A “UV+IR” HISTORY OF STAR FORMATION AT $0 \lesssim Z \lesssim 1$

E. LE FLOC’H & the MIPS team

Steward Observatory, University of Arizona, 933 N. Cherry Avenue,
Tucson, AZ 85721, United States

The combination of both contributions from the observed UV emission and the absorbed radiations reprocessed in the infrared represents the ideal approach to constrain the activity of massive star formation in galaxies. Using recent results from GALEX and Spitzer, we compare the evolutions of the UV and IR energy densities with redshift as well as their contributions to the star formation history at $0 \lesssim z \lesssim 1$. We find that the comoving IR luminosity is characterized by a much faster evolution than seen in the UV. Our results also indicate that $\sim 70\%$ of the star-forming activity at $z \sim 1$ is produced by the so-called IR-luminous sources ($L_{\text{IR}} \geq 10^{11} L_\odot$).

1 Dust extinction and the limitations of the UV window

The multi-wavelength deep surveys performed in the last decade as well as the detection of the Cosmic Infrared (IR) Background by COBE revealed the dramatic effects of dust extinction in the distant Universe. This significant high-redshift reprocessing of short-wavelength radiations (e.g., UV, optical) into the thermal infrared appears to be associated very closely to the strong evolution that IR-luminous galaxies (i.e., $L_{\text{IR}} \geq 10^{11} L_\odot$) have undergone with lookback time. The luminosity of such objects is mostly powered by highly-embedded star formation or by the accretion of dusty material around active nuclei. As a result they emit the bulk of their energy between 8 and 1000 $\mu$m. It is now well established that they contributed significantly to the assembly of the present-day stellar mass and to the growth of supermassive black holes (e.g., Blain et al. 1999, Chary & Elbaz 2001).

This dominant contribution of IR-luminous systems in the building of structures simply demonstrates not only that the amount of radiations absorbed by dust can not be neglected when quantifying the cosmic evolution, but also that this dust extinction can not be properly quantified from the slope of the UV continuum as it has been proposed in the past few years. Based on a local sample of luminous and ultra-luminous infrared galaxies observed with the STIS camera on-board the HST, Goldader et al. (2002) have shown that the characteristic IR excess of these sources (defined as the ratio between their IR and UV luminosities) is significantly larger than what can be predicted based on the attenuation of their UV continuum and the relation initially proposed by Meurer et al. (1999). This can be explained by the existence of optically-thick dusty environments that contribute to a non negligible fraction of the total energy output of these luminous galaxies but where the UV radiations are almost completely hidden and absorbed by dust. It can also be due to the absence of physical correlation between the dusty regions emitting the bulk of the bolometric luminosity and the other unobscured components dominating the UV emission. This has been observed in local IR-luminous systems resulting from the interaction of a UV bright source with another red
and dusty galaxy (Charmandaris et al. 2004). As an illustration, we show in Fig. 1 the cases of VV 114 and Arp 299, which clearly reveal a mis-connection between the regions where are concentrated the IR and the UV emission. Such systems, if located at $z \gtrsim 1$, would barely be resolved. The measured UV continuum would obviously originate from the only contribution of the UV-bright and unabsorbed components, leading to a distorted picture of the IR properties of these objects.

Recent observations from the Spitzer Space Telescope actually show a similar result regarding IR-luminous objects at high redshift (Papovich et al., in prep.). This clearly reveals the severe underestimate of dust extinction (and therefore bolometric luminosity) that can affect studies of high redshift galaxies when relying on the UV and optical wavelengths only.

### 2 Estimating the star-forming activity of galaxies from the contributions of their UV and IR luminosities

The UV photons produced by massive stars and redshifted into the optical window allow us to trace on-going starburst episodes within distant galaxies. They are nevertheless very efficiently absorbed by dust grains, and we showed in the previous section that a correct estimate of this dust extinction cannot be derived solely from the optical wavelengths. Consequently, the cleanest approach to infer the star-forming activity of galaxies is to account for both the energy observed in the rest-frame UV and the dust-reprocessed light emerging in the far-infrared (e.g., Adelberger & Steidel 2000, Bell 2003). We present hereafter an estimate of the star formation history at $0 \lesssim z \lesssim 1$ based on this approach.

#### 2.1 Contribution from the observed UV luminosity

The GALEX satellite now provides new opportunities for probing the high redshift Universe with great sensitivity in the far-UV. Based on surveys conducted with this new facility, Arnouts et al. (2005) and Schiminovich et al. (2005) have derived the evolution of the luminosity function and the evolution of the luminosity density at rest-frame 1500 Å. They detect a clear increase...
which follows an evolution in \((1+z)^{2.5\pm0.7}\) at \(0 \lesssim z \lesssim 1\). Assuming standard conversions from UV to star formation rate (SFR, Kennicutt 1998), they have translated their results into an estimate of the contribution of the observed UV luminosity to the star formation history. It is consistent with the initial measurements derived by Madau et al. (1996) and Lilly et al. (1996), and it is represented by the dashed line in Fig. 2.a.

2.2 Contribution from the dust-reprocessed thermal IR emission

In addition to GALEX, the successful launch of the Spitzer Space Telescope in August 2003 opened new perspectives for our understanding of IR galaxy evolution. Spitzer operates between 3.6 and 160 \(\mu\)m with unprecedented sensitivity and better spatial resolution compared to previous infrared satellites (e.g., IRAS, ISO).

In the context of our Guarantee Time Observer program, we have imaged several cosmological fields (“Chandra Deep Field South” (CDFS), “Lockman Hole”, “Hubble Deep Field North”, “NOAO Deep Wide-Field Survey”, ...) with the MIPS instrument (Rieke et al. 2004). MIPS is the “Multi-Band Imaging and Photometer” on-board Spitzer. This instrument can cover large sky areas with high efficiency, simultaneously acquiring data at 24, 70 and 160 \(\mu\)m. We have cross-identified our 24 \(\mu\)m observations of the CDFS with various libraries of spectroscopic and photometric redshifts published in the literature. Within an area of \(\sim 775\) arcmin\(^2\), this allowed us to build a sample of \(\sim 2600\) 24 \(\mu\)m-selected galaxies identified with a reliable redshift at \(0 \lesssim z \lesssim 1\) (see Le Floc’h et al. 2005). We found that this sample is mostly complete up to \(z \sim 0.8\). Assuming that the usual IR spectral energy distributions characterizing the IR properties of local galaxies are still valid in the distant Universe (Elbaz et al. 2005), we derived the following:

- Total IR luminosities
- Correlation between optical and IR luminosities
- IR to UV ratio as a function of IR luminosity
- Stellar masses as a function of IR luminosity
- IR luminosity function
- Evolution of the comoving IR energy density and equivalent SFR

In particular, we showed that the IR luminosity density has undergone a strong evolution in \((1+z)^{3.9\pm0.4}\) at \(0 \lesssim z \lesssim 1\). Assuming the standard calibration between star formation rate and IR luminosity (Kennicutt 1998), we finally derived an equivalent dusty star formation history illustrated by the solid line in Fig. 2.a.

2.3 The “UV+IR” history of star formation

As pointed out previously, the proper estimate of the star-forming activity in a given redshift bin must be obtained by taking into account both the radiations absorbed by dust and the UV photons directly escaping the HII regions. The corresponding addition of the observed-UV and dusty-IR star formation histories is represented by the dotted line in Fig. 2.a. For comparison, we also show integrated star formation rate densities and their uncertainties estimated within various redshift bins and taken from the literature (see the compilation by Hopkins 2004 for references).
2.4 Some caveats

In the conversion between the comoving IR luminosity and the dusty star formation rate density, we have assumed that 100% of the IR energy was powered by star formation. The contribution of active galactic nuclei (AGNs) within our mid-IR selected sample has been therefore neglected. We believe that such contamination should not be larger than 15-20% up to \( z \sim 1 \). This estimate is roughly based on the number of objects that we identified as AGNs using the multi-wavelength surveys of the CDFS found in the literature. It is consistent with estimates derived by other groups (Fadda et al. 2002, Franceschini et al. 2005).

It should also be noted that the uncertainties in the evolution of the UV and the IR comoving energy densities are not negligible. This originates from the unconstrained faint-end slope of the luminosity function at high redshift, and the subsequent degeneracy that appears when quantifying its evolution. In spite of these uncertainties however, the difference between the IR and the UV densities is sufficiently large for being statistically significant.

3 Discussion

Figure 2.a reveals that the relative contribution of the uncorrected UV light to the total star formation is decreasing with redshift. This is a direct consequence of the stronger evolution of the IR energy density (in \( (1+z)^{3.9 \pm 0.4} \)) compared to the evolution of the UV luminosity (in \( (1+z)^{2.5 \pm 0.7} \)).

This strong evolution observed at infrared wavelengths is not due to a global increase of the density of galaxies across the full range of luminosities. The IR luminosity functions (LF) that we derived from the CDFS (Le Floc’h et al. 2005) rather reveal a significant evolution of the characteristic luminosity \( L^*_\text{IR} \) describing the knee of the LF. This is consistent with the analysis that have been inferred from the ISO and SCUBA surveys, and it shows that the evolution has been in fact driven by a strong increase of the relative contribution from the most IR-luminous sources to the total IR energy output. We estimate that such objects were dominating the star formation history at \( z \gtrsim 0.7 \), representing \( \sim 70\% \) of the star formation rate density at \( z \sim 1 \).
is illustrated on Fig. 2.b, which compares the evolution of the comoving IR luminosity densities for IR-luminous sources (i.e., $L_{\text{IR}} \geq 10^{11} L_\odot$) and fainter galaxies with $L_{\text{IR}} \leq 10^{11} L_\odot$.

From the GALEX observations, Schiminovich et al. (2005) have noted that the population of the most UV-luminous galaxies (UVLGs) has also experienced a dramatic evolution with lookback time. Investigating the relationship between these UVLGs and the IR-luminous sources should give us more clues to better understand the origin of the characteristic decline of the star formation history from $z \sim 1$ down to $z = 0$.

We finally note that, according to our current knowledge, the IR emission alone provides a rather good estimate of the total star formation history even at low redshifts. Indeed, the uncertainties affecting the current estimates (from the IR or the other multi-wavelength surveys) are clearly larger than the correction made when taking into account the additional contribution of the UV (see the dispersion in Fig. 2.a). This situation might change however in the near future. More data from Spitzer should allow us to reduce the uncertainties dominating our estimate of the IR energy density (e.g., translation from $24 \mu m$ fluxes to total IR luminosities, cosmic variance, AGN “contamination”). The “IR+UV” view should then provide the most accurate constraint on the star formation history.

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