Starbursts at space ultraviolet wavelengths

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Abstract

Starbursts are systems with very high star formation rate per unit area. They are the preferred place where massive stars form; the main source of thermal and mechanical heating in the interstellar medium, and the factory where the heavy elements form. Thus, starbursts play an important role in the origin and evolution of galaxies. The similarities between the physical properties of local starbursts and high-z star-forming galaxies, highlight the cosmological relevance of starbursts. On the other hand, nearby starbursts are laboratories where to study violent star formation processes and their interaction with the interstellar and intergalactic media, in detail and deeply. Starbursts are bright at ultraviolet (UV) wavelengths, as they are in the far-infrared, due to the 'picket-fence' interstellar dust distribution. After the pioneering IUE program, high spatial and spectral resolution UV observations of local starburst galaxies, mainly taken with HST and FUSE, have made relevant contributions to the following issues:

- *The determination of the initial mass function (IMF)* in violent star forming systems in low and high metallicity environments, and in dense (e.g. in stellar clusters) and diffuse environments: A Salpeter IMF with high-mass stars constrains well the UV properties.
- *The modes of star formation*: Starburst clusters are an important mode of star formation. Super-stellar clusters have properties similar to globular clusters.
- *The role of starbursts in AGN*: Nuclear starbursts can dominate the UV light in Seyfert 2 galaxies, having bolometric luminosities similar to the estimated bolometric luminosities of the obscured AGN.
- *The interaction between massive stars and the interstellar and intergalactic media*: Outflows in cold, warm and coronal phases leave their imprints on the UV interstellar lines. Outflows of a few hundred km s^{-1} are ubiquitous phenomena in starbursts. These metal-rich outflows and the ionizing radiation can travel to the halo of galaxies and reach the intergalactic medium.
- *The contribution of starbursts to the reionization of the universe*: In the local universe, the fraction of ionizing photons that escape

from galaxies and reach the intergalactic medium is of a few percent. However, in high-z star-forming galaxies, the results are more controversial.

Despite the very significant progress over the past two decades in our understanding of the starburst phenomenon through the study of the physical processes revealed at satellite UV wavelengths, there are important problems that still need to be solved. High-spatial resolution UV observations of nearby starbursts are crucial to further progress in understanding the violent star formation processes in galaxies, the interaction between the stellar clusters and the interstellar medium, and the variation of the IMF. High-spatial resolution spectra are also needed to isolate the light from the center to the disk in UV luminous galaxies at z=0.1-0.3 found by GALEX. Thus, a new UV mission furnished with an intermediate spectral resolution long-slit spectrograph with high spatial resolution and high UV sensitivity is required to further progress in the study of starburst galaxies and their impact on the evolution of galaxies.

1 Introduction

1.1 Starburst galaxies: Definition and general properties

Starbursts are a very significant component of the universe. They are the preferred place for the formation of massive stars, and hence they are a relevant energy source that drives the cosmic evolution of galaxies. Heckman (1998) finds that in the local universe, within 10 Mpc, the four most luminous starburst galaxies (M82, NGC 253, NGC 4945, M83) account for about 25% of the recent star formation rate in this volume. Massive stars have a significant impact on the evolution of galaxies. They are responsible for the thermal and mechanical heating of the interstellar medium. They are the factory where most of the heavy elements form; which are dispersed throughout the interstellar medium when massive stars explode as supernovae. From this enriched gas, new stars will form.

Starburst galaxies are systems with a high star formation rate. However, this rate can be sustained for much less than a Hubble time, because the gas reservoir in a galaxy may only last for a few 10^8 yr (the gas consumption time). Starbursts have a significant large population of massive stars that are able to produce large numbers of Lyman continuum photons to ionize the interstellar medium. When the gas cools down, hydrogen Balmer and other recombination lines form with intensities that can exceed 10^{39} erg s^{-1}. A fraction of the Lyman continuum photons are, however, absorbed by dust grains and their energy is re-emitted at far-infrared wavelengths.

Starburst galaxies are mainly selected on the basis of their strong continuum at ultraviolet (UV) wavelengths (defined here simply as the range 900 Å – 3300 Å), their nebular optical emission lines, and/or strong far-infrared radiation. Due to these selection criteria, starbursts constitute a mixed type of star-forming systems, which include:

- Giant-extragalactic HII regions, such as 30 Doradus in the Large Magellanic Cloud, which is considered by Walborn (1991) as a Rosetta Stone. These star-forming regions are regarded as mini-starbursts.

- Starburst dwarf galaxies, such as IZw 18. They have blue colors and an optical HII region spectrum, but with signs of an underlying stellar population older (a few 10^8 yr to 1 Gyr) than the ionizing population. They include HII galaxies (Terlevich et al. 1991), blue compact galaxies, and blue irregular galaxies, such as NGC 1569.

- Nuclear starbursts, such as the prototype NGC 7714 (Weedman et al. 1981). They have a strong UV continuum, and strong optical emission lines. Their hosts are spiral galaxies. Balzano (1983) found that about 40% of the Markarian galaxies can be classified as nuclear starbursts.

- Very luminous infrared galaxies. The IRAS satellite has discovered many of these galaxies. They have far-infrared luminosities larger than 10^{11} $L_\odot$. In most of these galaxies, the far-infrared flux is thermal emission by dust grains heated by massive stars. A typical very luminous far-infrared starburst is NGC 1640.

- Lyman break galaxies (LBG). They are star-forming galaxies at cosmological distances ($z \geq 2$) (Steidel et al. 1996; Williams et al. 1996) that provide a significant fraction of the global star formation rate of the universe (Madau et al. 1996). LBG show a strong rest-UV continuum with absorption lines very similar to those of local UV-bright starburst galaxies (Meurer et al. 1997; González Delgado et al. 1998a; Heckman et al. 2005). The most famous LBG is MS1512-cB58 at z=2.7276, known simply as cB58.

Terlevich (1997) proposed to distinguish between starburst galaxy and starburst region. The former is when the galaxy luminosity is totally provided by the starburst, while in a starburst region, the starburst luminosity is substantial but smaller than the galaxy luminosity. So, starbursts may simply be defined as compact (10–10^3 pc) sites of recent star formation (10^6–10^8 yr), that often show dust obscuration.

In the conference 'Starbursts - From 30 Doradus to Lyman break galaxies' (de Grijs & González Delgado 2005), Heckman (2005) has argued against the gas consumption time definition of starburst, proposing an alternative definition. The inverse of the consumption time, b, is related to the birth-rate parameter; b is the ratio between the current and the past average star formation. This parameter varies significantly and systematically with the properties of the galaxy, and leads to a steep decline in the fraction of starbursts with increasing galaxy mass, and a strong redshift dependence. For this reason, Heckman proposes a more physically meaningful definition, which is based on the star formation intensity. Starbursts are defined as systems that have a star formation rate per unit area which is much larger than that in the disks of normal galaxies. Nearby starbursts have star formation intensities ranging from 1 to 100 $M_\odot$ yr^{-1} kpc^{-2}, and similar values are found for LBG (Meurer et al. 1997).

The Galaxy Evolution Explorer (GALEX) satellite (Martin et al. 2005) has already made a significant contribution to establish the physical properties of starburst galaxies. Two categories of local ($0.1 \leq z \leq 0.3$) UV luminous galaxies (UVLG) have been found (Heckman et al. 2005). The main differences arise from the different UV luminosity per unit area, i.e., the variation in the star formation intensity. The large UVLG ($I_{FUV} \leq 10^8$ $L_\odot$ kpc^{-2}) are not starburst galaxies. They are massive, late-type disk galaxies that have star formation rates sufficient to build their stellar mass in a Hubble time. In contrast, compact UVLG, which can clearly be classified as local starbursts, are low-mass galaxies ($M_{star} \sim 10^{10}$ $M_\odot$) with half-light radii less than a few kpc. They have large enough star formation rates to build the present galaxy in ∼1–2 Gyr.

1.2 The relevance of space UV observations of starburst galaxies

UV observations of starbursts are relevant because:

- This range is very sensitive to the star formation history. In fact, the UV energy distribution shows a strong evolution from very young to intermediate age (∼ 1 Gyr) stellar populations.
- The UV light allows a direct detection of massive stars, thus, it provides a direct measurement of the star formation rate.
- UV wavelengths contain valuable tracers of the cold and molecular phases of the interstellar medium, and are an important probe of the ionized interstellar medium in starburst galaxies. Low and high-ionization absorption lines allow us to study the interaction of the starburst with the interstellar medium in an ample range of physical (density and temperature) conditions.

We owe much of our understanding of the starburst phenomenon to the International Ultraviolet Explorer (IUE) which provided the first UV (1200–3300 Å) spectra of starburst galaxies (Kinney et al. 1993); the Hubble Space Telescope (HST), for its impact with UV high spatial resolution images and spectra of starbursts (Meurer et al. 1995; Leitherer et al. 1996); the Hopkins Ultraviolet Telescope (HUT) and FUSE for collecting spectra of starbursts below Lyα, down to the Lyman limit (Leitherer et al. 1995b). The impact of the GALEX mission has just started (see the first results in ApJL, volume 619), but there is no doubt about its important contribution to our understanding of the cosmic evolution of galaxies and, in particular, of starbursts.

Along this paper, we discuss the relevance of high spatial and spectral resolution observations of starbursts at space UV wavelengths and their impact on the following issues: the stellar content of starbursts, the interaction of massive stars with the interstellar medium, the relation between starburst clusters and the formation of globular clusters, the role of starbursts in AGN, and the contribution of starbursts to the reionization of the universe.

2 UV imaging morphology

HST has been the first telescope to provide UV high spatial resolution images of nearby starbursts. FOC, WFPC2, STIS and ACS/HR on board HST have been able to dissect the anatomy of nearby starbursts with a spatial sampling better than 0.025 arcsec/pixel (Figure 1). Other instruments, on board UIT, FOCA and now GALEX, are quite useful to study the general UV morphology of galaxies at intermediate resolution (e.g. Bianchi et al. 2005) and to map the extended outflows in starbursts (Hoopes et al. 2005), but they have much less spatial resolution than HST.

In a pioneer work, Meurer et al (1995) obtained HST/FOC images (at 2200 Å with a spatial sampling of 0.014 arcsec/pixel) of a sample of 9 starbursts, selected for their high UV flux in the IUE aperture (Kinney et al. 1993). All galaxies show an irregular UV morphology, but they reveal two important structural characteristics: compact knots embedded in a diffuse UV background.

Compact knots are marginally resolved stellar clusters and provide about 25% of the total UV emission. These clusters are distributed irregularly over the UV background, but the brightest ones are located in the center of the starburst. Their UV absolute magnitude ranges from -19 to -10, and their sizes are less than 10 pc. Their masses, estimated from the UV luminosity, range from 10^4 to 10^7 $M_\odot$. These knots have ages of a few Myr to $\sim$100 Myr, and they may be formed in bursts. The brightest knots are named super-stellar clusters (SSCs). The luminosity function (LF) of the stellar clusters follows a power law, $dN/dL \sim L^{-\alpha}$, with index $1.5 \leq \alpha \leq 2$, similar to that found in merger systems observed at optical wavelengths (Whitmore et al. 1993). Meurer (1995) argues that SSCs have properties similar to globular clusters if fading and a spread of the star formation time is taken into account.

The UV diffuse emission accounts for about 75% of the total UV flux from the starburst. It extends about a few 100 pc. Several origins have been proposed: a) Continuous star formation (csf) lasting for a few 100 Myr; originally, the stars form in clusters over the last few 100 Myr, but clusters dissolve with age and disperse across the field. b) The UV radiation originates in dusty compact stellar clusters, but it is scattered by dust to the field. c) Individual massive stars, unresolved even at the HST spatial resolution. Long-slit UV spectra of starbursts taken with STIS point to the csf origin, so that the UV field light is created via dissipation of aging star clusters (Tremonti et al. 2001; Chandar et al. 2005).

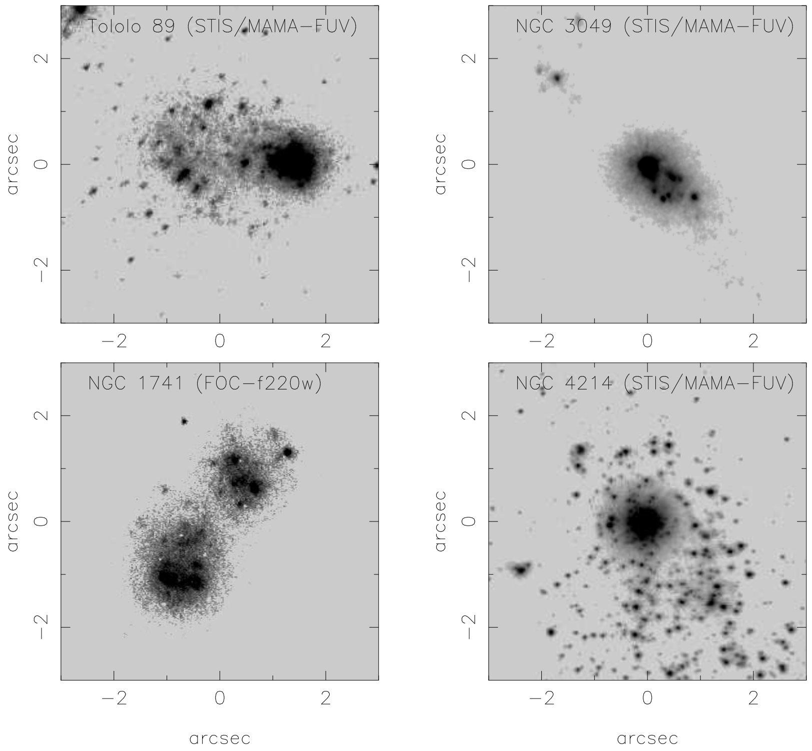

Figure 1: UV images of starburst galaxies taken with HST+FOC (NGC 1741), and HST+STIS/MAMA (NGC 4214, NGC 3049 and Tololo 89) with a spatial sampling of 0.014 and 0.0244 arcsec, respectively; 1 arcsec corresponds to 260 pc (NGC 1741), 25 pc (NGC 4214), 80 pc (NGC 3049) and 100 pc (NGC 3049). Clusters and diffuse extended emission are detected.

3 UV spectral morphology

Starbursts are recognized at optical wavelengths by their nebular emission line spectrum. In contrast, in the UV, starbursts show a continuum filled with absorption lines (Figures 2 and 3). This spectral dichotomy is caused in part by the massive stars that power the starburst. Massive stars emit photons with energies of several eV that are absorbed and re-emitted in their stellar winds, producing ultraviolet resonance transitions. However, stellar winds are optically thin to most high energy ($\geq$ 13.6 eV) ultraviolet photons, that can travel tens of parsecs from the star before they are absorbed and photoionize the surrounding interstellar medium. Subsequently, this ionized gas cools down via an emission spectrum. Beside the stellar wind origin, absorption lines can also form in the photosphere of massive stars, and in the interstellar medium. The wind and the interstellar absorption lines are resonant transitions. Usually, low-ionization lines have an interstellar origin, but high-excitation lines can be wind lines with some interstellar contribution.

The most important characteristics of these lines are described below, and labeled in Figures 2 and 3.

- **Photospheric:** These lines form in layers that are in hydrostatic equilibrium. Mainly from C, N, O, S, Si and Fe ions of low and high-excitation potential, they originate from excited levels, so they are not resonant transitions, and thus not contaminated by interstellar components. Although much weaker, they are not too much affected by stellar wind lines. These lines are useful to constrain the age of the starburst, but also the metallicity (de Mello et al. 2000; Robert et al. 2003). In particular, blends of these lines in the ranges 1360-1380 Å and 1415-1435Å show a strong dependence with metallicity (Leitherer et al 2001). Rix et al. (2004) find also that the FeIII (1935-2020) index is a strong metallicity indicator. Some of the most relevant of these lines in starburst are: SV λ1502, CIII λ1426-1428 and CIII λ1176.

- **Wind:** Hot stars develop strong wind stellar lines due to the radiation pressure in ultraviolet resonance lines. As a result, all the strong ultraviolet lines show a blueshifted absorption (about 2000–3000 km s^{-1}) or a P Cygni profile. The shape of the profile reflects the stellar mass-loss rate, which is related to the stellar luminosity, and thus to the stellar mass. Therefore, the shape of the line profiles in the UV integrated light of a stellar population is related to its content in massive stars. Thus, these features can be used to constrain the properties (such as age, and the slope and upper mass limit of the IMF) of the starburst. But due to the dependence of the mass-loss rate with the metallicity (Maeder & Conti 1994), wind lines are also strongly affected by metallicity. The most relevant wind lines in starburst are: NV λ1240, SiIV λ1400, CIV λ1550, and HeII λ1640.

- **Interstellar:** Low ionization lines are very useful to study the kinematics of the ionized gas because the interstellar component usually dominates over the stellar contribution in starbursts (González Delgado et al 1998a). They are also useful to derive the metallicity of the gas (e.g. Pettini et al 2000; Savaglio et al. 2004). The high ionization interstellar lines are blended with the wind lines, and a careful separation between both components is necessary. However, when the starburst is young (2-8 Myr), wind lines dominate over the interstellar ones.

In addition, the UV spectra of starbursts may show the Lyman series in emission or absorption. In particular the two strongest lines, Lyα and Lyβ are very useful to study the interaction of the starburst with the interstellar medium.

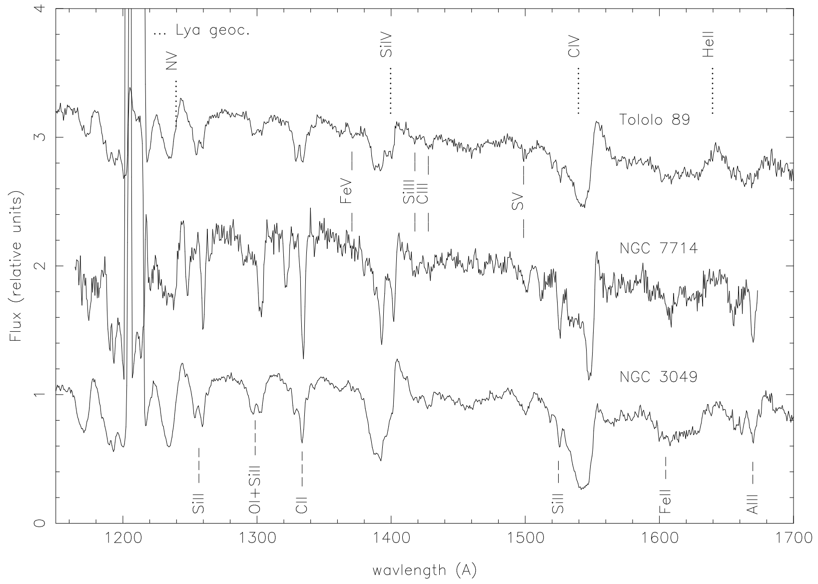

Figure 2: UV spectra of starburst galaxies taken with HST+STIS/MAMA (NGC 3049 and Tololo 89) and HST+GHRS (NGC 7714). Some of the most relevant photospheric (full line), wind (dotted) and interstellar lines (dashed) are labeled. The spectra correspond to the main cluster only (see Figure 1).

These lines may be in emission, if they are from the starburst HII region; but they may be in absorption due to the interstellar medium within the starburst. Photospheric components may also contribute to these lines. Lyα and Lyβ are weak in very hot stars but they increase with decreasing effective temperature (Valls-Gabaud 1993; González Delgado et al. 1997). Section 6 below is devoted to explain the relevance of Lyα in starburst galaxies.

4 Dust opacity in starbursts

The most direct way to measure the star formation rate in starbursts is through the UV luminosity. Unfortunately, starbursts are often dusty, and the presence of dust affects significantly the UV emission. The UV is more affected by extinction than any other wavelength. So, objects that are optically thin at visible wavelengths may be optically thick in the UV. Dust absorbs a fraction of the UV photons and reradiates in the far-infrared. Analyzing a sample of UV selected local galaxies observed with GALEX, Buat et al. (2005) have found that only

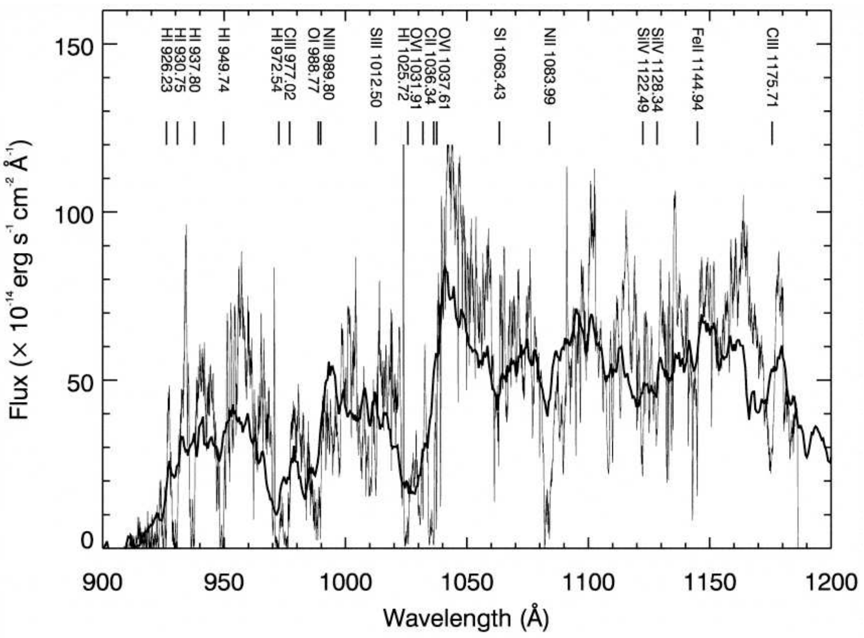

Figure 3: FUV spectra of M83 taken with FUSE (thin line) and HUT (thick line). The main lines are labeled. (Figure adapted from Leitherer et al. 2002).

33% of the UV emission escapes from the galaxies and the remaining 66% is absorbed by dust and reradiated in the far-infrared.

Using IUE spectra of a variety of starburst galaxies (blue compact, starburst nuclei, also some luminous infrared galaxies, etc), Calzetti et al. (1996) found that the UV spectral energy distribution is well parametrized by a power-law, $F \propto \lambda^{\beta}$, and the spectral slope of the continuum, β, correlates with the nebular optical extinction derived using the Balmer decrement. On the other hand, from population synthesis models, Leitherer & Heckman (1995a) found that starbursts have an intrinsic spectral slope that changes very little with the initial mass function (IMF) or the age of the starburst, taking values around -2.3. Then, according with these results, any deviation of the spectral slope from the intrinsic value can be interpreted as a reddening effect. This provides a nice recipe to correct the UV observed emission for extinction, and to find an effective attenuation law to perform the extinction correction (Calzetti 1997).

Gordon et al. (1997) built a model of the stars and dust distribution in a starburst, and concluded that the grey starburst extinction law is compatible with a clumpy shell geometry, with the UV radiation from the starburst viewed filtered through the dusty gas clouds (see also Charlot & Fall 2000). This distribution explains why the ionized gas extinction (derived using the Balmer decrement) is a factor of two higher than the stellar extinction (derived from the UV slope) in starbursts, because the emission lines are seen through a larger column of dust than the UV continuum (Fanelli et al. 1988).

Meurer et al. (1997) show that β correlates with the ratio of the far-infrared to UV fluxes, L_{IR}/L_{UV}. The straightforward interpretation of these results is that dusty starbursts absorb a large fraction of the UV radiation, that is subsequently reradiated in the far-infrared. This is an energy balance relationship, that allows us to recover the UV radiation without a detailed understanding of the dust grain properties or the extinction law. Following in the same line, Heckman et al. (1998) found that at low-metallicity, starbursts have blue colors and a significant fraction of the UV radiation escapes from the starburst. But at solar metallicity starbursts have redder UV colors. They have $L_{IR}/L_{UV} \geq 10$, indicating that only less than 10% of the intrinsic UV luminosity escapes from the starburst. These results imply that dustier starbursts are more frequent in more metal-rich galaxies. Note also, that the galaxies with higher star formation rate are, by the simple principle of causality, the most massive ones. Due to the mass-metallicity relation, they are the dustiest ones (Heckman 2005). So, the most massive galaxies host more powerful, more metal-rich and dustier starbursts.

Is the $L_{IR}/L_{UV} - \beta$ correlation found for UV selected starbursts applicable to other objects? Goldader et al. (2002) obtained FUV and NUV STIS images for 9 ultraluminous infrared galaxies (ULIRGs). They found that, after correcting for dust reddening using the $L_{IR}/L_{UV} - \beta$ correlation, the UV luminosity is insufficient to account for the far-infrared luminosity. On the contrary, GALEX data of several samples of normal galaxies with star formation show that the observed UV luminosity overestimates the far-ultraviolet attenuation of these galaxies predicted from the relationship (Buat et al. 2005; Seibert et al. 2005).

Several attenuation laws have been proposed in the 1200–3000 Å spectral range (Rosa & Benvenuti 1994; Mas-Hesse & Kunth 1999; Calzetti 1997) to be applied to star forming regions, but all of them are coincident in showing a 2175 Å bump weaker than in the galactic extinction law. Recently, Leitherer et al. (2002) and Buat et al. (2002) have used HUT and FUSE data to extend the starburst attenuation law to the FUV.

5 Stellar content

Most starbursts are far enough that the stellar population is unresolved in individual stars even with the high spatial resolution of HST. Thus, the stellar content of starbursts has to be estimated through their integrated light. The first deep integrated spectra of galaxies were taken by IUE with apertures of 10×20 arcsec (see the spectral atlas by Kinney et al. 1993). Sekiguchi & Anderson (1987) were the first to build a stellar library of galactic O and B stars that could be used to predict the equivalent width of CIV $\lambda1550$ and SiIV $\lambda1400$ of a non-evolving stellar population of massive stars. Later, Mas-Hesse & Kunth (1991) extended this work using evolutionary models to predict the starburst properties as a function of age. The stellar content of starburst galaxies (e.g.

Mas-Hesse & Kunth 1999) and giant extragalactic HII regions (e.g. Vacca et al. 1995; González Delgado & Pérez 2000; Jamet et al. 2004) have been estimated using these IUE spectra. High spatial resolution (sub-arcsec) HST spectra have been obtained (Leitherer et al. 1996; Conti et al. 1996; González Delgado et al. 1999; Johnson et al., 2000; González Delgado et al. 2002; Chandar et al. 2003a) and the results attained are discussed in section 5.2.

Starbursts have a strongly absorbing interstellar medium, and a significant fraction of the equivalent width of the CIV λ1550 and SiIV λ1400 may be due to the interstellar component. This is particularly true if very massive stars do not form or if the starburst is not very young (10 Myr or older). In fact, the low spectral resolution of IUE (about 1000 km s^{-1}) did not allow us to separate the stellar from the interstellar components in most of the starbursts observed. The analysis of these spectra has provided an uncertain determination of the age and stellar content of some starbursts. IUE had also the capability of taking spectra at higher resolution; however, no starburst was bright enough to be observed in this mode. It has been later, in the HST era with higher spatial and spectral resolution observations, that some galaxies previously classified as very young starbursts have been recognized as evolved starbursts with a strong interstellar medium; NGC 1705 is a good example (Heckman & Leitherer 1997a).

FOS, GHRS and STIS on board HST were used to obtain deep spectra at a resolution ($\sim$ 200 km s^{-1}) sufficient to resolve the interstellar from the stellar wind components. These observations allow detailed profile analysis of the wind lines of nearby starbursts to investigate their stellar content. Evolutionary synthesis models that predict the UV wind profiles of a stellar population are used to estimate the age and the initial mass function (IMF) of the starburst. These models have been developed mainly in two spectral ranges, 1200–2000 Å and at the FUV, 1000-1200 Å. We first describe the models and then comment on the general properties of starbursts from the UV line synthesis.

5.1 UV line synthesis

Stellar wind lines contain information on the stellar mass; this is the basis of the UV line synthesis. Stellar winds are driven by radiation pressure. In O stars, a fraction of the radiative momentum (L/c) is converted to kinetic momentum ($\dot{\mathrm{M}}\,\mathrm{v}_\infty$); so

$$\dot{\mathrm{M}}\,\mathrm{v}_\infty \propto (\mathrm{L/c})$$

where $\dot{\mathrm{M}}$, v_∞, L and c are the mass-loss rate, the wind terminal velocity, the radiant luminosity of the star and the speed of light. The profile of the wind line contains information about the terminal velocity and, via the previous relationship, about the stellar luminosity. So, the wind line profiles of the integrated spectra carry information about the massive stellar population of the starburst, hence about its IMF.

Range 1200–2000 Å. Robert et al. (1993) and Leitherer et al. (1995c) have computed an atlas of evolutionary synthesis models that predict the line profile of NV λ1240, SiIV λ1400, CIV λ1550, HeII λ1640 and NIV λ1720 as a function of age and IMF, for an instantaneous burst and for continuous star formation. Figures 4 and 5 show these lines for several ages and different IMF. The results indicate: a) CIV always shows a P Cygni profile when O stars with M$\geq$ 50 $M_\odot$ are in the zero-age main sequence; it is a good age diagnostic of the stellar population. b) SiIV shows a conspicuous wind profile when O blue supergiants are present. A strong P Cygni profile appears between 3 to 5 Myr for a burst stellar population. It is also strong, when there is a large fraction of blue supergiants with respect to O main sequence stars, i.e., when the stellar population forms with a top-heavy IMF. c) NV has a similar behavior to SiIV. d) HeII and NIV appear as a strong broad emission-feature when a large fraction of Wolf-Rayet stars are present, in the age range $\sim$ 3–4 Myr.

Photospheric lines, such as CIII λ1426,1428, SV λ1502, are also strong when the burst is only a few Myr old and the UV light is dominated by O stars. The contribution of B stars to the UV light has been predicted by de Mello et al. (2000). Si lines, such as SiIII λ1295,1297,1299, SiIII λ1417, SiII λ1485, are good age diagnostics for evolved starbursts (age $\geq$10 Myr).

Initially, the spectral library used as input to the models was built with hot stars of solar or slightly subsolar metallicity. However, photospheric lines are much weaker at lower metallicity; and the stellar-wind properties are affected by line-blanketing, since the mass-loss rate scales with $(Z/Z_\odot)^{0.5}$ (Kudritzki et al. 1999). Leitherer et al. (2001) built a new stellar library with O and B stars in the LMC and SMC observed with HST. They implemented it in Starburst99 (Leitherer et al. 1999), providing new evolutionary synthesis models at 1/4 $Z_\odot$. However, the behavior of the stellar wind lines is complex; while NV λ1240 and SiIV λ1400 do not scale monotonically with metallicity, CIV λ1550 is significantly affected, showing a weaker P Cygni profile. Thus, while the wind NV and SiIV may be equally well predicted using the solar stellar library, CIV and the photospheric lines are overpredicted in low metallicity starbursts, inducing a wrong estimation of the age and of the IMF parameters.

Range 1000–1200 Å. The first evolutionary synthesis models at intermediate spectral resolution in the FUV were computed by González Delgado et al. (1997). Using a stellar library built with hot O and early B stars observed with Copernicus and HUT, they predicted the wind line OVI λ 1032,1038 and the photospheric component of Lyβ. OVI develops a P Cygni profile when formed in stellar winds of the most massive stars. When these stars are absent, no OVI is formed. In contrast, Lyβ is a very sensitive indicator of B stars. If these stars dominate, as is the case in evolved starbursts (age $\geq$ 10 Myr), Lyβ is present as a strong absorption feature. Because of the constant strength of OVI in O stars, OVI is not a good discriminator between instantaneous versus continuous star formation for ages when the starburst is in the nebular phase, but the absence of OVI and the presence of stellar Lyβ is a good indicator of a short burst duration and of the galaxy being in an evolved starburst phase (age $\geq$ 10 Myr). However, careful attention to interstellar absorption of Lyβ is needed before estimating the ages and stellar content in starbursts using these lines. Robert et al. (2003) have made an extension of these models predicting also the photospheric lines in the 1000–1200 Å range using O, B and Wolf-Rayet stars in the Galaxy and in the LMC and SMC observed by FUSE. Other wind lines observed in starbursts are NIV λ955, CIII λ977, NIII λ991 and NII λ1083 (Keel et al. 2004).

In contrast to wavelengths above 1200 Å, the FUV continuum suffers from an age-reddening degeneracy. Because at $\lambda \leq 1200$ Å hot stars are outside the Rayleigh-Jeans regime, the age effects are no longer negligible in the continuum slope for starbursts in an instantaneous burst (Leitherer 2005). For starbursts in the continuous star formation regime, the FUV continuum is less sensitive to the age than the near-UV, because the rate of death and birth of stars is reached earlier.

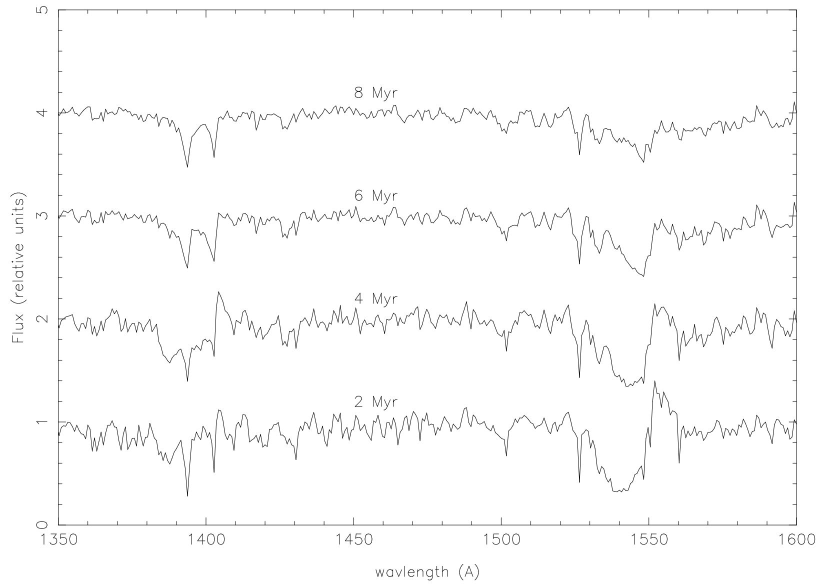

Figure 4: UV synthetic spectra generated with Starburst99 for an instantaneous burst at different ages that follows a Salpeter IMF in a mass range of 1 to 100 $M_\odot$. Note the change of the SiIV and CIV profile with the age of the burst.

5.2 Results: Ages and IMF

Stellar clusters. Intermediate (∼1 arcsec) and high (∼0.1 arcsec) spatial resolution spectra with HST have been obtained to constrain the IMF and age in stellar knots detected in starbursts. The main results derived from the UV light provided by stellar clusters can be summarized as follows: the spectral

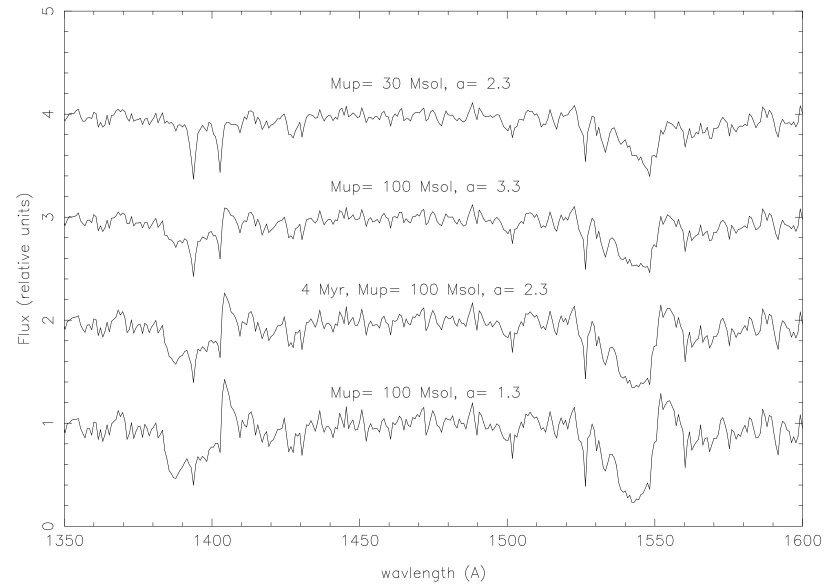

Figure 5: As in Figure 4 for an instantaneous burst 4 Myr old with different assumptions of the IMF. Note how weak become SiIV and CIV when very few massive stars form in the starburst.

range 1200-2000 Å can be characterized by an instantaneous burst a few Myr old, populated by a Salpeter IMF with stars more massive than 50 $M_\odot$ (e.g. Conti et al. 1996; Leitherer al. 1996; González Delgado et al. 1999; Chandar et al. 2003b). When the integrated light is emitted by extended areas ($\sim$ 100 pc), the UV spectra are equally well fitted by continuous star formation lasting for a few Myr. These results indicate that clusters form with a very small age spread. In fact, this is the case for the starburst He2-10 (Johnson et al. 2000; Chandar et al. 2003a) in which the clusters are chained along $\sim$ 100 pc with a mean separation $\leq$ 10 pc, and they are all 4-5 Myr old. These clusters have masses of several 10^4 to several 10^5 $M_\odot$, that are typical of proto-globular clusters (Ho & Filippenko 1996).

There are indications that the IMF and the global star formation processes are the same in metal rich clusters as they are in metal poor ones. A good example is the metal-rich, barred starburst NGC 3049. HST observations done with STIS/MAMA (FUV) indicate that most of the UV light is emitted within the central arcsecond. The wind lines detected in the spectrum indicate that the cluster(s) in the inner 50 pc formed 3-4 Myr ago in an instantaneous burst. Even though the metallicity of the stars is supersolar, stars more massive than

50 $M_\odot$ form in the cluster(s) (González Delgado et al. 2002). This result has been confirmed by Chandar et al. (2003b) for other metal-rich starbursts. HeII λ1640 has been detected in these objects, indicating the presence Wolf-Rayet stars in these starbursts. This finding provides an additional evidence of the population of the upper part of the IMF in high metallicity starbursts.

Diffuse UV light. The main results in this topic come from high spatial observations taken with HST+STIS. The narrow slit (~0.1-0.2 arcsec) capability of STIS is needed to isolate the stellar clusters light from the diffuse component. Tremonti et al. (2001) have obtained long slit spectra of several stellar clusters plus the inter-cluster regions of diffuse light in the low-metallicity galaxy NGC 5253. They find that the UV light of clusters and that of the diffuse component have different spectral properties. The clusters are well fitted by an instantaneous burst with ages of several Myr that follow a Salpeter IMF extending up to 100 $M_\odot$. However, the field spectrum is better fitted by continuous star formation models with either M_{up}=30 $M_\odot$ or an IMF slope steeper than Salpeter's. Alternatively, the field stellar population could be formed following a Salpeter IMF but older than the clusters. Similar results have been obtained by Chandar et al. (2005) for a sample of starbursts. They propose that if the field is composed of older, dissolving clusters, they have to dissolve on timescales 7-10 Myr to create the field. If the field is composed of young clusters that are unresolved in the STIS observations, they would consist only of a few 100 $M_\odot$ in order to be deficient in O stars. However, sampling effects in the IMF (Cerviño et al. 2002) must be taken into account before obtaining any realistic conclusion.

Lyman break galaxies. The UV-rest frame spectra of LBGs have been obtained from the ground with ~10m class telescopes. These spectra are quite similar to local starburst galaxies in the sense that they are dominated by absorption lines (e.g. Shapley et al. 2003; Noll et al. 2004). They have strong high- and low-ionization interstellar lines that are thick in their cores. Photospheric and wind lines are also present. But, most of the high-ionization lines are dominated by the interstellar contribution. Probably due to the large spatial extension covered by these observations (1 arcsec=8 kpc at z=2.5, assuming a standard cosmology), the wind profiles of the integrated light look weaker than in many nearby starbursts, suggesting that star formation proceeds continuously, they have older ages, and/or the metallicity is lower.

Because of its gravitationally lensed nature, cB58 has the highest signal-noise rest-frame UV spectrum obtained to date for LBG (e.g. Pettini et al. 2002). Even so, the wind lines can not constrain well the age. The PCygni profiles of CIV and NV are compatible with csf during the last several 10 Myr, and a Salpeter IMF extended beyond 50 $M_\odot$. No evidence exists for a flatter IMF or an IMF deficient in massive stars (Pettini et al. 2000; de Mello et al. 2000). Photospheric lines were detected and they are compatible with a metallicity below solar, 1/4 $Z_\odot$. Spectra for other LBGs have been obtained with much lower signal-noise, and only a few of the individual objects can be analyzed. Composite spectra with the average of more than several dozen objects are more suitable to be studied. The results obtained in this way for LBGs at the 'redshift desert' ($1.4\leq z \leq 2.5$) indicate that these galaxies have stellar properties similar to cB58 (Steidel et al. 2004). But the metallicity can be higher, closer to solar. Mehlert et al. (2005) have found an increase of the average metallicity of bright starbursts with cosmic time (decreasing redshift). A metallicity higher than solar has also been estimated using the photospheric 1425 Å index in the K20 survey (Daddi et al. 2004).

6 Starbursts in AGN

HST ultraviolet observations of Seyferts 2 and LINERs have contributed significantly to establish the role that starbursts play in the active galactic nuclei (AGNs) phenomena. The high spatial resolution provided by HST has been crucial to detect starbursts formed by stellar clusters in the center of galaxies with an AGN. This result implies a significant advance to establish a connection between violent star formation processes and nuclear activity, because in the IUE era, it was assumed that all the UV light obtained in the Seyfert spectra was produced by the AGN. An extended review of the role of UV observations in establishing the nature of AGNs is given elsewhere else in this book by Kollatschny & Ting-Gui.

6.1 Starbursts in Seyfert 2 nuclei

According to the unified scheme of AGNs, the main components of a Seyfert nucleus are: 1) A super-massive black hole and its associated accretion disk. 2) A circumnuclear dusty torus that collimate the AGN radiation through its polar axis. So, a Seyfert 2 nucleus should be a Seyfert 1 that is viewed close to the equatorial plane. This torus will facilitate the detection of starbursts in the cirmunuclear region, blocking away the continuum radiation from the AGN. 3) A mirror of dust and warm electrons located along the polar axis of the torus, that reflects and polarizes the AGN radiation. Seyfert 2 nuclei exhibit a featureless continuum (FC) that comprises much of the near-UV. It was long-thought that this FC was light from the hidden Seyfert 1 nucleus. However, optical spectropolarimetry (Tran 1995) showed that this is not the case. Cid Fernandes & Terlevich (1995) proposed that a heavily-reddened starburst provides this FC.

Because of the high sensitivity of UV wavelengths to the presence of massive stars, HST UV observations were done to prove the role of starbursts in Seyfert 2 nuclei (Heckman et al. 1997b; González Delgado et al. 1998b). HST high spatial resolution (0.014 arcsec/pixel sampling) imaging shows that the UV continuum source is spatially extended ($\sim$ 100 pc) and it is resolved in knots with sizes of a few parcsecs and properties similar to the stellar clusters detected in starburst galaxies (Figure 6). GHRS spectra for four galaxies, corresponding to the central $\sim$ 100 pc, were obtained. These galaxies were selected to have high UV surface brightness. The data provided direct evidence of the existence of a nuclear starburst. Absorption features formed in the photospheres and in the stellar winds of massive stars are detected (Figure 6). Interstellar lines blueshifted by a few hundred km s^{-1} with respect to the systemic velocity are also detected, indicating an outflow driven by the nuclear starburst (see section 7). Their UV colors indicate that the starburst is quite reddened. Their bolometric luminosities are similar to the estimated luminosities of the hidden Seyfert 1 nuclei.

Subsequently, near-UV and optical spectra of a large sample of Seyfert 2 were obtained proving the unambiguous identification of circumnuclear starburts in ∼40% of nearby Seyfert 2 galaxies as well as their energetic significance (González Delgado et al. 2001; Cid Fernandes et al. 2001).

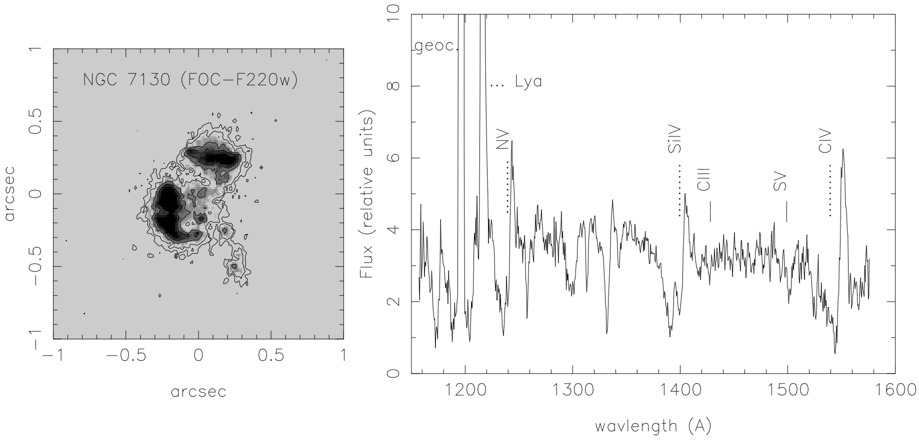

Figure 6: UV image and nuclear spectrum of the Seyfert 2 galaxy NGC 7130 taken with HST+GHRS and 1.74×1.74 arcsec aperture. The UV light is dominated by the nuclear starburst that has an effective radius of ∼ 80 pc. See González Delgado et al. 1998b for further explanations.

6.2 Starbursts in LLAGNs

Low-luminosity active galactic nuclei (LLAGNs) constitute a significant fraction of the nearby AGN population. These include LINERs, and transition-type objects (TOs, also called weak-[OI] LINERs) whose properties are in between classical LINERs and HII nuclei. LLAGNs comprise ∼ 30% of all bright galaxies and are the most common type of AGN (Ho, Filippenko & Sargent 1997). What powers them and how they fit in the global picture of AGN has been at the forefront of AGN research for over two decades. Are they all truly "dwarf Seyfert galaxies" powered by accretion onto a nearly dormant super-massive black hole, or can some of them be explained at least partly in terms of stellar processes?

HST observations at UV wavelengths of a few LLAGNs have also proven that at least weak-[OI] LINERs could be powered by young massive stars (Maoz et al. 1998; Colina et al. 2002; Gabel & Bruhweiler 2002). Nuclear stellar clusters are detected in these objects through high spatial resolution UV imaging and spectra. NGC 4303 is probably the best example of the few objects observed (Colina et al. 2002). STIS imaging (0.027 arcsec/pixel sampling) shows that the nuclear knot has a size of only a few parcsecs and its spectrum (taken with a slit width of 0.2 arcsec) shows characteristic broad P Cygni lines produced by the winds of massive young stars. These features are quite similar to those detected in the spectra of stellar clusters located in the starburst ring (Figure 7). The line profile analysis suggests that the nuclear cluster formed in an instantaneous burst 4 Myr ago with a mass of 10^5 $M_\odot$.

HST UV monitoring observations of 17 LLAGNs have detected variability with amplitudes from a few percent to 50% (Maoz et al. 2005). The variability is more frequently detected in those LINERs that have a compact radio core, as expected from bona fide AGNs.

Subsequent optical studies of a large sample of LLAGNs have shown that the contribution of an intermediate age stellar population is significant in TOs (González Delgado et al. 2004). Unfortunately, the premature death of STIS has not allowed us to find out the fraction of LLAGNs that have a young nuclear stellar cluster like NGC 4303 and which are "dwarf Seyfert galaxies" like those that show UV variability.

7 Interstellar lines: Starburst outflows

The large-scale outflow of interstellar material is a generic property of starbursts, since it is a consequence of the high star formation activity in these galaxies. Outflows are driven by the mechanical energy provided by the combined effect of stellar winds and supernovae in the starburst. Only a few Myr after the onset of the star formation in the starburst, the massive stars start to explode as supernovae. Hot gas bubbles (superbubbles) form inside the starbursts due to the deposition of mechanical energy. The hot gas expands, preferably along the direction perpendicular to the galaxy disk, sweeping up ambient material. When the superbubble reaches several vertical scale heights of the galaxy, Rayleigh-Taylor instabilities develop, and the wall of the bubble can dissipate. This allows the interior of the hot gas to blow out into the galactic halo in the form of a collimated bipolar outflow, called superwind (e.g. MacLow et al. 1989; Tenorio-Tagle & Muñoz-Tuñón 1996). These outflows can accelerate the ambient halo gas, producing the bipolar regions of emission lines detected in the spectra of

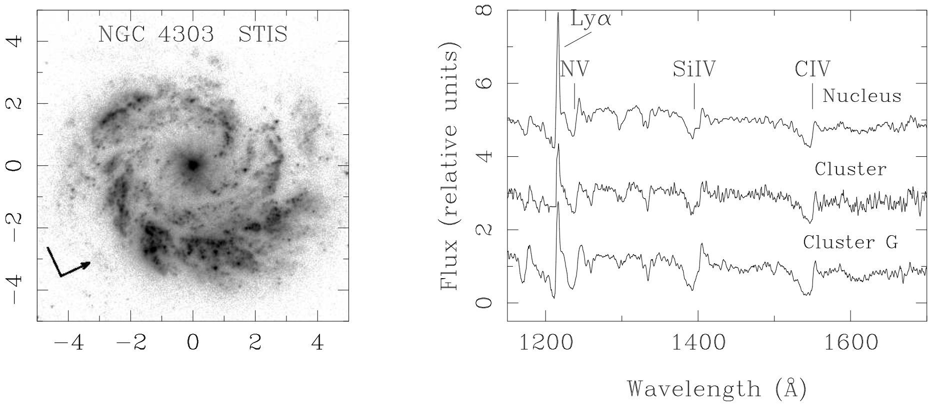

Figure 7: UV image and spectra of the LLAGN NGC 4303 taken with HST+STIS/MAMA. The nucleus has a compact cluster of 3 pc size. The spectrum of the nuclear cluster is quite similar to the stellar clusters in the ring. See Colina et al. 1998b for further explanations.

many starbursts at optical wavelengths, as well as the blueshifted interstellar absorption lines at UV.

Thus, outflows are ubiquitous phenomena not only in nearby starbursts, but also in LBGs. Note that, at some evolutionary phases of the starburst (ages older than 10 Myr if the starburst formed in a burst), the mechanical luminosity injected into the interstellar medium can dominate over the ionizing luminosity (Leitherer et al. 1992), becoming almost the only heating source of the interstellar medium. Outflows might also be the main source of chemical enrichment of the intergalactic medium, because they can blow out and escape from the gravitational potential of the galaxy, venting the metals produced by massive stars into the intergalactic medium. Outflows constitute an important energy source for the evolution of galaxies through the heating and enrichment of the interstellar and the intergalactic media.

UV is the perfect wavelength range to study the neutral, cold and warm phases of outflows. FUV is also useful to study the coronal phases, being the observations in this spectral range complementary to the X-ray data. Lyα emitting gas traces the neutral HI outflows (cf. section 8 below); low (e.g. CII, SiII) and high-ionization (CIV, SiIV, NV) interstellar lines trace the cold and warm phases, respectively, while interstellar OVI traces the coronal phase. GHRS+HST, HUT and FUSE spectra of nearby starbursts have contributed significantly to our understanding of the different outflow phases.

Dusty outflows have been detected through near and FUV images of the halo of the nearby starburst galaxies M82 and NGC 253 taken with GALEX (Hoopes et al. 2005). The UV luminosity in the halo is too high to be provided by continuum and line emission from shock-heated or photoionized gas. They find that the UV halo light may be stellar continuum of the starburst scattered into our line of sight by dust in the outflow.

One critical point related with the outflows is to know which fraction of the kinetic energy supplied by supernovae is radiatively lost and which fraction is carried out into the outflow. If radiative cooling is not negligible, outflows can break out and are able to escape from the gravitational potential of the galaxy injecting metals into the intergalactic medium. This process is relevant for the evolution of starbursts and the intergalactic medium. A study of the different phases of the outflows is needed to settle its relevance.

Cold phase. Most starbursts have low-ionization absorption lines with equivalent widths of several Å. These lines are optically thick, and they are in the flat part of the curve of growth. This means that the equivalent width of these lines is not proportional to the column density of the gas, as would be the case if they were in the linear part of the curve of growth. In fact, these lines are saturated because the ratio of the equivalent widths of two transitions of the same ion is not proportional to the ratio of the $f\lambda^2$ of each transition, where λ is the rest-frame wavelength of the transition and f the oscillator strength. Instead, the equivalent width is determined by the velocity dispersion of the gas, and therefore an equivalent width of 2-3 Å implies a velocity dispersion larger than 200-300 km s^{-1}. This may indicate that several unresolved velocities are observed. This is the first evidence suggesting that the interstellar lines are not virialized but rather they are related with large-scale motions.

Other evidence of the large-scale motions of the interstellar gas in starbursts comes from the broadening of the low-ionization interstellar lines. The line profiles are asymmetric, and when observed at high spectral resolution, they are resolved into several interstellar components (González Delgado et al. 1998a).

An additional and the strongest evidence for outflows comes from the radial velocity of the lines. Many starbursts show the low-ionization lines, such as SiII λ1526, CII λ1335, SiII λ1260, blueshifted by several hundred km s^{-1} with respect to the systemic velocity of the starburst determined with the photospheric lines, or with respect to the HI systemic velocity of the galaxy (e.g. González Delgado et al. 1998a). Because these interstellar lines cover more than 50% of the UV light, they cannot be produced by isolated clouds, and they must be associated with a galactic-scale outflow. The shift to blue wavelengths detected in these lines is an unequivocal prove of the outflows in these galaxies.

Warm and coronal phases. High-ionization interstellar lines, such as NV λ1240, SiIV λ1400, and CIV λ1550, can trace warm ionized gas outflows which are at $T \geq 10^4$ K. This gas is ionized by radiation from the massive stars in the starburst as well as by collisional processes associated with the outflow. However, measuring the blueshift of these lines is more difficult than in the low-ionization lines. This is due to the difficulty in isolating the wind and the interstellar components of these lines in intermediate spectral resolution observations. But when the starburst is not in a wind phase, and/or the spectral resolution is better than 100 km s^{-1}, the blueshift of the line is also a measure of the outflow speed.

The hot phase gas is traced by the OVI $\lambda\lambda$1032,1038 interstellar component. OVI could arise from collisionally ionized gas with $T \geq 10^5$ K. OVI has been detected in a sample of nearby starbursts observed by FUSE. The center of the lines is blueshifted by several 100 km s^{-1}. The lines are also very broad, with maximum outflow speeds of $\sim$ 1000 km s^{-1} (Heckman 2004).

These two outflow phases have been measured in the nearby dwarf starburst galaxy NGC 1705. This galaxy hosts a 12 Myr old super star cluster (Vázquez et al. 2004). Outflows in the warm phase were detected in the SiIV high-ionization lines by Heckman & Leitherer (1997a). More recently, FUSE observations have shown that the warm gas outflow has a lower velocity ($\sim$ 50 km s^{-1}) than the coronal interstellar gas ($\sim$ 80 km s^{-1}, Heckman et al. 2001a). The kinematics of the warm gas is compatible with a model of an adiabatic expansion of the superbubble driven by the kinetic energy supplied by the supernova. However, the expansion speed of the superbubble is too small to produce OVI behind its shock front. Instead, the column density and velocity of the OVI is compatible with a model in which the superbubble has begun to blow out of the interstellar medium of NGC 1705. OVI absorption is produced during the blowout phase, in which the superbubble shell is accelerated and fragmented. The interaction between the outflowing gas and the shell fragments create a high temperature coronal gas that produces the OVI absorption. Heckman et al. (2001a) found that the cooling rate in this phase is much less than the supernova heating rate; thus, they concluded that probably the outflow in NGC 1705 is able to blow out and to vent the metals into the intergalactic medium.

8 The Lyα line: outflows of neutral H gas

Lyα in emission can in principle be produced by recombination of hydrogen photoionized by the O and B stars. Massive stars in the starbursts provide enough ionizing photons to produce a large Lyα flux. In fact, evolutionary stellar population models predict Lyα to be the strongest emission feature in the spectra of young starbursts. This is particularly true for primordial galaxies because in the absence of metals the cooling is produced by Lyα and He recombination lines (Schaerer 2002). Lyα has been used to spectroscopically confirm galaxies at high-z. However, many observational programs in the past have failed to find a significant population of primordial galaxies based on the detection of Lyα. The reasons have to be found in the complex structure of the Lyα line.

The complexity of the line was noted more than 20 years ago with IUE. Lyα observations of nearby starbursts show that the line is weaker than the value expected from recombination, and there was a tendency to smaller Lyα/Hβ ratios with metallicity (Meier & Terlevich 1981; Hartmann et al. 1988; Terlevich et al. 1993). Several arguments were proposed:

- Resonance scattering by neutral hydrogen: Lyα photons are attenuated by dust as a result of multiple resonant scatterings by hydrogen atoms that increase the path length of the Lyα photons and thus the probability that they will be absorbed by dust.
- Extinction: The Lyα light is affected by dust more than any other Balmer

recombination line since extinction curves peak in the FUV. In fact, some starbursts have Lyα/Hβ ratio consistent with simple recombination theory if the ratio is corrected for reddening using the appropriate extinction law for the metallicity of the galaxy and the age of the burst is taken into account (Calzetti & Kinney 1992; Valls-Gabaud 1993).

However, these arguments contrast with observations of low metallicity starbursts that are very little extinguished. No Lyα emission was detected in galaxies like IZw18 (Kunth et al. 1994), even though the metallicity and dust content are very low. HUT and HST observations of nearby galaxies have brought new insight into the nature of Lyα (Lequeux et al. 1995; González Delgado et al. 1998a; Kunth et al. 1998; Mas-Hesse et al. 2003; Kunth et al. 2003). GHRS and STIS spectral resolution has been crucial to understand the role played by outflows in the structure of the Lα emission.

- Neutral HI outflows: Many nearby starburst galaxies in which Lyα is detected in emission show an asymmetric profile, with the peak emission redshifted with respect to the systemic velocity, and a deep Lyα absorption is detected blueshifted by several 100 km s^{-1} with respect to the emission (see Figure 8). This shift is in agreement with the blueshift observed in the interstellar lines of the same galaxy. The natural explanation is that the neutral HI gas producing the absorption is outflowing from the starburst.

Tenorio-Tagle et al. (1999) have developed a detailed model to explain the different Lyα profiles, that requires the time evolution of an expanding shell created by the supernova explosions in the starburst. Some of the most relevant phases are:

- An expanding supershell forms by the SN action. Lyα photons will be absorbed by the HI galaxy disk. If the HI column density is very high, Lyα will show an absorption profile centered at the systemic velocity of the galaxy. The starburst in IZw18 is in this phase.
- Rayleigh-Taylor instabilities produce the shell fragmentation, and the shell will blow out. Ionizing radiation escapes into the halo and the IGM, producing an extended biconical emission line region. Lyα will be detected in emission at the systemic velocity of the galaxy. Recombination in the shell will produce an additional Lyα emission blueshifted at the shell expanding velocity. Tol1214 could be in this phase (Mas-Hesse et al. 2003).
- An HI trapped ionization front is formed at the external side of the expanding shell. Lyα photons are absorbed there. Lyα will show a PCygni profile. Backscattering and emission from the receding part of the shell will produce an extended red wing in the Lyα emission. IRAS 0833+6517 is in this phase (see Figure 8).
- Finally the shell is slowed down in its expansion, and it will be completely recombined. A damped Lyα core profile will be observed with only a small blueshift.

Thus, Lyα emission, like the interstellar lines, is driven by the dynamical effects of the violent star formation processes ongoing in the starburst, rather than by the gravitational potential well of the galaxy.

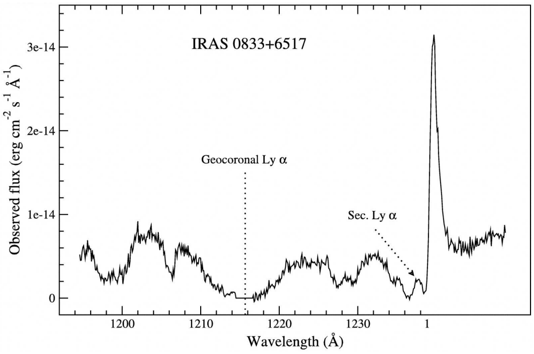

Figure 8: Lyα profile of the starburst galaxy IRAS 0833+6517 taken with HST+STIS/MAMA. Note the PCygni profile of Lyα and a second blueshifted Lyα emission that forms in the expanding shell. (Figure adapted from Mas-Hesse et al. 2003.)

9 Lyman continuum: The escape of ionizing radiation

The origin of the diffuse ultraviolet background that reionized the early universe is still unknown. Quasi-stellar objects (QSOs) are considered one of the main sources. However, QSOs alone cannot account for all the background radiation that maintains the diffuse intergalactic medium and the Lyα forest clouds highly ionized. Two other possible sources are: highly obscured QSOs that cannot be observed because of dust, and a large fraction of high-mass stars formed in primordial galaxies (Miralda-Escudé & Ostriker 1990).

Observations of the Lyman continuum of starbursts have been done to estimate the contribution of massive stars to the reionization of the universe. However, this estimation depends critically on the determination of the fraction of ionizing photons (f_{esc}) that escape from the galaxies and reach the intergalactic medium.

Evidence exists that the HI disks surrounding galaxies may not be totally opaque to the ionizing photons. Bland-Hawthorn & Putman (2001) estimate that 5-10% of the ionizing photons escape from the Milky Way halo. Others (e.g. Castellanos et al. 2002) have found that a significant fraction of ionizing photons may locally escape from the HII regions in nearby galaxies, but it is unknown whether these photons will escape from the galaxies. Starbursts outflows may be an efficient mechanism to open channels in the HI halo disks of the galaxies through which the ionizing photons can escape and reach the intergalactic medium.

HUT and FUSE have contributed significantly in determining the value of f_{esc} in local starbursts. Leitherer et al. (1995b) find, in a small sample of four starburst galaxies, that $f_{esc} \leq 3\%$. Later, Hurwitz et al. (1997) reevaluate f_{esc} applying a detailed model of the absorption by interstellar gas in our Galaxy. They are not able to detect the Lyman continuum flux, but they derive un upper limit $f_{esc} \sim 10\%$. Deharveng et al. (2001) obtained FUSE observations of Mrk54 and found that the Lyman continuum radiation is not detected above the HI absorption edge in our Galaxy. Comparing with the number of ionizing photons derived from the Hα flux, they estimate that $\sim$6% of Lyman continuum photons escape the galaxy without being absorbed by interstellar material. Heckman et al (2001b) also obtained FUSE data of five of the UV-brightest local starburst galaxies. They found that the interstellar line CII λ1036 is essentially black. Because the opacity of the neutral ISM below the Lyman edge is larger than in the CII line, the residual UV intensity of the line can be used to put a constrain on f_{esc}. They found an upper limit of 6%. Thus, local starburst galaxies seem to be very opaque and they leak out only a few percent of their ionizing radiation.

Observations of the Lyman continuum flux in LBGs have provided more discrepant f_{esc} results. Steidel et al. (2001) built a composite spectrum of 29 LBGs at $z=$ 3.4. These galaxies belong to the group of strong Lyα emitters found by Shapley et al. (2003). They estimate $f_{esc} \geq 50\%$. The implication of this result is that LBGs contribute at least as many ionizing photons as QSOs at z$\sim$ 3. However, these results have not been confirmed by others. Giallongo et al. (2002) obtained VLT spectra of two of the LBGs from the sample of Steidel and collaborators. They set an upper limit of 16% to f_{esc}. Lyman continuum has been estimated also from deep HST images of the HDF (Fernández-Soto et al. 2003) and LBGs at 1.1$\leq z \leq$1.4. Both works also found f_{esc} of a few % ($\leq$ 4%). High spectral resolution data are required to better constrain the Lyman continuum flux in LBGs, and to determine whether LBGs are opaque like local starburst galaxies or they are leaking out most of their photons as Steidel et al. estimate.

However, in most of the LBGs the absorption part of the Lyα PCygni profile is completely black. Therefore, the star-forming regions seem to be completely covered by neutral gas, and f_{esc} should be close to zero, unless the covering is not isotropic and the escape is produced along other directions.

Note, however, that many of the nearby starbursts for which f_{esc} has been estimated in a few % also have high-velocity outflows of neutral gas. But these outflows are also an ubiquitous phenomenon in LBGs. Thus, as it was pointed out by Heckman et al. (2001a) these outflows could be a necessary but not sufficient mechanism to open paths within the interstellar medium through which the ionizing radiation can escape.

10 Interstellar lines: Abundances

The large number of line transitions of many different ions that occur at UV wavelengths, makes this spectral range quite suitable to determine the chemical abundances and to study the chemical evolution of galaxies. Because metal transitions that form in the neutral gas phase are common in the UV, this range is quite suitable to determine the chemical abundances of the HI phase. Note, however, that most of our knowledge about the chemical abundances in starbursts comes from the collisional emission lines formed in the ionized gas associated to the HII regions that are observed at optical and infrared wavelengths. Thus, these abundances correspond to the gas ionized phase. This difference between the abundances determined using optical or UV transitions (collisional vs. recombination lines, HII vs. HI) is especially important for the study of the chemical evolution of galaxies and, in particular, for starburst galaxies.

As we pointed out earlier, many of the strongest interstellar lines in the spectra of starburst galaxies observed with an intermediate spectral resolution are saturated. Thus, the strength of these lines is related more with the kinematics of the gas than with the metallicity. But, unsaturated absorption interstellar lines have a suitable information of the gas metallicity. So, when a line is in the linear part of the curve-of-growth, its equivalent width is proportional to the column density of the corresponding species, and the metallicity of the element can be estimated. On the contrary, when the line is in the flat part of the curve-of-growth, the profile is quite insensitive to the abundances. For example, as shown in Pettini & Lipman (1995), the range of possible values of (O/H) admitted by the profile of the saturated OI λ1302 absorption line is very large, spanning a factor of ~1000. Then, only unsaturated, and presumably weak lines with a moderate or low transition-strength, $f\lambda$, are useful to estimate the column density of the ions. Therefore, only with good signal-to-noise and high spectral resolution spectra is it possible to determine the gas abundances.

Different approaches can be followed to determine the column densities of the different ions in starbursts. They are: 1) The curve-of-growth method, which relates the equivalent widths of the lines with $Nf\lambda^2$, where N is the column density. 2) The direct method, based on the fit of the absorption profiles to all the lines in the spectrum arising from transitions of the same ion. 3) The optical depth method. The optical depth is deduced from the observed intensity in the line at velocity v, and then, the column density that best fits the line profile is inferred (Savage & Sembach 1991). Metal abundances are then determined through the column densities and assuming some ionization correction fraction. A hypothesis about the dust depletion has to be made to obtain the final values of the abundances.

Abundances for starbursting dwarf galaxies are easier to obtain than for nuclear starbursts since the former have lower metallicities. Starbursting dwarf galaxies are very interesting systems from the cosmological point of view. According to the hierarchical galaxy formation scenario, dwarf galaxies could be the building blocks of larger and massive galaxies that formed by merging. Thus, local starbursting dwarf galaxies could be considered the closest analogue to primeval galaxies. Local starbursting dwarf galaxies are gas rich and chemically relatively unevolved objects, as their low abundances indicate. They have HII region abundances between ∼1/50 to 1/3 $Z_\odot$, which are certainly not primordial. But Kunth & Sargent (1986) suggested that the ionized gas could be enriched with metals ejected by supernovae in a very short time-scale, the time-scale of a burst of star formation. Then, the HII abundances would not necessarily reflect the actual abundance of the HI phase, being the former lower if self-pollution is important. However, this hyphotesis is not supported by Tenorio-Tagle (1996) that predicts a larger time-scale for the mixing of supernova ejected metals with the interstellar medium. This time-scale would be of the order of several 10^8 yr.

FUV observations of nearby starbursting dwarf galaxies taken with FUSE have contributed significantly to test if these galaxies are primeval, experiencing their first burst of star formation (Thuan et al. 2002; Lecavelier des Etangs et al. 2004; Aloisi et al. 2003; Lebouteiller et al. 2004; Aloisi et al. 2005; Cannon et al. 2005). These works agree in finding lower α element abundances in the neutral HI gas phase than in the HII regions. However, because these abundances are not really primordial, starbursting dwarf galaxies are not experiencing their first burst of star formation, and they are not primeval galaxies.

UV interstellar lines have also been used to estimate how chemically evolved are high-z star forming galaxies. In contrast to local starburst galaxies, HII region abundances are not known for LBGs, since collisional lines at the rest-frame optical wavelengths have not been observed yet for a significant population of high-z star forming galaxies. Neutral gas phase abundances have been determined for cB58 (Pettini et al. 2002). They found that the interstellar medium of this galaxy is highly enriched in elements released by type II supernovae, with abundances of O, Mg, Si, P and S $\sim 2/5$ $Z_\odot$. But, N and Mn, Ni and Fe are underabundant by a factor ∼3. Because these elements are produced by intermediate-mass stars, the enrichment in cB58 has probably taken place within the last 300 Myr, which is the lifetime of these stars and the release time scale for N.

Savaglio et al. (2004) have estimated column densities of Fe, Mg and Mn for a sample of 13 galaxies at redshifts $1.3 \leq z \leq 2$. These column densities are similar to those derived for cB58. But they are considerably larger than typical values in damped Lyα systems. Making a rough estimation of the HI column density and assuming a moderate Fe dust depletion, they estimate an abundance of 1-0.2 $Z_\odot$. Then, these galaxies are also metal-rich.

11 Summary and Future Prospects

IUE has made an important initial contribution to our knowledge of starbursts providing the first high quality UV spectra; however, most of our actual knowledge about UV in nearby starbursts comes from HST and FUSE observations. Along this paper, we have emphasized the contributions of high spatial (≤ 0.025 arcsec/pixel) resolution imaging and intermediate (~ 100 km s^{-1}) dispersion spectra taken with FOC, GHRS and STIS in the UV, and the high-resolution spectra with FUSE in the FUV (1200 Å down to the Lyman break). A significant progress has been made in the determination of the stellar content of starburst galaxies and the physical, chemical and dynamical properties of the interstellar medium in these galaxies. In particular, it has been possible to advance in our understanding of the role that stellar clusters play in starbursts and AGNs only thanks to the high spatial resolution of the imaging and spectral observations taken with the instruments on board HST. Stellar clusters have sizes of a few pcs, so they can be isolated from the background radiation in very nearby starbursts if they are observed with resolution better than 0.1 arcsec.

During the next few years, the GALEX mission will certainly provide the means for an important progress in the study of the cosmic evolution of starburst properties, as well as providing a larger sample of local starbursts. But the limited capabilities of its spectroscopic mode (low spatial and spectral resolution and sensitivity) will not help to progress in understanding most of the physics that regulates the violent star formation processes in galaxies. Spatial resolution below 0.1 arcsec is needed to isolate the UV light of the center from the disk in the UV bright galaxies discovered by GALEX at z=0.1-0.3. This resolution can provide in these galaxies a spatial sampling better than 500 pc which is the typical size of nuclear starbursts.

Thus, the lack of any actual (or scheduled) UV mission with a high spatial (better than 0.1 arcsec) and intermediate (better than 100 km s^{-1}) spectral resolution long slit spectrograph and a high spatial resolution imager with high sensitivity will slow down the progress in our knowledge of starbursts, and of their impact on the origin and evolution of galaxies.

There are still many open questions in starburst galaxies that need to be answered through space UV observations. Some of them, listed below, have been proposed by experts in the field.

Dr. Veronique Buat

- GALEX will observe thousands (and even millions) of galaxies in its imaging mode and new classes of objects will certainly be discovered, an example are the local ($0.1 \leq z \leq 0.3$) UV luminous galaxies (Heckman et al. 2005). The UV spectroscopic follow-up of these GALEX sources detected in the broad NUV and FUV bands is of prime importance. Indeed, the FUV-NUV color only gives a very crude estimate of the shape of the UV continuum, especially at high redshift (Burgarella et al. 2005). The GALEX capabilities in the spectroscopic mode are only limited to the brightest objects. The combined effects of the star formation history, the IMF and the interstellar dust will only be quantified with intermediate resolution spectra to model the SED between 1000 and 3000 Å.

- Our knowledge of the UV spectral distribution of starburst galaxies relies almost entirely on the IUE observations of bright nearby starbursting objects. But the IUE aperture can cover only the central starburst of many of the most nearby galaxies. The recent photometric observations of GALEX not only confirm that the UV characteristics of the central starbursts are not valid for normal star forming galaxies (cf. section 4) but also show that these central properties may well not be representative of the entire starbursting galaxies: the interplay of the star formation history and the dust attenuation are likely to modify the UV spectrum in a rather complex way varying from place to place even in starburst galaxies. Unfortunately, the spectral capabilities of GALEX (slitless mode) will not allow us to carry out a detailed analysis of the UV spectral energy distributions in various media. The ideal mode for such studies is integral field spectroscopy on a large field with medium resolution (or at least slit spectroscopy) in order to be also sensitive to the diffuse emission.

Dr. Rosa M. González Delgado & Dr. Luis Colina

- There are still many open questions related with the starburst-AGN connection. In particular, the role that young stellar clusters play in the energetics of AGNs; the frequency of nuclear young stellar clusters in AGNs; their properties (luminosities, masses, ages, IMF, metallicities, etc). High spatial resolution spectroscopy is needed to isolate stellar clusters (of a few pc size) in the region where the dynamical influence of the black hole is significant, within 10 pc of the Seyfert nuclei (Ferrarese et al. 2001). Intermediate spectral resolution (better than 100 km s^{-1}) is needed to isolate the interstellar from the stellar component of the high ionization UV lines.

Dr. Claus Leitherer & Prof. Timothy Heckman

- Is there direct evidence for macroscopic turbulence in the ISM? Interstellar absorption lines are thought not to indicate gravity but rather stirring by winds and supernovae. Testing this hypothesis requires spectrographs with resolving power of tens of thousand and higher sensitivity than, e.g., STIS. Such data would allow us to probe the kinematic structure and morphology of the ISM and construct a kinematic model for all its phases, including the outflow.

- Do starburst galaxies enrich the IGM in metals? There is paramount evidence for the existence of large-scale galactic superwinds transporting the nucleosynthetic products out of the star-forming regions into the galaxy halos. The question of material actually escaping from starburst galaxies is still unanswered. The next generation of spectrographs will need higher sensitivity to probe starburst galaxy environments out to tens of kpc using background quasars. This could be a decisive test of the metal escape likelihood and IGM enrichment.

Dr. J. Miguel Mas-Hesse

- The emission of Lyα photons is of paramount importance to study star formation episodes at redshifts $z \geq 2$, when the line becomes visible in the optical range, and Hα is already shifted to the NIR. As discussed in Sect. 8 the visibility of the line depends on several factors, including the distribution and kinematics of the neutral gas, the covering by dust,... Understanding the process of emission and absorption of Lyman alpha photons requires not only spectroscopy, but also imaging, especially if combined with Hα imaging of the same region. Kunth et al. (2003) and Hayes et al. (2005, A&A, in press [astro-ph/0503320]) have shown that it is possible to obtain Lyα emission maps of starburst galaxies, though the instrumental setup of HST/ACS was not optimized for it.

The process of Lyα emission and absorption could be better understood by performing imaging observations of starburst galaxies at redshifts z = 0 to 1, looking for correlations between the visibility of the line and the morphology, evolutionary state, size or metallicity of the different galaxies. This could be achieved with an UV imaging camera with the adequate set of narrow/broad band filters covering the 1200 - 2400 Å range. Complementary Hα observations at this redshift range could be obtained from ground.

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