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30 DORADUS: FROM HERE TO ETERNITY

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RESUMEN

Este trabajo presenta un viaje hacia atrás en el tiempo, usando como vehículo únicamente la espectroscopía de regiones de formación estelar violenta, partiendo desde regiones H II gigantes cercanas como 30 Dor en la Nube Mayor de Magallanes y NGC 604 en M 33, pasando por galaxias H II, a corrimientos al rojo intermedios y altos ($z > 0.1$ a $z \sim 3$), y alcanzando los dominios de la nucleosíntesis del "big bang" a $z > 1,000,000$. En el viaje se contempla también la perspectiva promisoria que vislumbramos de estudiar, en un futuro cercano, zonas de formación estelar violenta sumergidas en polvo, hasta $z \sim 10 - 20$.

ABSTRACT

This paper represents a journey with look-back time, using the interplay between clusters of hot young massive stars and the interstellar medium, by means of spectroscopy of violent star-forming regions from the nearby giant H II regions 30 Dor in the LMC and NGC 604 in M 33, to star-forming galaxies at intermediate and high redshifts ($z > 0.1$ to $z \sim 3$), reaching the big bang nucleosynthesis realm at $z > 1,000,000$. Included in the journey are also the promising prospects for the near future, for studying similar objects enshrouded in dust up to $z \sim 10 - 20$.

Key words: **COSMOLOGY: EARLY UNIVERSE — GALAXIES: IRREGULAR — GALAXIES: STARBURST — ISM: ABUNDANCES — ISM: HII REGIONS**

1. INTRODUCTION

30 Doradus, like NGC 604, represent prototypes of the kind of object sometimes called Giant Extragalactic H II region (GEHR). Their properties have been discussed in this Conference (e.g., Selman et al. 1999). They represent the closest examples of complex regions forming stars in large quantities and as such can be studied in great detail. They display characteristic features that appear also in larger samples of similar objects discovered at higher redshifts, that can be studied spectroscopically thanks to their strong narrow line emission. These are the H II Galaxies (HIIG) that are star-forming gas-rich dwarf galaxies in which giant bursts of star formation dominate the spectrum. A typical optical spectrum is shown in Fig. 1. Strong narrow emission lines of the H Balmer series, plus forbidden lines of ions such as [O II], [O III], [N II], [Ne III], [Ar II], [S II] and [S III], and permitted He I, sometimes He II, and WR features are characteristic of their spectrum. Analysis of their emission lines indicates that they are normally under-abundant in heavy elements with respect to the Sun and photoionized by normal hot young stars. HIIG appear to undergo discrete intense bursts of star formation, separated by long quiescent periods. Their strong narrow emission lines indicate ages in the stellar population of less than 10 Myr. They are probably the youngest galaxies that can be studied in any detail (Terlevich

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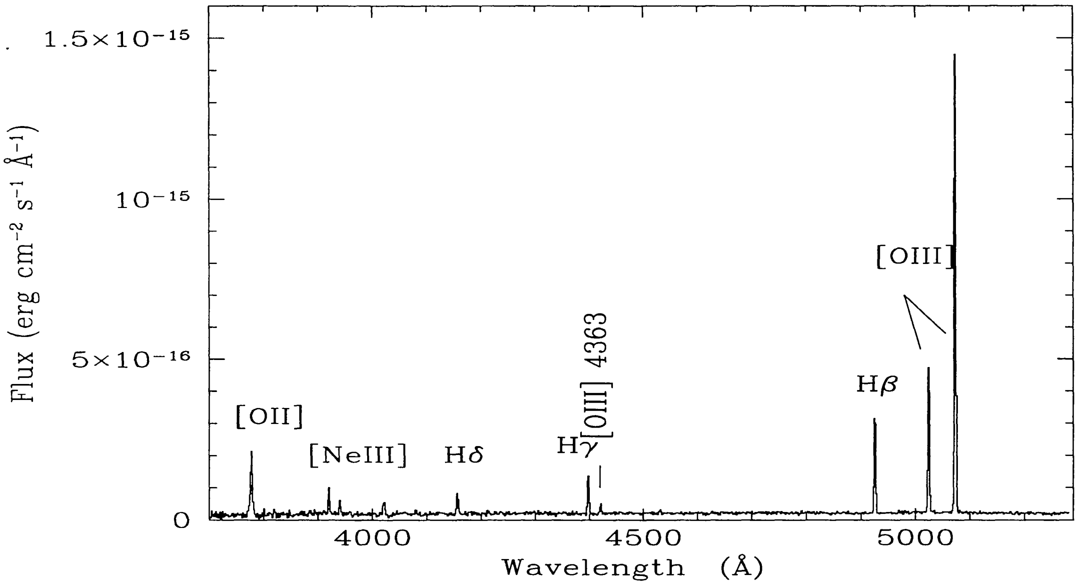

Fig. 1. Optical spectrum of a typical GEHR at intermediate redshift. Prominent emission lines are shown.

et al. 1991, Melnick 1992). The study of these HIIG where the interstellar matter has very low heavy element abundance has a direct impact on a variety of problems such as the formation and evolution of galaxies and primordial or big bang nucleosynthesis.

2. $z = 0$

GEHR are known to have an excellent correlation between their intrinsic luminosities and the width of their emission lines, the $\sigma - L(\mathrm{H}\beta)$ relation (Terlevich & Melnick 1981). Melnick, Terlevich, & Moles (1988) have shown that the relation found for GEHR holds also for HIIG. The scatter in the $\sigma - L(\mathrm{H}\beta)$ relation (and specially if corrected for a metallicity effect) is small enough to allow this correlation to be used to determine accurate distances to GEHR and HIIG.

The $\sigma - L(\mathrm{H}\beta)$ relation as a distance estimator has an r.m.s. error larger than that of the $D_n - \sigma$ relation for elliptical galaxies or the Fisher-Tully relation for spirals, but has the advantage that at first order is not affected by evolution of the stellar population with redshift. This is a problem that has rendered useless the other methods when working with samples with substantial look-back time. This distance estimator is unaffected because the luminosity emitted per mass-unit by the stellar population in these star-forming galaxies does not change with redshift as, unlike ellipticals or spirals, the stellar population in HIIG does not get systematically younger with increasing look-back time. The stars in HIIG are as young as they can be independently of the redshift. A second serious problem in the distance estimator for ellipticals or spirals is the uncertainty associated with the reddening correction. In the case of the HIIG this is not a serious problem because the reddening can be directly measured from the observed Balmer decrement.

Thus the $\sigma - L(\mathrm{H}\beta)$ relation in GEHR and HIIG provides a distance estimator that has calibrators in the Local Group (Melnick, Terlevich, & Moles 1988), i.e., the nearby GEHR for which independent distance determination of the parent galaxies is available. Different authors have found discrepancies in the slope of the $\sigma - L(\mathrm{H}\beta)$ relation (Roy, Arsenault, & Joncas 1986; Hippelein 1986; Melnick et al. 1987). The large intensity of their emission lines, allows very good and reliable determination of the velocity dispersion of the gas in these star-forming complexes. This suggests that the discrepancies arise from the lack of reliable photometry of these large regions. The main problem is that all the available line photometry was done either with photographic plates or using aperture photometry with phototubes. The calibration therefore can be improved thanks to the availability of modern linear panoramic CCD detectors and almost simultaneous Hα and Hβ photometry that allow good reddening corrections (Bosch et al. 1999, in preparation).

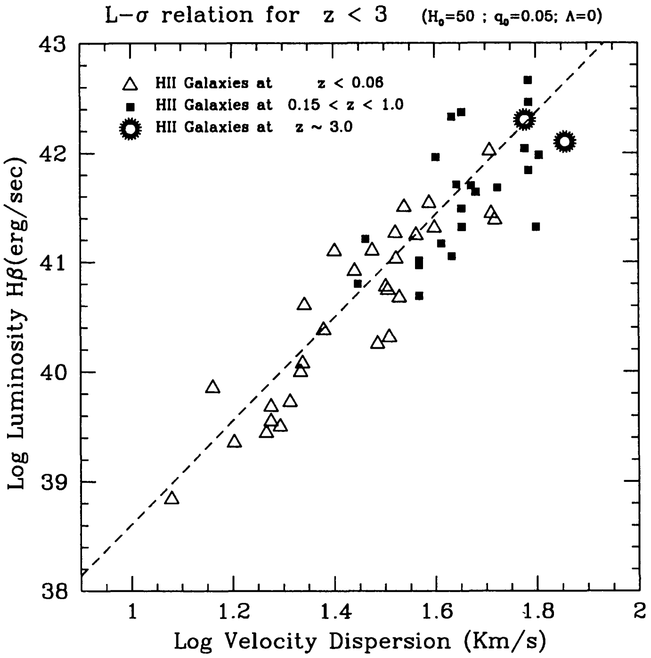

Fig. 2. $\log L(\mathrm{H}\beta)$ vs. σ using nearby H II regions and HIIG (Melnick et al. 1988), HIIG at $z \sim 1$ (Koo et al. 1995) and at $z \sim 3$ (Pettini et al. 1998).

3. $z = 0.1 - 1$

Deep optical galaxy counts have shown a strong excess of faint, blue galaxies (Tyson 1988) absent; however, in the near-infrared K-band (Gardner, Cowie, & Wainscoat 1993). Surprisingly, the deepest redshift surveys at $B \simeq 24$ find that the bulk of this faint population is at intermediate redshifts, remarkably local ($z < 0.6$; see, e.g., Broadhurst, Ellis, & Shanks 1988; Colless et al. 1990; Lilly, Cowie, & Gardner 1991). High-resolution spectra (*FWHM*= $8\,\mathrm{km\,s^{-1}}$) with the Keck telescope (Koo et al. 1995) of a sample of 17 very faint blue galaxies ($B = 20 - 23$) and at intermediate $z = 0.1 - 0.7$, have been obtained recently. The intrinsic colours (Koo et al. 1994) and very strong and narrow emission lines indicate that most of these objects are dominated by a young burst of star formation. All exhibit narrow line widths, $\sigma = 28 - 157\,\mathrm{km\,s^{-1}}$ rather than the $200\,\mathrm{km\,s^{-1}}$ typical of galaxies of similar luminosities. Their luminosity and line width range are also similar to those of nearby HIIG. All this supports the identification of at least a substantial fraction of faint blue galaxies as distant HIIG. The galaxies with $\sigma < 65\,\mathrm{km\,s^{-1}}$ follow the same correlations (σ, B, $L(\mathrm{H}\beta)$) as local HIIG. This distance estimator can be used up to at least $z \sim 1$ observing with 4-m class telescopes.

These galaxies, also called compact narrow emission line galaxies (CNELG), are only 20% of the population at intermediate redshifts; still, the star formation rate (SFR) derived from the intensity of their emission lines accounts for 50% of the SFR of the Universe at these epochs (Phillips et al. 1997). This result, coupled with the number evolution of these sources, probably provides the key to the global density evolution of the SFR in the Universe (Madau et al. 1996).

4. $z \sim 3$

A small fraction of faint blue galaxies ($\sim 3\%$) are found at much higher redshifts; some at $z > 3$ and even up to $z \sim 5$ (Lowenthal et al. 1997; Steidel, Pettini & Hamilton 1995). Fig. 2 shows the $\sigma - L$ correlation, using nearby H II regions and H II galaxies (Melnick et al. 1988), HIIG at 0.15< $z < 1$ from Koo et al. (1995), and at $z \sim 3$ from Pettini et al. (1998). The tightness of the correlation up to redshifts of about 3 is striking.

Their luminosities are similar to the brightest nearby HIIG, i.e., $L(\mathrm{H}\beta) \sim 10^{42}$ $\mathrm{erg\,s^{-1}}$($L_{\mathrm{bol}} \sim 3 \times 10^{10} L_{\odot}$).

Still, the mean equivalent width of H$\beta \sim 25$ Å for objects at $z > 1$ (Lowenthal et al. 1997) —compared to ~ 100 Å for the local ones (Terlevich et al. 1991)— makes it clear that the very youngest population is missing and special searching techniques should be implemented.

We have investigated with numerical simulations this possibility, and reached the clear conclusion, using the properties of the numerous star-forming galaxies at faint magnitudes, that deep wide field slitless spectroscopy surveys hold the promise of providing thousands of redshifts per night down to $I = 24$ using 4-m class telescopes.

Such a targeted survey will produce the strong emission line candidates for detailed work with 8-m class telescopes allowing accurate nebular abundance determinations well outside the Local Supercluster and over substantial look-back times.

The discovery of HIIG at high redshift provides a unique opportunity for mapping the Hubble flow up to relatively large z, thus providing a good indication of the rate of expansion in distant enough regions where the anisotropies of the Hubble flow do not introduce an appreciable scatter. It may prove to be the best method to measure H_0 and q_0.

5. $z \sim 10$

The results presented in §§ 3 and 4 are all based on optical searches for blue systems and colour dropouts. Detailed follow-up of these systems is possible now thanks to the availability of 8-m class optical and near-infrared telescopes in both hemispheres (Keck and VLT, and soon GEMINI).

A puzzling result so far has been that, in contrast to the high-surface density of faint blue galaxies, no high redshift dusty starburst —similar to the Luminous and Ultraluminous *IRAS* galaxies— has been detected in optical searches.

These are dusty star-forming galaxies with luminosities similar or even higher than QSOs, i.e., with $L_{\rm bol} > 10^{11} L_{\odot}$ and in some cases reaching almost $10^{13} L_{\odot}$.

Most IR luminous star-forming galaxies were discovered in large numbers by *IRAS* by detecting high-galactic latitude compact far-infrared (FIR) emitters. Early work showed that these sources were associated with very faint and heavily reddened optical galaxies emitting most of their radiation at about 60 to 100 μm; the source of this radiation being warm dust associated with the huge star formation rate of a massive starburst.

Before the *IRAS* revolution in this subject, most of the detailed information regarding star-forming galaxies relied almost entirely in Schmidt surveys of either blue compact galaxies (BCG) or UV excess galaxies. These systems are of lower luminosity, low metal content and associated with dwarf galaxies, i.e., they sample a completely disjoint parameter space to that of the *IRAS* starbursts. The only parameter in common with *IRAS* starbursts is their redshift range.

Strong observational support for the existence of high redshift dusty starburst galaxies comes from very recent deep maps at mm wavelengths with SCUBA at the JCMT in Hawaii. These observations have shown the presence of large and luminous mm emitters not associated with peculiar objects but detected in a mm/sub-mm survey of distant clusters having strong gravitational lensing magnification (Smail et al. 1998; Ivison et al. 1998). Smail et al. (1998) conclude that the luminosity density of the brightest sub-mm sources must increase out to at least $z \sim 2$, thus apparently contradicting the claims of a deficit of luminous star-forming galaxies in optically selected samples. Smail and colleagues suggest that the optically selected samples may be missing a considerable population of luminous dust-obscured star-forming galaxies.

Dusty starbursts are faint in the UV/optical (rest frame) rendering hopeless the popular optical colour-colour search techniques. While the average far-infrared to blue flux ratio $F_{\rm FIR}/F_{\rm b}$ is about 400 for normal galaxies and about 100 for HIIG, in *IRAS* galaxies the average ratio is about 10,000 (Soifer, Houck, & Neugebauer 1987). The bolometric luminosity and emitted flux of dusty starbursts peaks at 60 to 100 μm and their optical luminosity is about 3% of their FIR luminosity, thus the best method for finding high redshift dusty starbursts is to detect their redshifted $60 - 100\,\mu$m emission from the dust.

This requires a large *mm* telescope capable of sub-mJy sensitivity and with an angular resolution of about $4''$, (representing 15 kpc at $z = 10$, $q_0 = 0.5$ or 30 kpc for $q_0 = 0.1$). This resolution matches the expected FIR size of young ellipticals or Ultra Luminous infrared galaxies. One such telescope is the 50-m Large Millimeter Telescope (LMT/GTM) that is being built as a joint Mexican-American project (INAOE/UMASS), expected to be fully operational in 2002.

The ability of *mm* telescopes to detect dust at high-z has been proved in the past few years. Mainly by the detection of many $3 > z > 5$ QSOs, both radio-loud and radio-quiet at the level of few to tens of mJy (Andreani, La Franca, & Cristiani 1993; McMahon et al. 1994; Omont et al. 1996).

We will be *actively watching this space* in the next few years.

6. $z \gg 1,000,000$

$z \gg 1,000,000$? Well, that is when, according to standard models of the origin of the Universe, big bang nucleosynthesis was taking place in the most powerful particle accelerator known. This is when light elements (H, D, ^{3}He, ^{4}He, ^{7}Li) formed for the first time. The number of neutrino species and the half-life of the neutron together with the nucleon mass density, relate directly to the relative abundances of the light elements just after the big bang. Therefore, a determination of the light elements abundance and, under the assumption of the standard hot big bang model of nucleosynthesis (SBBN) their primordial values, provides a fundamental parameter in cosmology: the nucleon density in the early universe (η).

Of all the light elements, ^{4}He is the most abundant after H and the easiest to derive. The empirical evidence of the existence of primordial He, that is that He was present before the heavy elements were produced in the interior of stars, comes from the early discovery of a plateau in the relation of the abundance of He to metals (Y vs. Z). Y varies very little and tends to a value much larger than zero as Z tends to zero. Therefore, one can gauge the relative contributions of primordial and post-primordial Helium by measuring the abundance of a heavier element (e.g., Oxygen, the most abundant) that was not produced in the big bang. The most accurate method of measuring helium abundance is to observe diffuse gas which has been ionized by the ultraviolet photons of a nearby cluster of hot young stars. The goal then is to measure Y in ionized gas of low oxygen abundance and extrapolate the He/H vs. O/H linear relation to zero Oxygen abundance to obtain the primordial value ($Y_{\rm p}$). This method requires the **best quality data** for high-excitation, high-surface brightness H II regions.

The study of HIIG provides direct information about star formation processes in galaxies with low abundances of Oxygen and other elements synthesised in stars. Since these galaxies have undergone only a minimal amount of chemical processing, they are ideal to determine from their observed Helium abundance, the primordial value with very small systematic errors (e.g., Skillman et al. 1994).

Early studies (Peimbert & Torres-Peimbert 1974, 1976; Lequeux et al. 1979) pioneered the method of extrapolating the He/H vs. O/H linear relation to zero Oxygen abundance. The intercept gives the value of the primordial Helium. This method has been refined by Pagel et al. (1992, PSTE) and it requires high S/N, high-dispersion spectroscopic data of high-excitation, high-surface brightness HIIG. This is why, zero redshift objects like 30 Dor, can tell us about what happened at $z \gg 1,000,000$ in the realm of big bang nucleosynthesis.

A main problem in all the determinations of $Y_{\rm p}$ has been the lack of galaxies with abundances below 1/20th of solar, as the method is extremely sensitive to the value of Helium in the most metal poor system known IZw 18 ($\sim 1/50$th of solar). The difficulty of finding young, unevolved galaxies has been recognized by most researchers in the field. It requires a considerable effort in order to build up a significant sample. Indeed although we have used in the past 5 years a novel approach that has proved very successful and has produced a new list of about 20 HIIG with abundance less than $\sim 1/20$th of solar still *none* was found below that of IZw 18. The reasons for this are unclear but probably it has something to do with the fact that we are dealing with too small a sample of objects. On the other hand, Kunth & Sargent (1986) have argued that HIIG are gas polluted with heavy elements on timescales comparable to the lifetime of the most massive stars formed during the ongoing burst. However, recent unpublished *HST* measurements indicate that even the H I reservoir in IZw 18 may have a comparable metal content to that of its H II gas. Metals, if not the consequence of self-enrichment, may come from external contamination or simply from one or several previous bursts.

Probably the best way to clarify this issue is to construct an abundance distribution over a sample of more than 10^4 at different redshifts. Building an abundance distribution as a function of redshift would have major impact on our understanding of galaxy evolution.

Searching for very metal poor HIIG we have compiled a list of about 100 low luminosity blue galaxies from the Second Byurakan Survey (SBS) of ultraviolet excess galaxies based on the premise that low luminosity dwarf irregular galaxies are chemically much less evolved than our own (Lequeux et al. 1979; Talent 1980). We obtained spectra of these candidates (Skillman et al. 1993a,b, 1994; Terlevich, Skillman, & Terlevich 1994) and found only ten objects with Oxygen abundances in the range 2% to 5% of the solar value, while none was found with an oxygen abundance lower or equal to that of IZw 18. Similar results were obtained by Izotov, Thuan, & Lipovetsky (1994). Nevertheless, this represented a substantial progress with respect to the previous situation.

Fig. 3 displays our results, plotted together with PSTE He/H vs. O/H relation. Relevant to the determination of $Y_{\rm p}$ is that the upper bound of the x-axis represents an Oxygen abundance of only 25% of the solar value. All of our galaxies lie in the first quarter of the diagram (O/H$\leq 5 \times 10^{-5}$), where the magnitude

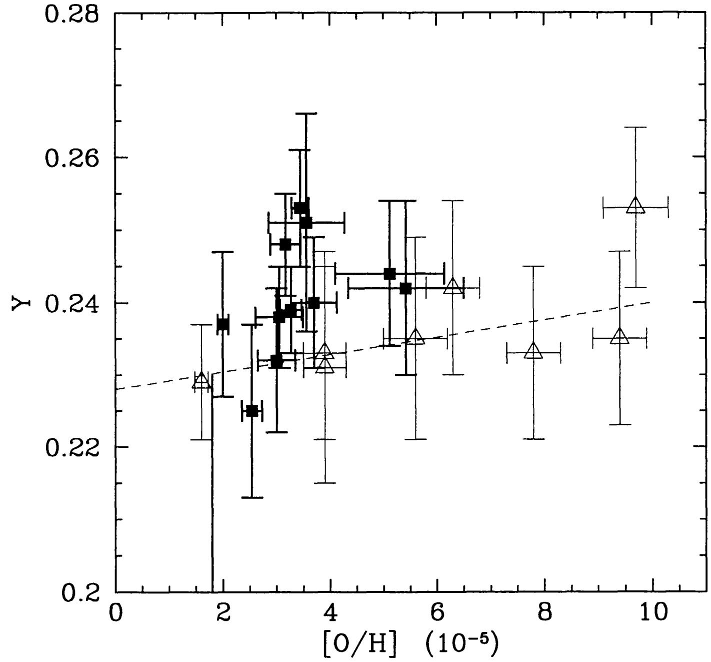

Fig. 3. O/H values for our new objects (thick lines, squares) shown together with PSTE values and regression line (light lines and triangles), against He abundance by mass (Y).

of the extrapolation to the $Y_{\rm p}$ value is of the order of the size of the individual point errors. A second point to be noted is the size of the error bars. In order to put a significant constraint on the standard model, $Y_{\rm p}$ must be known to better than 3%.

We developed a new method to select extremely low metallicity candidates based on first principles and searching through established redshift surveys like the Durham/UKST Galaxy (Ratcliffe et al. 1996) at low redshifts or the Stromlo/APM (Loveday et al. 1992; Hall et al. 1996) at intermediate ones. The method is based on diagnostics using strong line ratios that are indicators of low metallicity, and comparing them against photoionization models.

This method has proven extremely successful: from a pool of 5300 galaxies, we selected 15 as high priority candidates based on the line ratios from the low S/N survey spectra; out of 9 galaxies observed in just two nights at the AAT we discovered 5 new extremely metal poor HIIG, one of them almost as metal-poor as IZw 18, thus doubling the number of known extremely low metallicity HIIG with $Z < Z_{\odot}/15$ that took almost 30 years to build.

In the last couple of years, the consistency of SBBN with the relative abundance of light elements derived from astrophysical objects, has been challenged by an apparent crisis between determinations of D, ^{4}He and ^{7}Li on the one hand, and the predictions that, through SBBN are made for their primordial values ($\rm D_p$, $Y_{\rm p}$, $\rm Li_p$) and η. The conflict has been exacerbated by disparate claims of D measurements in high-redshift low-metallicity QSO absorption systems, each of them eloquently defended by critical reviews by Carswell et al. (1994) and Songaila et al. (1994) ($4 \times 10^{-5} < \rm D_p < 2.4 \times 10^{-4}$) and by Tytler, Fan, & Burles (1996) ($\rm D_p = 2.4 \times 10^{-5}$).

Sasselov & Goldwirth (1995) have challenged the practice of using HIIG for the determination of primordial Helium, on account of what they claim to be higher systematic errors than previously assumed. Different He lines are affected differently by various effects (underlying absorption, radiative transfer, collisional excitation, ionization correction fractions, etc). The high-surface brightness very metal poor galaxy SBS 0335 – 052 which we studied in great detail, allows the accurate measurement of the relative fluxes of several He emission lines. By plotting the ratios of $\rm He^+/H^+$ derived from $\lambda\lambda$ 4471, 5876, and 6678 Å we found evidence for underlying absorption larger than previously assumed (Skillman, Terlevich, & Terlevich 1998). For IZw 18, (on which He value determinations of $Y_{\rm p}$ rest heavily), we found by a similar analysis that the *EW* of the underlying He absorption can be as large as 0.5Å (Skillman et al. 1998) concluding that the uncertainty in the He abundance has been underestimated in the past. The unfortunate result is that there are fewer extremely low abundance objects with reliable He abundance, so that the present derivation of $Y_{\rm p}$ is more reliant on the assumption of a perfectly linear relationship between Y and Z especially down into the region of very low metallicity, where present theories of galactic wind dominated evolution imply a deviation from a linear relationship. This is why it is now more important than ever to succeed in finding by number the very low abundance candidates for primordial He determination.

Presently our best estimate of the primordial helium abundance gives a value slightly higher than that of PSTE, i.e., more in line with the predictions of the SBBN. Perhaps equally important, we find a considerable scatter in the Helium values at a given metallicity (see Fig. 3): an indication of possible differences in the chemical evolution history of these dwarf galaxies since this scatter remains although that due to observational errors has been considerably reduced over the last ten years thanks to the advent of panoramic linear detectors.

Our journey thus ends here, full of hope for the possibilities that will open up in the next few years, for unprecedented progress in the field.

But not before saying that we feel a big debt of gratitude to the Conference organizers, and very especially to Virpi and Nidia who made our long dreamt-of visit to La Plata Observatory a reality. *Muchas gracias.* We would also like to thank our collaborators in this work Evan Skillman, Jorge Melnick, Guille Bosch, Rafa Guzmán, David Koo, Daniel Kunth, and Alfonso Aragón, with whom we have so much fun.

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André Maeder exponiendo.