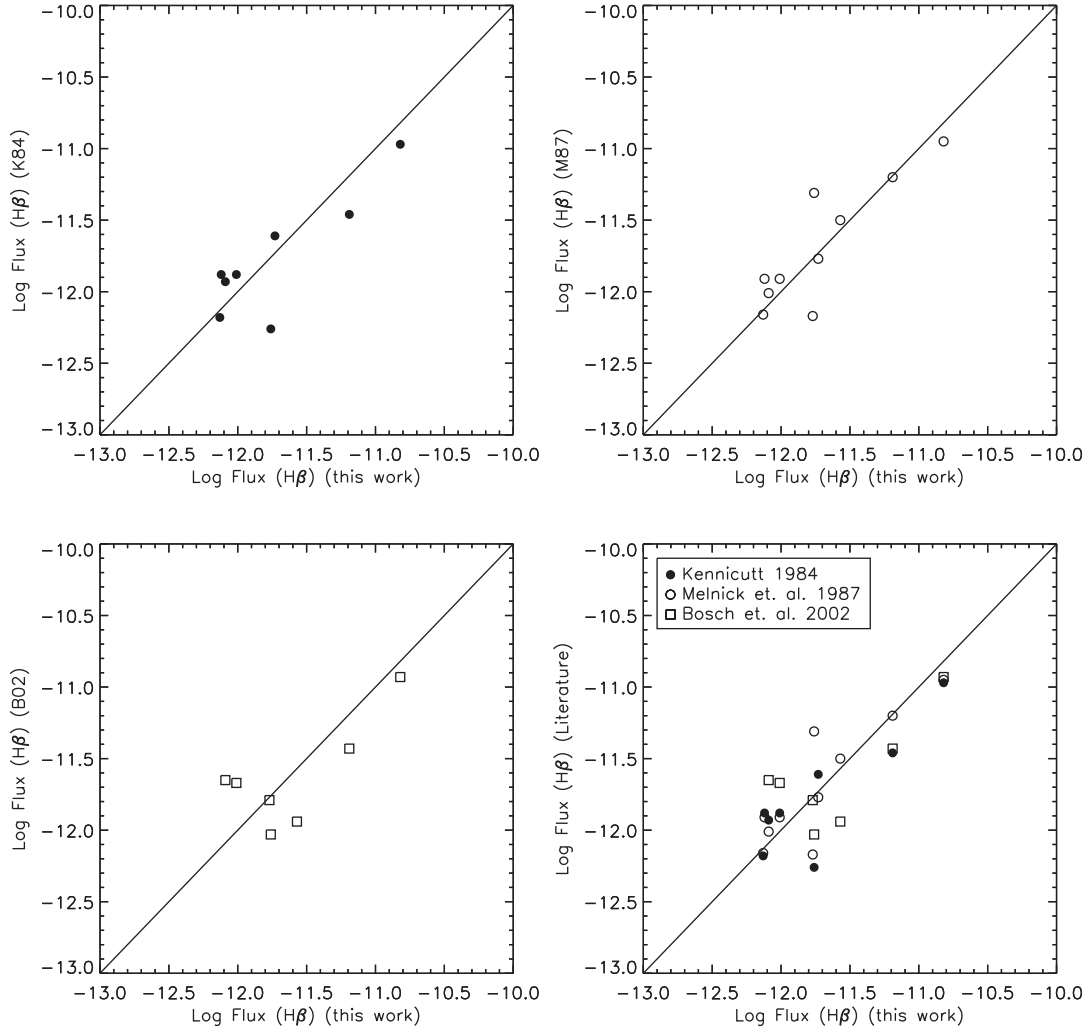
Repeated observations of 10 targets were obtained with MEZCAL and CanHis in order to estimate observational errors and night-to-night variations and to compare the performance of both instruments. NGC 595 (a GHIIR in M 33) high-resolution spectra are shown as an example in Fig. 4. Fig. 5 shows a comparison of the  $\sigma$  values obtained with both instruments.

### 2.1.6 Line profiles

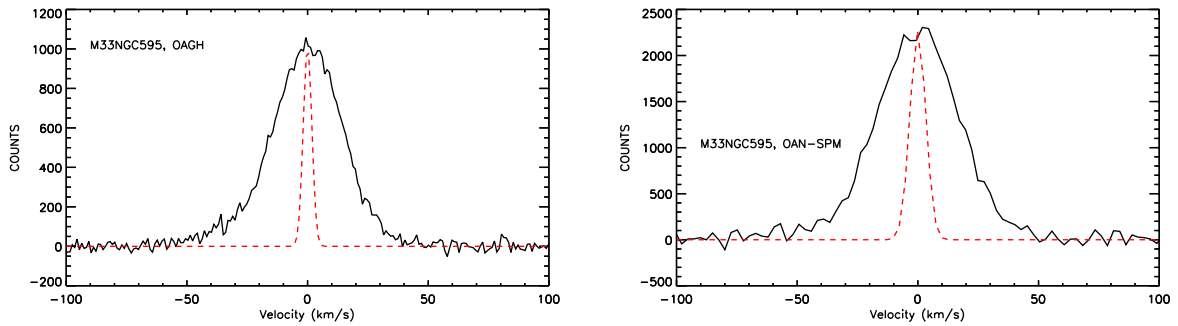
A commonly used method to study the distribution of gas and its kinematic properties is based on fitting the profile of the emission lines with Gaussians, although asymmetric non-Gaussian profiles in the emission lines are frequently found in the literature (e.g. Bordalo & Telles 2011; Hägele et al. 2013; Chávez et al. 2014). To compensate, multiple Gaussian curves or Lorentzian functions are fitted, in which case the information contained in the wings might be lost or strongly dependent on the adopted initial values.

The presence of weak extended non-Gaussian wings in the profiles of the emission lines may introduce a small systematic effect in the determination of the FWHM. This effect may be associated with stellar winds and multiple simultaneous starbursts. This can equally affect the determination of the FWHM of HIIGs and GHIIRs and hence, the distance estimator used to calculate  $H_0$ .

The alternative strategy of eliminating objects that have multiple profiles or extended wings in the profiles seems risky because multiplicity will sometimes appear as a structure in the velocity dispersion and sometimes as brighter spots depending on the relative radial velocity of the regions that are superposed along the line of sight. So for the distance indicator, it seems safer to include all the objects in the sample, paying the price of a larger scatter in



**Figure 3.** Comparison between our photometry and Kennicutt (1984) (top left), Melnick et al. (1987) (top right) and Bosch et al. (2002) (bottom left). All together are shown at the bottom right panel.



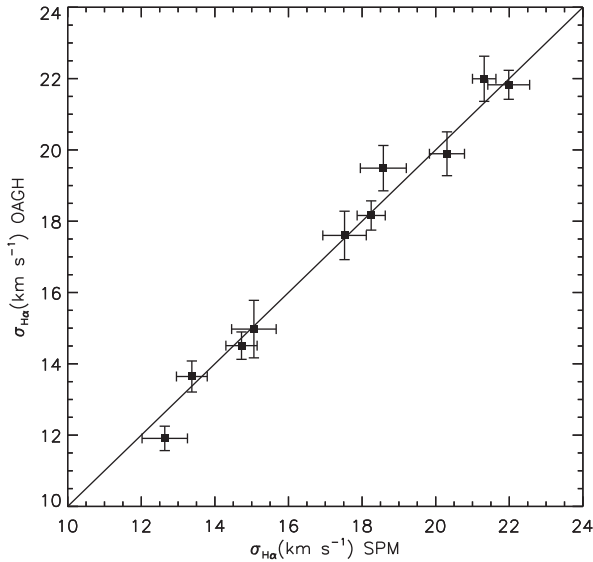
**Figure 4.** Spectrum of NGC 595 using OAGH CanHis (left) and OAN-SPM MEZCAL (right) in  $H\alpha$ . The dashed (red) line is the fit to the instrumental profile obtained for the calibration lamps at 6585.3 and 6583.9 Å at OAGH and OAN-SPM, respectively.

the correlation as in Bordalo & Telles (2011) and in Chávez et al. (2014).

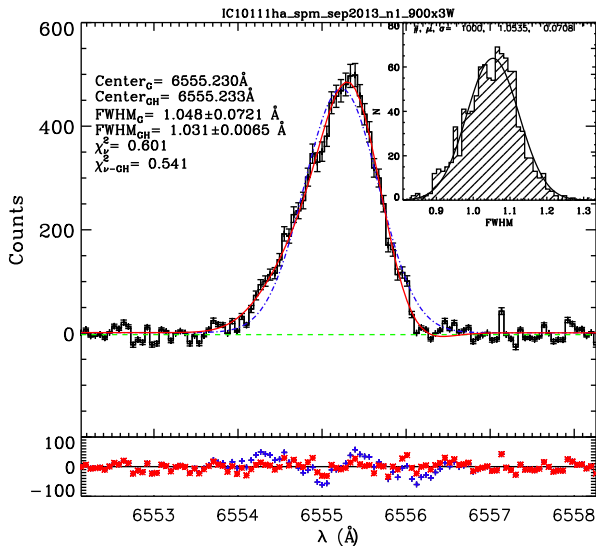
Our approach for this work is to obtain the FWHM of  $H\alpha$  from the high-resolution spectra and to fit both a single Gaussian and a Gauss-Hermite series to the line profile.

The Gauss-Hermite function preserves the information of the velocity of the gas by fitting the wings of the emission-line profiles. It has the added advantage that this fitting can be implemented

in a hands-off routine, by varying the moments of the function automatically (Riffel 2010). An example profile comparison using both methods is shown in Fig. 6. For most of our data the profiles are not far from Gaussian and therefore the estimates of the FWHM by both methods are not very different. In Fig. 7 we show the comparison of the FWHM obtained by fitting Gauss or Gauss-Hermite functions to the line profiles. Both methods are equivalent within the errors, indicating that the presence of wings or slight



**Figure 5.** Velocity dispersion for the 10 objects observed with both OAGH CanHis and OAN-SPM MEZCAL.



**Figure 6.** Fit of the  $H\alpha$  profile using a Gaussian (blue dashed line) and a Gauss–Hermite fit (continuous red). The residuals are shown in the lower panel with the same colour code. The inset shows the results of a Monte Carlo simulation to estimate the errors in the parameters of the best fit.

asymmetries in the sample does not affect the measurement of the FWHM of the emission lines.

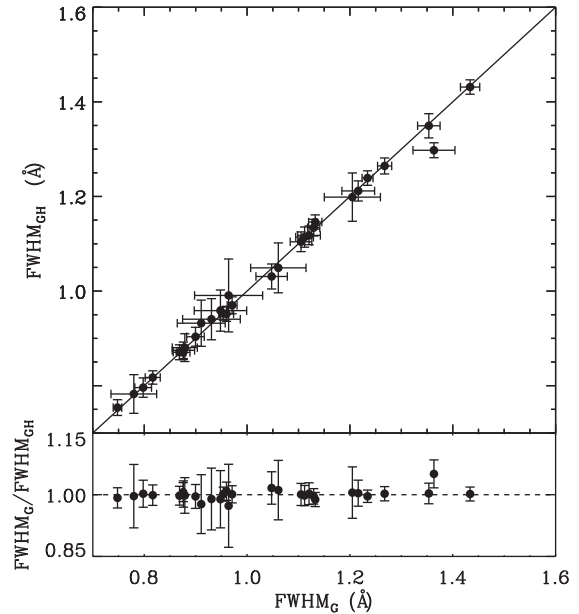
The observed velocity dispersions ( $\sigma_{\text{obs}}$ ) are then corrected by thermal ( $\sigma_t$ ) and instrumental ( $\sigma_i$ ) broadening, thus the intrinsic velocity dispersion is given by:

$$\sigma = \sqrt{\sigma_{\text{obs}}^2 - \sigma_i^2 - \sigma_t^2} \quad (1)$$

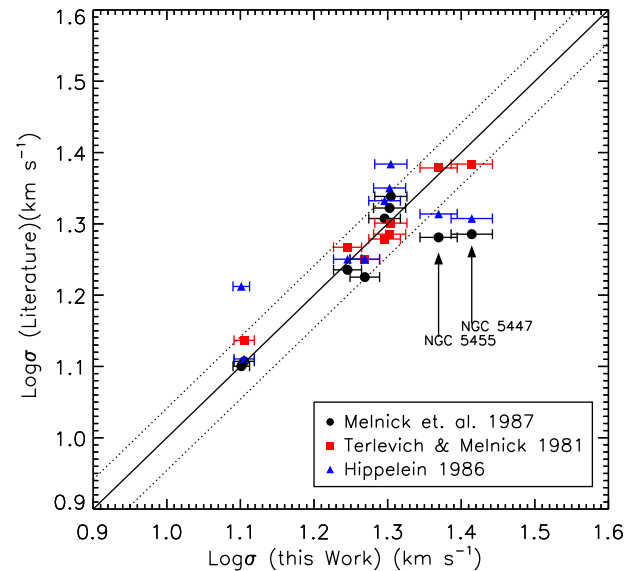
where the thermal broadening was calculated assuming a Maxwellian velocity distribution of the hydrogen ion, from the equation:

$$\sigma_t = \sqrt{\frac{kT_e}{m}} \quad (2)$$

where  $k$  is the Boltzmann constant,  $m$  is the mass of the ion and  $T_e$  is the electron temperature in kelvin. The instrumental broadening is



**Figure 7.** FWHM obtained applying Gauss versus Gauss–Hermite fits. Lower panel: the ratio of the FWHM obtained using these fits.



**Figure 8.** Comparison of the velocity dispersion for the eight GHIIRs in common with M87, H86 and TM81. The dotted lines indicate  $\pm 10$  per cent.

$\sigma_i = 3$  and  $6 \text{ km s}^{-1}$  for data obtained with CanHis and MEZCAL, respectively.

### 2.1.7 Comparison with previous work

Eight of our GHIIRs have published determinations of their velocity dispersion. Fig. 8 shows the comparison of our measurements with M87, TM81 and Hippelein (1986) (hereinafter H86). The dotted lines indicate concordance within 10 per cent. The points with the greatest discrepancy correspond to NGC 5447 and NGC 5455 in M 101. NGC 5447 has multiple ‘knots’ that could have led to a different pointing when the M87 data were obtained as discussed in Section 2.1.4. On the other hand, our values for NGC 5447 and NGC 5455 agree within 10 per cent with those reported by



TM81. It is interesting to note that while TM81 (as this work) uses only the Balmer line FWHM measurements, M87 uses the average between the [O III] and Balmer FWHM. Because the [O III] lines are systematically narrower than the Balmer emission lines (see Melnick et al. 2017), it is expected that M87 FWHM values will be systematically smaller than the pure H $\alpha$  ones.

From this comparison we can conclude that there is agreement in the values of the FWHM inside  $\pm 10$  per cent with TM81 and also with M87 except for NGC 5447 and NGC 5455 in M101. The comparison with H86 however shows a larger scatter with five GHIIRs outside the  $\pm 10$  per cent band out of eight GHIIRs in common.

## 2.2 H II galaxies

We use the data for 107 nearby ( $z \leq 0.16$ ) HIIGs defined by Chávez et al. (2014) as their ‘best data set’; we will refer to it as the Ch14 sample obtained, as the GHIIRs in this work, with both low and high spectral resolutions in order to measure the total fluxes and the emission line profiles, respectively. The high-resolution observations were performed with the HDS on Subaru, and UVES on the VLT and the low-resolution ones with the Mexican 2 m telescopes at OAN-SPM and OAGH.

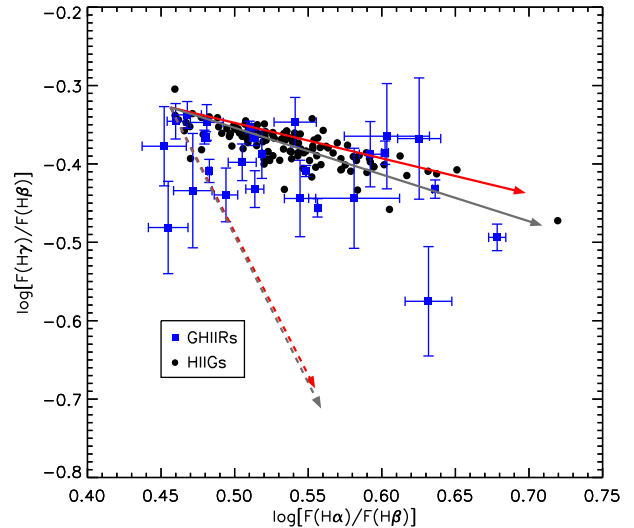
The line fluxes in Chávez et al. (2014) were measured through a very wide (typically 8 arcsec) entrance slit. As the HIIGs in the sample are quite compact (typical diameters of less than 5 arcsec) the use of 8 arcsec wide slits guarantees a complete sampling of the line emitting region. These large aperture observations have a systematic effect with respect to the SDSS spectrophotometry for those objects with sizes larger than the 3 arcsec fibre aperture of SDSS. Here we use the Chávez et al. (2014) measurements to compute the H $\beta$  luminosities and compare them with those resulting from the SDSS photometry.

The Chávez et al. (2014) HDS observations were taken through a 4 arcsec slit, which nominally corresponds to an instrumental velocity dispersion  $\sigma_{\text{inst}} = 12.3 \text{ km s}^{-1}$ , although that results in an instrumental profile that is flat-top and not Gaussian. The UVES observations were obtained through a 2 arcsec slit corresponding to a nominal instrumental resolution of  $\sigma_{\text{inst}} = 4.65 \text{ km s}^{-1}$ , and again the instrumental profiles are flat-top. Although the seeing during the observations was substantially better than 2 arcsec, the sizes of most objects are larger than the slit width, so no elaborate procedure was required for the instrumental corrections as in the case of HDS. Notice, however, that for both UVES and HDS the box-shaped instrumental profiles imply that the emission-line profiles have non-Gaussian cores that can be appreciated in the residuals of the Gaussian fits (Chávez et al. 2014).

As the SDSS Petrosian diameters of most objects in the Ch14 sample are about 3 arcsec to 5 arcsec, the instrumental resolution in the HDS spectra under normal seeing conditions is biased by the surface brightness profile of the objects. Although this effect is difficult to quantify with the available data, Chávez et al. (2014) corrected their observations for instrumental broadening using an ‘equivalent SDSS Petrosian diameter, with reasonably good results.

## 3 EXTINCTION AND UNDERLYING ABSORPTION

Massive bursts of star formation are embedded in large amounts of gas and dust and this dust is responsible for the extinction of light in the line of sight due to absorption and scattering. The



**Figure 9.** Balmer decrement plane  $\log(F(H\alpha)/F(H\beta))$  versus  $\log(F(H\gamma)/F(H\beta))$ . The vectors indicate the direction of shifts due to extinction [solid lines for two different extinction laws (red: Gordon et al. (2003), grey: Calzetti et al. (2000))] or to underlying absorption (dashed line) from the intrinsic values given by recombination.

amount of extinction can be estimated using hydrogen recombination lines through the Balmer decrement, although contamination by underlying stellar Balmer absorption lines changes the ratio of observed emission lines such that the internal extinction can be overestimated.

We have derived the ‘true’ visual extinction and determined the underlying Balmer absorption using two different extinction laws, the one by Calzetti et al. (2000) which has been widely used for massive starburst galaxies and the one by Gordon et al. (2003) which corresponds to the LMC2 supershell near the prototypical GHIIR 30 Doradus in the LMC. Notice that since the photometric errors in the H $\beta$  fluxes of the HIIGs in Chávez et al. (2014) are small, the errors in their luminosity are dominated by the errors in the extinction correction. As in our previous papers (see e.g. Chávez et al. 2014), the uncertainties in the fluxes and equivalent widths have been estimated using the expressions from Tresse et al. (1999). When more than one measurement was available, the fluxes were calculated using a mean weighted by the errors.

To correct for extinction, we used a modification of the Balmer decrement method. We corrected the Balmer line emissions for the effect of stellar absorption lines using the technique proposed by Rosa-González, Terlevich & Terlevich (2002, see equations therein). This method allows us to obtain simultaneously the values of  $Q$  and  $A_V$  that correspond to the underlying absorption and the visual extinction, respectively. In Fig. 9 we represent the Balmer decrement plane  $\log(F(H\alpha)/F(H\beta))$  versus  $\log(F(H\gamma)/F(H\beta))$ . In the absence of underlying absorption, all points should be distributed along the extinction vector, while in the absence of extinction all points should be distributed along the underlying absorption line. We can see from the figure that most of our objects fall, within the errors, in the region close to the reddening vector and to the right of the underlying absorption vector.

We calculated  $A_V$  and  $Q$  using the theoretical ratios for case B recombination  $F(H\alpha)/F(H\beta) = 2.86$  and  $F(H\gamma)/F(H\beta) = 0.47$  (Osterbrock 1989). We measured the Balmer lines from the SDSS

spectra, and propagate the uncertainties by a Monte Carlo procedure. Errors in the luminosities are dominated by uncertainties in the correction for extinction. The dereddened fluxes were obtained from the expression:

$$F_0(\lambda) = F_{\text{obs}}(\lambda)10^{0.4A_V k(\lambda)/R_V} \quad (3)$$

where  $k(\lambda) = A(\lambda)/E(B - V)$  is given by the extinction law either Calzetti et al. (2000) or Gordon et al. (2003), and  $R_V = A_V/(B - V)$  is the optical total-to-selective extinction. We adopted  $R_V = 4.05$  and 2.77 from Calzetti et al. (2000) and Gordon et al. (2003), respectively.

Finally the dereddened fluxes were corrected by the underlying absorption (equation from Rosa-González et al. 2002):

$$F(\lambda) = \frac{F_0(\lambda)}{1 - Q} \quad (4)$$

## 4 EVOLUTION CORRECTION

In young SSCs, as the ones in our sample, the UV luminosity and therefore their emission line luminosity decay rapidly in less than 7 million years while the optical luminosity remains relatively constant or increases due to the evolution of the cluster main sequence to lower temperatures and smaller bolometric correction.

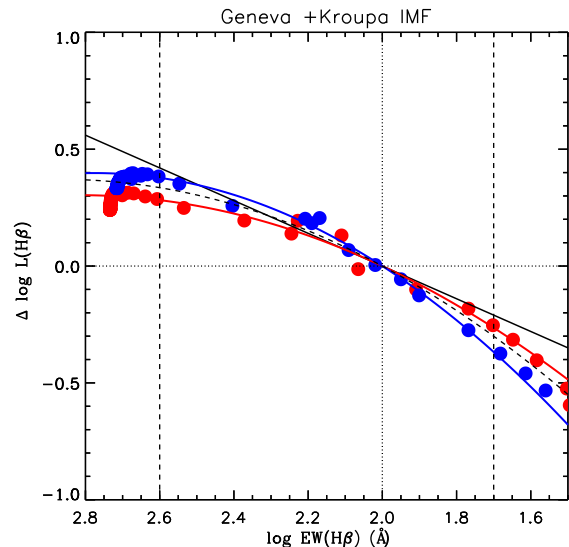
Even in our sample of HIIGs and GHIIRs, chosen to be the youngest systems, it is crucial to verify that the rapid luminosity evolution of the stellar cluster does not introduce a systematic bias in the distance indicator. This would happen, for example, if the average age of the GHIIRs is different from that of the HIIGs or if luminous and faint HIIGs have different average ages. In general, if velocity dispersion measures mass, younger clusters will be more luminous than older ones for a given  $\sigma$ .

The evolution effect can be scrambled by the superposition of bursts of different ages along the line of sight. Nevertheless, even small systematics can have a sizeable effect in the value of  $H_0$  so it is important to remove the evolution effect from the data in a similar fashion as for the dust extinction. The equivalent width of  $H\beta$  [EW( $H\beta$ )] is a useful age estimator (Dottori & Bica 1981; Stasińska & Leitherer 1996; Martín-Manjón et al. 2008) or at least it provides an upper limit of the age of the burst (Terlevich et al. 2004). Indeed there is some empirical evidence for this as discussed by Melnick et al. (2000) and Bordalo & Telles (2011). Chávez et al. (2014) explored the possibility that the age of the burst is a second parameter, using the EW( $H\beta$ ) as an age estimator in the  $L - \sigma$  relation for HIIGs, and found a rather weak dependence.

### 4.1 Determining the evolution correction with stellar population synthesis models

The ionizing luminosity of young stellar clusters and consequently the Balmer line luminosity of the associated  $H_{II}$  region remain almost constant during the first  $10^6$  yr of evolution and then decay rapidly after the first 3 Myr while the continuum luminosity remains approximately constant during the first 8 Myr. This combined effect is illustrated in Fig. 10, where we can see the change in the  $L(H\beta)$  versus EW( $H\beta$ ) for instant bursts with a Kroupa IMF and the Geneva tracks for metallicity  $Z = 0.004$  and  $Z = 0.008$  computed using STARBURST99 (Leitherer et al. 1999, SB99).

We corrected the luminosities to the value they would have when the EW is equal to the median EW of the GHIIR of the anchor



**Figure 10.** Differential change in the  $L(H\beta)$  versus  $EW(H\beta)$  for a Kroupa IMF with upper mass limit of  $120 M_{\odot}$  and Geneva tracks for metallicities  $Z = 0.004$  and  $Z = 0.008$  computed using SB99. The vertical dotted line shows the median of the equivalent width of the sample. The vertical dashed lines indicate the extremes of the EW in the samples. The solid black line is the linear fit to the models, in colour the quadratic fits: blue and red for the different metallicities  $Z = 0.004$  and  $0.008$ , respectively, and the dashed line is the total fit.

sample. The median EW ( $w_{\text{med}}$ ) defines therefore a ‘median-age’ for the corrected sample.<sup>3</sup>

The changes can be quantified through the relation  $\Delta L(H\beta) = c \times \Delta EW(H\beta)$  (equation 3 in Hägele et al. 2013), where  $c$  varies between 0.5 and 0.9 for different stellar synthesis models. Clearly, however, as shown in Fig. 10 the relation between  $\log(L)$  and  $\log(EW)$  is not linear, but for the range of ages of interest it can be approximated by a parabola of the form

$$\log L(H\beta) = \text{constant} + a_1[\log EW(H\beta)] + a_2[\log EW(H\beta)]^2 \quad (5)$$

Thus we corrected the observed flux as,

$$\Delta \log F(H\beta) = (w_i - w_{\text{med}})[a_1 + a_2(w_i + w_{\text{med}})] \quad (6)$$

where  $w_{\text{med}}$  and  $w_i$  are the log median[EW( $H\beta$ )] and the individual log EW( $H\beta$ ) respectively.

The fit to the average of the models gives values of the coefficients of  $a_1 = 2.55 \pm 0.08$  and  $a_2 = -0.44 \pm 0.02$ .

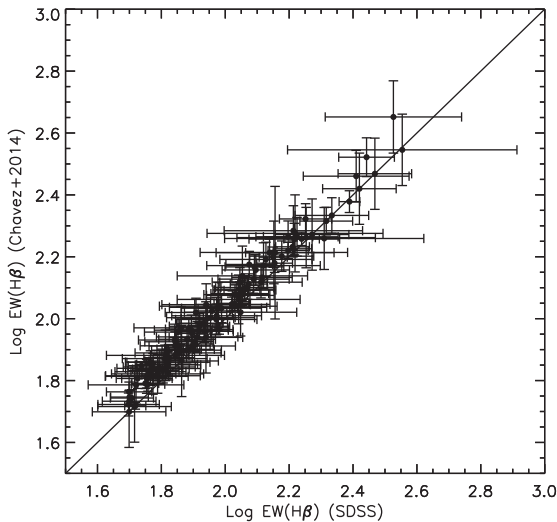
The associated error is:

$$\delta \Delta \log F(H\beta)^2 = (w_i - w_{\text{med}})^2 (\delta a_1)^2 + (w_i^2 - w_{\text{med}}^2)^2 (\delta a_2)^2 + (a_1 + 2a_2 w_i)^2 (\delta w_i)^2 \quad (7)$$

with  $\delta a_i$  being the error in the fit coefficients.

The EW values in Chávez et al. (2014) are systematically larger than those from the SDSS spectra. This result is as expected for the larger spectral apertures used in Chávez et al. (2014) if the nebular emission is significantly more extended than the continuum

<sup>3</sup> In Melnick et al. (2017), we erroneously concluded that the choice of  $w_{\text{med}}$  strongly influences the value of  $H_0$ . This mistake was due to a numerical error that has now been corrected. For any value of  $w_{\text{med}}$ , the correction to the fluxes of the HIIGs is almost exactly offset by the change in zero-point resulting from the correction of the GHIIRs luminosities.



**Figure 11.** Comparison between the equivalent widths of H  $\beta$  from Chávez et al. (2014) and those from SDSS spectra. The 1:1 line is shown.

as it is probably the case in these systems. This is illustrated in Fig. 11, where we show the comparison between the equivalent width measured from Chávez et al. (2014) and those from SDSS including the observational error bars.

#### 4.1.1 Caveats

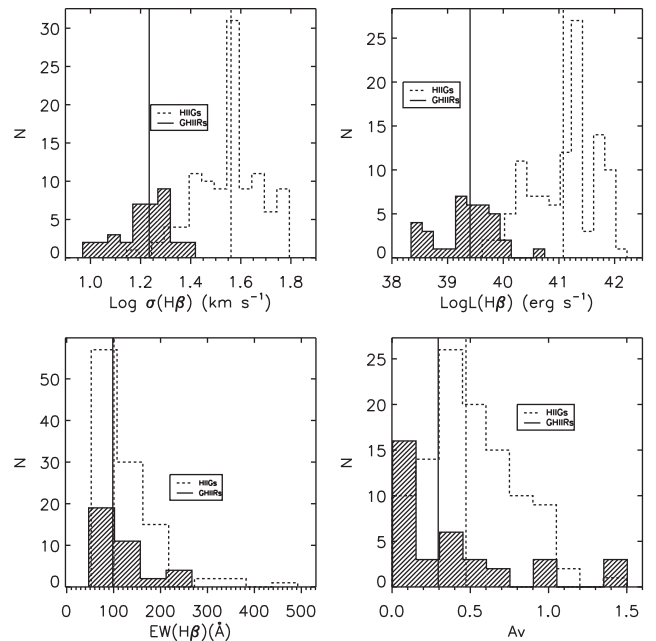
There are four main uncertainties associated with our approach to evolution correction: first, as discussed in Calzetti et al. (2000), in local star-forming galaxies there is a differential extinction between stars and ionized gas being the nebular lines more attenuated than the stellar continuum by a factor of about 2, thus also biasing the observed EW to lower values.

Secondly, as discussed in Terlevich et al. (2004); Melnick et al. (2017), and Telles & Melnick (in preparation) the observed EW of HIIGs is biased to lower values due to the contribution of an underlying older stellar population to the observed continuum. This effect can be seen in the images of the GHIIRs of the Appendix with about half of the objects showing a complex morphology. The fact that the distribution of EW in GHIIRs is similar to that of HIIGs (see Fig. 12) supports the view that the underlying continuum and differential reddening effects in the measured EW are similar in the two samples.

Thirdly, there is a dearth of models of the evolution of SSCs that include self-consistently the photoionization of the interstellar gas. SB99 includes Balmer emission line EW estimates, but these estimates are simply based in the total UV ionizing flux without taking into account H II region parameters such as metallicity, density or ionization parameter.

Finally, SB99 models do not include massive interacting binaries or the contribution of stars more massive than  $120M_{\odot}$ , all of which are expected to be important in massive SSCs. In fact, studies of local SSCs like 30-Doradus indicate that the binary fraction among the most massive stars could be as high as 100 per cent (Bosch, Terlevich & Terlevich 2009), and that a substantial fraction of these could be interacting (Sana et al. 2013). These effects imply that our corrections are still rather tentative and should be considered as indicative of the effect of evolution.

In Section 7.1.3, we discuss the effect of a contribution to the observed EW of an underlying older stellar population and of the differential extinction on the value of  $H_0$ .



**Figure 12.** Comparison of the distribution of properties of the GHIIRs (shaded area) and the Chávez et al. (2014) HIIGs sample (dashed line); upper left: H  $\beta$  velocity dispersion, down left: EW(H  $\beta$ ), upper right: H  $\beta$  luminosity, down right:  $A_V$  extinction parameter obtained using Gordon et al. (2003) extinction law. The vertical lines represent the median value for each sample.

## 5 DISTANCES AND LUMINOSITIES

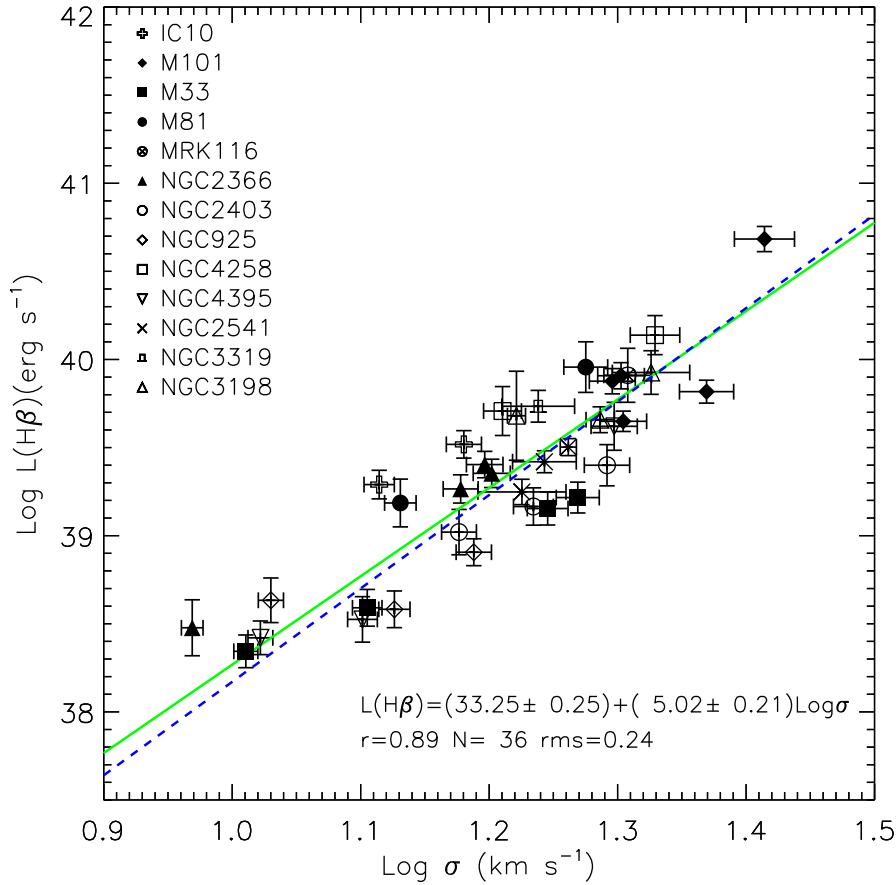
We computed the luminosities  $L$  for the HIIG from the observed fluxes  $F$  as  $L = 4\pi F D_L^2$ , where the luminosity distance  $D_L$  was derived using either the linear Hubble law  $D_L = cz/H_0$ , or the complete set of cosmological parameters. In general the former  $D_L$  is smaller than the latter.

For systems with  $z < 0.1$  using the linear Hubble law to determine  $D_L$  underestimates the luminosity distance  $D_L$  by less than 8 per cent relative to the distances computed using standard cosmology. Thus, using the linear relation for objects with  $z > 0.1$  will result in  $H_0$  being overestimated. On the other hand, estimating  $D_L$  using the cosmological parameters makes the method sensitive to the choice of cosmological parameters such as  $\Omega_{\Lambda}$  that will slightly change  $D_L$  and therefore the derived  $H_0$ . To estimate the size of this effect, we built from our primary sample (hereinafter S1) a subsample (S2) constrained to HIIGs with  $z < 0.1$  and use for it the linear relationship to estimate the distance independently of cosmology.

In summary, the extinction-corrected fluxes were used to calculate the luminosity of the HIIGs, ( $L = 4\pi D_L^2$ ), where  $D_L$  was derived (depending on  $z$ ) using either the linear relationship of the Hubble law ( $D = cz/H_0$ ) or a flat cosmology with  $\Omega_m = 0.29$ . The distribution of the parameters used for the distance estimator is shown in Fig. 12.

### 5.0.2 Aperture effects

From the very beginning of this project our conventional wisdom has been to measure the velocity dispersions through relatively narrow slits to preserve the spectral resolution and the luminosities through wide apertures to include all the flux. The underlying assumption is that the turbulence is isotropic and the internal extinction modest, so that even through a narrow slit we still sample the full turbulent



**Figure 13.**  $L(H\beta)$ – $\sigma$  relation for the GHIIRs. The adopted distances to the parent galaxies (see Table 34) are derived from primary distance estimators. The green solid line is the fit to the data given in the inset and the dashed line is the fit to the anchor sample of Chávez et al. (2012).

cascade. This is a pretty good assumption for single objects, but a small fraction of our objects have complex profiles, a sign of complex structure. Thus, even narrow slits may encompass more than one starburst along the line of sight. Therefore, using different entrance apertures for luminosities and velocity dispersions may introduce systematic effects that need to be quantified (see Melnick et al. 2017 for further discussion).

Notice also that while the fluxes have been measured through wide slits, the extinction correction is derived using SDSS fluxes measured through a 3 arcsec fibre aperture. The evolution correction on the other hand is determined using Chávez et al. (2014) spectrophotometry for the Ch14 data and SDSS spectrophotometry for the SDSS data. This is relevant because the luminosity errors are dominated by the uncertainties in the extinction and evolution corrections.

## 6 THE HUBBLE CONSTANT

The Hubble constant is determined as follows: first we fix the slope of the  $L - \sigma$  relation using the velocity dispersions and luminosities of the HIIGs. The slope is independent of the actual value of  $H_0$ . The said slope is then used to determine the zero-point of the relation using our new data of 36 GHIIRs whose  $L - \sigma$  relation is shown in Fig. 13. The slope and zero-point define the distance indicator that is then applied to the sample of HIIGs to determine  $H_0$ .

### 6.1 Methodology

The method used for the determination of the Hubble constant using the  $L - \sigma$  relation and the analysis of the propagation of errors follows the formalism presented in Melnick et al. (2017).

The error propagation includes the observational errors plus the covariance of the two variables which must be included even when the observational errors are uncorrelated.

The error  $\delta Y_i$  in the prediction of a linear correlation of the form  $y = a + bx$  at a given value of  $x = x_i$ , when the parameters  $a$  and  $b$  are determined using least-squares techniques and including the experimental errors in both variables ( $\delta x_i, \delta y_i$ ) is,

$$(\delta Y_i)^2 = (\delta y_i)^2 + (b \times \delta x_i)^2 + (\delta a)^2 + (\delta b)^2(x_i - \langle x \rangle)^2. \quad (8)$$

The standard least-squares solution is in general biased when the independent variable is subject to error. In such cases equation (8) is a very good approximation, but is not exact.

To estimate the Hubble constant, we use the slope ( $\alpha$ ) of the  $L - \sigma$  relation of the HIIGs and our anchor sample to calibrate the zero-point ( $Z_p$ ) of the distance indicator as follows:

$$Z_p = \frac{\sum_{i=1}^{36} W_i (\log L_{\text{GHR},i} - \alpha \times \log \sigma_{\text{GHR},i})}{\sum_{i=1}^{36} W_i}, \quad (9)$$

where  $L_{\text{GHR},i}$  is the  $H\beta$  luminosity of each GHIIR and  $\sigma_{\text{GHR},i}$  the corresponding velocity dispersion. The statistical weights  $W_i$  are

**Table 5.** Model parameters for  $H_0$  computation.

M	Sample	$N$	Extinction	Photometry	Distance
1	S1	107	C00	Ch14	LR
2	S2	92	C00	Ch14	LR
3	S1	107	C00	SDSS	LR
4	S2	92	C00	SDSS	LR
5	S1	107	C00	Ch14	$\Omega_\Lambda = 0.71$
6	S2	92	C00	Ch14	$\Omega_\Lambda = 0.71$
7	S1	107	C00	SDSS	$\Omega_\Lambda = 0.71$
8	S2	92	C00	SDSS	$\Omega_\Lambda = 0.71$
9	S1	107	G03	Ch14	LR
10	S2	92	G03	Ch14	LR
11	S1	107	G03	SDSS	LR
12	S2	92	G03	SDSS	LR
13 <sup>a</sup>	S1	107	G03	Ch14	$\Omega_\Lambda = 0.71$
14	S2	92	G03	Ch14	$\Omega_\Lambda = 0.71$
15	S1	107	G03	SDSS	$\Omega_\Lambda = 0.71$
16	S2	92	G03	SDSS	$\Omega_\Lambda = 0.71$

Notes. Column 1: Model code (<sup>a</sup> denotes the preferred model). Column 2: Sample. Column 3: Number of HIIGs. Column 4: Extinction law. Column 5: Source of  $H\beta$  photometry. Column 6: Distance estimate of HIIGs.

calculated as follows:

$$W_i^{-1} = \left(0.4343 \frac{\delta L_{\text{GHR},i}}{L_{\text{GHR},i}}\right)^2 + \left(0.4343\alpha \frac{\delta \sigma_{\text{GHR},i}}{\sigma_{\text{GHR},i}}\right)^2 + (\delta\alpha)^2(\sigma_{\text{GHR},i} - \langle \sigma_{\text{HIIG}} \rangle)^2, \quad (10)$$

where  $\langle \sigma_{\text{HIIG}} \rangle$  is the average velocity dispersion of the HIIGs that define the slope of the relation. Thus, the calibrated  $L - \sigma$  relation or distance estimator is:  $\log L(H\beta) = \alpha \log \sigma + Z_p$ . To calculate the Hubble constant, we minimize the function,

$$\chi^2(H_0) = \sum_{i=1}^N [W_i(\mu_i - \mu_{H_0,i})^2 - \ln(W_i)] \quad (11)$$

where  $\mu_i$  is the logarithmic distance modulus to each HIIG calculated using the distance indicator and the  $H\beta$  flux  $F(H\beta)$  as

$$\mu_i = 2.5[Z_p + \alpha \times \log \sigma_i - \log F_i(H\beta) - \log 4\pi] \quad (12)$$

**Table 6.** The  $L - \sigma$  relation without correction for evolution.

N	Sample	$H_0$	$a$	$b$	rms(HIIG)	rms(DI)	$\chi_{\text{min}}^2/\text{dof}$
1	S1-C00-Chavez14-LIN	77.1 <sup>+3.1</sup> <sub>-3.0</sub>	33.49 ± 0.25	4.81 ± 0.14	0.343	0.343	0.931
2	S2-C00-Chavez14-LIN	75.4 <sup>+3.3</sup> <sub>-3.1</sub>	33.39 ± 0.25	4.89 ± 0.16	0.365	0.365	1.048
3	S1-C00-SDSS-LIN	72.8 <sup>+2.9</sup> <sub>-2.8</sub>	33.20 ± 0.26	5.05 ± 0.14	0.372	0.372	1.075
4	S2-C00-SDSS-LIN	70.3 <sup>+3.1</sup> <sub>-2.9</sub>	33.04 ± 0.26	5.18 ± 0.16	0.398	0.398	1.220
5	S1-C00-Chavez14- $\Omega_\Lambda = 0.71$	75.4 <sup>+3.0</sup> <sub>-2.9</sub>	33.29 ± 0.25	4.97 ± 0.14	0.343	0.353	0.970
6	S2-C00-Chavez14- $\Omega_\Lambda = 0.71$	74.3 <sup>+3.2</sup> <sub>-3.1</sub>	33.23 ± 0.25	5.02 ± 0.16	0.365	0.373	1.088
7	S1-C00-SDSS- $\Omega_\Lambda = 0.71$	71.1 <sup>+2.9</sup> <sub>-2.8</sub>	32.99 ± 0.26	5.22 ± 0.14	0.372	0.384	1.119
8	S2-C00-SDSS- $\Omega_\Lambda = 0.71$	69.1 <sup>+3.0</sup> <sub>-2.9</sub>	32.87 ± 0.26	5.32 ± 0.17	0.398	0.408	1.262
9	S1-G03-Chavez14-LIN	76.3 <sup>+3.0</sup> <sub>-2.9</sub>	33.46 ± 0.23	4.84 ± 0.14	0.345	0.345	0.976
10	S2-G03-Chavez14-LIN	74.3 <sup>+3.1</sup> <sub>-3.0</sub>	33.35 ± 0.23	4.93 ± 0.16	0.367	0.367	1.105
11	S1-G03-SDSS-LIN	71.7 <sup>+2.8</sup> <sub>-2.7</sub>	33.16 ± 0.24	5.09 ± 0.14	0.374	0.374	1.136
12	S2-G03-SDSS-LIN	68.8 <sup>+2.9</sup> <sub>-2.8</sub>	32.99 ± 0.24	5.23 ± 0.17	0.401	0.401	1.294
13*	S1-G03-Chavez14- $\Omega_\Lambda = 0.71$	74.6 <sup>+2.9</sup> <sub>-2.8</sub>	33.27 ± 0.23	5.00 ± 0.14	0.345	0.355	1.020
14	S2-G03-Chavez14- $\Omega_\Lambda = 0.71$	73.2 <sup>+3.1</sup> <sub>-3.0</sub>	33.19 ± 0.24	5.06 ± 0.16	0.367	0.376	1.147
15	S1-G03-SDSS- $\Omega_\Lambda = 0.71$	70.0 <sup>+2.8</sup> <sub>-2.7</sub>	32.96 ± 0.24	5.25 ± 0.14	0.373	0.385	1.182
16	S2-G03-SDSS- $\Omega_\Lambda = 0.71$	67.6 <sup>+2.9</sup> <sub>-2.8</sub>	32.82 ± 0.24	5.37 ± 0.17	0.401	0.410	1.338

and  $\mu_{H_0,i}$  is the distance modulus calculated from the redshift using either the linear relation  $D_L = zc/H_0$  or the full cosmological prescription with  $\Omega_\Lambda = 0.71$ .

The best value of  $H_0$  is then obtained minimizing  $\chi^2$  with statistical weights  $W_i^{-1} = \delta\mu_i^2 + \delta\mu_{H_0,i}^2$  calculated as,

$$W_i^{-1} = 6.25 \left[ (\delta Z_p)^2 + \left(0.4343 \frac{\delta F_i}{F_i}\right)^2 + \left(0.4343\alpha \frac{\delta \sigma_i}{\sigma_i}\right)^2 + (\delta\alpha)^2(\sigma_i - \langle \sigma \rangle)^2 \right] \quad (13)$$

## 7 SYSTEMATICS

### 7.1 Exploring the parameter space

In previous sections we have discussed the known statistical uncertainties associated with our sample. Genuine systematic errors are difficult to estimate, so in this section we include a range of parameters to quantify at least part of the systematic error component. In particular, we explore alternative parametrizations that cannot be easily included in the error scheme, as follows:

(i) Two samples: S1 with 107 galaxies or S2 with  $z < 0.1$  and 92 galaxies;

(ii) Two different sources for the  $H\beta$  photometry: Chávez et al. (2014) (Ch14) or SDSS;

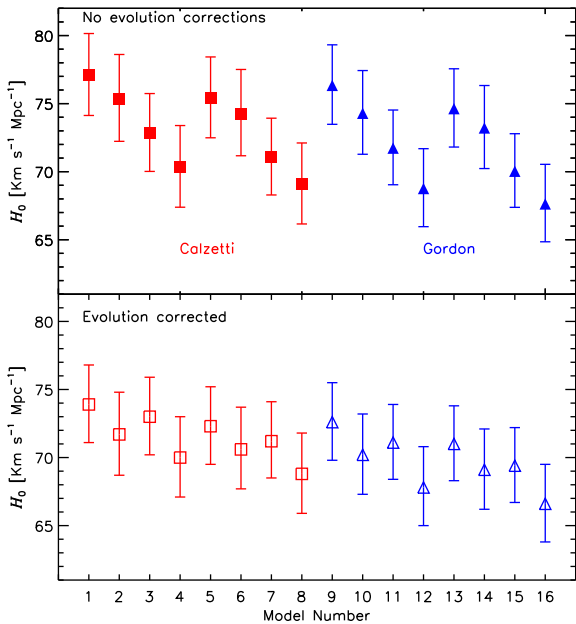
(iii) Two formulations for the luminosity distance for the HIIGs:  $D_L = H_0/cz$  (LR) or full  $\Lambda$ CDM cosmology with  $\Omega_\Lambda = 0.71$ ;

(iv) For these three cases we use two different extinction laws: Calzetti et al. (2000) (C00) or Gordon et al. (2003) (G03).

This yields 16 different combinations (models; the preferred one is model 13 as we will discuss below) see Table 5, which we compute for the two evolutionary scenarios discussed above: no evolution, and evolution corrected using quadratic fits to SB99 models as detailed in Section 4. The resulting parameters of the  $L - \sigma$  relation for each case are listed in Tables 6 and 7, and shown in a graphical form in Fig. 14 that illustrates the sensitivity of the value of  $H_0$  to the adopted combination.

**Table 7.** The  $L - \sigma$  relation corrected for evolution using EW( $H\beta$ ).

N	Sample	$H_0$	$a$	$b$	rms (HIIG)	rms(DI)	$\chi^2_{\min}/\text{dof}$
1	S1-C00-Chavez14-LIN	$73.9^{+2.9}_{-2.8}$	$33.33 \pm 0.24$	$4.93 \pm 0.14$	0.355	0.354	1.014
2	S2-C00-Chavez14-LIN	$71.7^{+3.1}_{-3.0}$	$33.18 \pm 0.24$	$5.05 \pm 0.17$	0.375	0.374	1.124
3	S1-C00-SDSS-LIN	$73.0^{+2.9}_{-2.8}$	$33.07 \pm 0.25$	$5.14 \pm 0.14$	0.388	0.383	1.179
4	S2-C00-SDSS-LIN	$70.0^{+3.0}_{-2.9}$	$32.88 \pm 0.25$	$5.30 \pm 0.17$	0.411	0.407	1.307
5	S1-C00-Chavez14- $\Omega_\Lambda = 0.71$	$72.3^{+2.9}_{-2.8}$	$33.13 \pm 0.24$	$5.09 \pm 0.14$	0.355	0.364	1.046
6	S2-C00-Chavez14- $\Omega_\Lambda = 0.71$	$70.6^{+3.1}_{-2.9}$	$33.03 \pm 0.25$	$5.18 \pm 0.17$	0.375	0.382	1.159
7	S1-C00-SDSS- $\Omega_\Lambda = 0.71$	$71.2^{+2.9}_{-2.7}$	$32.87 \pm 0.25$	$5.30 \pm 0.15$	0.388	0.395	1.215
8	S2-C00-SDSS- $\Omega_\Lambda = 0.71$	$68.8^{+3.0}_{-2.9}$	$32.71 \pm 0.26$	$5.44 \pm 0.18$	0.411	0.416	1.346
9	S1-G03-Chavez14-LIN	$72.6^{+2.9}_{-2.8}$	$33.28 \pm 0.24$	$4.98 \pm 0.14$	0.360	0.359	1.033
10	S2-G03-Chavez14-LIN	$70.2^{+3.0}_{-2.9}$	$33.13 \pm 0.25$	$5.11 \pm 0.17$	0.381	0.380	1.147
11	S1-G03-SDSS-LIN	$71.1^{+2.8}_{-2.7}$	$33.01 \pm 0.25$	$5.21 \pm 0.14$	0.394	0.389	1.203
12	S2-G03-SDSS-LIN	$67.8^{+3.0}_{-2.8}$	$32.79 \pm 0.25$	$5.38 \pm 0.18$	0.418	0.414	1.337
13*	S1-G03-Chavez14- $\Omega_\Lambda = 0.71$	$71.0^{+2.8}_{-2.7}$	$33.09 \pm 0.25$	$5.14 \pm 0.14$	0.360	0.369	1.064
14	S2-G03-Chavez14- $\Omega_\Lambda = 0.71$	$69.1^{+3.0}_{-2.9}$	$32.97 \pm 0.25$	$5.24 \pm 0.17$	0.381	0.388	1.180
15	S1-G03-SDSS- $\Omega_\Lambda = 0.71$	$69.4^{+2.8}_{-2.7}$	$32.81 \pm 0.25$	$5.37 \pm 0.15$	0.394	0.401	1.237
16	S2-G03-SDSS- $\Omega_\Lambda = 0.71$	$66.6^{+2.9}_{-2.8}$	$32.63 \pm 0.26$	$5.52 \pm 0.18$	0.418	0.424	1.374


**Figure 14.** Graphic representation of the values of  $H_0$  for the various parameters listed in Tables 6 and 7. *Top.* Resulting  $H_0$  without correcting the luminosities for evolution. *Bottom.* Same as the top panel, but using the fluxes corrected for evolution; see Section 4. As discussed in the text, the difference between models 1–8 (in red) and models 9–16 (in blue) is the adopted extinction law as indicated by the figure legends.

### 7.1.1 Sensitivity to $H\beta$ photometry

The sensitivity to  $H\beta$  photometry was explored by comparing SDSS and Chávez et al. (2014) photometric measurements. A cursory inspection of Fig. 14 and Tables 6 and 7 reveals that the values of  $H_0$  are on average systematically lower by about  $4.9 \text{ km s}^{-1} \text{ Mpc}^{-1}$  for SDSS fluxes and no evolutionary corrections, this systematic difference is reduced to  $1.7 \text{ km s}^{-1} \text{ Mpc}^{-1}$  when evolutionary corrections are included. The smaller value of  $H_0$  for the SDSS photometry is related to the systematically steeper slope of the  $L - \sigma$  relation compared with that obtained when using Chávez et al. (2014)

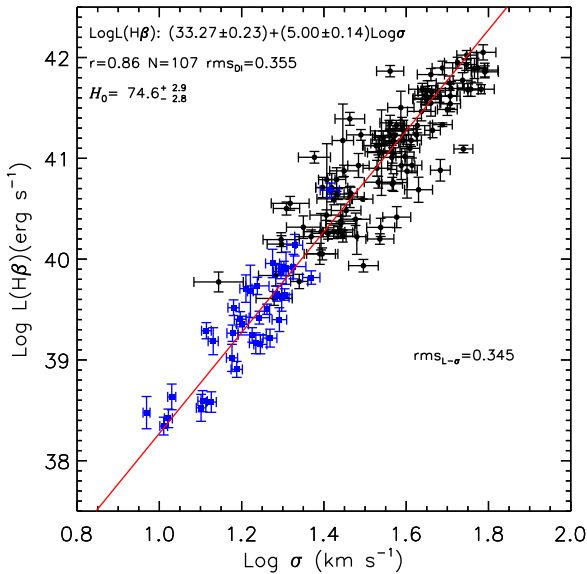
photometry, both with and without evolution correction. Since the lower luminosity HIIGs are also the closer ones, the steepening is a consequence of the smaller SDSS aperture, compared with that of Chávez et al. (2014), underestimating the line fluxes of the nearest galaxies. We therefore favour the results with the larger aperture photometry from Chávez et al. (2014).

### 7.1.2 Sensitivity to extinction laws

The effect of using different extinction laws [(Calzetti et al. 2000, Models 1–8) or (Gordon et al. 2003, Models 9–16)] is explored next. In general the Calzetti et al. (2000) law yields larger values of  $H_0$  than Gordon et al. (2003) typically by about  $1.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . The Calzetti et al. (2000) law was derived from a sample of eight heterogeneous starburst galaxies where only two, Tol 1924-416 and UGCS410, are bonafide HIIGs and the rest are evolved high metallicity starburst galaxies, while the Gordon et al. (2003) extinction curve corresponds to the LMC2 supershell near the 30 Doradus star-forming region, the prototypical GHIIR, in the Large Magellanic Cloud. Therefore, we are inclined to prefer the results using the Gordon et al. (2003) extinction law.

### 7.1.3 Sensitivity to evolution corrections

Fig. 14 shows the resulting values of  $H_0$  for the models without (upper panel) and with evolution correction (lower panel). Comparing the upper and lower panels, we clearly see that we obtain lower values for  $H_0$  when we apply the evolutionary corrections particularly in those models using the Chávez et al. (2014) photometry. The difference between the SDSS and the Chávez et al. (2014) correction is probably linked to the systematic difference in the measured EW as discussed above and is an indication of the systematic errors involved in this correction. The values of  $H_0$  obtained after applying the evolution correction show as a family less scatter (r.m.s. =  $1.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ) than the uncorrected results (r.m.s. =  $2.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ), indicating that the evolution-corrected results are more self-consistent.



**Figure 15.** The  $L - \sigma$  relation for the Chávez et al. (2014) sample using the velocity dispersions in the original paper; the fluxes have been corrected using the Gordon et al. (2003) extinction law. The solid line is the fit to the HIIGs points. The inset equation is the distance indicator where the slope is obtained from the fit to the HIIGs and the  $Z_p$  determined following the procedure described in the text.

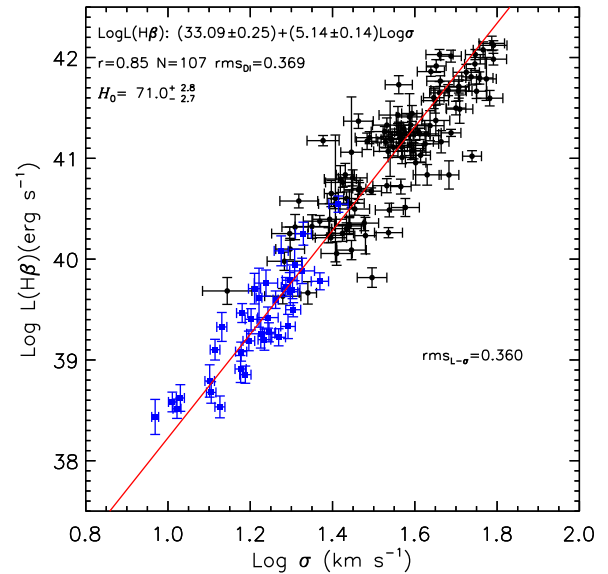
The evolution correction should be taken with care because, as we have already mentioned (see Section 4.1), even for pure starbursts the SB99 models provide only indicative values. Furthermore the observed EWs are contaminated by underlying populations of older stars and the nebular lines are a factor of 2 more attenuated than the continuum regions. These two effects act in the same direction and as a consequence the observed EWs are smaller than the intrinsic EW.

We have included in the estimate of the evolution correction the contribution of an underlying older stellar population and of the differential extinction. To this end we have computed models where the observed EW was increased by a factor that represents the change in the EW after the removal of the presumed older stellar population continuum and the correction due to the differential extinction. Telles & Melnick (in preparation) have estimated from SED fits to the observed spectrum of HIIGs that the contribution of the underlying older population is on average less than 50 per cent of the intrinsic continuum. Regarding the differential extinction effect, given that in general nebular extinction is small in our sample, we can assume that such effect will be smaller than that of the older population. We have therefore assumed for our evolution-corrected estimates that the intrinsic EW of the ionizing SSC is on average over the whole sample about 33 per cent larger than the observed EW. In all 16 models, increasing the EW of GHIIRs and HIIGs by 33 per cent results in a decrease of the slope of the distance indicator that translates in an increase of  $H_0$  of less than  $1 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

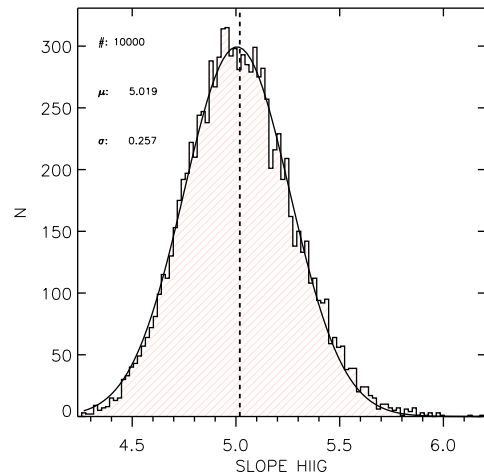
Figs 15 and 16 show the  $L - \sigma$  relation using the data for model  $N = 13$  before and after correcting for evolution.

#### 7.1.4 Robustness of the slope

Variations in the sample used to derive the  $L - \sigma$  relation can affect the values of the slope and  $Z_p$ . If by removing or replacing a few data points the slope and  $Z_p$  change, and therefore also does the value of  $H_0$ , then the  $L - \sigma$  relation is not robust.



**Figure 16.** The  $L - \sigma$  relation for the Chávez et al. (2014) sample using the velocity dispersions of H  $\beta$  and the luminosities corrected to the median of EW(H  $\beta$ ) as discussed in the text. The solid line is the fit to the HIIGs. The inset equation is the distance indicator where the slope is obtained from the fit to the HIIGs and the  $Z_p$  determined following the procedure described in the text.



**Figure 17.** Frequency distributions obtained using the bootstrap method for the slope of the HIIGs sample for model 13 of Table 6.

To address this issue, we applied a bootstrap sample test (Simpson & Mayer-Hasselwander 1986) selecting a subset of samples of our primary sample of HIIGs, by random resampling with replacement for 10 000 trials. The statistic of interest is calculated for each bootstrap sample and the frequency distribution of the statistic over all the bootstrap samples is taken to represent our best information on the probability distribution of the parameters, in this case the slope. For this test we choose the combination of parameters given by model 13.

The resulting frequency distribution is shown in Fig. 17. The bootstrap gives  $5.019 \pm 0.257$  while for the single solution we obtain  $5.00 \pm 0.14$ . Since the results of the bootstrap and of the single solution are similar, we can conclude that the slope of the  $L - \sigma$  relation is robust to random changes in the sample.

### 7.1.5 Sensitivity of $H_0$ to changes in the sample.

As already mentioned, the sub-sample S2 has an upper redshift cut-off of  $z = 0.1$  instead of the  $z = 0.16$  limit for our primary sample S1. Comparing S1 (in which the distances were computed using a flat cosmology with  $\Omega_m = 0.29$ ) with sample S2 (using the linear Hubble relation for the distances), Fig. 14 shows that using S2 reduces the value of  $H_0$  typically by about  $2 \text{ km s}^{-1} \text{ Mpc}^{-1}$  with a range from 1.1 to  $3.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ; the results for S2 give a slightly larger uncertainty than for S1, which is to be expected given the smaller size of the sample. The sensitivity of  $H_0$  to the actual value of  $\Omega_m$  is low, amounting in our case to an uncertainty of about 0.1 per cent in  $H_0$  for an uncertainty in  $\Omega_m$  of 0.02 (see Betoule et al. 2014). This, together with the larger uncertainty when using S2, drives us to use S1 with the distance determined using a flat cosmology with  $\Omega_m = 0.29$ .

Putting together these points with the aspects discussed in the previous sections led us to choose model 13 (S1-G03-Ch14- $\Omega_\Lambda = 0.71$ ) as our preferred one. Model 13 gives  $H_0$  values of  $74.6 \pm 2.9$  and  $71.0 \pm 2.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$  for the uncorrected and evolution-corrected cases, respectively.

It is important to notice that the  $H_0$  results for model 10 (S2-G03-Ch14-LR) are close to the results for model 13; they are  $H_0 = 74.3 \pm 3.1$  and  $70.9 \pm 3.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$  for the uncorrected and evolution-corrected cases, respectively. Since in model 10 we are using the linear Hubble relation (restricting the sample to objects with  $z < 0.1$ ), this reinforces the point that we are not biasing the results by using additional Cosmological parameters.

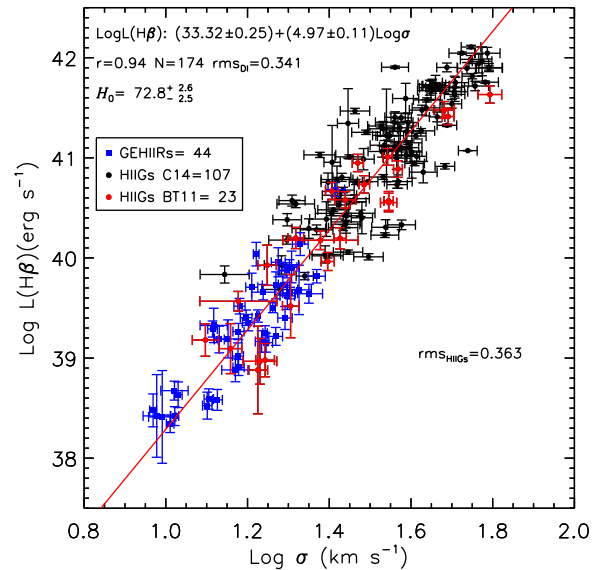
### 7.1.6 Additional checks

Following Melnick et al. (2017), we have also analysed the effect of expanding the sample by incorporating the data of HIIGs published in Bordalo & Telles (2011) and GHIIRs from Chávez et al. (2012). The resulting sample includes a total of 130 HIIGs and 44 GHIIRs. To homogenize the enlarged sample, we were forced to use the SDSS photometry for the 107 HIIGs (Chávez et al. 2014) in order to make it compatible with Bordalo & Telles (2011). Extinction correction was performed using the Gordon et al. (2003) law and the HIIGs luminosities were computed using a flat cosmology with  $\Omega_\Lambda = 0.71$ . The  $L - \sigma$  relation, using the data of Chávez et al. (2014) plus Bordalo & Telles (2011), can be seen in Fig. 18. Using this relation as the distance estimator, we obtain a value of  $H_0 = 72.8 \pm 2.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$  that should be compared with the result of  $H_0 = 70.0 \pm 2.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$  obtained for model  $N = 15$  in Table 6.

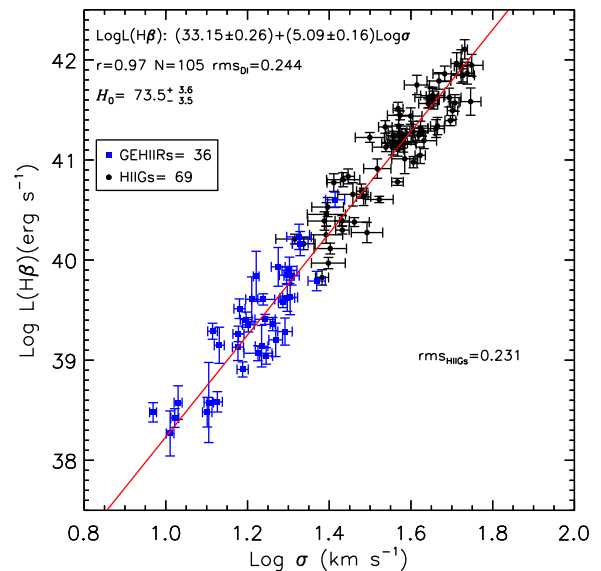
A final check was done by including the more restrictive sample of HIIGs from Chávez et al. (2012) where galaxies with asymmetric or multiple line profiles in either  $H\beta$  or  $[O III] 5007 \text{ \AA}$  and galaxies with large photometric errors or uncertain extinction corrections were removed, thus reducing the sample to 69 HIIGs. We computed  $H_0$  using these 69 galaxies from Chávez et al. (2012) and our new anchor sample of 36 GHIIRs as shown in Fig. 19) and obtain  $H_0 = 73.5 \pm 3.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , in good agreement with the value of  $H_0 = 74.6 \pm 2.9$  from model 13 in Table 6.

## 7.2 Summary of systematics effects

From the results of the different models in Tables 6 and 7 and the discussion in this section, we can infer that the systematic effects cause changes in the  $L - \sigma$  relation that translate into r.m.s. variations in the value of  $H_0$  of  $1.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $2.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$



**Figure 18.**  $L - \sigma$  relation for Chávez et al. (2014) and Bordalo & Telles (2011) combined samples. The solid line is the fit to the HIIGs. The inset equation is the distance indicator where the slope is obtained from the fit to the HIIGs and the  $Z_p$  determined following the procedure described in the text.



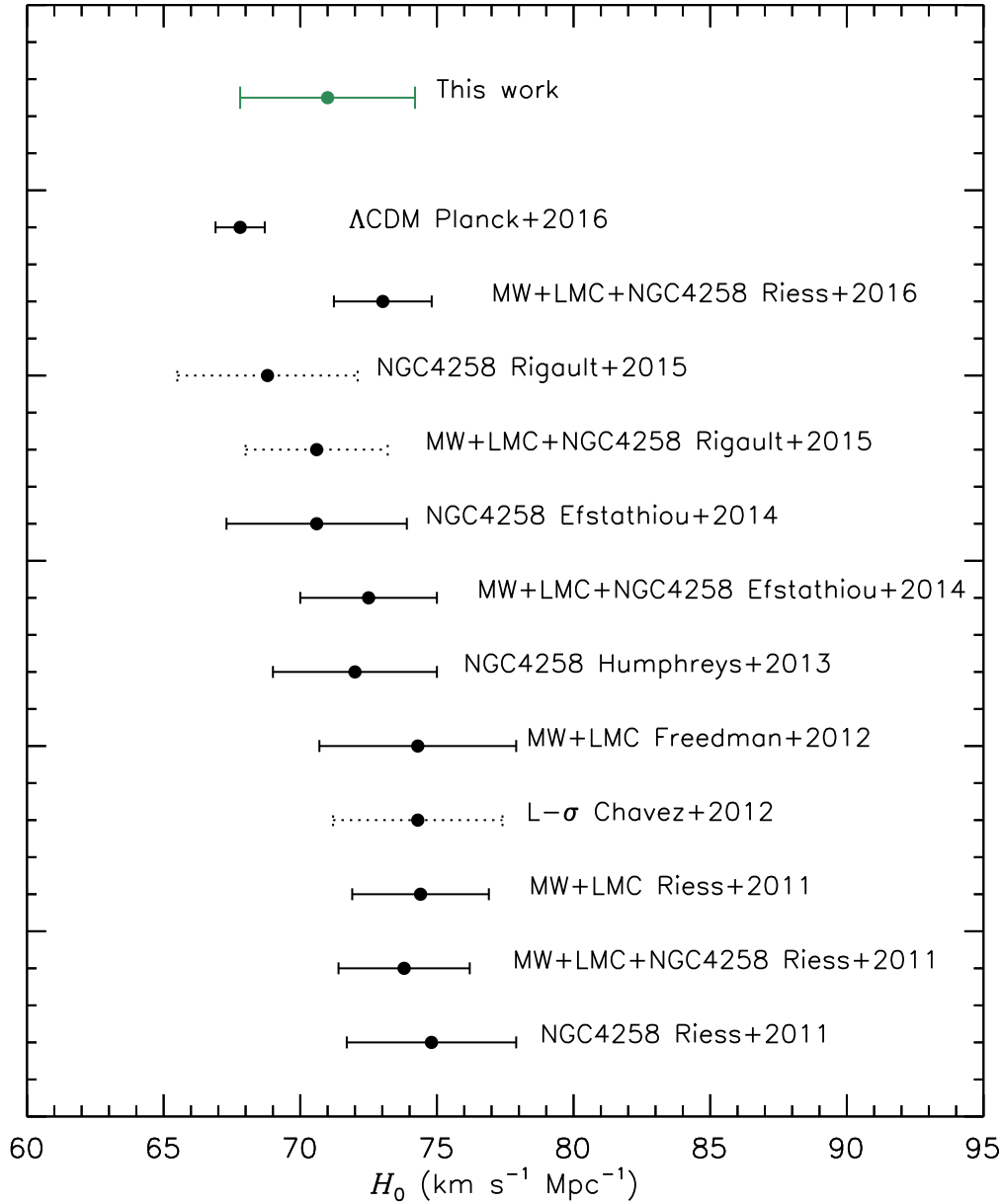
**Figure 19.** The  $L(H\beta) - \sigma$  relation and  $H_0$  determination using the sample of 69 HIIGs of Chávez et al. (2012). The solid line is the fit to the HIIGs. The inset equation is the distance indicator where the slope is obtained from the fit to the HIIGs and the  $Z_p$  determined following the procedure described in the text.

for the solutions with and without evolution correction, respectively, and of  $2.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$  for the 32 solutions.

## 8 COMPARISON WITH SNIa AND Planck CMB

The direct determination of the value of  $H_0$  derived from the HST Key Project and Carnegie Hubble Program (Freedman et al. 2001, 2012) reached an accuracy of 3 per cent reporting values of  $H_0 = 73.8 \pm 2.4$  and  $H_0 = 74.3 \pm 2.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , respectively. Humphreys et al. (2013), using the megamaser galaxy NGC 4258, estimated  $H_0 = 72.7 \pm 2.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . These





**Figure 20.** Most recent estimates of  $H_0$  from the literature. The top line shows our evolution-corrected result. Dotted error bars indicate only random errors while continuous bars indicate random plus systematic errors. See discussion in Section 8.

determinations, together with the estimate by Riess et al. (2011) of  $H_0 = 73.8 \pm 2.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , showed a  $2.5\sigma$  tension with the Planck Collaboration XVI (2014) derived value of  $H_0$ . Efstathiou (2014) re-analysed Riess et al. (2011) Cepheid data, found that a change in the colour cut removes the problem and concluded that there is no evidence for a need to postulate new physics.

Rigault et al. (2015), using the Nearby Supernova Factory sample, found that SNIa are dimmer in star forming than in passive environments. As the majority of Cepheid-based distances are for late type and star-forming galaxies, this can lead to a bias in cosmological measurements. Correcting for this bias, they find a value of  $H_0 = 70.6 \pm 2.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$  when using the Large Magellanic Cloud distance, Milky Way parallaxes, and the NGC 4258 measurements as the Cepheid zero-point, and  $H_0 = 68.8 \pm 3.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$  when using only NGC 4258. This last value is within

$1\sigma$  of the Planck collaboration result. It has to be mentioned that the Rigault et al. (2015) result was reanalyzed by Jones, Riess & Scolnic (2015), who found no evidence that SNIa in star-forming environments are significantly fainter than in locally passive environments.

Riess et al. (2016) presented a comprehensive and thorough analysis of an enlarged sample of SNIa and improved distances to the anchor sample. This most recent result from Riess et al. (2016) has reinstated the tension, now at the  $3.1\sigma$  level, between the value obtained by Planck Collaboration XIII (2016) of  $H_0 = 67.8 \pm 0.9 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and Riess et al. (2016) of  $H_0 = 73.2 \pm 1.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

Our main result incorporating the evolution correction, is  $H_0 = 71.0 \pm 3.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (random+systematic), a value that is half way between the Planck Collaboration XIII (2016) estimate and Riess et al. (2016) determination.

## 9 CONCLUSIONS

We have used the  $L - \sigma$  distance indicator to derive an independent local value of the Hubble parameter  $H_0$ . To this end we have combined new data for 36 GHIIRs in 13 galaxies of the ‘anchor sample’ that includes the megamaser galaxy NGC 4258, with the data for 107 HIIGs from Chávez et al. (2014). Our new data are the result of the first 4 yr of observation of our primary sample of 130 GHIIRs in 73 galaxies with Cepheid distances.

The determination of  $H_0$  is a rather delicate undertaking and that is reflected in the range of values that we obtain for it. Fig. 14 shows the values obtained with different combinations of parameters such as redshift, extinction laws, luminosities derived using either the linear relation for the distance or cosmological parameters, the photometry derived from SDSS or Chávez et al. (2014) and the correction using a second parameter related to the age of the burst as parametrized by the EW( $H\beta$ ).

The results from stellar population synthesis models, such as SB99, allow to estimate a theoretical evolutionary correction for all GHIIRs and HIIGs. One major problem with this approach is that different sets of isochrones give somewhat different correction coefficients, and also that the observed EW( $H\beta$ ) is affected by the presence of an underlying older population and differential extinction in a degree that is not simple to estimate. Furthermore, present-day evolutionary models do not include the effect of massive binaries or the photoionization is not fully modelled. All the aforementioned effects add to the uncertainty of the result.

Using the SDSS photometry gives values of  $H_0$  slightly lower than those calculated using the photometry of Chávez et al. (2014). This is probably related to the fact that the small aperture of the SDSS spectroscopy underestimates the emission line fluxes in the nearest objects, that happen to be also the lowest luminosity ones. The result is a steeper slope in the  $L - \sigma$  relation leading to a smaller value of  $H_0$ .

We estimated the effect of varying the extinction law on the derived value of  $H_0$ . For this we have used two different extinction laws: Calzetti et al. (2000), which has been widely used for starburst galaxies, and the one for 30-Doradus given by Gordon et al. (2003). Using the extinction law from Calzetti et al. (2000) tends to produce values of  $H_0$  slightly larger than when using the extinction law from Gordon et al. (2003) but with a systematic difference inside the  $H_0$  errors. Given that Gordon extinction law is derived from the prototypical massive star-forming region 30-Doradus, while Calzetti extinction law is derived from global properties of mostly massive star-forming galaxies and therefore includes aspects related to the parent galaxy, we chose to use the former.

A very small change in the Hubble constant is obtained when we take into account the effect of the underlying absorptions on Balmer emission lines. This effect is larger for the high-order Balmer lines and  $H\beta$  is only weakly affected; moreover, the selection criterion with EW( $H\beta$ ) > 50 Å minimizes this effect.

We also investigated the stability of the solutions using an expanded sample that included the data from Bordalo & Telles (2011) and GHIIRs from Chávez et al. (2012) leading to a total of 137 HIIGs and 45 giant GHIIRs. Using in this case SDSS photometry, we obtain a value of  $H_0 = 72.8 \pm 2.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

From our determinations of  $H_0$  we estimate that the systematic errors are  $2.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$  including the error associated with the evolution correction; the way we propagate errors is not completely rigorous, however we consider it is an appropriate statistical tool to investigate the systematic effects of the  $L - \sigma$  relation to determine distances and  $H_0$ .

In sum our preferred model incorporates the reddening law from Gordon et al. (2003),  $H\beta$  photometry from Chávez et al. (2014) and luminosity distances with complete cosmology using the whole sample S1 (for full details, see Section 7). Under these conditions we obtain  $H_0 = 74.52 \pm 2.85 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , almost identical to the value reported by Chávez et al. (2012) of  $H_0 = 74.3 \pm 3.1$  and consistent within errors with the new results from SNIa (Riess et al. 2016) of  $H_0 = 73.24 \pm 1.74 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (see model 13 marked with an asterisk in Table 6).

Including an evolution correction leads to our best estimate,  $H_0 = 71.0 \pm 2.8(\text{random}) \pm 2.1(\text{systematic}) \text{ km s}^{-1} \text{ Mpc}^{-1}$  (see model 13 marked with an asterisk in Table 7), a value that is between the two best results so far, i.e. Planck Collaboration XIII (2016) estimate of  $H_0 = 67.8 \pm 0.9 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , and Riess et al. (2016) determination of  $H_0 = 73.2 \pm 1.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

Regarding future improvement of the  $L - \sigma$  distance indicator, our first priority is to increase the anchor sample from the present 13 galaxies to the 43 galaxies of our primary sample. Much of the error in the value of  $H_0$  is related to the uncertainty in the value of the slope of the  $L - \sigma$  relation, thus it will be important to include low luminosity HIIG, i.e. those with luminosities similar to the luminosity of GHIIR, and also GHIIR in more distant galaxies. The addition of a second parameter in the  $L - \sigma$  relation can lead to important improvements in the distance indicator. In particular, the size of the star-forming region has proven to be a real possibility potentially reducing the scatter by about 40 per cent. We also plan to expand the analysis to include TRGB distances to the galaxies in the primary sample. Finally the evolution correction needs a quantitative approach that takes into account the underlying stellar continuum and differential reddening effect in the measurement of the EW of the emission lines.

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## APPENDIX: RESULTS FOR INDIVIDUAL OBJECTS

In this Appendix we show for each GHIIR: On the left-hand panel the slit positions over the  $H\alpha$  image obtained from NASA/IPAC Extragalactic Data base (NED). The wider slit oriented E-W corresponds to the low dispersion spectrophotometry observations. The much narrower slit corresponds to the high dispersion spectroscopy.

The central panel shows the high-resolution  $H\alpha$  profile and two different fits: Gaussian (blue dashed line) and Gauss–Hermite (continuous red). The residuals from the fits are shown in the lower panel with the same colour code. The inset shows the results of a Monte Carlo simulation to estimate the errors in the parameters of the best fit.

The right-hand panel shows the low-resolution spectrum and the name of the GHIIR.

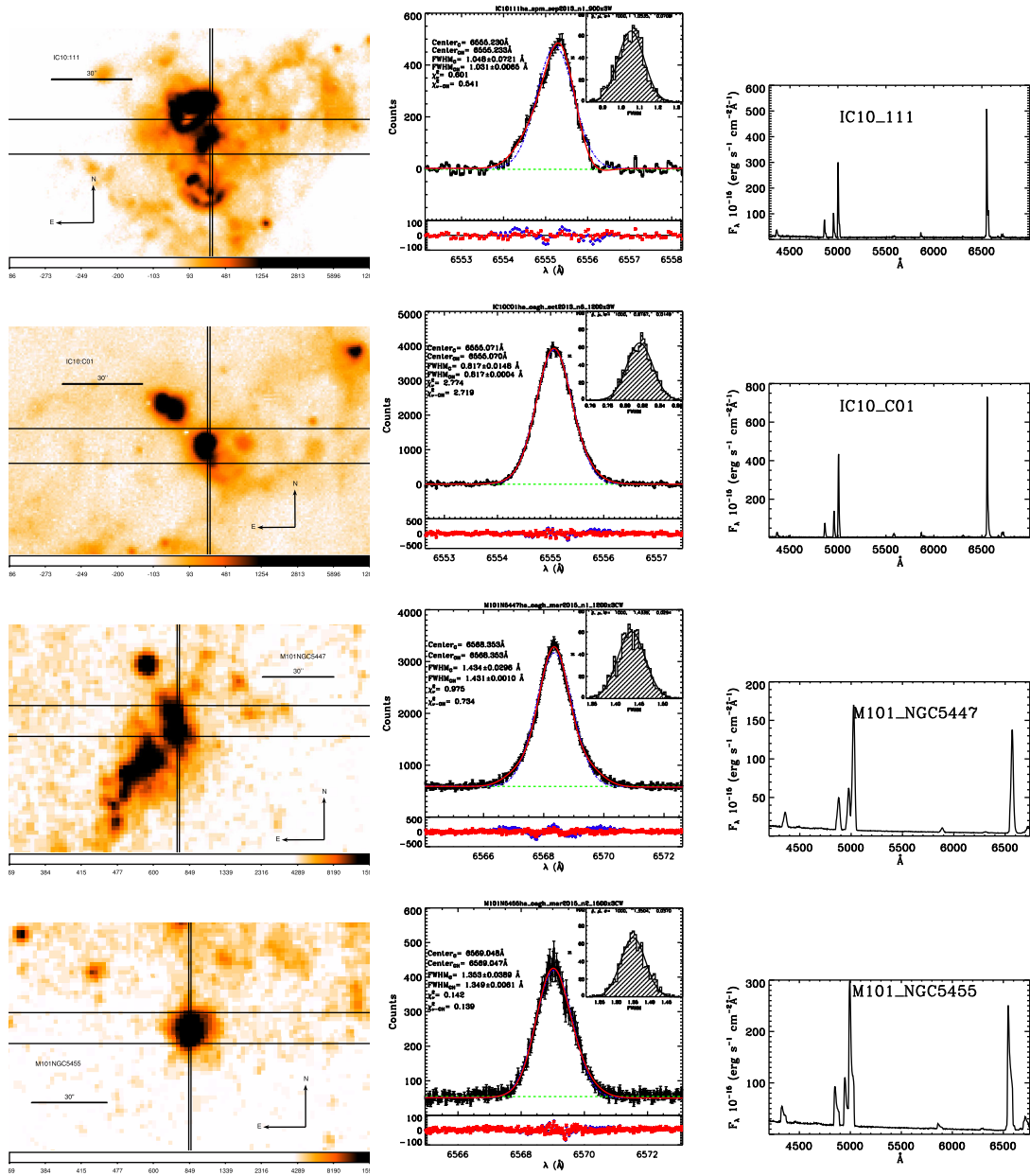


Figure A1. H $\alpha$  image obtained from NASA/IPAC Extragalactic Data base (NED), high-resolution profile for the GHIIR and low-resolution spectrum.

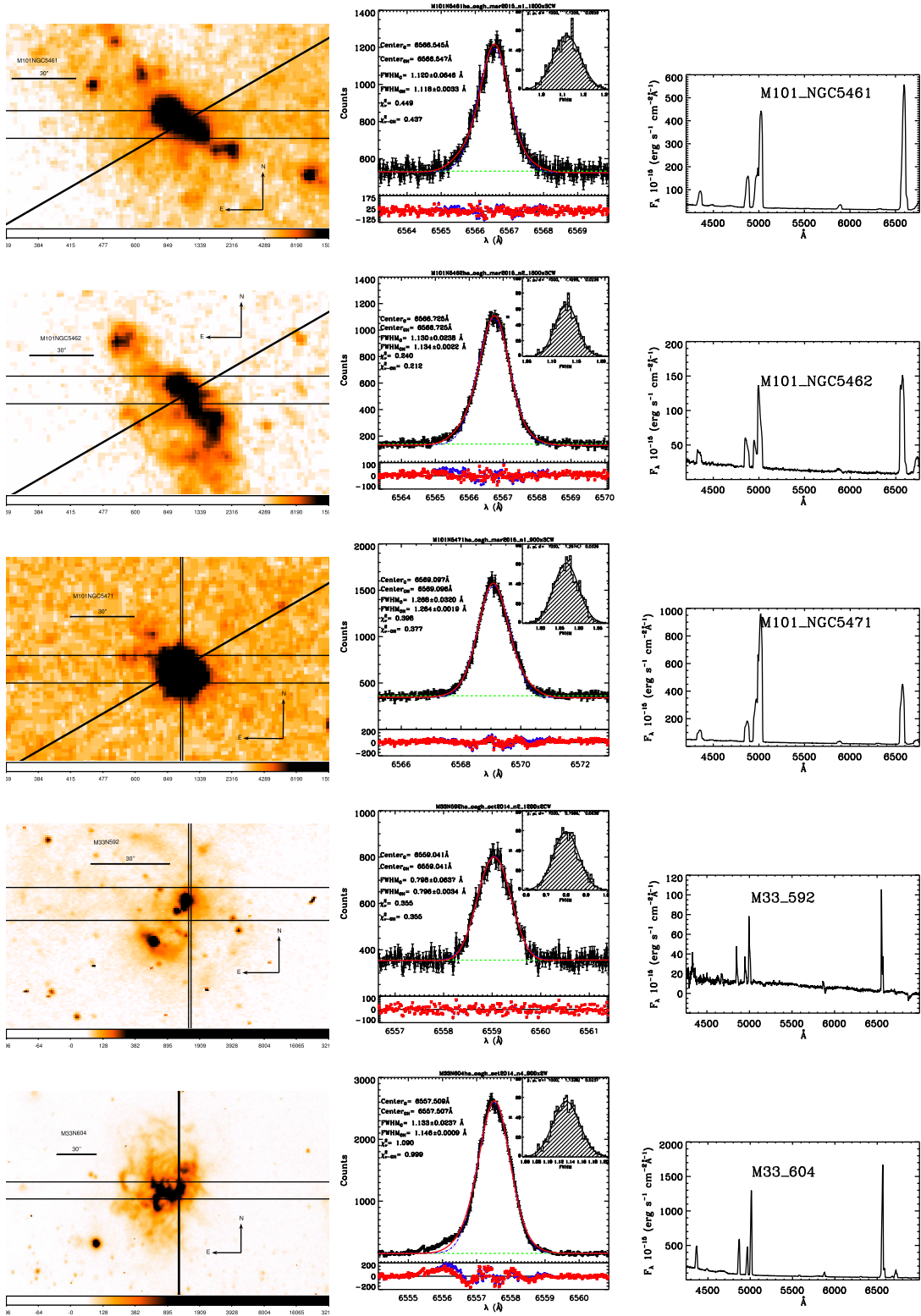


Figure A1 – continued

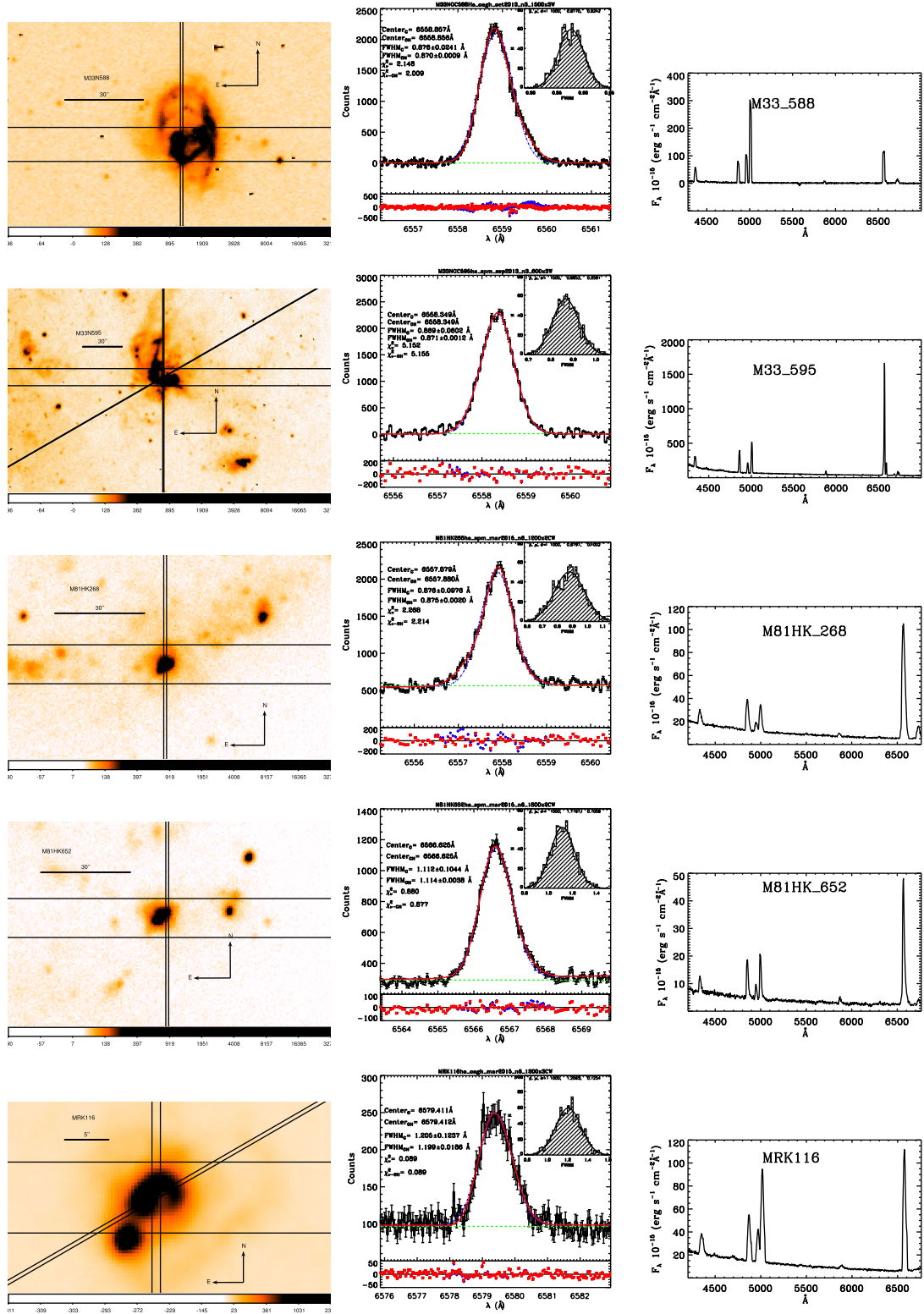


Figure A1 – continued

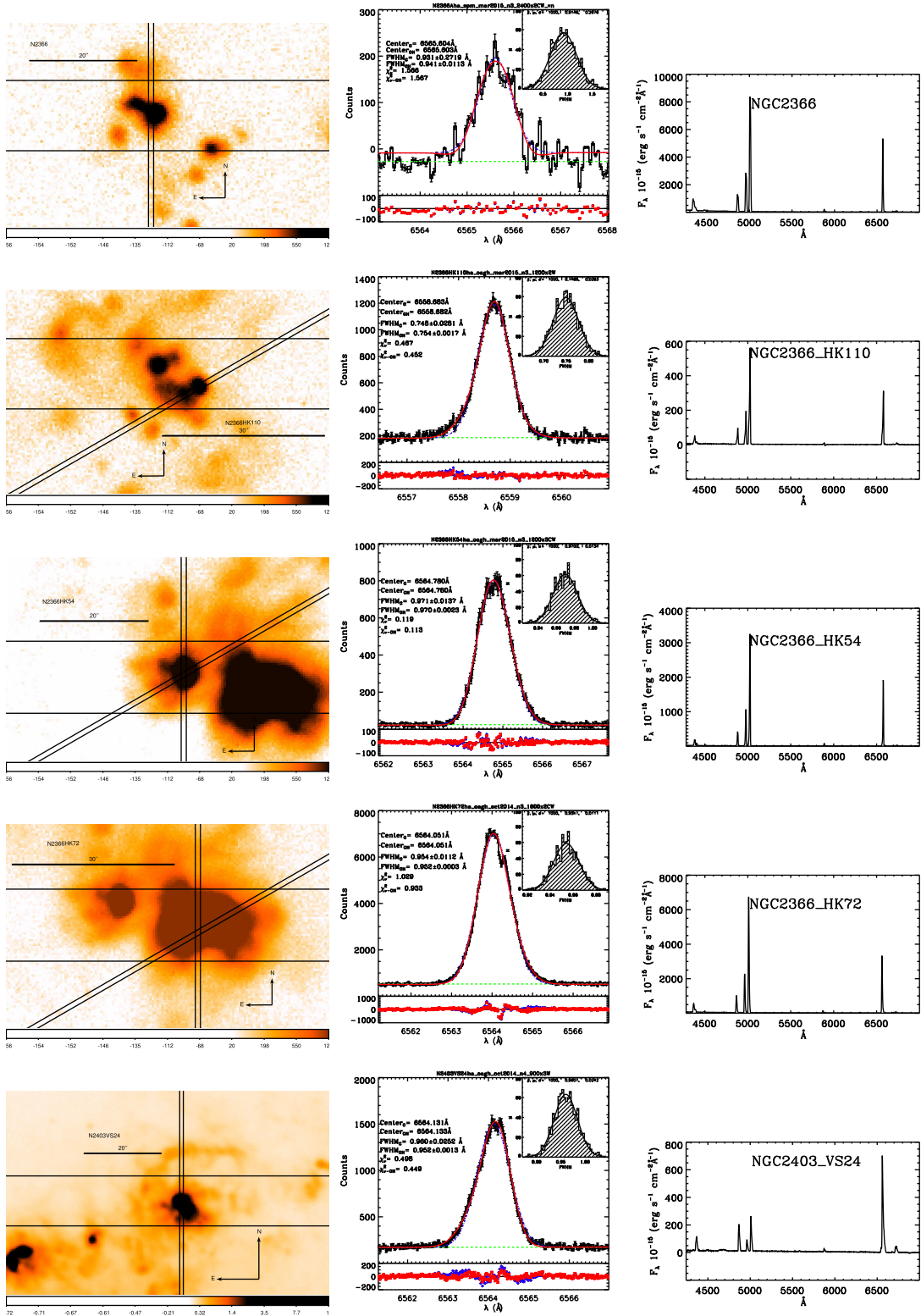


Figure A1 – continued

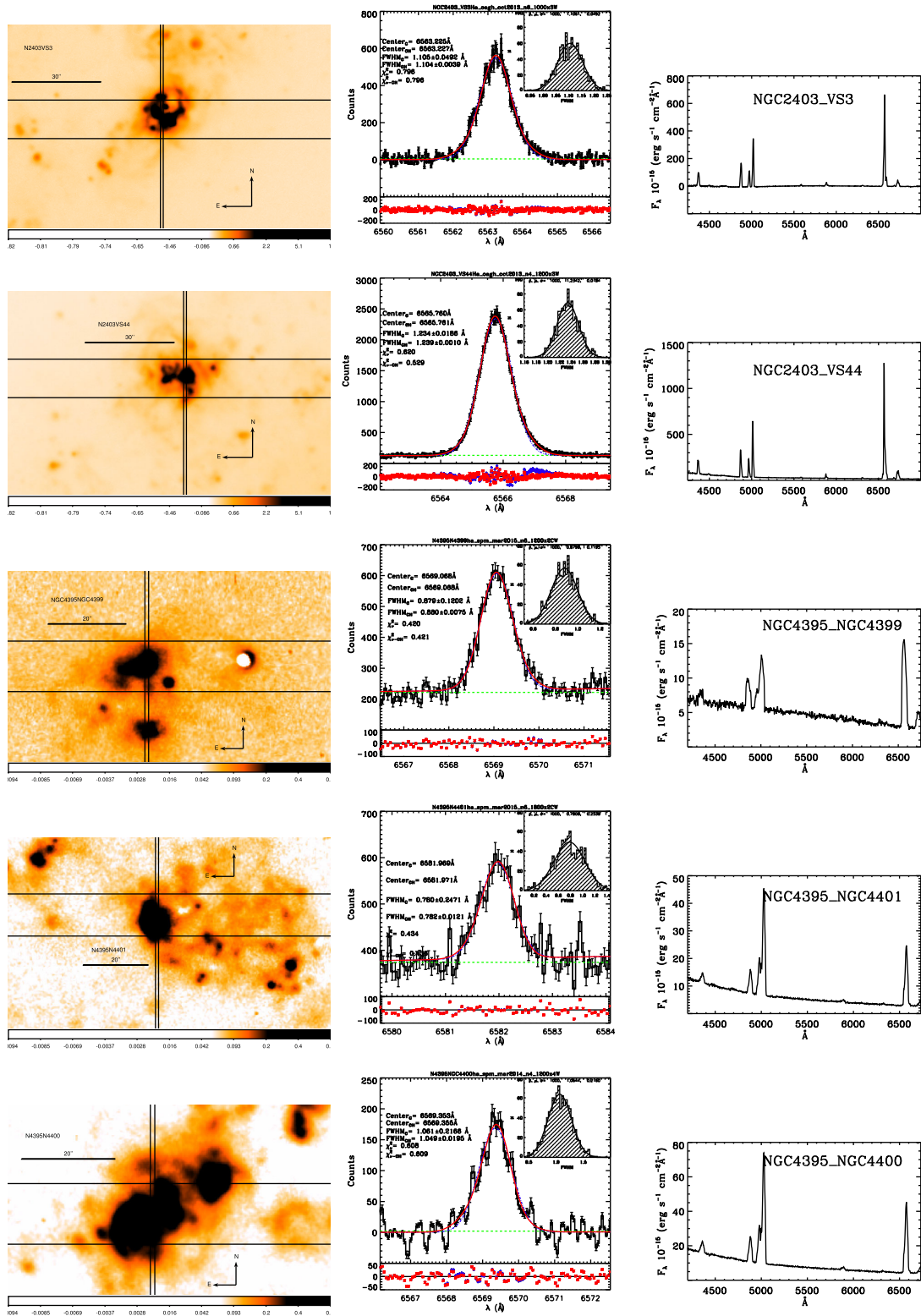


Figure A1 – continued



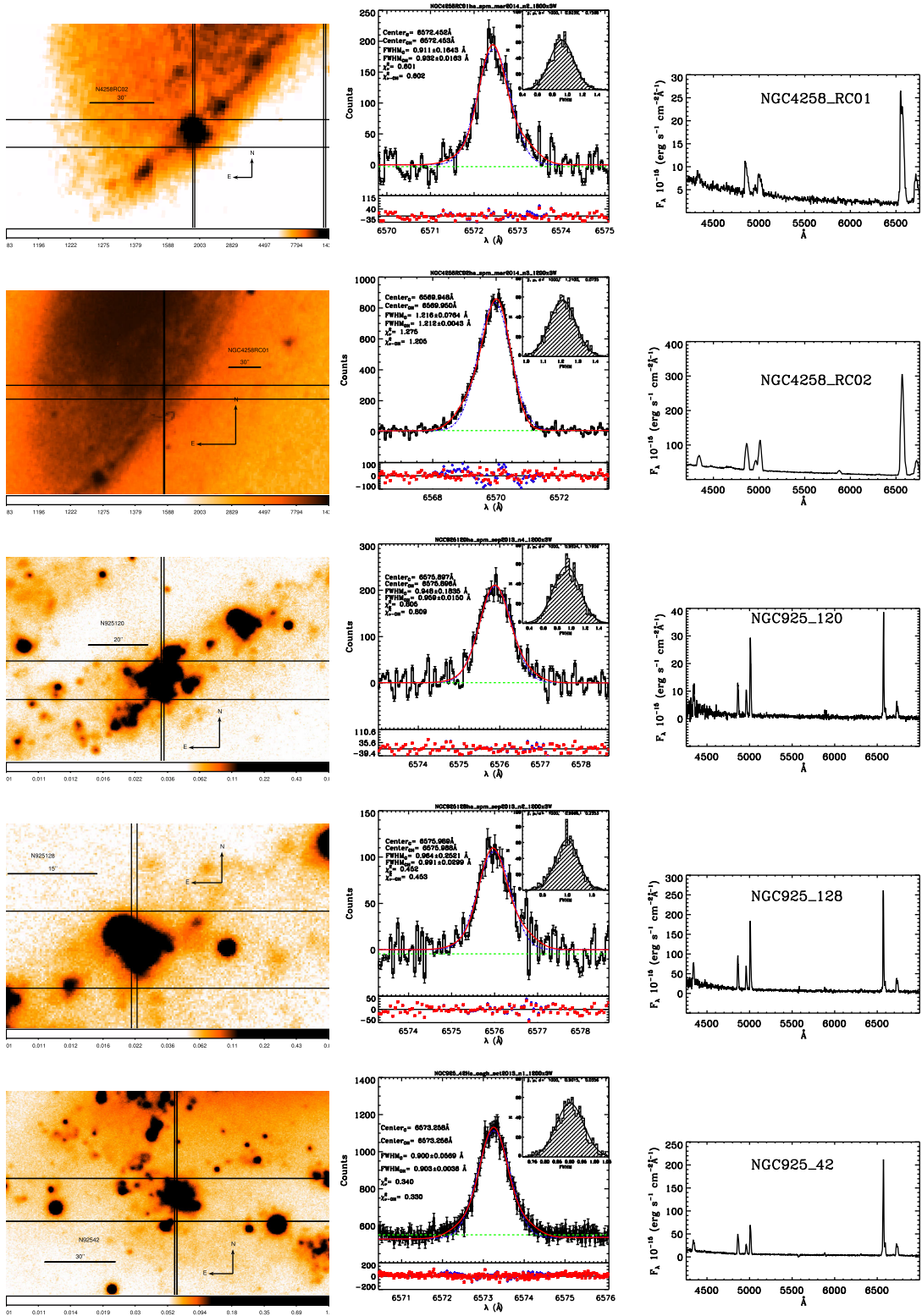


Figure A1 – continued

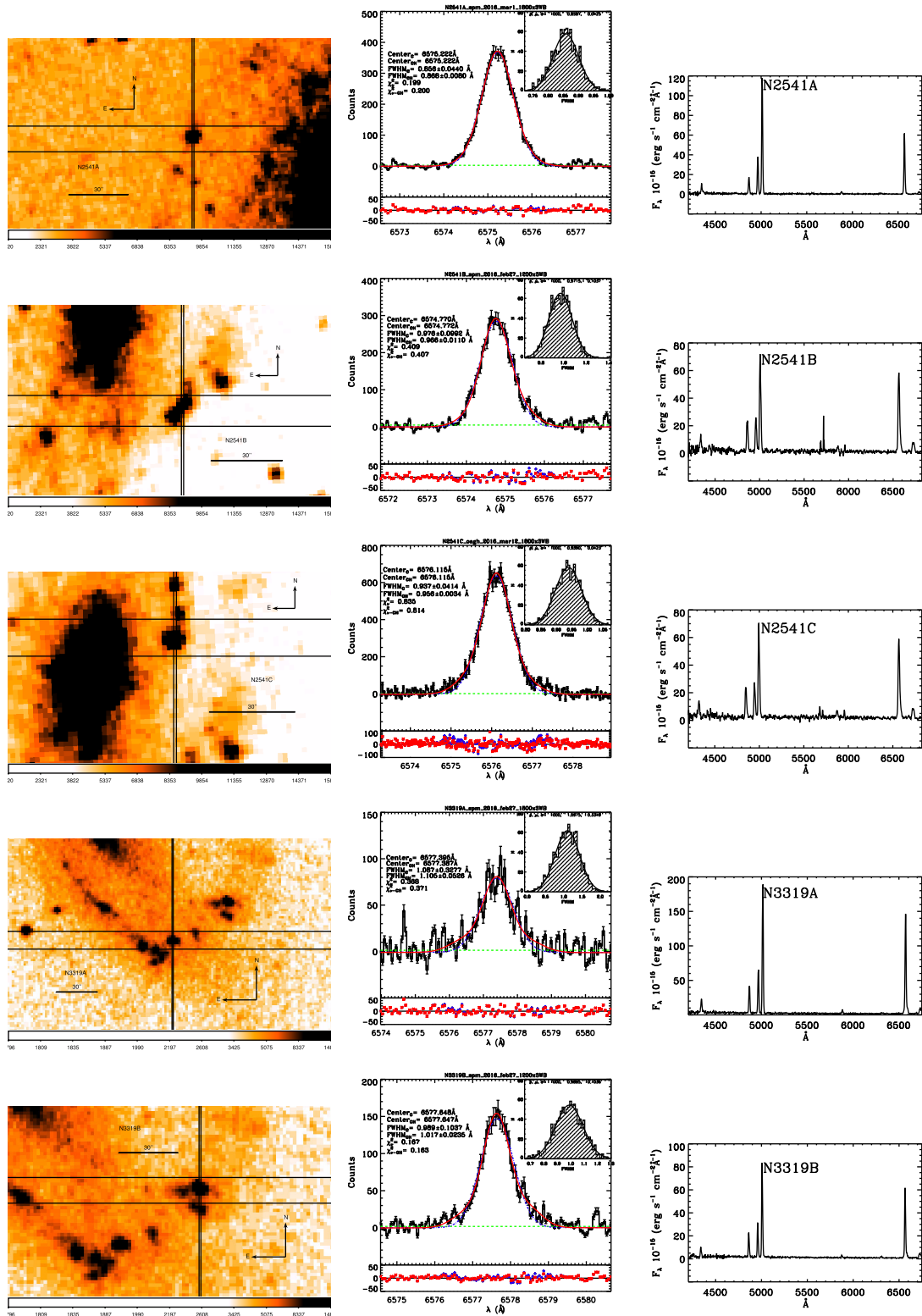


Figure A1 – continued

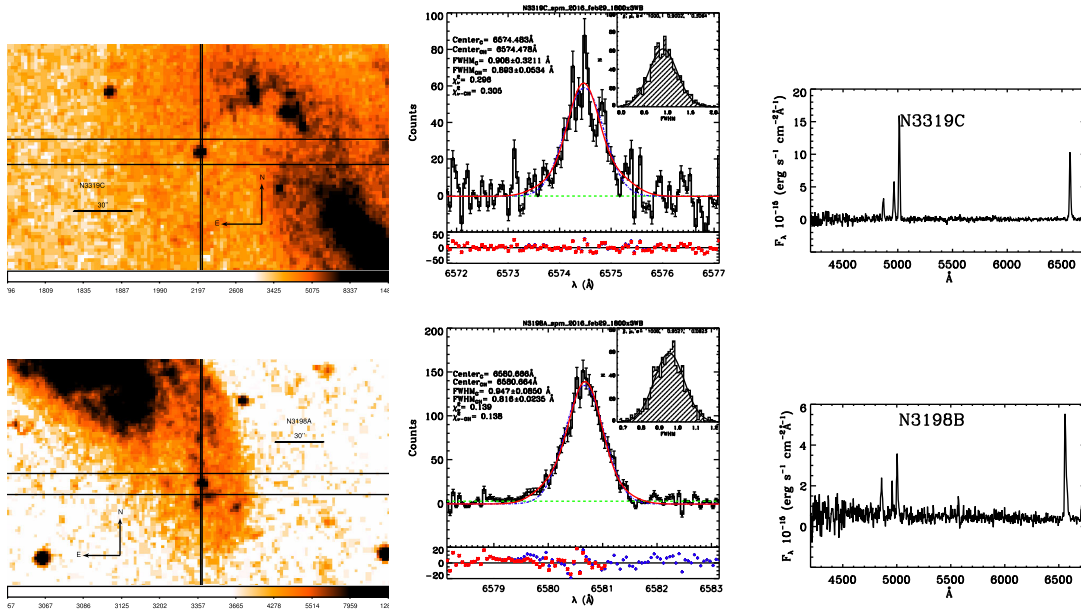


Figure A1 – *continued*

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