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DUST ATTENUATION AND FUV+FIR STAR FORMATION RATE DENSITY: WHAT DID WE LEARN FROM *HERSCHEL* AND WHAT WOULD *WISH* BRING?

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Abstract. In this paper, we present a work on the evolution in redshift of the dust attenuation (A_{FUV})and the total (FUV + FIR) star formation rate density ($SFRD_{TOT}$). Our main conclusions are that: 1) the dust attenuation A_{FUV} is found to increase from $z = 0$ to $z \sim 1.2$ and decreases until our last data point at $z = 3.6$; 2) At $z > 2$, we observe either a plateau or a small increase to $z \sim 3$ and then a decrease to $z = 3.6$; 3) the peak of A_{FUV} is delayed with respect to the maximum of $SFRD_{TOT}$ but the origin of this delay is not understood. This work is further detailed in (Burgarella et al. 2013). To better understand this and try to move further in redshift, we present a space mission project called *WISH*. The primary goal of WISH is to push back the high-redshift frontier well into the epoch of reionization by utilizing its unique imaging and spectroscopic capabilities in the 1 - 5 μm range and a dedicated survey strategy.

Keywords: galaxies, cosmology, star formation rate density, dust attenuation, re-ionization, early Universe

1 Introduction

Even though astronomers have tried to measure the evolution of the cosmic star formation rate density (SFRD) by moving higher and higher in redshift. It quickly became clear that at low-z (i.e. at least $z \sim 2$), one of the main issues was to account for the total SFRD and not only for the far-ultraviolet (FUV) because of dust. This translates into either a dust correction of the FUV SFRD or, better, a measure of the total i.e., FUV plus far-infrared (FIR = bolometric IR) SFRD. Takeuchi et al. (2005) estimated the cosmic evolution of the SFRD from the FUV and FIR. An increase of the fraction of hidden SFR is found to $z = 1$ where it reaches 84%. The dust attenuation increases from $A_{FUV} \sim 1.3$ mag locally to $A_{FUV} \sim 2.3$ mag at $z = 1$. From the FUV only Cucciati et al. (2012) show that the mean dust attenuation A_{FUV} agrees with Takeuchi et al. (2005) over the range $0 < z < 1$, remains at the same level to $z \sim 2$, and declines to ~ 1 mag at $z \sim 4$.

Using FUV luminosity functions (LFs) published in Cucciati et al. (2012) and FIR LFs from *Herschel*[*] (Gruppioni et al. 2013), we are able to constrain the redshift evolution of $\log_{10}(L_{FIR}/L_{FUV})$ (IRX) to $z \sim 4$ for the first time directly from FIR data. With this information, we estimate the redshift evolution of ρ_{FIR}/ρ_{FUV} as well as $\rho_{TOT} = \rho_{FIR} + \rho_{FUV}$.

Through the last decades, the deep surveys unveiled the history of formation and evolution of galaxies. Yet, the high redshift frontier in the study of the early universe still remains almost closed or at most ajar. This is the epoch of the formation of the first-generation of stars and galaxies. The objects formed in the first couples of 100 Myrs are considered to have reionized the baryonic matter and made a dramatic change in the thermal history of the universe. We present a space mission project called Wide-field Infrared Surveyor for the High-redshift (*WISH*) dedicated to discover and study primordial galaxies at $3 < z < 15$.

Throughout this paper we adopt a ΛCDM cosmology with $(H_0, \Omega_m, \Omega_\Lambda) = (70, 0.3, 0.7)$, where H_0 is in $\mathrm{kms^{-1}Mpc^{-1}}$. All SFR and stellar masses presented assume, or have been converted to, a Salpeter IMF.

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2 Cosmic Dustiness

Fig. 1 (left) presents the dust attenuation in the FUV vs. z and the ratio of the FIR-to-FUV luminosity densities (LDs). The FUV dust attenuation is estimated from the IRX and converted to A_{FUV} using Burgarella et al. (2005)†. The redshift evolution of A_{FUV} agrees with Cucciati et al. (2012) (no FIR data). Fig. 1 (left) suggests a maximum at $z \sim 1.2$ followed by a decrease to $z \sim 4$ of A_{FUV}. From the UV slope, β, a continuous decline at least to $z = 6$ is found (Bouwens et al. 2009). At $z = 3.6$, A_{FUV} is about at the same level as measured at $z = 0$. Beyond $z = 4$, we do not expect any increase.

3 Cosmic Star Formation Rate Density

Fig. 1 (right) suggests a flattening of the total SFRD up to $z \sim 3$ where the UV data favor a peak followed by a decrease. All in all, our total SFRD agrees fairly well with that of Hopkins & Beacom (2006) in the same redshift range. Barger et al. (2012) published a FIR SFRD based on SCUBA-2 data that also agrees with ours at $2 < z < 4$. Preliminary results from *Herschel*/SPIRE estimated by Vaccari et al. (2013, in prep.) agree with these trends. We fit $SFRD_{TOT}$ by combining two Gaussians (see Burgarella et al. 2013). The cosmic SFRD presents a (weak) maximum at $z \sim 2.5 - 3.0$ (i.e., between 2.6 - 2.1 Gyr) while the dust attenuation presents a maximum at $z \sim 1.2$ (i.e. 5 Gyr). We have no definite explanation for this delay of ~ 3 Gyr so far.

The bottomline from this analysis is that it appears to be better to study the early universe at $z > 5$ in the rest-frame FUV than in the rest-frame FIR because of the low dust attenuation (lower than locally). The rest-frame FUV is redshifted in the near-infrared (NIR) at $z > 5$. This is the main reasons why the WISH mission will observe in the wavelength range 1 - 5 μm.

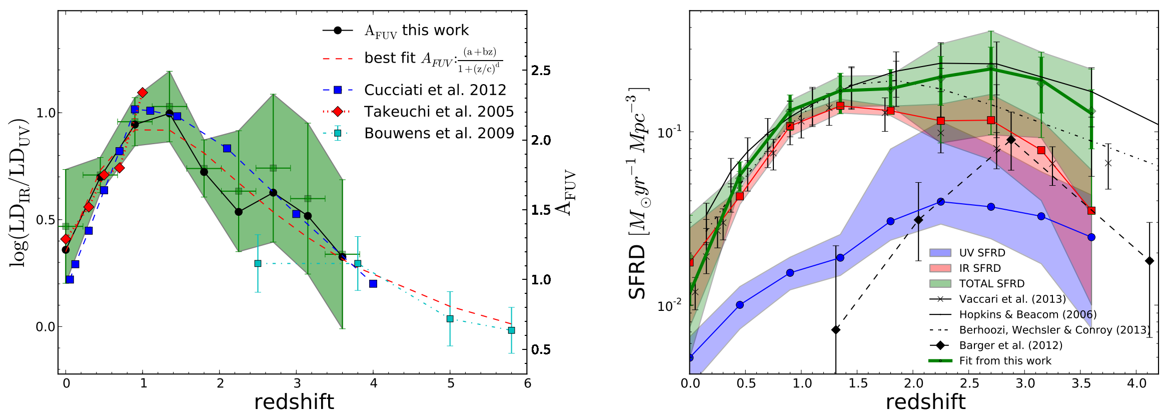

Fig. 1. Left: ratio of the FIR-to-FUV LDs (IRX) on the left-hand axis and FUV dust attenuation (A_{FUV}) on the right-hand axis. The red dotted line with red diamonds is taken from Takeuchi et al. (2005). The green filled area and green dots are the associated uncertainties. Black dots denote the values directly computed from the LFs. At $z = 3.6$, A_{FUV} reaches about the same value as at $z = 0$. Takeuchi et al. (2005) (red diamonds) used an approach identical to ours while a SED analysis (no FIR data) is performed in Cucciati et al. (2012) (blue boxes). Bouwens et al. (2009) are estimates based on the UV slope β. Right: SFRD in the FUV (blue), in the FIR (red), and in total (i.e., FUV + FIR) in green (other colors are due to overlaps of the previous colors). The lines are the mean values, while the lighter colors show the uncertainties.

4 The WISH space mission

The Wide-field Imaging Surveyor for High-redshift (WISH) is a proposed mission concept being developed by the WISH Working Group in Japan under the Science Committee of ISAS and JAXA (Yamada et al.

† The conversion from IRX to A_{FUV} from Burgarella et al. (2005) is valid at $\log_{10}$ (L_{FIR}/L_{FUV})>-1.2: A_{FUV} = -0.028 $[\log_{10} L_{FIR}/L_{FUV}]^3$ + 0.392 $[\log_{10} L_{FIR}/L_{FUV}]^2$ + 1.094 $[\log_{10} L_{FIR}/L_{FUV}]$ + 0.546

(2010), Yamada et al. (2012)). French institutes propose to the French space agency (CNES) to contribute to WISH both scientifically and instrumentally (spectrograph and tests) under the coordination of the Laboratoire d'Astrophysique de Marseille. Tab1 gives the mains characteristics of WISH.

Table 1. WISH in a nutshell

Launch	$\sim$ 2020	
Optics	1.5m M1	cooled to 100K
Optics	Diffraction limited at 1 - 5 μm	0.2 - 0.4" FWHM
Wavelength range	1 - 5 μm	
FOV	900 arcmin^2 (photometry)	0.5 - 1 arcmin^2 (spectroscopy)
Main surveys		
Ultra Deep Survey (UDS)	100 deg^2	Photometry to ABmag 28
Multiband survey (+ UDS)	100 deg^2	Photometry to ABmag 28
Ultra Wide Survey (UWS)	1000 deg^2	Photometry to ABmag 24-25
Extreme Survey (XS)	0.25 deg^2	Photometry to ABmag 29-30
Deep Spectroscopic Survey (DSS)	1 deg^2	Spectroscopy to 8 $\times$ 10^{-17} erg cm^{-2} s^{-1}
Wide Spectroscopic Survey (WSS)	10 deg^2	Spectroscopy to 8 $\times$ 10^{-16} erg cm^{-2} s^{-1}

Name	λ_{center} µm	FWHM µm
Filter 0	1.040	0.280
Filter 1	1.360	0.360
Filter 2	1.775	0.470
Filter 3	2.320	0.620
Filter 4	3.030	0.800
Filter 5	3.965	1.070
Filter 5e	4.215	1.570
Filter 6	4.500	1.000

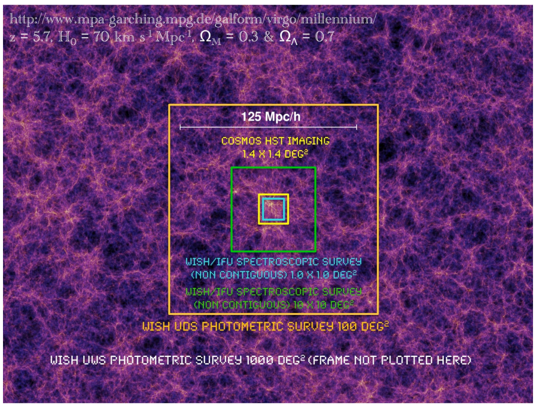

Fig. 2. Definition of the filters and sensitivity in imaging.

The definition of the filters and sensitivities in imaging are given in Fig. 2. The conceptual design and the optimum survey strategy of WISH has been developed to detect photometrically a large number of the rest-frame UV-luminous galaxies: $\sim$ 10^4 galaxies at z=8 - 9, $\sim$ 10^{3-4} galaxies at z=11 - 12, and $\sim$ 10^2 galaxies at z=14 - 17. As a reference, estimations for Euclid comes to about a few hundreds LBGs and a few tens QSOs at $z > 8$. More details about WISH can be found on the following websites: `http://people.lam.fr/burgarella.denis/denis/WISH.html` and `http://www.wishmission.org/en/index.html`.

5 Conclusions

On the one hand, the variation of the cosmic dust attenuation with redshift suggests a peak in the dust attenuation at $z \sim 1.2$ followed by a decline to $z = 3.6$. On the other hand, the total (FUV+FIR) cosmic SFRD increases from $z = 0$ to $z \sim 1.2$, remains flat to $z \sim 2.5 - 3.0$ followed by a decrease at higher redshifts and reaches the same level at $z \sim 5 - 6$ as is measured locally if we assume no variations in this trend. The peak of the dust attenuation is delayed with respect to the maximum of the total SFRD by about 3 Gyrs.

Fig. 1 taken at face value would suggest that the universe's dusty era (meaning dust attenuation higher than in the local universe) started at z = 3 - 4 simultaneously with the rise of a universe-wide star-formation event.

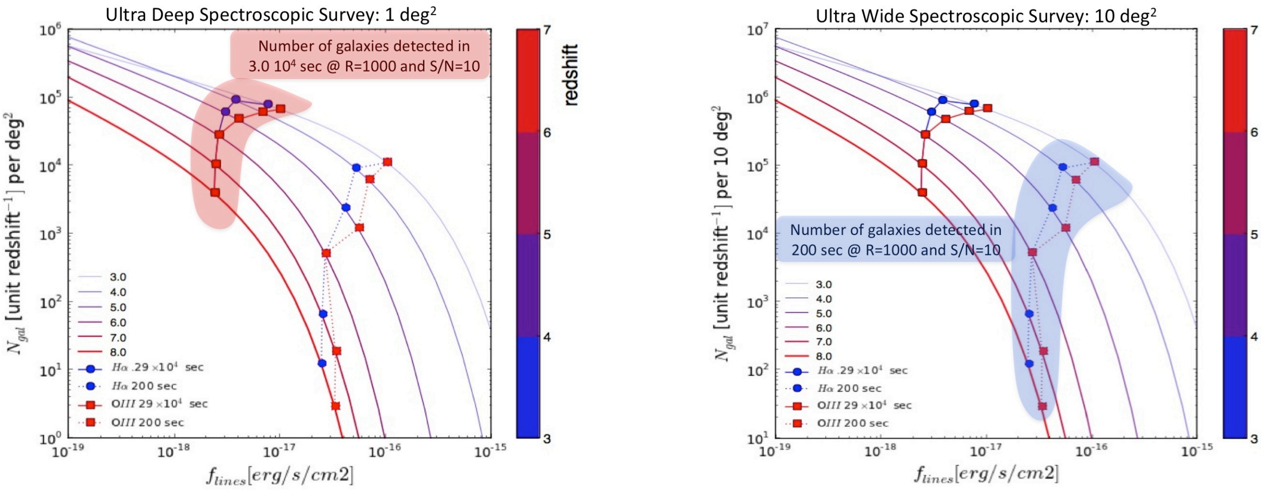

Fig. 3. Both the Ultra Deep (left) and Ultra Wide Spectroscopic(right) Surveys will provide large galaxy samples at $3 < z < 8$. For the first time, we will have data in hand to seriously constrain the formation and early evolution of galaxies in this redshift range from line spectroscopy for several to millions of galaxies. Even JWST would have a hard time performing this science unless a large part of the observing time would be dedicated to this theme (about 80 % of WISH time will). Vertical lines (with boxes and dots) refer to the observational limits with WISHSpec for the two surveys, as scaled down from the performances of JWST accounting for the size and the resolutions. An instantaneous field of view of 1 arcmin is assumed.

Figs. 1 also allows us to follow the SFRD over most of the Hubble time in a consistent way. However, large uncertainties prevented us from closing the case. This work is further detailed in (Burgarella et al. 2013).

To go further in redshift, we need to detect and characterize galaxies at higher redshifts. WISH will dedicate 80% of its observing time to studying the first galaxies and the very early formation of stars and elements. More specifically, WISH will:

- Find the very first gravitationally-bound structures that were assembled in the Universe – precursors to today's galaxies, groups and clusters of galaxies – and trace the subsequent co-evolution of galaxies and super-massive black holes.
- Trace the formation and evolution of the super-massive black holes at galactic centres – in relation to galaxy and star formation – and trace the life cycles of chemical elements through cosmic history.

Finally, it is important to underline that WISH will be very a valuable facility to provide exotic and $z > 10$ galaxies for the ELTs, JWST and ALMA thanks to its wide field of view.

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