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ON "PRELIMINARY NOTE ON BLUE EMISSION-LINE GALAXIES" BY HARO (1956)

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RESUMEN

El artículo "Nota preliminar sobre galaxias azules con líneas de emisión" por G. Haro, 1956, BOTT, 2, 14, 8 será analizado. Discutiré su impacto y su influencia en estudios modernos de galaxias compactas azules en general y en métodos de relevamientos de galaxias en particular.

ABSTRACT

I review the paper "Preliminary Note on Blue Emission-line Galaxies" by G. Haro, 1956, BOTT, 2, 14, 8, and discuss its merits, and the influence of the paper on modern studies of blue compact galaxies in general and on galaxy survey methods in particular.

Key Words: galaxies: starburst

1. INTRODUCTION

A clever method was developed at the Observatorio de Tonantzintla for the study of stars with strong UV emission (like T-Tauri in Haro & Herbig 1955, white dwarfs or very blue or UV objects of the kind reported by Humason & Zwicky 1947). This photographic technique was used for the paper reviewed here (Haro 1956) and consists of taking three exposures slightly displaced on the same plate with three different filters to obtain yellow, blue and ultraviolet images of one particular object (Figure 1). The duration of the exposures was chosen as to provide equal intensity on the three colours for an A0 unreddened star. Objects were selected that have a $V-U$ colour similar to that of a B9 (or earlier) star and follow-up objective prism spectra were obtained for them, either with the Schmidt camera at Tonantzintla or by N.U. Mayall at the Lick-Crossley spectrograph. The spectra of the blue emission-line galaxies (Figure 2) show strong emission lines corresponding to the hydrogen Balmer series, [O II] λ 3727 Å, [O III] $\lambda\lambda$4959,5007 Å that we have come to expect in HII galaxies. Haro published a list of 44 objects with ultraviolet excess in this paper (objects that we now know by their Haro number) and subsequently identified a list of some 2000 objects, that remained unpublished (M. Peimbert, private communication). Haro pointed out that, even if the spectral characteristics of these galaxies are similar to those of the nuclei of the objects reported by Seyfert (1943), there is an obvious difference regarding the integrated colours of both type of objects, Seyfert galaxies being considerably redder than Haro blue galaxies.

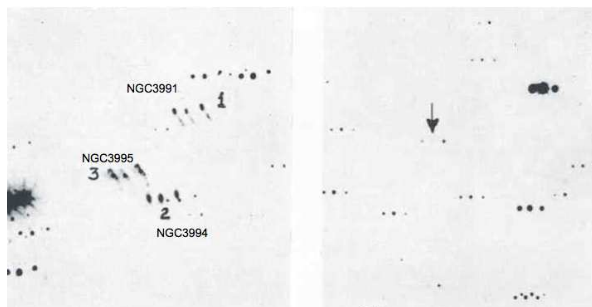

Fig. 1. Example of the three colour plate discovery method (from Haro 1956). Left to right images are Blue, Yellow and UV; the arrow indicates a "very violet galaxy".

1.1. *Colour indices, morphologies and stellar populations*

Colour searches therefore are statistically useful. Galaxies presenting UV excess still have varied morphologies (Irr and different types of S) and their Colour Indices (CI) show a dispersion of about 1 magnitude per class, larger than observational errors.

Baade's discovery and characterization of stellar populations (fortuitously aided by World War II; see `http://science.jrank.org/pages/6498/Stellar-Populations-History.html`) was still very recent and their implications not yet fully understood. Haro realized that CI and stellar populations (I and II) conspire against interpreting

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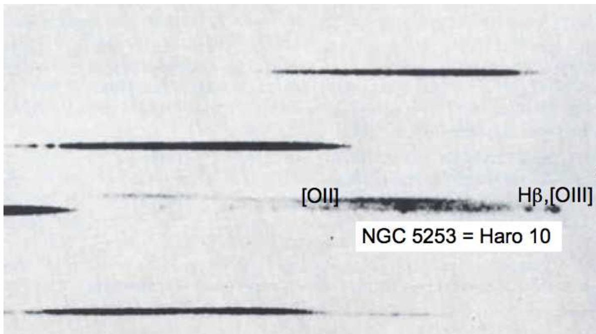

Fig. 2. Objective prism plate where the spectrum of a blue compact galaxy (BCG) (NGC 5253, Haro 10) can be clearly distinguished through the strong emission lines (from Haro 1956).

the Hubble sequence as an evolutionary one. He points out that it is very important to search for and study apparently peculiar examples as they "will help to interpret realistically a complex natural phenomenon". Zwicky (1955) had indicated that galaxies that look identical on a direct photograph, are in fact completely different when analysed by combined images. In a visionary statement, Haro writes: "A more realistic representation of evolutionary paths in galaxies will have to consider, by force, not only the morphology but other undoubtedly significant parameters like: colour, spectral characteristics, distribution and relative abundances of the different stellar populations, etc.".

If Figure 3 (CI *vs.* Hubble type) has evolutionary significance there are three possible paths: (1) Hubble's is an evolutionary sequence or (2) within each Hubble type the stellar population will evolve at the same time, according to specific initial conditions for galaxy formation or (3) a combination of elements from both.

1.2. *Results*

The result of this investigation (confirmed by subsequent similar work) was the discovery that all objects with UV excess show strong emission lines, and that they are Blue Compact Galaxies, Seyferts, QSO (mostly radio-quiet) plus a good harvest of white dwarfs, T-Tauri stars and PN cores.

There are some caveats that need to be taken into account. The galaxies found are rather faint ($m_{\rm ph} = 11 - 16$) and the photographic plates have small scale. Those combined facts made it very difficult to perform a good morphological classification. We now know that the method finds a particular kind of BCG as the search is biased towards *strong* emission line objects. Another problem is that the CI

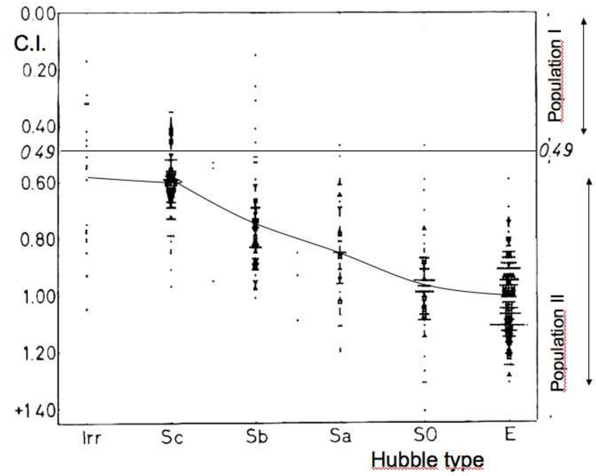

Fig. 3. Colour index vs. Hubble type (from Haro 1956). Indicated are the CI regions covered by Populations I and II, and the full line represents the trend of the mean value for each Hubble type.

are determined from large apertures (order of minutes) that correspond to integrated galaxy colours.

2. SPIN-OFFS

It is remarkable that a paper that appeared in an obscure Latin-American journal with an impossible to pronounce name, written in Spanish, not available in the Internet, still gets a steady quota of citations (92 to date in the ADS). I believe that the reason is the considerable number of offshoots this work has generated, not only by the importance of the objects it discovered, but for the search method itself, that is behind many of today's discovery methods, albeit with modern telescopes, detectors and technologies.

The spin-offs cover a wide variety of topics, a handful of which I will discuss below. Haro galaxies are nowadays called equally H II galaxies, blue compact dwarfs (BCD) or blue compact galaxies. Figure 4 shows a composite image of Haro 11, obtained with the ACS on board *HST*, for a project to study the spatial distribution of Lyα emission in local star-forming galaxies, by Daniel Kunth and collaborators.

2.1. *Technique for surveys*

The basic principle of the method developed in Tonantzintla has been used by different groups over the years, the work leading to the discovery of large number of Lyman break galaxies among others (Steidel & Hamilton 1993). In an attempt to analyse whether possible systematic differences could arise from the discovery technique, Petrosian et al. (2003) selected from the Second Byurakan Survey (SBS)

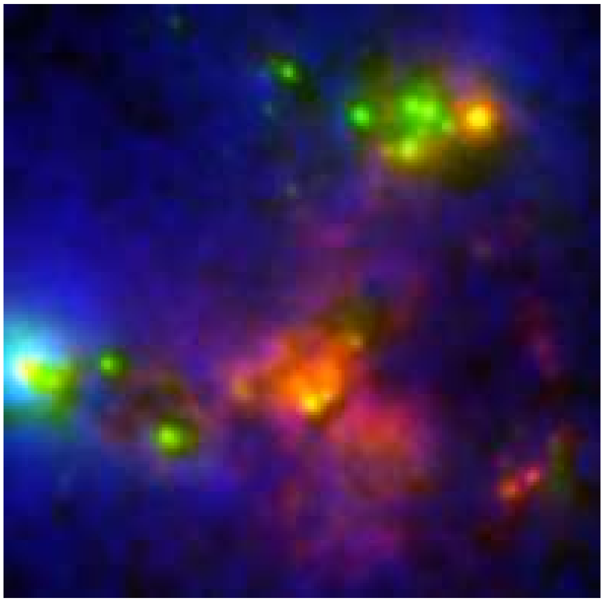

Fig. 4. Haro 11 composite image obtained with the ACS camera on board *HST*. Red is Hα, green is the continuum at 1500 Å due to young stars, blue is Lyα emission. Image obtained from `http://obswww.unige.ch/~hayes/LymanAlpha`.

524 galaxies found through UV excess (UVX) and 340 objects found by their strong emission lines (EL) and compared some of their characteristics.

Their findings are summarized below:

- EL selection allows to obtain a deeper sample.
- The UVX method allows to cover a larger redshift spread.
- More AGN are discovered with the UVX technique.
- Star-forming galaxies with $z < 0.1$ and discovered by their UVX have median Luminosity larger than those found by their EL.
- No major difference is found in either UVX or EL AGN or star-forming galaxies morphology.
- Similar fraction of mergers or interacting systems as well as incidence of pairs (galaxies within distances smaller than 50 kpc from each other) are found among objects discovered by both methods. However, the strongest UVX galaxies are always in close pairs/interactions.
- The EL method allows the building of a sample with lower apparent magnitude and higher z among the low luminosity ($M > -17$) galaxies, and is more efficient at discovering galaxies with compact or irregular morphologies.

2.2. *Statistics*

In Terlevich et al. (2004) we performed a statistical analysis using BCD galaxies, to investigate whether the Star Formation History (SFH) of low mass systems is preferentially dominated by bursts or by more quiescent and continuous modes. To that end, we applied an inversion method to the distribution of the EW(Hβ) for a sample of more than 400 BCGs from the *Spectrophotometric Catalogue of HII Galaxies* (Terlevich et al. 1991) and compared it to continuous or bursting star formation models. We found that a continuous mode of star formation reproduces better the distribution than an instantaneous starbursting mode.

A similar result was recently found by Lee et al. (2009) using a volume limited sample of 300 star-forming galaxies within 11Mpc (11HUGS sample) from narrow band Hα images. The whole program when completed will include the use of *GALEX* images too. They conclude that a continuous, steady state of star formation dominates at the present epoch.

2.3. *Physical properties*

I will just present here a couple of the multiple examples of studies on the global physical properties of BCD galaxies.

One interesting spin-off from the study of the physical properties of BCD comes from the analysis of the Lyα production, detection and escape in local starburst galaxies, like Haro 2 and Haro 11 among others.

Meier & Terlevich (1981) with *IUE* spectroscopy of three star-forming galaxies, found a relation between the intensity of Lyα and metal abundance, not unexpected as Lyα, being a resonant line, is easily destroyed by dust which should be more abundant at higher metallicities. They also found that even when Lyα emission was detected, it was much weaker than the value expected from recombination, from the observed Hα intensity. These results were confirmed a few years later by Hartmann, Huchra, & Geller (1984); Hartmann et al. (1988) and by Terlevich et al. (1993) with the conclusion that the I(Lyα) cannot be used either as a bonafide tracer of the star formation rate, nor as a method for searching for primaeval galaxies. The original correlation I(Lyα) – Z was not confirmed by contemporary and subsequent papers (e.g., Calzetti & Kinney 1992 using better extinction laws). The data collected so far covers a wide metallicity range.

With these observations, the *IUE* data era came to an end, and the *HST* era began. We (Kunth et al. 1998) observed 8 nearby star-forming galaxies (including Haro 2) with GHRS on board *HST* and found, irrespective of their Z and dust content, either PCyg profiles consistent with large scale outflows of the Interstellar Medium (ISM) or damped Lyα absorptions, *instead of emission.* Thuan & Izotov (1997) found a strong and symmetric Lyα line in emission in Tol1214-277. Tenorio-Tagle et al. (1999) modelled all of the observed profiles by the evolution of a superbubble surrounding a starburst in a host galaxy, H I gas included. Whenever the neutral gas is outflowing, Lyα photons redward of 1216 Å can escape. No emission is detected if a slab of static neutral gas with surface density $N > 10^{18}$ cm^{-2} shields the ionized gas. With STIS on board *HST* observations of 3 of the galaxies, we analysed the 2D spectra (Mas-Hesse et al. 2003) and confirmed the probability of large Lyα escape when most of the neutral gas is velocity shifted relative to the ionized region, with expanding shells of neutral gas reaching a few kpc in diameter. We concluded that if the starburst is very young or the H I cover is static but porous, the emission might be seen directly from the H II region, but with an intensity that is weaker than the recombination value. To see whether the probability of Lyα escape depends on column density, distribution of neutral gas and dust, morphology of supershells, luminosity of the host galaxy, etc, Kunth et al. (2003) started a pilot study with the ACS camera on board *HST*. They observed Haro 11 (O/H=1/8th solar) and SBS0335-052 (O/H=1/30th solar) and confirmed that the kinematics of the gas is the dominant regulator of Lyα escape.

A large input towards understanding the physical conditions of star-forming galaxies came from Calzetti, Kinney, & Storchi-Bergmann (1994) work on deriving a specific reddening law for this kind of objects, and this law (and others) was used by Rosa-González, Terlevich, & Terlevich (2002) to compare different SFR estimators and to derive the shape of the cosmic evolution of the star formation history of the universe.

2.4. *Interacting galaxies (building blocks)*

A controversy had arisen in the past decade as to whether interaction between galaxies trigger the formation of starbursts or not and if dwarf galaxies represent the building blocks of large spiral bulges, of spiral and elliptical galaxies or even of large globular clusters with a complex star-formation history.

Answers to these questions should come from detailed studies of dwarf (star forming or otherwise) galaxies (see e.g., Tosi 2003; Bergvall, Laurikainen, & Aalto 2003; Ferraro et al. 2009; Frebel, Kirby, & Simon 2010).

These studies in turn, contribute to set constraints on models of galaxy formation and evolution.

2.5. *Chemical evolution and abundances of galaxies*

One of the many examples of the determination of abundances of the interstellar medium of Haro galaxies can be found in recent work by López-Sánchez and collaborators (López-Sánchez et al. 2007) who performed a detailed study on one of the starbursts closest to us, NGC 5253 = Haro 10. The ionized gas was studied using deep VLT echelle spectroscopy while the neutral gas was analysed with data from the LVHIS (The Local Volume H I Survey) project (Koribalski 2008). The VLT data allowed the authors to study in depth the physical conditions (electron density, temperature, reddening) chemical abundances of the most common elements and kinematics of the ionized gas for 4 star-forming regions in the galaxy. The main results were the confirmation of a localized He pollution (fundamental for projects that require fine abundance determinations; see e.g. Pagel et al. 1992) consistent with the presence of Wolf-Rayet stars, and the detection for the first time in a starburst of O and C recombination lines (see also Peimbert & Peimbert 2011, for an analysis of the relevance of this finding).

2.6. *Haro galaxies as standard candles*

Melnick, Terlevich, & Terlevich (2000) reinvestigated the use of the Hubble diagram to measure the cosmological constant (Λ) and the mass density of the universe (Ω_M). We found a focusing effect that implies that the apparent magnitude of a standard candle at redshifts $z = 2 - 3$ has almost no dependence on Λ for $\Omega_M > 0.2$, hence Ω_M can be measured independently of Ω_Λ for certain redshift values, chosen according to an estimate of Ω_M.

Melnick, Terlevich, & Moles (1988) had suggested that in the local universe H II galaxies behave as standard candles and therefore can be used as distance estimators up to quite high z values. We (Melnick, Terlevich, & Terlevich 2000) compiled literature data for H II galaxies up to $z \sim 3$ confirming this suggestion, and discussed thoroughly different systematic effects such as age, extinction, kinematics and metallicity.

Recently, we started to recalibrate the luminosity-velocity dispersion correlation determined using the H II galaxies strong emission lines, in the local universe (soon to be extended to high

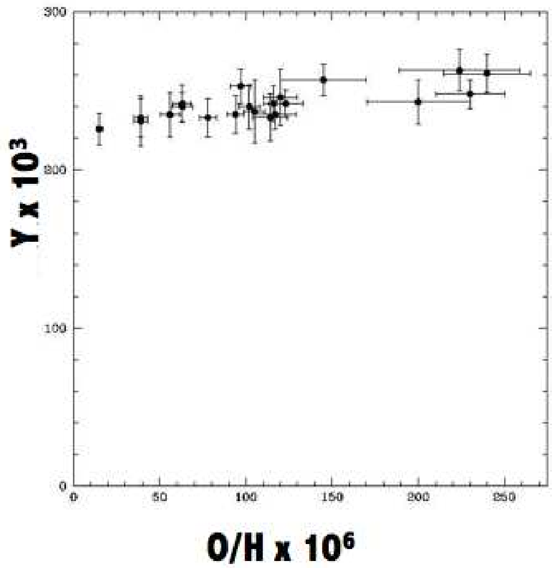

Fig. 5. He abundance by mass (Y) vs. O/H for low metallicity H II regions and H II galaxies, adapted from (Terlevich et al. 1994). The He plateaux can clearly be seen, as O/H tends to zero, and Y tends to a finite value, Yp.

redshifts). We are currently exploring their use as an alternative method to constrain (independently of supernovae) the dark energy equation of state at high z and the matter content of the universe (Plionis et al. 2009).

2.7. *Primordial He*

The determination of a value for the primordial abundance of ^{4}He (Yp) is relevant for cosmology and for setting constraints to Big Bang nucleosynthesis models (e.g., Yang et al. 1984) independently of the Cosmic Microwave Background (CMB) results (derived at present mainly from the *WMAP* experiment value of the universe baryon density, see e.g., Komatsu et al. 2009). To this end, Yp has to be determined to better than 1%. The high precision required, and the way by which Yp is usually derived, brought as a consequence the detailed scrutiny of low metallicity-low mass galaxies including the development of more efficient search mechanisms, more precise methods for abundance determinations and a thorough investigation into systematic errors. This investigation has produced many papers in the last 20 years, the latest of which is Aver et al. (2010).

The method, pioneered by Manuel Peimbert and Silvia Torres-Peimbert (Peimbert & Torres-Peimbert 1974) uses the He plateaux (see Figure 5) discovered by Leonard Searle (private comunication) during his studies of abundance gradients in spiral galaxies. It is based on the fact that, as you look at smaller and smaller values of the metal abundances (traditionally O/H, but also N/H) in the ionized gas of the ISM of star-forming galaxies, the He abundance tends to a finite value, different from zero. The extrapolation of the abundance of ^{4}He for zero metals, should correspond to the value of Yp, the amount of He originated during Big Bang nucleosynthesis, long before stellar nucleosynthesis created the rest of ^{4}He and all the metals that we see today. It is clear from the figure, that a large number of extremely low metal abundance objects (difficult to find) are essential for determining the Yp intersection more accurately. The systematic uncertainties inherent to this method have been analysed in depth in recent years, and procedures have been deviced for determining Yp in self-consistent ways. New atomic data for helium emissivities were produced and their uncertainties analysed (Porter et al. 2009); new methods were attempted for correcting for underlying absorption due to the young stars ionizing the ISM (Skillman et al. 1998; Rosales 2006; Peimbert, Luridiana, & Peimbert 2007; Izotov et al. 2007). See also Peimbert & Peimbert (2011). These latest papers recovered the previous consistency with CMB results.

As a collateral result, we have advanced our understanding of atomic data, chemical evolution of low mass galaxies, violent star-forming processes, procedures to search for extremely low abundance galaxies, and other fundamental topics in Astrophysics.

2.8. *Surveys and H I*

Neutral hydrogen studies of UV-excess and blue compact galaxies (i.e., the kind of objects that were the subject of Haro's paper and have been discovered using the principles of the Tonantzintla method discussed in § 1) have been performed to assess the amount of neutral gas that these objects possess (Thuan & Martin 1981; Gordon & Gottesman 1981; Staveley-Smith et al. 1992). Similar investigations have been carried out in objects that were selected for the intensity of their emission lines like galaxies from the University of Michigan Catalogue (Smoker et al. 2000). With respect to the H I content, and its relation to the blue luminosity of the galaxy, the results are found to be similar (albeit with minor differences) for objects selected by their UV-excess and compactness, and for those selected by their strong emission-line spectra, in agreement with the results discussed in § 2.1. The galaxies are found to be H I rich, and the ratio of its neutral hydrogen mass to

L_B increases with decreasing luminosity, with important consequences for the understanding of galactic evolution.

Yet unsolved in the study of H II galaxies is the understanding of the early stages in the evolution of massive super star clusters, as they are, when young, heavily cocooned by the interstellar medium that surrounds them. Radio observations have been successful in detecting some of these young embedded clusters. We (Rosa-Gonzalez et al. 2007) studied the radio properties of a sample of H II galaxies selected because of their extreme youth (as evidenced by their optical spectrum). Several Haro galaxies were included in the sample. By comparing the integrated radio spectral energy distribution of nascent starburst candidates, with the optical emission line spectral properties, we were able to propose a qualitative evolutionary model.

3. CONCLUDING REMARKS

The variety and volume of work that I reviewed here (even if incomplete) proves that Haro was right when he envisaged the relevance for unravelling astrophysical mysteries of the blue compact objects he kept on discovering during the Tonantzintla observing nights.

I am grateful to Silvia Torres-Peimbert and to Omar López Cruz for organizing this illuminating Symposium.

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