The cosmic infrared background (CIRB) and the role of the “local environment of galaxies” in the origin of present-day stars

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Abstract. A combination of evidence is presented suggesting that the majority of the stars in today’s galaxies were born during a luminous infrared phase (LIRP) triggered by the local environment of galaxies. The CIRB is a fossil record of these LIRPs and therefore reflects the influence of triggered star formation through galaxy-galaxy interactions, including non merging tidal encounters. This scenario, in which galaxies experienced several LIRPs in their history, is consistent with the measured redshift evolution of the cosmic density of star formation rates and of stellar masses of galaxies.

1 Introduction

Stars represent only 15% of the cosmic baryonic density, itself only equal to about 4% of the critical density ($\Omega_0 \approx 0.04$), and are unequally distributed into spheroids (10% of $\Omega_0$, including spiral bulges) and disks (5% of $\Omega_0$, Fukugita, Hogan & Peebles). It is usually assumed that disk stars formed quiescently while bulge stars formed more efficiently and rapidly, as suggested by their redder colors and overabundance in $\alpha$-element over iron ratio, typical of a SNII origin. However recent studies of the history of the star formation of the disk of the Milky Way indicate that during the last 2 Gyr it has experienced about five major events of star formation, starbursts, whose signatures can be found in the peaked ages of these open clusters (de la Fuente Marcos & de la Fuente Marcos 2004, and references therein). As a result we may wonder whether quiescent star formation did play a major role in the formation of present-day stars at all. There are some evidence that star formation mostly takes place in globular clusters and is rarely isolated. These clusters are thought to evolve into unbound stellar associations, which evolve and dissolve in a time-scale of about 50 Myr. This timescale is longer than the lifetime of massive stars which dominate the luminosity of starbursting galaxies or regions of galaxies. Hence, it is logical to expect that if star formation occured mainly in starburst episodes within galaxies, then the bulk of galaxies luminosity will be absorbed by dust in the giant molecular clouds, while if star formation is quiescent then only a minor fraction of a galaxy’s luminosity will be affected by dust extinction. We will argue in the following that there is presently a solid collection of evidence suggesting that most stars that we see in the local universe formed during starburst episodes.

A major piece of evidence for that comes from the detection of a strong diffuse cosmic infrared background (CIRB, Puget et al. 1996, Hauser & Dwek and
references therein) which is majoritarily produced by luminous infrared phases (LIRP) within galaxies located around $z \sim 0.7$, for the peak of the CIRB at $\lambda \sim 140 \mu m$, while the $\lambda \geq 240 \mu m$ is due to galaxies at $z \sim 2$ and above (Elbaz et al. 2002, Chary & Elbaz 2001). We have introduced the term LIRP instead of the classical one, luminous and ultra-luminous infrared galaxies, i.e. LIRGs and ULIRGs, because we wish to emphasize the idea that the scenario that is emerging from the study of distant galaxies is that LIRGs do not represent a population of galaxies that would require to be studied independantly in order to determine which present-day galaxies are the remnants of these LIRGs, but what is suggested instead is that they illustrate the omnipresence of rapid and efficient star formation as a leading process in shaping the present-day universe, i.e. that any galaxy that we see today must have experienced a phase when it radiated the bulk of its light in the infrared (see also Elbaz & Cesarsky 2003). This phase should not be restricted to LIRGs and ULIRGs, i.e. galaxies with infrared (IR) luminosities larger than $10^{11} L_\odot$ or star formation rates (SFR) larger than $\sim 20 M_\odot yr^{-1}$, since the closest starburst M82, for example, presents a spectral energy distribution typical of most LIRGs, with the bulk of its luminosity radiated in the IR although its luminosity is only $4 \times 10^{10} L_\odot$.

We present evidence suggesting that the bulk of local stars formed during a LIRP. A spectroscopic diagnostic is used to quantify the typical duration of this phase and the amount of stars that formed during it. From the combination of both we will advocate that not only did all galaxies experience a LIRP but that they must have experienced several of them. Finally we will discuss the physical origin of the LIRP and present evidence that a major event in the lifetime of galaxies was probably underestimated: the effect of the “local environment of galaxies” (LEG) and its impact in terms of driving the conversion of gas into stars through passing-by galaxies.

2 Luminous IR phases and the origin of present-day stars

The detection of a CIRB came as a surprise since local galaxies only radiate $\sim 30\%$ of their bolometric luminosity in the mid to far IR range, i.e. sharing as a common origin stellar photons reprocessed by dust above $\lambda \sim 3 \mu m$. With about half of the diffuse background light radiated above and below this wavelength cutoff, the extragalactic background light tells us that in the past, major star formation events were strongly affected by dust extinction even when galaxies were less metal rich. Deep surveys in the mid infrared ($\lambda \sim 15 \mu m$ with ISOCAM onboard ISO, Elbaz et al. 1999) brought independent evidence that infrared was more ubiquitous in the past. These surveys detected ten times more objects at faint flux levels than expected from the extrapolation of the local universe (no evolution models). These galaxies turned out to belong to the class of LIRGs and ULIRGs discovered by IRAS in the local universe but located at a median redshift of $z \sim 0.7$. They do not exhibit any optical signature of such strong SFRs neither in their optical colors nor in their emission lines, except if careful correction for extinction is applied using the Balmer decrement (Cardiel et al. 2003,
Flores et al. 2004). Only less than 20% of them were found to harbor or be dominated by an active galactic nucleus (AGN; see Fadda et al. 2002). Unexpectedly, because of the complex and multiple physical origins of the mid and far IR photons (PAHs, Very Small Grains, Big Grains), local galaxies do exhibit a strong correlation between their mid and far IR luminosities over three decades in luminosity, including the extreme LIRGs and ULIRGs (Elbaz et al. 2002). When applied to galaxies up to \( z \sim 1 \) these correlations can be used to derive far IR luminosities, i.e. SFRs, which are consistent with those derived from the radio, using the radio-far IR correlation, suggesting that these correlations are still valid at these redshifts (Elbaz et al. 2002).

**Fig. 1.** a) Cosmic star formation rate (CSFR) as a function of redshift and universe age, in a \( H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and \( \Omega_0 = 0.5 \) cosmology (Fig. 15 of Chary & Elbaz 2001). The data represent the SFR density derived from UV or H\( \alpha \) uncorrected for extinction (the various authors are quoted on the plot and the references can be found in Chary & Elbaz 2001). b) Cosmic stellar mass history (CSMH) or redshift evolution of \( \Omega_\star \), the cosmic stellar mass density over critical density (cosmology: \( \Lambda = 0.7, \Omega_m = 0.3, H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \)). The data are from Dickinson et al. (2003). See text for description.

The median SFR of the galaxies responsible for the evolution of the mid IR counts is \( \sim 50 \text{ M}_\odot \text{ yr}^{-1} \) and their contribution to the CIRB from 100 to 1000 \( \mu \text{m} \) is derived to be as large as two thirds of its measured intensity. Hence the bulk of the CIRB results from LIRPs at redshifts of the order of \( z \sim 1 \), but due to cosmological dimming the influence of more distant galaxies is more limited to the large wavelength tail of the CIRB. Some models have been designed to reproduce number counts in the mid IR (ISOCAM, 15 \( \mu \text{m} \)), far IR (ISOPHOT-90, 175 \( \mu \text{m} \)) and sub-mm (SCUBA, 850 \( \mu \text{m} \)) together with the CIRB which can be used to derive the cosmic star formation history of the universe (CSFH) unaffected by dust extinction and to disentangle the relative roles of rapid (LIRPs) and quiescent star formation. In Chary & Elbaz (2001), we suggested to define a region delimiting all possible histories of star formation (see Fig. 1a), instead of a single line for any favorite model that would not represent the uncertainties of the model and observational constraints. One way to check the robustness of such models consists in comparing to direct measurements the resulting cosmic stellar
masses history (CSMH), i.e. the redshift evolution of \( \Omega_\star \), the mass density of stars per comoving volume over the critical density of the universe. The hatched area of Fig. 1a which represents the range of possible CSFH was converted into a range of possible CSMH in Fig. 1b, with the thin plain line showing the mean value and the range of possible histories delimited by the two dot-dashed thin lines. The model fits the data collected in Dickinson et al. (2003), where stellar masses were directly measured from optical-near IR magnitudes.

Before deriving any conclusion, we wish to remind our assumptions: the CSFH was derived assuming mid to far IR correlations similar to locally (in agreement with the radio), the AGN fraction was supposed to make a minor contribution (see above), we assumed a universal IMF (we used the one of Gould et al. 1996, which combines a Salpeter IMF with the now standard inflexion of the IMF below 1 M\(_\odot\)). If these assumptions are indeed justified, then the fit of the data in Fig. 1b illustrates the fact that the photons emitted by star forming regions do reflect the stellar mass building of galaxies and as a consequence, it is now possible to derive which fraction of present-day stars were formed in a LIRP. The model CSFH was separated into three components shown as thick grey lines in the Fig. 1b, with 63\% of present-day stars born during an IR phase of the LIRG type, which would be the dominant mode of star formation in the universe. The shape of the redshift evolution of \( \Omega_\star \) implies that \( \sim 80\% \) of present-day stars were born below \( z=2 \), and \( \sim 50\% \) below \( z=1 \), most of which during a LIRP, leaving little room for quiescent star formation.

If most of today’s stars formed during a LIRP and if this phase reflects efficient and rapid star formation then this suggests that some “positive feedback”, i.e. triggering, might be at play. This idea is comforted by the morphology and local environment (LEG) of distant LIRGs. It is well-known that galaxies lie in large-scale structures made of walls, filaments and clusters but LIRGs tend to appear exclusively in high density environments around \( z \sim 0.7 \). The deepest ISOCAM survey was performed in a region of \( 27''^2 \) centered on the Hubble Deep Field North (HDFN), detecting 95 galaxies among which 47 lie above the completeness limit of \( \sim 0.1 \) mJy.

The histogram of field galaxies presents several redshift peaks. The location and the extent of these peaks can be quantified by adopting a tresholding S/N ratio of 3, where the "background" is simply the redshift distribution smoothed with a gaussian with \( \sigma = 15,000 \) km s\(^{-1}\). Monte-Carlo simulations performed by extracting 100 random samples from the real distribution of field galaxies show that the probability of reproducing by chance the level of clustering of the ISOCAM galaxies is much less than one chance over ten (largest error bars). These results are illustrated on Fig. 2a, where we plot the fraction of ISOCAM galaxies included in redshift peaks above a given S/N ratio as a function of this S/N. The corresponding curves for the field galaxies and the simulated samples are also indicated. The thin (resp. thick) error bars show the 68 \% (resp. 90 \%) confidence level. The strong clustering of ISOCAM galaxies illustrates that at \( z \sim 0.7 \), galaxies experiencing a LIRP are more clustered on average than field galaxies. On the contrary, the study of LIRPs in the local universe using the
Fig. 2. a) Cumulative fraction of galaxies located in a redshift peak of a given S/N, i.e. number of galaxies in all redshift peaks above a given S/N (see text). b) Equivalent width of the high-order Balmer absorption line, H8, as a function of the 4000 Åbreak. Data with error bars are a sub-sample of \( z \sim 0.7 \) LIRGs. Dots were generated by a Monte Carlo simulation of 200,000 galaxies. The darkest region is populated by galaxies dominated by continuous star formation, or bursts older than \( \sim 2 \) Gyr.

shallower ELAIS survey (Oliver et al., in these proceedings) shows that they are less clustered than field galaxies locally. The natural explanation for this behavior is that galaxies might experience a LIRP when located in a region which is collapsing over a large scale, i.e. star formation would be triggered by large-scale structures in the process of formation.

How much stellar mass does a LIRG form? We addressed this question using an optical spectroscopic diagnostic combining the equivalent width of the high order Balmer absorption line H8 to the 4000 Åbreak to characterize these starburst events (Marcillac et al., in prep.). The advantage of using H8 instead of H\( \delta \) is that it is in a bluer side of the spectrum, hence less affected by sky lines, and that its underlying nebular emission line can be neglected. Fig. 2b shows a sub-sample of 22 LIRGs, at \( z \sim 0.7 \), selected in three different locations of the sky compared to a Monte Carlo simulation of 200,000 galaxies using the code of Bruzual & Charlot (2004) such as those used by Kauffmann et al. (2003) to reproduce the behavior of local galaxies in the Sloane survey. This simulation can be used to determine which histories of star formation would reproduce these galaxies. It is found that only galaxies presently experiencing a burst of star formation can fall in this region of the diagram and that this burst lasts approximately \( 10^8 \) years and produce about 10% of the stars of the galaxies. These numbers were both derived by the simulation but they perfectly agree with the measured median mass of the ISOCAM galaxies of \( \sim 5 \times 10^{10} \) M\( \odot \) (from Dickinson et al. 2003). Indeed in \( 10^8 \) years and with their median SFR\( \sim 50 \) M\( \odot \) yr\(^{-1} \), they produce \( \sim 5 \times 10^9 \) M\( \odot \) of stars, i.e. 10% of the galaxy mass. The mass of newly formed stars is also consistent with the typical mass of molecular gas found in local LIRGs. The model used in the Fig. 1 predicts that nearly 50% of present-day stars were formed in a LIRP below \( z \sim 1 \), hence
if this phase only makes up 10% of a galaxy’s stars then the majority if not all of today’s galaxies experienced up to five or even more LIRPs. This suggests that the dense surrounding of galaxies can trigger successive luminous IR phases, LIRPs, in galaxies. Finally, the optical morphology of $z \sim 0.7$ LIRGs derived from HST-ACS observations (Elbaz et al., in prep, see also Hammer et al. in these proceedings) shows that less than half of them look like the major mergers that we see locally in LIRGs. Major mergers might not be numerous enough to explain such a behavior and passing-by galaxies might play an important role by triggering strong star formation events through tidal effects. Hence the local environment of galaxies, or LEG, might be considered as a better candidate to understand the origin of distant LIRGs. The cosmic star formation history is therefore probably strongly dependant on the local density of galaxies which will also possibly determine their final morphology, i.e. spirals versus ellipticals, instead of the standard picture of the merger of two massive disks.

The recently launched Spitzer satellite will provide ideal observations to check the robustness of this scenario by observing larger patches of the sky (in particular the SWIRE legacy program), lowering the effect of cosmic variance, and to extend the study of luminous IR phases to higher redshifts and lower luminosities (with the MIPS GTO and GOODS legacy program).

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