STAR FORMATION IN STARBURST GALAXIES

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Abstract

Some of the basic properties of star formation in starburst galaxies are reviewed. I discuss triggering and termination mechanisms in starbursts and provide estimates of star-formation rates. Galaxies with ongoing star formation at low and high redshift are compared.

Key words: ISM: HII regions – galaxies: star clusters – galaxies: interaction – galaxies: starburst – galaxies: stellar content

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1. Introduction: How To Find Starburst Galaxies

Mapping the history of star formation in the universe from the early generations of stars to the present has been one of the major achievements of the past years (Madau et al. 1996; Calzetti 1999). While the average star-formation rate (SFR) versus redshift relation suggests a smooth, global star-formation process, a significant fraction of stars forms in short, episodic events. Such *starbursts* are the subject of this paper. In the local universe they account for about a quarter of all star formation (Heckman 1997a), and this fraction may be larger in the younger universe. Therefore local starburst galaxies may help us understand the star-formation process in the distant universe as well.

Star formation in starburst regions is limited to durations of less than about 10^8 yr. Observational evidence comes from, e.g., color-magnitude diagram analyses of local resolved galaxies (Grebel, this conference), estimates of outflow timescales of starburst driven winds (Heckman et al. 1990), or galaxy statistics (Balzano 1983). In order to qualify as a starburst, galaxies require SFRs of at least an order of magnitude above the SFR in the field outside the starburst region. Terlevich (1997) gives a comprehensive categorization of starbursts and "normal" galaxies.

Most starburst galaxies are found in ultraviolet/blue (Markaryan 1967; Balzano 1983), emission-line (Terlevich et al. 1991; Gallego et al. 1995), and far-infrared (Soifer et al. 1987; Rowan-Robinson et al. 1999) surveys. Each of these techniques is sensitive to the copious ionizing and non-ionizing photons produced by young, massive stars — either by direct detection of stellar light, or by radiation reproduced by gas and dust. A summary of the detected galaxy types and specific examples are in Table 1.

Essentially all systematic surveys of starbursts trace the most recent star formation over timescales of $\sim 10^8$ yr. It is therefore a matter of definition and selection effects to categorize "post-starburst" galaxies. These are commonly considered galaxies which underwent a previous starburst episode but have no longer a significant OB-star population. The so-called E+A galaxies (Dressler & Gunn 1983) may belong into this category.

Table 1. Starburst galaxy types detected in different surveys.

Survey type	emission line	far-infrared	ultraviolet
diagnostic	gas	dust	stars
stellar mass	50 $M_\odot$	20 $M_\odot$	10 $M_\odot$
timescale	5 Myr	20 Myr	50 Myr
galaxy type	HII, BCD	$> L_\star$, pec	SB nuc, Sd
example	I Zw 18	Arp 220	NGC 7714

2. Triggering and Termination of Starbursts

2.1. Triggering

The suggestion that gravitational interaction (not necessarily merging) of galaxies leads to enhanced star formation or even starburst activity has been made soon after the recognition of the starburst phenomenon. Larson & Tinsley's (1978) classical study of a normal and peculiar (Arp) sample of galaxies demonstrated that recent (timescale of about 10^8 yr) star formation is more likely to occur in interacting than in non-interacting galaxies.

The fraction of interacting galaxies and — in the most extreme cases — of mergers increases with the observed far-infrared luminosity (Sanders 1997), the latter being a direct measure of the SFR (Schaerer 1999). About 10% of galaxies with far-infrared luminosities less than 10^{11} $L_\odot$ are in interacting/merging systems. Above 10^{12} $L_\odot$ this fraction becomes almost 100%. This is, however, an upper limit to the occurrence of starbursts since an unknown fraction of ultraluminous galaxies is powered by an active galactic nucleus, rather than a starburst.

Barton et al. (1999) used the CfA2 survey to define a sample of galaxies in close groups and searched for evi-

Proc. of 33rd ESLAB Symp. *"Star formation from the small to the large scale"* (F. Favata, A. A. Kaas & A. Wilson eds., ESA SP-445, 2000)

dence for tidally triggered star formation. They found an anti-correlation between the Hα equivalent width (indicating the SFR) and spatial and velocity separation (indicating age and strength of the interaction). This result is consistent with interaction leading to enhanced star formation over tens to hundreds of Myr.

In addition to statistical studies of the previous type, numerous morphological studies of individual galaxies have revealed the fossil remnants of interaction/merging activity. For instance, Smith et al. (1996) discuss shell and ripple patterns in the classical ultraviolet-bright starburst galaxy NGC 3310. These patterns are attributed to earlier accretion of a low-mass companion galaxy.

Not all starburst galaxies show evidence for prior interaction/merging. In some cases the interacting partner galaxy may simply not have been detected, but this does not apply to all isolated starburst galaxies. Therefore starbursts are not only related to the dynamical effects of other galaxies but additional, self-contained internal processes are required. The two most likely processes capable of stirring and moving cold molecular gas to star-formation sites are instabilities in nuclear bars (Shlosman 1990) and energy injection from winds and supernovae (Heckman et al. 1990).

2.2. Termination

At some point the starburst terminates. As explained before, this typically occurs within less than 10^8 yr. A hard upper limit to the starburst duration can be derived from the timescale of the exhaustion of the gas reservoir to form stars. This argument can even be used to *define* a starburst in terms of the exhaustion timescale versus the Hubble time (Weedman 1987). For a specific example consider a luminous starburst galaxy with a star-formation rate of 100 $M_\odot$ yr^{-1} (see Heckman et al. 1990). After 10^8 yr, more than 10^{10} $M_\odot$ of stars have been generated, which starts exceeding the total HI masses in typical $L_\star$ galaxies.

The previous estimate strongly depends on the formation rate of low-mass stars, a quantity which is difficult to determine observationally. If such low-mass stars do not form and the stellar initial mass function (IMF) is “top-heavy” (Rieke et al. 1980), the time to exhaust the gas reservoir can be increased by a factor of several (Leitherer 1998).

Even without the previous IMF argument it is easy to argue that a closed-box model for a starburst is too simplistic for an estimate of the available gas reservoir. Both infall and outflow should be taken into account.

Figure 1 shows the cumulative mass return for a typical starburst as a function of time (Leitherer et al. 1999). Massive stars return about 50% of the gas consumed for star formation back to the interstellar medium. Unless a substantial low-mass star population is formed, this figure suggests that in principle the starburst can last for up to a Hubble time since the gas is returned almost instantaneously. Of course, most of this gas will be heated due to the wind interaction with the ambient interstellar gas and may not be entirely available for further star formation.

In addition to this additional *source* of interstellar material, winds and supernovae act as *sinks* as well. They are capable of initiating large-scale outflows of interstellar gas via so-called galactic superwinds (Chevalier & Clegg 1987; Heckman 1997b). Pettini et al. (2000) estimated the mass-loss rate of the interstellar medium of the high-z star forming galaxy 1512-cB58 to be about 60 $M_\odot$ yr^{-1}. Interestingly, this is comparable to, or even larger than the derived SFR of 40 $M_\odot$ yr^{-1}. Taken at face value, this results suggests that the available gas reservoir will not only be depleted by the star-formation process but, more importantly, by removal of material due to galactic-scale outflows.

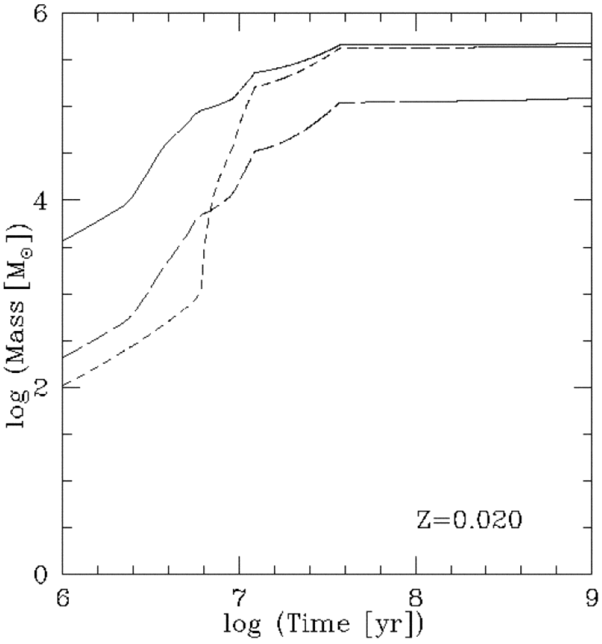

Figure 1. Mass return from winds and supernovae of a single stellar population versus time. Total initial stellar mass: 10^6 $M_\odot$; solar metallicity; Salpeter IMF with lower and upper mass limits of 1 and 100 $M_\odot$, respectively; from Leitherer et al. (1999).

The case of 1512-cB58 is not clear-cut since the measured outflow velocities and the estimated galaxy mass leave open the possibility that the wind material does not escape from the galaxy but will eventually stall and be retained. A more convincing case may be the local blue compact dwarf galaxy He 2-10 (Johnson et al. 2000). As for 1512-cB58, a mass-loss rate similar to the SFR is derived. In Figure 2 the HST/GHRS ultraviolet spectrum of He 2-10 is compared to a synthetic model for an instantaneous burst of age 4 Myr. Apparently all *stellar* photospheric and wind lines are reproduced extremely well by the model. Compare, for instance, the blue wings of the Si IV λ1400 and C IV λ1550 wind lines, the standard indicators for massive stars. On the other hand, C II λ1335, Si II λ1526, and the deep, narrow absorption components of Si IV λ1400 and C IV λ1550 are much broader and more blue-shifted in the observations than in the model. The lines are purely interstellar, arising in an outflow from the starburst. The sharp interstellar lines seen in the model spectra can be used to measure the outflow velocity in He 2-10, suggesting a bulk motion of at least –360 km s^{-1}. Since the expansion velocity exceeds the escape velocity, the material will most likely not be retained by the gravitational well.

If the results for He 2-10 apply to starburst galaxies in general, galactic superwinds are an important, or even the dominant regulation mechanism for the duration and termination of the starburst.

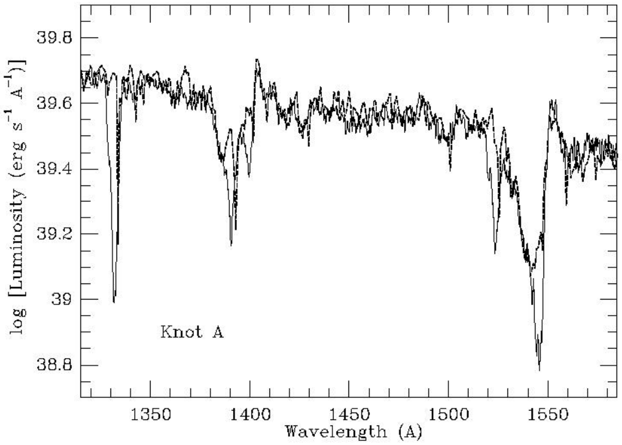

Figure 2. HST/GHRS spectrum of He 2-10. The dashed spectrum is a model fit to the broad *stellar lines. The* narrow *interstellar lines are offset by ~360 km s^{-1}.*

3. Quantifying Star Formation in Starbursts

In this section I will address the observed star-formation rates in starburst galaxies and their dependence on time, space, and host galaxy properties. For a general review of the different techniques to derive SFRs in starburst galaxies, see Schaerer (1999).

3.1. Time dependence

When observed at higher and higher spatial resolution, starburst regions split into individual "cells". These cells may be the smallest natural unit of a starburst, containing a single stellar population. An example is shown in Figure 3. The nuclear region of the starburst galaxy NGC 3049 splits into several individual massive star clusters, each being much more luminous than R136, the center of the 30 Doradus region in the Large Magellanic Cloud. It is likely (but yet unproven) that individual clusters have different ages as a result of propagating star formation. The star forming regions LH9/10 in the LMC are local analogs (Walborn & Parker 1992).

Extensive studies of Galactic and LMC/SMC star clusters and OB associations have demonstrated that star formation occurs almost instantaneously (Massey et al. 1995). Typical age spreads are about 2 Myr or less. This is short in comparison with stellar evolutionary timescales, except for the most massive stars. Observations of more distant starburst regions which can no longer be resolved into individual stars are consistent with the local results *as long as the spatial resolution is high enough to isolate the starburst cells.* The strongest support comes from Wolf-Rayet galaxies, which contain a population of Wolf-Rayet stars, the short-lived descendants of O stars (Kunth & Joubert 1985; Conti 1991). The observed strength of their spectral features in these galaxies can only be understood if we observe a single stellar population just at the right time when Wolf-Rayet stars are present. Photoionization models for the ionized gas argue against extended star formation as well. The measured line strengths in HII galaxies are inconsistent with non-coeval populations (Dopita, private communication).

3.2. Space dependence

Studying the space dependence of star formation in starburst galaxies is a challenge. Even the closest starbursts are at distances of at least a few Mpc. Therefore the resolution is often limited to tens or hundreds of pc.

Spatially resolved infrared spectroscopy in M82 and M83 (Satyapal et al. 1997; Puxley et al. 1997) permits mapping the age and space distribution of the newly formed stars. Comparison with evolutionary synthesis models then gives the relative and absolute ages of the star forming regions. Eventually, the propagation speed of star formation can be derived. Typical values are of order 50 to 100 km s^{-1}. This velocity sets the coherence length over which individual starburst regions can communicate and the starburst can be synchronized.

If a starburst region is observed with an aperture whose size exceeds the coherence length, individual starburst cells are unlikely to communicate and should have random age. Observationally, quasi-continuous star formation is mimicked. This test was performed by Calzetti (1997) who

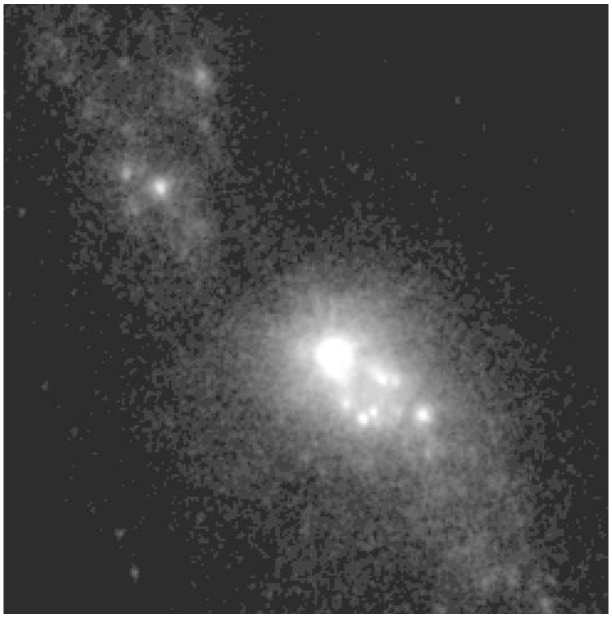

Figure 3. HST/STIS ultraviolet (~1600 Å) image of the center of the nuclear starburst NGC 3049. The field size is about 600 pc by 600 pc. The nuclear region is dominated by one luminous starburst cluster having less than 5 pc diameter. Several less luminous clusters are present as well (Leitherer et al., in preparation).

performed multi-wavelength observations of a sample of starburst galaxies through large, matching apertures. Utilizing spectral diagnostics which are sensitive to younger and older stars, mixed populations were found.

3.3. SFRs and relation to the host galaxy

SFRs are notoriously uncertain (see Schaerer 1999). Recall that the observed quantity is the photon generation rate at some wavelength whereas the desired quantity is the total mass conversion rate from gas into stars. Assumptions and models are required for stellar atmospheres (to extrapolate from monochromatic to bolometric fluxes), for stellar evolution tracks (to compute a mass-luminosity relation and its time dependence), and for the IMF (to estimate the mass contribution of those stars not directly observed). Furthermore, if stellar light is not observed, some assumption on the properties of gas and dust must be made. These caveats should be kept in mind for the following discussion.

Starburst galaxies exhibit a broad range of SFRs, with typical values ranging between 0.1 and 10 $M_\odot$ yr^{-1} kpc^{-2}. This is very similar to the *total* SFR of the Milky Way but recall that starbursts have sizes of less than about 1 kpc. The SFR per unit surface in starburst regions is orders of magnitude higher than in the Milky Way. For comparison, the average star-formation density in the Galaxy is 10^{-3} – 10^{-2} $M_\odot$ yr^{-1} kpc^{-2}.

Starburst galaxies with the highest SFRs tend to be metal-rich, nuclear starbursts. The highest rates are observed in infrared-luminous galaxies, whose rates can reach up to 10^3 $M_\odot$ yr^{-1} kpc^{-2}. This is close to the maximum rate possible if the entire gas reservoir is converted into stars on a dynamical timescale.

It is instructive to correlate the SFR per unit surface area with the gas density per unit surface area in starburst galaxies (Kennicutt 1998). The two quantities correlate with little scatter over the entire range of observed SFRs. Moreover, they form a smooth extrapolation of the power law derived for the nuclei of normal disk galaxies towards higher density. Starbursts follow a classical Schmidt law with a power-law exponent of $n = 1.4$. This suggests that the SFR in starburst galaxies is high because the gas density is high.

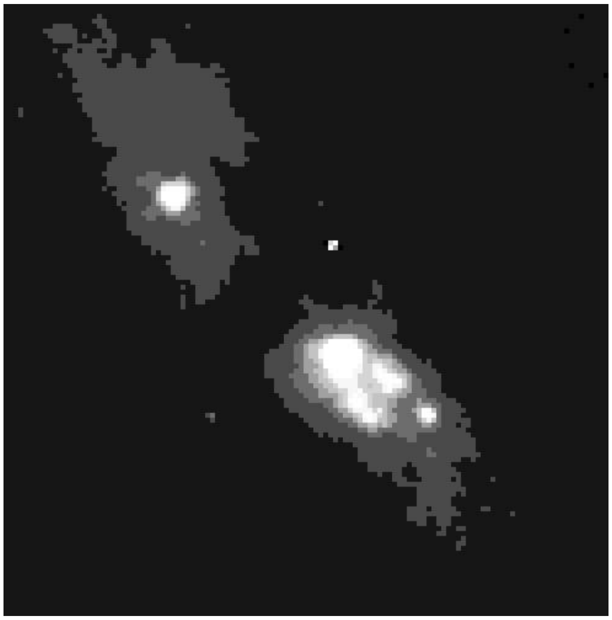

Figure 4. HST/STIS optical image of the center of NGC 3049. The passband includes Hα. Therefore most of the light in this image is nebular emission. The field size is the same as in Figure 3. Note the very similar morphology seen in Hα and in the ultraviolet.

4. Comparison with Distant Star-Forming Galaxies

What can we learn from local starburst galaxies that is relevant to star formation at high redshift? Before making the comparison between star formation at low and high redshift, morphological K-corrections need to be addressed. In Figure 4 an HST/STIS image of NGC 3049 is reproduced which was taken through an optical longpass, sampling nebular Hα and some red stellar light. The orientation of this image and the field size are identical to those of the ultraviolet image in Figure 3. The similarity between the two images is striking, suggesting that

(i) gas and stars have similar spatial distribution and (ii) dust obscuration acts almost screen-like in this galaxy. This is consistent with morphological studies of galaxies in the Hubble Deep Field (Williams et al. 1996), which appear rather similar at restframe-ultraviolet and -optical wavelengths (Dickinson, private communication). Therefore the ultraviolet and optical can often (but not always) give us an unbiased (although attenuated) view of the star-formation process.

Meurer et al. (1997) compared the star-formation density at low and high redshift and found comparable values, with high-redshift galaxies possibly having somewhat higher densities (see also Weedman et al. 1998). In particular they found that there exists an upper limit on the *global* star-formation density of $10^2 - 10^3$ $\mathrm{M}_\odot$ yr^{-1} kpc^{-2}, both at low and at high redhshift. This can be interpreted as a physical mechanism limiting the starburst intensity. Apparently this mechanism acts similarly in the low- and in the high-redshift universe.

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