PHOTON AND METAL PRODUCTION IN STARBURST GALAXIES

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Abstract

Starburst galaxies are significant contributors to the production of light and matter in the local universe. I review the results of recent surveys of starburst galaxies from the radio to X-rays for a panchromatic picture of a "typical" local starburst. The two prototypical examples NGC 7714 and M 82 are discussed in some detail. The overall galaxy properties are tightly related to those of the underlying stellar population. Implications for the interpretation of star-forming galaxies in the early universe are highlighted.

1 Starburst definition

Starbursts are concentrated regions of ongoing or recent star formation. They range between 10^{12} and 10^7 $L_\odot$ in bolometric luminosity L, the high end overlapping with typical QSO luminosities, and the low end with values observed for very luminous H II regions. These overlaps give rise to ambiguity and confusion. In this paper I will follow the empirical starburst definition by [27]: in a *starburst galaxy* the entire luminosity is due to the starburst itself ($L^{\rm Burst} \approx L^{\rm Galaxy}$); if the starburst luminosity is substantial but smaller than the host galaxy luminosity ($L^{\rm Burst} < L^{\rm Galaxy}$), a *starburst region* in a galaxy is observed; if $L^{\rm Burst} << L^{\rm Galaxy}$ for any individual star forming region, the object is classified as a *star-forming galaxy.*

Since starbursts are young (a few Myr to many tens of Myr) and star formation propagates with velocities of order 100 km s^{-1} ([24]; [22]), starburst regions are very compact with size of a few to hundreds of pc. Starbursts are often — but not always — found in the centers of galaxies. A few examples should clarify the nature of a starburst:

- Our Galaxy has been forming stars at a roughly constant rate for at least the past Gyr. The total star-formation rate from COBE far-infrared (IR) photon counting ([2]) is comparable to rates in starbursts. However, after normalization to unit surface area, even the most powerful Galactic star-formation regions pale in comparison with genuine starbursts. The Milky Way does not qualify as a starburst galaxy.

- 30 Doradus in the LMC is a giant extragalactic H II region. The total stellar luminosity from the integrated Hα flux ([15]) is of order 10^8 $L_\odot$ if a standard initial mass function (IMF) is assumed down to the lowest stellar masses. This is about 1/10 of the total LMC luminosity derived from star counts. 30 Dor is at the low-luminosity end of a starburst in a galaxy.

- NGC 7714 and M 82 will be discussed in more detail below. These galaxies have comparable bolometric luminosities of $2 - 3 \times 10^{10}$ $L_\odot$, as determined mainly from their IRAS fluxes ([4]; [13]). They both harbor central star-forming regions whose luminosities are comparable to the IRAS far-IR luminosity of the entire galaxy. Therefore they are frequently considered "prototypical" starburst galaxies.

2 Energy distribution of local starburst galaxies

In this section I will provide an empirical description of the average, energy distribution of the local starburst galaxy population from the radio to X-rays. The emphasis will be on global properties of the spectrum and its relation to the stellar and interstellar component of the galaxy. An interpretation in terms of the underlying physical properties will be given in Section 4.

Most of the results I am quoting are taken from a recent survey by [25] who used a predominantly ultraviolet (UV) selected sample of 26 starburst galaxies to construct average, global energy distributions. We need to be concerned about dust obscuration in a UV-selected sample. [28] estimates from a comparison of the far-IR and UV luminosity functions of a sample of Markarian galaxies that on average about 10% of the (non-ionizing) UV radiation escapes from galaxies with significant dust amount. This escape fraction may approach 100% in the absence of dust. A picket-fence model for the interstellar dust provides a natural explanation: the interstellar medium (ISM) is clumpy ([3]) so that the escape probability of UV radiation is non-negligible even in dusty galaxies. Nevertheless, one should keep in mind that a UV-selected local starburst sample represents only the tip of the iceberg on terms of the observed stellar population. Since the restframe wavelength of a galaxy at redshift $z \approx 3$ observed in the optical is similar to that in a local starburst observed in the UV, the same selection effects apply at high redshift, and the local sample can be used as a training set.

The average energy distributions between 6 cm and 10 keV compiled by [25] are shown in Fig. 1. The sample is subdivided in high- ($E(B-V) > 0.4$) and low-reddening ($E(B-V) < 0.4$) starbursts. High- and low-reddening starbursts have similar overall spectral characteristics, except in the far-IR and the non-ionizing UV, which are anti-correlated: objects with lower reddening have higher UV and lower far-IR flux, whereas the opposite holds for objects with higher reddening. The interpretation is obvious: starbursts with larger reddening have higher dust content and are more effective in absorbing UV photons and re-emitting the processed radiation in the far-IR. The flux difference between the two data sets at ~1500 Å is about a factor of 5 to 10 and corresponds to the escape fraction of non-ionizing UV radiation discussed in the previous paragraph.

Starburst galaxies peak around 60 to 100 μm, irrespective of the reddening. Even a small dust amount is sufficient to produce significant radiation reprocessing. This property has important consequences for the prospects of detecting high-redshift starburst galaxies. This restframe wavelength, if observed at $z > 3$, is accessible to SCUBA at the JCMT. Since far-IR fluxes provide an unbiased, reddening-free starburst count and since K-corrections work in favor of detecting fainter objects, SCUBA observations of distant starburst galaxies can provide important constraints on the cosmic star-formation history ([1]).

The photons seen in starburst spectra originate either in stars or in the ISM. Star light dominates from the near-IR to the far-UV (2.2 μm to 912 Å). All other parts of the energy distribution in Fig. 1 are due to interstellar dust (60 μm) and gas (6 cm and X-rays). As I will discuss in Section 4, the entire spectrum is of course powered by stellar energy input, and the radio and X-ray radiation have their origin in the non-thermal stellar luminosity by winds

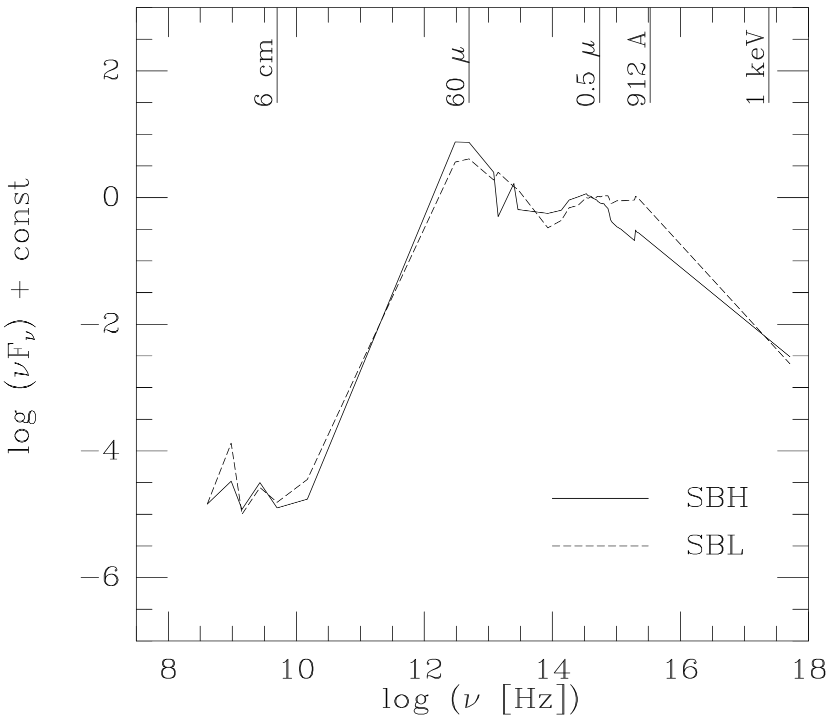

Figure 1: Average spectral energy distributions from the radio to X-rays for high- (SBH) and low-reddening (SBL) starburst galaxies (from [25]). The spectra are normalized such that $\log(\nu F_\nu) = 0$ at 5500 Å.

and supernovae (SN). Fig. 1 can be used for a rough estimate of the ratio between the radio- and X-ray luminosity over the bolometric luminosity, assuming the peak at about 60 μm is indicative of L. The average starburst galaxy has $L^{\mathrm{X-ray}}/L \approx 10^{-3}$ and $L^{\mathrm{radio}}/L \approx 10^{-5}$.

3 The Lyman continuum

Fig. 1 seems to suggest that starburst galaxies are significant emitters immediately shortward of the Lyman edge. This is of course an artifact of the lack of empirical data in this wavelength domain. Although it is clear that starburst galaxies harbor powerful production sites of ionizing photons, the question remains unanswered if these photons can leave the galaxies and account for the intensity of the intergalactic UV background radiation at low and high redshifts. If QSOs were insufficient to ionize the early universe, primeval starburst galaxies could in principle provide the requisite UV radiation. Lyα forest clouds with $\log N_{\mathrm{HI}} > 14.5$ have measurable C IV λ1550 absorption lines with metallicities of $[C/H] \simeq -2.5$ ([11]). This suggests that the intergalactic medium (IGM) at high redshift is contaminated by the products of stars and that the associated ionizing photons may be a significant contributor to the UV background radiation ([20]) *if the ionizing radiation escapes into the IGM.*

Does the porosity of the ISM seen in the non-ionizing continuum ($\sim$1500 Å) apply to the *far*-UV, ionizing radiation as well? The effects of the ISM below 912 Å are much more uncertain and may well dominate the shape of the emergent spectrum. An H I column density of $\sim 1 \times 10^{18}$ cm^{-2} is sufficient to absorb essentially all the ionizing radiation. Since the measured extinctions imply column densities that are three or four orders of magnitude higher than this, it might appear that essentially no ionizing radiation can escape. On the other hand, there is ample evidence that starbursts can blow out interstellar matter in the form of galactic winds and fountains (e.g., [13]).

The situation is sufficiently complex that the only way to determine the escape fraction of the ionizing radiation is via a direct measurement. [16], using HUT, observed four starburst galaxies with radial velocities larger than 5000 km s^{-1}. 2σ upper limits of the Lyman continuum flux suggest average escape fractions of less than about 3% in the four galaxies. While this result could be highly significant if verified in a larger galaxy sample, [14] subsequently pointed out the possibility of unresolved Galactic interstellar H_2 absorption lines. These would remain undetected at HUT resolution and could lead to an upward revision of the originally derived upper limit by up to an order of magnitude. On the other hand, [7] derived an escape fraction of less than 1% from a comparison of the observed diffuse far-UV radiation field and the production rate of ionizing photons determined from the local Hα luminosity function.

Currently there is no unambiguous observational measurement of the starburst spectral energy distribution below 912 Å and above the X-ray domain. Future space missions, like FUSE, will hopefully let us come closer to deriving the escape fraction of the ionizing radiation.

4 NGC 7714 and M 82 in detail

What is the underlying physics responsible for the global spectral energy distribution of starburst galaxies? I will discuss studies of NGC 7714 and M 82 to identify some of the processes operating in starbursts. The two objects are complementary in their properties. Despite having similar chemical composition ($\sim$1/2 $Z_\odot$) and luminosities ($\sim 3\times10^{10}$ $L_\odot$), their apparent morphologies are strikingly different. NGC 7714 is seen face-on, thereby minimizing dust obscuration effects. This allows stellar population studies in all wavebands where stellar light is emitted. M 82 is observed almost edge-on, and high dust obscuration hides most of the star light in the UV and optical. This geometry, however, favors direct observations of starburst driven interstellar material which follows the maximum pressure gradient along the minor axis.

4.1 NGC 7714

NGC 7714 is an SBb galaxy with a compact starburst in its nucleus ([29]). Extensive IUE, HST, and ground-based data were obtained and interpreted by [9] and [8]. UV, optical, and near-IR spectra of the starburst nucleus in NGC 7714 were all taken through similar aperture sizes.

Due to its young age (of order 10^7 yr), the starburst is rich in ionizing O stars. The hot, massive stars can be observed directly via their strong Si IV λ1400 and C IV λ1550 lines in the UV, or indirectly via nebular emission lines in the optical and near-IR. The Lyman continuum luminosity is 10^{53} photons s^{-1}, which is about 10 times the output of 30 Dor in the LMC. The starburst encompassed by the aperture is extended and has been proceeding for a period that is comparable to the lifetime of the massive stars. Therefore, red supergiants (RSG), the evolved descendants of O stars are observed in the red and IR as well. Analysis of the individual populations suggests that the RSG population seen in the IR is heavily obscured. The associated hot-star population, after dereddening, would be 10 times more luminous than the actually observed population at 1500 Å. In other words, even after reddening correction, the observed UV flux accounts for only about 10% of the actual luminosity — 90% of the UV light is totally hidden from view. This is again the same result found for starburst galaxies in general. Applied to observations of galaxies at high redshift, this suggests that star-formation rates derived from the restframe-UV luminosity may underestimate the true rates by up to a factor of 10.

The nucleus of NGC 7714 was detected in the 0.3 to 2 keV band by ROSAT/PSPC ([26]). The derived X-ray luminosity is 4×10^{40} erg s^{-1}. The softness of the spectrum makes X-ray binaries unlikely candidates as sources. The most natural explanation is in terms of thermal emission by 10^7 K gas heated via energy input from stellar winds and SNe. Hydrodynamical modeling by [26] can account for the stellar population and X-ray properties in a self-consistent way. It is found that the energy requirements to power the hot gas are met by the combined effects of winds and SNe in a 4 to 10 Myr old starburst.

The measured non-thermal radio flux at 20 cm allows a further consistency check. Theoretical modeling does not provide strong constraints but a comparison with compact SN remnants in the Galaxy and the LMC is useful. These nearby SN remnants have $L^{\rm radio}/L^{\rm X-ray} \approx 10^{-2}$. It is encouraging that about the same ratio is found for NGC 7714, supporting similar underlying mechanisms. Recall that $L^{\rm radio}/L^{\rm X-ray} \approx 10^{-2}$ is the average value found in the local starburst galaxy population as well.

4.2 M 82

M 82 is the prototype of a dusty starbursting dwarf galaxy. It is observed almost edge-on, with an associated visual extinction of $A_{\rm V} \approx 12$ mag. Therefore the observing window of choice is the IR. The continuum light in the IR is due to a combination of RSG and red giant populations, and the challenge is to determine the relative proportions. The nucleus of M 82 has a relatively high K-band luminosity, together with a relatively small dynamical mass. This results in a low M/L ratio which can be understood if red giants and dwarfs (which produce mass) are deficient with respect to supergiants (which produce near-IR light). This translates into an IMF with a deficit of stars in the mass range below 3 – 5 $\rm M_\odot$ ([23]). The issue is not completely settled since assumptions made for the adopted dynamical mass, the extinction correction, and the star-formation history can significantly affect this conclusion. If the starburst is not condensed in a central cluster but rather spread out over a few hundred pc as a result of sequential star formation, the observational constraints can be satisfied with a standard Salpeter IMF extending to 0.1 $\rm M_\odot$ ([24]). However, such a model would use up 30% of the total dynamical mass. This is an uncomfortably large percentage since it is unlikely that the starburst accounts for most of the stellar mass due to the presence of an older pre-existing population.

Most of the following arguments are independent of the low-mass end of the IMF since only properties of high-mass stars are relevant. Nevertheless, one should keep in mind that absolute quantities which include low-mass stars, such as the total star-formation rate, can change by factors of several due to the IMF uncertainty. I will assume a standard Salpeter IMF between 1 and 100 $\rm M_\odot$ for the following.

The near-IR carries not only the signatures of RSGs, but also of SNe. Imaging of M 82 in the [Fe II] $\lambda1.6$ μm line was performed by [10]. Iron is one of the most abundant elements but has a relatively low gas-phase abundance due to severe depletion by dust. Shocks following SN explosions can destroy dust in the vicinity of a starburst and raise the gas-phase abundance of Fe substantially. Therefore the strength of the [Fe II] 1.6 μm (and 1.3 μm) lines correlates well with the energy input by SNe and can be used to infer the SN rate (e.g., [3]). The result for M 82 is a SN rate of $\sim$0.05 yr^{-1}.

The mechanical energy input from stellar winds and supernovae into the ISM is significant. In Fig. 2 I have plotted the mechanical luminosity relative to the radiative (bolometric) luminosity. Once the SN phase is reached, these models predict an approximately constant ratio of $\sim$0.01. About 1% of the starburst luminosity is released non-thermally and can be used to

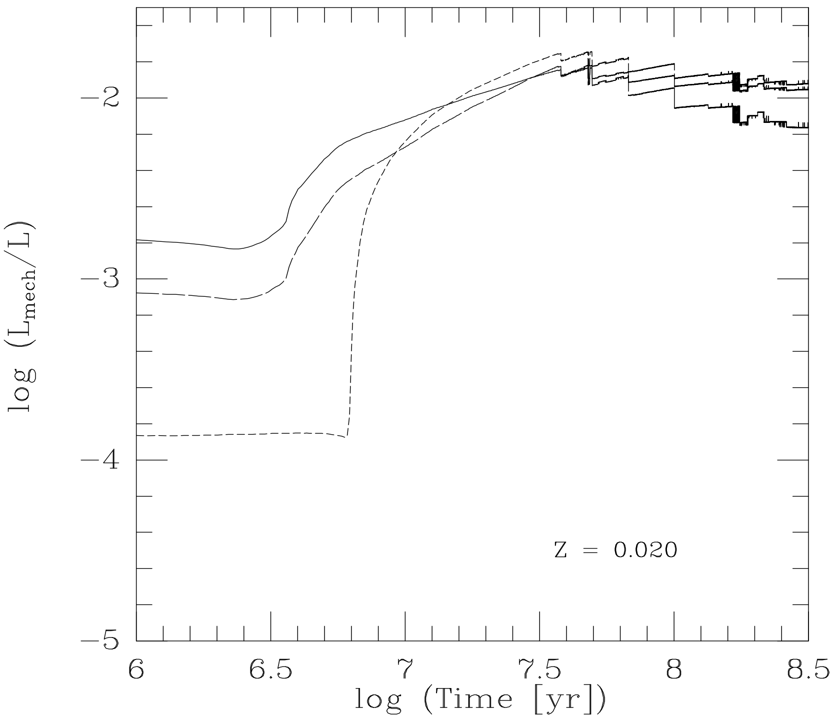

Figure 2: Ratio of the mechanical over bolometric luminosity vs. starburst age for a starburst with continuous star formation (from [18]). Solid line: IMF with $\alpha = 2.35$ between 1 and 100 $M_\odot$; long-dashed: $\alpha = 3.3$ between 1 and 100 $M_\odot$; short-dashed: $\alpha = 2.35$ between 1 and 30 $M_\odot$; solar metallicity.

heat the ISM via wind- and SN-driven bubbles, supershells, and superwinds.

The newly formed stars, via their winds and SNe, are the powering sources of the galactic superwind observed in M 82. Extended emission on kpc scales from cold and hot gas is detected in optical nebular lines and thermal X-rays, respectively ([13]). The energy requirements were estimated by [21] and found to be consistent with those of the underlying starburst population. A compilation of the relevant stellar population properties is in Table 1. The values are based on the models of [17]. The two ages of 10 and 50 Myr are approximate lower and upper limits to bracket the starburst age in M 82. The lower limit is suggested by the size of the superwind and the upper limit is imposed by the available gas reservoir for star formation. About half of the gas mass returned to the ISM comes from stellar winds (mostly Wolf-Rayet stars), the other half is from SNe. The hydrogen and helium content of the ejected material are approximately equal. Oxygen accounts for 4 to 8% of the total mass.

Table 1. Predicted energy and metal production for M 82.

Age (yr)	SN Rate (yr^{-1})	$\dot{M}^{\mathrm{Total}}$ ($M_\odot\ \mathrm{yr}^{-1}$)	$\dot{M}^{\mathrm{SNe}}$ (%)	$\dot{M}^{\mathrm{Winds}}$ (%)	$\dot{M}^{\mathrm{Total}}_{\mathrm{He}}$ ($M_\odot\ \mathrm{yr}^{-1}$)	$\dot{M}^{\mathrm{Total}}_{\mathrm{O}}$ ($M_\odot\ \mathrm{yr}^{-1}$)	Total Mass ($M_\odot$)
1×10^7	0.02	0.52	23	77	0.26	0.04	2.3×10^6
5×10^7	0.07	1.00	56	44	0.43	0.04	3.7×10^6

Starbursts are important sources for energizing and enriching the ISM and — via galactic superwinds — possibly the IGM. If it can be established that starburst galaxies can expel significant amounts of highly metal-enriched gas out into the galactic halo and beyond, then (integrated over a Hubble time):

- Starbursts might explain the existence of an intra-cluster medium whose metal content is comparable to that of the cluster galaxies, and the super-solar ratios of α-elements relative to Fe ([19]).
- Starbursts might explain the presence of metals in the Lyα forest at high redshift, possibly with a super-solar ratio of Si/C ([6]).
- Starbursts might be the mechanism by which galaxies episodically pump metal-enriched gas into their halos. The long-term consequences of these "eruptions" would be the metal-enriched halos seen as QSO metal-absorption-line systems ([5]).

5 Conclusions

Starbursts are a significant mode of high-mass star formation. About 25% of all massive stars in the local universe are formed in starbursts ([12]). Starburst galaxies are likely to be even more important at high redshift when the universe was young. I used a UV-selected sample of local starburst galaxies to discuss their global spectral characteristics and relate the overall properties to stellar and interstellar processes in these galaxies.

The average bolometric luminosity of the sample galaxies is 2×10^{43} erg s^{-1} ($= 5 \times 10^{9}$ L$_\odot$), somewhat above the LMC luminosity and possibly comparable to luminosities estimated for star-forming galaxies at high redshift. Most, or even all, of the bolometric luminosity L is due to the stellar luminosity produced in the starburst. It is found that

$$L \approx L^{\mathrm{far-IR}} + L^{\mathrm{UV}}$$
$$L^{\mathrm{far-IR}}/L^{\mathrm{UV}} \approx 10$$

suggesting that 10% of the non-ionizing UV radiation can escape from the galaxies and that the far-IR is an excellent tracer of the total starburst luminosity.

Nucleosynthetic energy production in stars alone (as opposed to, e.g., gravitation in AGN) can account for the observed spectral energy distribution from radio to X-ray wavelengths. Stars provide the luminosity either directly via their emitted photons or indirectly via non-thermal input by winds and SNe. The stellar non-thermal input can be quantified from the observed relative radio and X-ray luminosities:

$$L^{\mathrm{X-ray}}/L \approx 10^{-3}$$
$$L^{\mathrm{radio}}/L \approx 10^{-5}.$$

The associated metal production is significant for the enrichment of the ISM, and if the metals leave the galaxy, for the IGM as well. Chemical yields for typical starburst parameters are 10% for all elements, and 2 to 3% for metals excluding H and He.

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