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STARBURST GALAXIES - THE DAWN OF A NEW ERA

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RESUMEN

La labor pionera de Guillermo Haro en el estudio de galaxias "starburst" estimuló la busqueda de galaxias azules con líneas de emisión intensas. La actividad de los "starbursts" se observa no sólo en el Universo cercano, sino también a enormes distancias. Se presenta un método práctico para clasificar galaxias "starburst". Además, para fomentar la discusión durante la conferencia, he listado varios problemas no resueltos.

ABSTRACT

The pioneering work of Guillermo Haro in the study of starburst galaxies triggered several optical surveys of blue galaxies with emission lines. We are living exciting times in astrophysics with the clear evidence that starbursts span an enormous range in redshift: from zero up to more than 3. A practical classification method, based in the relative luminosity of the starburst and the parent galaxy, is presented. Several interesting problems, to stimulate their discussion during the conference, are presented.

Key words: **GALAXIES: ACTIVE — GALAXIES: STARBURST**

1. INTRODUCTION AND BRIEF HISTORICAL BACKGROUND

It is a great honor for me to open this conference on "**Starburst Activity in Galaxies**", the first one organized by the International Program for Advanced Studies in Astrophysics "**Guillermo Haro**". The Program is based at the Instituto de Astrofísica, Optica y Electrónica (INAOE), located in the grounds of the Tonantzintla Observatory in Puebla, México, and is aimed at promoting research in specific topics of Astrophysics. This conference is an integral part of the activities that the Program for Advanced Studies in Astrophysics **"Guillermo Haro"** will develop during the next 6 weeks. The core of those activities is the workshop on the subject **Starbursts and Active Galactic Nuclei** attended by some 30 researchers.

My relation with the Program "Guillermo Haro" started about 2 years ago when Drs. A. Serrano and G. Tenorio-Tagle invited me to participate in the elaboration of a project for an advanced study institute for the INAOE. It was already at the first meeting of the Directors Board (which includes Drs. H. Dottori, J. Franco, J. Melnick, A. Serrano, G. Tenorio-Tagle and myself) that became very clear the type of organization needed and that the majority of the Directors had scientific interests closely related to the pioneer work of Guillermo Haro. Particularly, his work on blue galaxies with strong narrow emission lines, i.e., the ones that these days we refer to as "starburst galaxies". I would like to give here a brief summary of Haro's pioneer work in this area of astrophysics.

In 1942, the recently inaugurated astrophysical observatory at Tonantzintla started to use a fairly large Schmidt camera with an aperture of 70 cm and Haro began to work with it. He turned his attention to emission line objects and soon compiled a list of 437 new emission line objects. Haro found 67 new planetary nebula, increasing the number of known planetary nebulae by almost a factor of two, and was able to estimate that the total number of planetary nebulae was in fact 10 times larger than previously thought. He discovered, simultaneously with George Herbig, many peculiar emission line objects in Orion, and proposed that they were due to young stars. Later, this hypothesis was confirmed and many corrections to the star formation scenario had to be made. These days we know these objects as Herbig-Haro objects, H-H for short.

More relevant for our meeting is that Haro initiated a new fundamental direction in astrophysics with his discovery of several galaxies with compact regions showing large ultraviolet excess in the continuum and strong emission lines (Haro 1956). Applying Humason & Zwicky's (1947) photographic colour technique he found

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several UV excess objects at the galactic poles. Follow-up spectroscopy of those with a compact nucleus showed that many had strong high excitation emission lines. He even compared these galaxies to the ones discovered by Seyfert (1943) and concluded that Seyfert's galaxies where in general redder than the ones in his list. This particular aspect of Haro's work had a strong influence and was further developed by fellow astronomers working with V. Ambartsumyan, at the Byurakan Observatory, noticeably Markaryan and co-workers. Following Haro's methods, and using their new 1-m Schmidt, they compiled 13 lists of galaxies with strong UV continuum, signature of the presence of hot stars (Markaryan 1967). These lists contained many star-forming galaxies and galaxies with an active nucleus. This first Byurakan survey together with the lists of blue compact galaxies compiled by F. Zwicky using the Palomar Schmidt direct plates, formed the basis of the early work on star-forming galaxies. The optical survey work reached its peak during the late 70's with the publication of two lists compiled using the CTIO Curtiss Schmidt (Smith et al. 1976; MacAlpine et al. 1977). These surveys have been very efficient in discovering large numbers of strong emission line Starbursts. I refer to them as H II galaxies.

Much of the recent work on starbursts was prompted not by the optical objective prisms surveys but by the discovery by *IRAS* of large numbers of IR luminous galaxies that are actively forming stars. A large impact was produced by these results, so much so that "*IRAS* galaxy" is sometimes used instead of Starburst galaxy. My general impression is that the samples are different. While *IRAS* has discovered many heavily reddened Starbursts associated with metal rich luminous galaxies (e.g., Soifer et al. 1989; Leech et al. 1990), the optical surveys have found mainly low metallicity, low reddening Starbursts in dwarf galaxies, i.e., H II galaxies (Campbell et al. 1986). The two samples do not necessarily represent the same phenomenon but perhaps two different representations of a similar one. Star formation in the inner parts of massive galaxies does not necessarily proceed or follow the same laws as the outer parts of disks, or in H II galaxies. In fact there is evidence that while *IRAS* starbursts are closely associated with galaxy-galaxy interactions, H II galaxies seem to avoid the company of other galaxies.

2. RECENT DEVELOPMENTS

A very important recent development is that deep optical galaxy counts have shown a large excess of faint, blue galaxies (Lilly et al. 1995) absent, however, in the near-infrared K-band surveys. Surprisingly, the deepest random field redshift surveys at $B \simeq 24$ find the bulk of the faint population remarkably local, $z < 0.5$, but spanning up to $z > 0.8$ (e.g., Broadhurst et al. 1988). Their intrinsic colours and strong and narrow emission lines, and line ratios, indicate that most of these galaxies are dominated by a recent burst of star formation (Koo et al. 1995).

Even more spectacular is that deep surveys of Lyman limit systems have shown that a substantial fraction of these blue galaxies ($\sim 5\%$) are star-forming galaxies at $z > 3$. The evidence suggests that these intermediate and high redshift star-forming galaxies are distant counterparts of the nearby H II galaxies (e.g., Koo et al. 1995; Steidel et al. 1996) These recently discovered high redshift H II galaxies offer, for the first time, the opportunity of sampling processes of star and galaxy formation, and evolution, at a substantial cosmological look-back time.

We know that starbursts associated with large spheroids can reach very large luminosities. B. Boyle and I have computed the expected luminosity function for the young cores of elliptical galaxies at high redshift, assuming that they were formed in a starburst, and compare it with the QSO luminosity function. To this end we scaled the present day luminosity function for elliptical galaxies, in both luminosity and space density, using the observed or established properties of nearby elliptical galaxies and their cores. The observed luminosity function of QSO and the young cores luminosity function show a very good agreement. Our central conclusion was that the young cores of ellipticals, containing only 5% of the total galactic mass, are capable of producing the luminosity of even the most luminous QSO, and that a simple model of galactic core formation can give a surprisingly good description of the whole QSO luminosity function (Terlevich & Boyle 1993).

3. WHAT IS A STARBURST?

Starbursts are the sites where many (most?) of the high mass stars are formed in the Local Universe. We usually call starburst galaxies those galaxies in which the present rate of star formation can be sustained only for a small fraction ($< 1/10$) of a Hubble time (Weedman 1983). Because starbursts are ubiquitous and appear in disks, bulges, and cores, and have a range of ages of up to 1 Gyr, this convenient definition is difficult to apply. This fact, I believe, has lead to much confusion in the use of the word starburst.

I would like to suggest instead a classification based in: a) the relative energy output of the starburst (L_{SB}) to that of the rest of the galaxy (L_G), and b) the starburst age.

Starburst galaxies	$L_{SB} >> L_G$
Galaxies with starbursts	$L_{SB} \sim L_G$
Normal galaxies	$L_{SB} << L_G$

The defining characteristic of starburst galaxies is that their spectrum is dominated by a young stellar population, either with H II region like emissions for very young bursts, or without it for older bursts. Taking into account this aspect I propose to divide the following three well defined phases:

a) Nebular phase. Characterized by the presence of strong emission lines from gas photoinized by young massive stars (hydrogen burning stars). The equivalent width of Hα > 100 Å and the starburst is less than 10 Myrs old. Typical examples are H II Galaxies and IR luminous *IRAS* starbursts.

b) Early continuum phase. Emission lines relatively weak, only Hα and perhaps [O II] 3727 Å are conspicuous. The continuum presents high Balmer series absorptions. The equivalent width of Hα < 100 Å. The starburst age is between 10 and 100 Myrs. Typical examples include most Blue Compact Dwarf Galaxies or Zwicky Blue Galaxies, Starburst nuclei and *IRAS* Galaxies plus the [O I] 6300 Å weak LINERS (Filippenko & Terlevich 1993).

c) Late continuum phase. The continuum is blue and dominated by Balmer absorptions. Only weak emission lines may be present. Typical age is several 100 Myrs up to ~1 Gyr. Examples include the so called E+A (Couch & Sharples 1987) galaxies and some Zwicky Blue Galaxies.

4. QUESTIONS AROUND STARBURSTS

On top of the exciting new results mentioned above, there are several questions that I hope we will find time to discuss during this meeting.

• **How Starbursts do start and end?** The central problems are, how to drive a large mass of gas into a small volume and then turn most of the gas into stars in a short time (perhaps less than 10^7 yrs)? This is a particularly difficult problem for the very luminous starbursts involving perhaps up to 10^{11-12} $M_\odot$ of gas.

• **Are nuclear starbursts identical to spiral arm ones?** This is a subject that needs more work. Given the large differences in the environments of the disk and the core of spiral galaxies it is reasonable to expect that star formation and evolution should show differences. I particularly believe that these differences may be very important and, given that the most luminous starbursts seem to be associated with the cores of interacting galaxies where the metal content of the young stars and their mass loss rates should reach maximum values, this topic should be an important one to follow in order to check stellar evolutionary model predictions and to improve the understanding of high redshift young galaxies. Important clues should come from the detailed studies of the galactic center. Interestingly, recent work in the K band has shown that the luminous output of the galactic core is dominated by a young stellar population inside 1 pc from the center. In this cluster many of the most luminous stars appear to be WN stars and not WC as present models would predict.

• **Starburst clusters are very compact and have a large range in luminosity but:** i) What is their total mass? ii) Are the low mass stars formed? iii) What is their IMF? iv) Is the IMF top heavy?

Given that is very difficult if not impossible to detect low mass stars in extragalactic starbursts we need to study their stellar and gas kinematics to estimate their total masses. I would like to recall two fundamental relations that hold for Giant H II regions and H II galaxies:

Smith & Weedman (1970) found that some giant H II regions have broad emission lines ($\sigma\sim$ 17 – 26 km s^{-1}) compared with normal Galactic H II regions implying supersonic gas motions. With J. Melnick I found (Terlevich & Melnick 1981) that the supersonic line widths are well correlated with the core size and luminosity of Giant H II regions as $L \sim \sigma^4$ and $R_c \sim \sigma^2$. Our $L \sim \sigma^4$ relation in giant H II regions has been later confirmed by several independent studies. We also demonstrated that giant H II regions followed the **same relationship** as globular clusters and elliptical galaxies, and concluded that giant H II regions themselves are gravitationally bound systems with line widths reflecting the virial motions (Terlevich & Melnick 1981). The observed velocity dispersion and size of the Giant H II regions are close to those of present day globular clusters. All these systems show clear evidence of large interaction between winds and the ISM, but both the slope and the normalization of the scaling laws are difficult to explain if the **only** emission line broadening mechanism is associated with the energetic of the massive stars mass loss mechanisms.

• **What is the role played by winds, bubbles and holes?** This is a central problem that deals with the effects of the stellar energy injection. Are starbursts controlled by winds and supernovae during their late stages?

• **Do starbursts show large abundance fluctuations?** If the chemistry of dwarf galaxies is dominated by massive stars and the yields reduced by a galactic wind, then there should be fluctuations in the ratio of the metals produced by massive stars to those produced by longer lived stars, like O/N, O/He, O/Fe, etc. One strong feeling I have, is that to make substantial progress in this field we need combined hydro-chemo-dynamical models.

• **Is there a universal lower limit for the metal content of young galaxies?** Accurate abundances are easily determined for those starbursts that present strong forbidden lines in their spectrum (Giant H II regions and H II galaxies). Presently there is a body of several hundreds of these systems with accurate abundance determination. The metal content goes from about 1/3 solar to that of IZw18, the galaxy with the lowest metal content, at about 1/50 solar for O/H. If the O/Fe ratio in low metallicity H II galaxies is similar to that of the galactic halo, 1/50 solar in O/H corresponds to about 1/150 solar in Fe/H. It is interesting that this apparent limit is similar to that found in distant damped Lyman α systems. In these systems it is possible to measure the properties of what are likely to be the progenitors of present-day luminous galaxies. The major conclusions of recent surveys of damped Lyman α systems are that the chemical enrichment of galaxies may have begun at $z \simeq 3$, and that at $z \simeq 2$ the typical metallicity was 1/15 solar with a lower limit about 1/150 solar. Is this apparent lower limit in metals real and universal? or is the consequence of self-enrichment or external contamination?

5. CODA

The understanding of the formation and evolution of galaxies is one of the most captivating unsolved problems in astronomy. In the last few years there have been an upsurge of new results that suggests that substantial progress will be made in the next decade. I personally believe that galaxy formation and evolution is the most important problem to be tackled with the next generation of large telescopes. Because clusters of massive young stars and the associated H II region can be easily observed even at large look-back times, much observational work will be devoted to searches and detailed studies of the properties of young galaxies or starbursts at intermediate and high redshifts. To understand that data it is of fundamental importance the understanding of nearby regions of massive star formation and the interaction between massive stars and the ISM. If only for this reason the detailed study of the local group rich regions of massive star formation (The Galactic Center and NGC 3603 in the Milky Way, 30-Dor in the LMC, Hubble V and X in NGC 6822, NGC 604, NGC 588 and NGC 595 in M 33) and their environment should be a prioritary enterprise.

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