CFRS follow up with ISO, VLA and HST: the cosmic star formation rate as derived from the FIR luminosity density

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Abstract

Properties of CFRS field galaxies up to z=1 are discussed. Estimations of the cosmic star formation rate (SFR) lead to serious problems if they not account for AGN emissions and for light reemitted at IR wavelengths. Deep ISOCAM and VLA photometries on one CFRS field have been performed. Multi-wavelength analyses from UV to Mid-IR and hence to radio allow us to classify sources from their spectral energy distributions. This provides an estimation of the FIR luminosity density related to star formation. The deduced SFR density is free of extinction effects and not contaminated by AGN emissions. About 55±20% of the star formation at z≤1 is related to FIR emission. If a non truncated Salpeter IMF is adopted, the derived stellar mass formed from z=0 to z=1 seems too high when compared to the present day stellar mass. An important fraction (30%) of the star formation at z=0.5-1 seems to be related to the rapidly evolving population of compact/Irr galaxies. Larger systems found at z=1, show a slower evolution of their star formation properties.

1 Introduction

The Canada France Redshift Survey (CFRS) has gathered a complete sample of ~ 600 field galaxies with $I_{AB} \leq 22.5$ with spectroscopic redshifts. This sample has been widely used to study galaxies at lookback times up to 10 Gyr. Evolution of galaxies has been evidenced: at z=0.85 the comoving densities of 2800Å and [OII]3727 were respectively 4.5±1 and 8±4 times larger than today (Lilly et al, 1996; Hammer et al, 1997).

It is beyond doubt that galaxy evolution is mainly associated to a decrease of the star formation in field galaxies, since epochs of ~ 10 Gyr ago. There were larger amounts of blue
galaxies in the past (Lilly et al., 1995) and the fraction of galaxies showing significant emission lines ($W_0([OII]) \geq 15\AA$) increases from 13% locally to more than 50% at $z \geq 0.5$ (Hammer et al., 1997). It has been investigated if AGN can substantially contribute to the reported evolution. The fraction of AGN (Seyfert2) is found to be $7.5 \pm 3.5\%$ at $z \sim 0.5$, higher than what is found today ($\sim 2\%$, see Huchra and Burg, 1992). But it is found nearly constant with the redshift, when calculated relatively to the population of emission line galaxies, and so AGNs cannot be seen as major contributors to the reported luminosity evolution.

40% of the field galaxy spectra show evidences for a significant population of A stars. This has been derived from continuum indices which are well correlated with $W_0(H\delta)$. It implies that star formation is primarily taking place over long periods of time (typically $\geq 1$ Gyr), rather than in short duration, high amplitude bursts (Hammer et al., 1997).

Having those facts in mind, there are important pending questions:

- how fair is the estimation of the SFR derived from UV ($\lambda_{2800}$ or [OII]3727) luminosities?
- can the extinction affect our view of the galaxy evolution?
- are $z \sim 1$ galaxies showing the same Hubble type distribution than those today?
- does evolution affect all galaxy morphological types in the same way?

In this paper we summarize recent developments made beyond the bulk of the CFRS study. Recall that the CFRS includes 5 fields of 10'X10' which probe a surface almost 100 times larger than the HDF, and so it is much more suited for galaxy studies limited in volume to $z=1$. The CFRS sample is limited by $I_{AB} \leq 22.5$, which is exactly coincident to the rest-frame $M_B(AB) \leq -20.5$ at $z=0.93$. It implies that the CFRS is basically a $(z \leq 1)$ volume limited sample for $M_B(AB) \leq -20.5$ galaxies. The paper is organised as follows:

- Section 2: calibration of the SFR based on UV luminosities and its deficiencies.
- Section 3: mid-IR and radio luminosities from deep ISOCAM and VLA observations, derivation of FIR luminosities by interpolations and a first estimation of the star formation history which is not affected by the extinction.
- Section 4: morphologies from a deep HST follow up, and the major contributors to the star formation evolution.

2 SFR calibration to $z=1$ and beyond

 Calibration of star formation rate in the optical is limited to $z=0.5$ when based on the $H\alpha$ line. Other SFR indicators are the 2800Å the [OII]3727 luminosities which could be used up to $z=2$ and to $z=1.5$, respectively. They are more dependent on the metallicity and on the extinction than the $H\alpha$ emission.

ISMs in distant field galaxies present different properties than that of local ones (Hammer et al., 1997). Emission-line ratio of HII regions in $z \sim 0.5$ galaxies showed higher ionization parameters than those of local HII galaxies. About 30% of the $z \geq 0.7$ galaxies show clues for abundances significantly lower than solar values. The [OII]3727/$H\alpha$ luminosity ratio is different on average in CFRS galaxies than in Kennicutt local ones. Indeed, when applied to...
distant galaxies, the Kennicutt (1992) calibration of the SFR from the [OII] luminosity leads to uncomfortably high values of stellar mass.

More recently we have got spectra up to 1μm for a sub-sample of z≤0.5 CFRS galaxies. Figure 1 presents relationships between the different SFR indicators: while [OII]3727 and 2800Å luminosities correlate fairly well, these SFR indicators present large dispersions when correlated to Hα luminosities. This suggests that extinction affects considerably UV luminosities, and hence the determination of the SFR.

3 FIR luminosity from multiwavelength analysis and SFR density from z=0 to z=1

This section summarizes two papers by Flores et al (1998a and b). One CFRS field (1415+52) has been deeply imaged with the Infrared Space Observatory (ISO) using ISOCAM at 6.75μm and 15μm, with integration times from 1100 to 1200 sec pixel$^{-1}$. Careful data analysis and comparison to deep optical (B, V and I), near-IR (K) and radio (1.4 and 5 GHz) data have allowed us to generate a catalog of 78 15μm sources with identifications. 22 redshifts of galaxies with $I_{AB} \leq 22.5$ are available in the CFRS database. They have higher median redshift (Figure 2) and are redder than other field galaxies. Almost all the star forming galaxies present evidences for an A star population.
Figure 2: The shaded histogram shows the redshift distribution of the 22 15\,\mu m sources with spectra found in the CFRS database. The non-shaded histogram shows the CFRS redshift distribution after rescaling.

Source densities are comparable at 6.75\,\mu m (1944 S>150\,\mu Jy sources per square degree, Flores et al, 1998a), 15\,\mu m (2808 S>250\,\mu Jy sources per square degree, Flores et al, 1998b) and 5 GHz (1440 S>16\,\mu Jy sources per square degree, Fomalont et al, 1991). Star-forming objects contribute respectively, 50\%, 73\% and 26\% of the extragalactic counts at 6.75\,\mu m, 15\,\mu m and 5 GHz. This suggests that the 60\,\mu m luminosity density is strongly dominated by emissions related to star formation. The fraction of z > 1 objects is found to be < 32\%, < 43\% and < 40\% of the extragalactic counts at 6.75\,\mu m, 15\,\mu m and 5 GHz, respectively.

Using deep photometry in rest-frame UV, visible, near-IR, mid-IR and radio, we have derived spectral energy distributions (SEDs) which samples the wavelength range in which most of the energy of field galaxies is emitted (Figure 3). These have been compared to well-known local galaxy templates (from Schmitt et al, 1998). All the CFRS 1415+52 have been spectrally classified using this technics, and their FIR luminosities derived by interpolation. Our classification allow us to estimate the AGN contribution, and then to remove it when deriving the SFR density.

We find that the SFR density derived by FIR fluxes is \sim 2.3 higher than that previously estimated from UV fluxes (Figure 4). No apparent changes with the redshift have been found within the range 0\leq z\leq 1. The corresponding global extinction is A_V = 0.55 \pm 0.12, very similar to the Gallagher et al (1989) average value for local irregulars. A subsample of sixteen 15\,\mu m galaxies observed by the HST indicates that about a third of the star formation hidden by dust is associated with interacting galaxies (Figure 5). One percent of the CFRS galaxies are strong and heavily reddened starbursts (Figure 3) with their SFR ranging from 120 to 330 M_{\odot} yr^{-1} and they contribute to 25\% of the SFR density up to z=1.

These results provide SFR density values by \sim 3.5 lower than those of Rowan Robinson (1997) from the small HDF area. On the other hand they are consistent with the Richards et al (1998) analysis who found only one strong starburst in the HDF. Nevertheless, our derived
Figure 3: Comparison of the spectral energy distribution (SED) of 6 heavily reddened starbursts (filled circles, separated by arbitrary vertical shifts) with a local averaged starburst SED (dashed line, from Schmitt et al., 1998). Fluxes at 60$\mu$m (open circles) are derived from radio fluxes according to the radio-FIR correlation ($S_{60\mu m} = 125S_{5GHz}$, Franceschini et al., 1994). Superposed to the fit of 14.9154 are vertical bars which display at each wavelength the standard deviation of the local template. The bottom panel presents the standard deviation of the 6 starbursts.

SFR density seems too high, because the derived stellar mass formed since $z=1$ until now is comparable or higher than the present day stellar mass. An alternative would be that the most powerful starburst were preferentially forming high mass stars, i.e. their IMFs are truncated at the low mass end. Another possibility would be an underestimate of the local stellar mass density.

Further results for an other CFRS field and spectroscopic follow up would provide a larger sample in order to test if extinction properties show redshift evolution as well as to extend the predictions until $z=1.5$ near the possible peak of the SFR density. Deep SCUBA observations of some portions of these fields will be soonly available (Eales et al and Lilly et al, 1998, in preparation).

4 Morphologies from the HST

4.1 Observations and classifications

During the last three years the CFRS team has merged their efforts with those of the LDSS team, in order to reach significant amounts of observing time at the HST. About 250 of the 600 CFRS galaxies have been observed with the WFPC2/F814W filter with integration times ranging from 4400 to 7400s.

Each galaxy has been analysed through two independent technics, including systematic fits
Figure 4: Metal production and star formation history for $z \leq 1$ galaxies (see text). SFR estimates are assuming a Salpeter IMF from $0.1 \, M_{\odot}$ to $100 \, M_{\odot}$. Our points (filled circles, labeled ISO-VLA-CFRS) are 2.3 times higher in SFR density or in metal production than those (open circles) previously derived from the UV flux density at 2800Å. Other points are from Gallego et al. (1995, open triangle), Connolly et al (1997) (open stars), Madau et al. (1998, HDF) (open squares), and have not been corrected for extinction.

Figure 5: HST 5''×5'' images obtained with the F814W filter of 16 sources detected at 15μm with $I_{AB} < 22.5$. For each galaxy, the morphological classification is given in the upper right corner.
of the luminosity profile by combination of bulge ($r^{1/4}$ law) and disk (exponential law) models, and a visual inspection of images by three independent team members (see Schade et al, 1995 and Brinchman et al, 1998). A morphological type has been given to each galaxy following a scheme similar to the Hubble classification (see Figure 6). Morphological studies should account for the shift in the rest-frame wavelength of the observation (for example the F814W filter samples the B band at $z=1$). This redshift dependent bias can be very important since galaxies appear much less structured in the UV than at redder wavelengths, and this can mimic an apparent evolution. By redshifting the Frei et al (1996) local galaxies it has been estimated that $\sim 24\% \pm 11\%$ of the true spirals would have been classified as peculiars at $z=0.9$ (Brinchman et al, 1998). All the numbers derived in the following have been computed after allowing for these biases.

Based on our classification, several subsamples of morphologically selected objects can be drawn. These include disk galaxies (those with bulge/total energy ratio smaller than $B/T=0.5$), elliptical galaxies ($B/T=1$) and compact galaxies. Determination of the scale length (for example the exponential scale length of disks, $\alpha^{-1}$) is limited by the pixel size of the HST, and is secure only for disks with $\alpha^{-1} > 3h_{50}^{-1}$kpc. The CFRS sample is well adapted for studying large systems (i.e. large disks and bulges) because it includes all galaxies from $z=0.1$ to $z=1$ with $M_B(AB) \leq -20.5$. 

Figure 6: Examples of the morphological types given to CFRS/LDSS galaxies, with the total number of objects in each class in the survey (from Brinchman et al, 1998).
4.2 Large systems

**Large disks:** $\alpha^{-1} \geq 4h_{50}^{-1}\text{kpc}$ and $B/T \leq 0.5$  
Lilly et al (1998) gathered a subsample of 42 such galaxies from $z=0.1$ to $z=1$. Their number densities show no apparent change from $z=0$ to $z=0.75$, and are consistent with a small decrease by $\leq 30\%$ beyond $z=0.75$. Based on UV and $\text{[OII]}3727$ fluxes, their star formation rates at $z\sim 0.85$ were 2.5-3 times higher on average than that at $z=0$. So the large reported evolution is not mainly associated with large disks. An interesting result shown by Lilly et al (1998) is that disk selected galaxies had later type at higher redshift (median type is Sab at $z=0.375$ compared to Scd at $z=0.85$).

**Large ellipticals:** $r_{1/4}$ luminosity profile and $r_e \geq 3h_{50}^{-1}\text{kpc}$  
30 such galaxies have been identified in the sample by Schade et al (1998, in preparation) from $z=0.2$ to $z=1$. Despite of the small number, there are no obvious changes in their number density from the low to the high redshift bins. This result apparently contradicts the Kauffman et al (1996) analysis of the CFRS sample, who found a decrease in the space density of galaxies redder than a rest-frame elliptical template. This contradiction is simply due to the different definitions of ellipticals by the two groups: a significant fraction of the spectrophotometric ellipticals of Kauffman et al (1996) are indeed disk dominated galaxies (50% of them have $B/T \leq 0.5$).

4.3 Irregular galaxies

After allowing for redshift biases, Brinchman et al (1998) found a large redshift increase of the fraction of irregular galaxies (from 9% at $z=0.375$ to 32% at $z=0.85$). This results is consistent with the migration of disk galaxies towards late type at higher redshift. At $z\sim 1$, galaxies were less regular than at present day.

4.4 Compact galaxies

It has been claimed that a considerable fraction of the star formation activity seen at high redshift occurs in compact galaxies (Guzman et al, 1997). Compact galaxies in the HDF have been selected as having small half light radius ($r_{1/2} \leq 0.5$ arcsec). Half light radii have been also computed for the CFRS galaxies, and Lilly et al (1998) found that large changes in the galaxies population are due to systems with $r_{1/2} \leq 5h_{50}^{-1}\text{kpc}$ (this corresponds to a disk scale $\alpha^{-1} \leq 3h_{50}^{-1}\text{kpc}$). We have also computed a compactness parameter which is based on the ratio of luminosities calculated within two different apertures (5 and $15h_{50}^{-1}\text{kpc}$, respectively), and has been corrected for possible disk inclination (axis ratio b/a):

$$compactness = I_{F814W}(5\text{kpc}) - I_{F814W}(15\text{kpc}) - 2.5\log(b/a). \quad (1)$$

This parameter correlates very well with the half radius and Figure 7 shows that beyond $z=0.5$ (and especially beyond $z=0.75$), a significant number of blue compact galaxies have very large UV luminosities.

Figure 8 presents the HST/WFPC2/F814W images of the 29 blue compact galaxies. These galaxies are the most rapidly evolving population in the CFRS sample: at $z=0.85$, their UV luminosity density was $\sim 15$ times larger than at $z=0$, and they contribute to as high as 30% of the global UV luminosity density. Of course these results could be modified if extinction is accounted for. This is however a good confirmation of the Guzman et al (1995) result. On the other hand, the CFRS is sampling much brighter galaxies ($M_B(AB) \leq -20.5$) than those selected by Guzman et al in the HDF. This implies that the CFRS compact galaxies at high
Figure 7: Compactness parameter against $M_{2800}$ for the whole CFRS-HST sample (125 galaxies with $M_B(AB) \leq -20.5$). Solid circles distinguish galaxies bluer than a rest-frame Sbc. Three redshift bins are displayed and the two highest redshift bins represent almost an equipartition of the comoving volume from $z=0.5$ to $z=1$. Compact galaxies (with $r_{1/2} \leq 5h_{50}^{-1}\text{kpc}$) are those with compactness $\leq 0.73$ (below the dashed line). Their contribution to the UV luminosity density increases very strongly with the redshift.

Redshift have sizes comparable to present-day dwarves (i.e. disk scale smaller than $3h_{50}^{-1}\text{kpc}$) while their blue luminosities are 10 to 100 times larger. Converted into star formation rates, these galaxies formed from 2 to $10M_\odot\text{yr}^{-1}$, a much higher rate than in present day dwarves. In the highest redshift bin ($z\sim 0.85$), they span the whole range of morphological types.

5 Conclusion

The CFRS probes $\sim 10$ Gyr lookback times, and the corresponding fields are the best suited for follow up at other wavelengths. The calibration of the SFR from UV luminosities is truly uncertain for individual objects, because of uncontrolled extinction effects. The calculation of the SFR density is also affected by the AGN contribution to the UV luminosity density ($\sim 30\%$). A multiwavelength analysis of field galaxies from UV to mid IR and hence to radio wavelength allow us to derive FIR luminosities by interpolation. It provides an estimate of the SFR which does not sensitively depend on the extinction. The global correction related to extinction is not as strong as previously reported by Rowan-Robinson et al (1997), and reaches factor of 2.3 until $z=1$. One percent of the CFRS galaxies are strong and heavily reddened starbursts with SFRs from 120 to $330M_\odot\text{yr}^{-1}$ and they contribute to 25% of the SFR density. A third of the star formation detected at FIR is related to interacting systems. In most of the galaxies spanning the whole range of SFRs there are evidences for an important A star population and hence for star formation occuring during long periods of time ($\sim 1$ Gyr).

The rapidly evolving population of compact/Irr galaxies contributed to 30% of the SFR density at $z\sim 0.85$. An important problem is the ”devenir” of these systems which produce
substantial amount of stars in small volumes (SFR of 2-10 $M_\odot yr^{-1}$ within a radius $\leq 3h^{-1}_{50} kpc$). One would like to know if large disks, still observed at $z\sim 1$, are stable or formed and then destroyed, knowing that the interaction rate is rapidly increasing with the redshift. Studies of the dynamical formation of galaxies require at an 8m telescope a 2D-spectrograph with high spectral resolutions, i.e. $R \geq 10000$ to resolve dynamical elements separated by $\sim 10km s^{-1}$.

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