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The dusty SF history of distant galaxies and modelling tools

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Abstract.
I review recent advances in the determination of the cosmic history of star formation, and its relevance in our understanding of the formation of structures. I emphasize the importance of dust reprocessing in the high–z universe, as demonstrated in particular by IR and sub-mm data. This demand a panchromatic approach to observations and suitable modelling tools. I summarize the basic requirements for these models and to what extent they are satisfied by models published so far.

1. Introduction

In the last few years, a remarkable number of studies of the high-z universe have been devoted to the determination of the cosmic history of star formation $SFR(z)$. The main motivation for these efforts is that baryons are the only observational tracers of the evolution of large scale structures, which are driven by the gravitational collapse of dark matter (DM). The function $SFR(z)$ in principle constrains cosmogonic theories for the build up of structures, with the obvious, but sometimes underestimated, caveat that baryons assembly is strongly affected also by a much more complex physics than dark matter.

In the local universe surveyed by IRAS $\sim 30\%$ of the energy is dust reprocessed: if the same were true at high–z, optical–UV observations would suffice to determine $SFR(z)$ with a small uncertainty. But the IRAS observations demonstrated as well that in local galaxies dust reprocessing is an increasing function of the star formation activity, and can't be reliably determined by UV and optical data alone. This is vividly illustrated for instance by figure 2 of Sanders and Mirabel (1996), which shows that infrared-selected galaxies range over 3 order of magnitude in L_{ir}, while the optical luminosity change only by a factor of 3-4, with minor differences in the shape of the optical-UV SED.

It is therefore quite natural to suspect that in the more active young universe an higher fraction of star luminosity was reprocessed by dust.

2. The dusty SF history of galaxies

Indeed, several pieces of evidence have shown that *most of the SF in the high–z universe is dust obscured or dimmed to a substantial degree:* (1) The discovery of a cosmic far-IR/sub-mm background by the COBE satellite (Puget et al 1996, Fixsen et al 1998, Hauser et al 1998), whose energy density, which is at least a factor 2-3 larger than the optical-UV one, indicates that a large fraction of the energy radiated by stars over the history of the universe has been reprocessed by dust. (2) The discovery that the population of star forming galaxies at $z \sim 2 - 4$ that have been detected through their strong Lyman-break features are substantially extincted in the rest-frame UV (Pettini et al 1998, Steidel et al 1999). (3) The discovery of a population of sub-mm sources at high redshift ($z > 1$) using SCUBA, whose luminosities, if they are powered by star formation in dust-enshrouded galaxies, imply very large star formation rates ($\sim 10^2 M_\odot \mathrm{yr}^{-1}$), and a total star formation density comparable to what is inferred from the UV luminosities of the Lyman-break galaxies (Smail et al 1997, Hughes et al 1998, Lilly et al 1999). (4) The ISO detection of a population of strong IR sources; 15 μm ISOCAM (Oliver et al 1997) and 175 μm ISOPHOT surveys (Kawara et al 1998, Puget et al 1999) show a population of actively star forming galaxies at $0.4 < z < 1.3$, which boosts the cosmic star formation density by a factor ~ 3 with respect to that estimated in the optical from the CFRS. For (1) and (3), there is the caveat that the contribution from dust-enshrouded AGNs to the sub-mm counts and background is currently uncertain, but probably the AGNs do not dominate (e.g. Granato, Danese & Franceschini 1997).

A summary of the present status of the determination of $SFR(z)$ is given for instance by figure 17 of Genzel and Cesarsky (2000). The main point is that while a few years ago it was claimed, based on optical observation, that this function has a peak at $z \simeq 1$ and declines at higher redshift, it is now clear instead that $SFR(z)$ steeply increases between $z = 0$ and $z = 1$, but than stays flat to at least $z \simeq 4$.

3. Implications

As already mentioned, the determination of $SFR(z)$ aims to constrain cosmogonic scenarios. In the past decades, two extreme opposite possibilities have been studied:

(1) *monolithic models* (e.g. Eggen, Lynden-Bell & Sandage 1962, Larson 1975, etc), characterized by a timetable for SF dependent on morphological type, and by an evolution of galaxies as individual units. In particular, ellipticals had a huge burst of SF at high z, followed by a monolithic/passive evolution.

(2) By converse, according to *hierarchical clustering models* (e.g. White & Rees 1978, White & Frenk 1991), massive objects formed at late times by the merging of smaller subunits, and therefore the assembly of massive ellipticals occurred at $z < 1$;

The early claims of a $SFR(z)$ peaking around $z \sim 1$ were warmly welcome as a success of the prediction of hierarchical clustering models, but as already remarked the observational situation has now changed.

Without going into the details of the evidences in favor or against the two scenarios above, it seems now that clear they are converging to some intermediate point. Indeed monolithic models have been originally developed focusing on astrophysical arguments concerning luminous matter. By converse, the merging picture has been mostly driven by the predicted evolution of dark matter halos through hierarchical clustering. For instance, on one hand, a more prolonged

SF for field ellipticals has been proposed (e.g. Franceschini et al. 1998) and a role of merging below $z \simeq 1$ is apparent from optical surveys (Schade et al. 1999 and references therein). On the other hand present semi-analytical models, while reproducing several observations, are seriously at odd with SCUBA counts (Silva 1999), and do not reproduce the observed trends of α-enhancement in ellipticals (Thomas & Kauffmann, 2000).

The emerging picture (say the *"middleman" scenario*, e.g. Schade et al 1999) is that massive ellipticals assembly most of their stellar mass early (e.g. $z > 3$) but some fraction of stars form later ($z < 2$). To obtain this, the simplified prescriptions adopted by semi-analytical models to describe the complex behavior of baryons in DM halos need some revision.

4. Modelling tools

In any case, the recent discoveries demonstrate that in order to understand the history of star formation in the universe from observational data, a unified picture, covering all wavelengths from the far-UV to the sub-mm, is indispensable. The UV and the far-IR are especially important, since young stellar populations emit most of their radiation in the rest-frame UV, but a significant fraction of this is dust reprocessed into the rest-frame far-IR. Therefore (i) panchromatic observations, with proper emphasis on the mid-IR to the sub-mm, are required and (ii) these observations should be interpreted using spectral synthesis tools taking into account dust reprocessing in a decorous way.

The spectral energy distributions (SEDs) of model galaxies are computed with the spectral synthesis technique. If dust were negligible in the system, as it is usually assumed to be the case in local elliptical galaxies, the only required ingredients would be (1) the distribution of stars in age and metallicity, and (2) a library of Simple Stellar Population spectra (SSPs), i.e. the integrated spectrum of a single generation of stars of given initial mass function (IMF), age and metallicity.

Then the galaxy SED at a given age t_G would be given by a simple integral over its past history. For a monolithic evolution model, were there is a one to one relationship $Z(t)$ between the galactic age and its metallicity, we have:

$$L_\lambda(t_G) = \int_0^{t_G} SSP_\lambda(t_G - t, Z(t)) \times SFR(t)\, dt \tag{1}$$

were $SFR(t)$ is the star formation rate.

In merging models there is no unique age-metallicity relation $Z(t)$, since each galaxy results from the 'combination' of several progenitor galaxies which have merged to produce that galaxy. The progenitor galaxies each had their own star formation and chemical history. In this case a birthrate function $\Psi(t, Z)$ is introduced, where $\Psi(t, Z)\, dt\, dZ$ gives the mass of stars that were formed in the time interval $(t, t+dt)$ with metallicities in the range $(Z, Z+dZ)$. The composite $\Psi(t, Z)$ in general has a broad distribution of metallicity at each age, and the above integral has to be replaced by a slightly more complicated computation:

$$L_\lambda(t_G) = \int dZ \int_0^{t_G} SSP_\lambda(t_G - t, Z) \times \Psi(t, Z)\, dt \tag{2}$$

But the true complexity arises whenever dust reprocessing must be taken into account, which is the rule for star forming systems. Dust absorbs and scatters photons very effectively below $\sim 1\mu$m, and thermally reradiates the absorbed energy above a few μm. This yields large modifications in the SED. These effects require radiative transfer computation of starlight through dust. This is by itself a major complication, since in any geometry with a minimum of realism the radiative transfer can be done only by means of numerical techniques. But the worst problem is that the results are a strong function of the optical properties of dust and of the geometrical arrangement of dust and stars, introducing several parameters and uncertainties in the models.

Concerning the dust optical properties, they are relatively well understood in our own galaxy, but they are known to be a function of the environment. At least three different sites of interaction between stellar photons and dust grains need separate consideration: AGB envelopes, molecular clouds (MCs), diffuse ISM. Moreover variations of dust properties even within each of these environments are known to exist. Further complications come from the presence of small grains, which are not in thermal equilibrium with the radiation field and whose emission has to be computed by means of statistical techniques, and/or by modelling the carriers of unidentified IR bands, likely Policiclyc Aromatic Hydrocarbons.

As for the geometry of stars and dust, it is certainly much more complex than that adopted in most models. At very least two phases in the ISM should be considered: besides a relatively smooth diffuse ISM, responsible in the Galaxy of the cirrus emission discovered by IRAS, a clumpy component, the MCs, is present. Moreover, since the birth and first evolutionary stages of stellar lives occur in MCs, the 'primary source' of radiation is clumpy as well, since the younger the stars the more closely associated to MCs they are.

Several papers in the last few years tried to address some of these technical or astrophysical difficulties, which are on the other hand the minimal requirements for a meaningful modelling of UV to sub-mm SED of star forming galaxies. A non exhaustive briefly commented list of most recent models follows:

- Witt, Thronson & Capuano (1992), Gordon, Calzetti & Witt (1997), Fioc & Rocca Volmerange (1997, PEGASE), Ferrara et al. (1999), Bianchi et al. (2000) considered only the extinction effects of dust. These models, with the only exception of PEGASE, use Monte Carlo methods, allowing a treatment of scattering with an accuracy difficult to reach with other methods, which however tend to be much faster. Monte Carlo computations are therefore particularly suited for detailed comparison with optical images of single spiral galaxies. However in all but Bianchi et al. (2000) paper the assumed geometry is more or less oversimplified with respect to real galaxies, lacking in particular the consideration of molecular clouds and their association with young stars.

- Other authors (e.g. Mazzei, De Zotti & Xu 1994; Devriendt, Guiderdoni & Sadat 1999: STARDUST) included also a computation of dust emission, but with substantial simplifications. In the latter paper, dust absorption is modelled assuming a 1D slab geometry, and the dust temperature distribution is not predicted. Instead, the dust emission spectrum is modelled as the sum of several components, whose temperatures and relative strengths are chosen so as to reproduce the observed correlations of IR colors with IR luminosity found by IRAS in the local Universe. While this kind of approach is undoubtedly very simple and has relatively few parameters, it is not directly linked to the physics of dust emission. Therefore it lacks of predictive power for systems very different from the local galaxies against which it has been calibrated. In particular it may be limitative for high redshift applications.

- Efstathiou, Rowan–Robinson & Siebenmorgen (2000) and Bianchi et al. (1999) also included dust emission, but still with some restrictions. The first paper introduces a simple physical treatment of the time evolution of GMC, but, being thought for applications to starburst galaxies, it neglects the effects of diffuse dust. These are important at least for normal spirals but to some level even for weak starbursts. The latter paper represents probably the state of the art of Monte Carlo models in this field. The only limitation, besides the intrinsic slowness of the method, is that small grains and PAH are not yet included, preventing the comparison with MIR data.

The only general purpose model in which all the geometric and optical properties issues listed above have been addressed is GRASIL (Silva, Granato, Bressan & Danese 1998, executables are available for download at *http://grana.pd.astro.it/*). This stellar population + dust model includes a realistic 3D geometry, with a disk and bulge, two phase dust in clouds and in the diffuse ISM, star formation in the clouds, radiative transfer of starlight through the dust distribution, a realistic dust grain model including PAHs and quantum heating of small grains, and a direct prediction of the dust temperature distribution at each point in the galaxy based on a calculation of dust heating and cooling. The adopted algorithm allows its use in applications requiring predicted SEDs from the UV to the sub-mm of thousands of galaxies, in reasonable computing time (e.g. Granato et al. 2000). The comparison with results from more precise Monte Carlo computations is on the other hand very positive (for details see *http://grana.pd.astro.it/*). GRASIL is the first published model taking into account a progressive escape of young stars from the thickest phase of the ISM, namely the parent molecular clouds. This feature has proven to be fundamental to understand UV properties of galaxies, in particular the shallow and featureless attenuation law of starburst galaxies (see Granato et al. 2000 for details).

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