FORMATION OF SPHEROIDAL GALAXIES: THE SUB-MM VIEW

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ABSTRACT. The intensity of the Cosmic Far-IR Background and the strong evolution of galaxies in the far-IR to mm wavelength range demonstrate that the bulk of starlight emitted during the early phases of galaxy evolution was reprocessed by dust. Therefore, the optical view of the galaxy formation process is highly incomplete and biased, and must be complemented with far-IR/sub-mm observations. We review the impact of sub-mm surveys on our understanding of the evolutionary history of spheroidal galaxies. A recent model, bringing into play also the inter-relationships between formation and early evolution of spheroidal galaxies and quasars, is described and some implications are outlined.

1. Introduction

The last ten years have seen a crescendo of discoveries that have revolutionized our understanding of the process by which the tiny graininess seen in the Cosmic Microwave Background (CMB) resulted in the formation of galaxies.

Up to a decade ago, galaxy evolution models followed the approach pioneered by Tinsley (1972), Larson & Tinsley (1974), Tinsley & Gunn (1976), the evolutionary population synthesis approach, wherein galaxies form at some redshift \( z_f \), perhaps varying by type, with some star formation history \( \psi(t) \) and some stellar initial mass function (IMF). The general framework was that postulated by Eggen et al. (1962) and Sandage (1986): elliptical galaxies had essentially a simple passive evolution after formation at high \( z \) in a rapid collapse and starburst, while the timescale for star formation of late type galaxies is much longer and in fact comparable with the Hubble time. Models were required to reproduce the photometric properties of local galaxies. The more refined models dealt simultaneously with both photometric and chemical evolution. Guiderdoni & Rocca-Volmerange (1987) were the first to introduce dust absorption. However, the general attitude was that dust extinction is a mere correction that does not change the main evolutionary trends seen in the optical band. This view appeared to be grounded by the fact that a comparison of the optical and far-IR luminosity densities in the local universe shows that only \( \approx 30\% \) of starlight is reprocessed by dust.

Mazzei et al. (1992, 1994) produced the first self-consistent chemical and photometric evolution models including both dust absorption and emission, to get complete spectral energy distributions (SEDs) from UV to far-IR both for late- and early-type galaxies.
These models showed that, while the SEDs of late-type galaxies are not expected to change drastically throughout their evolutionary history, under plausible assumptions spheroidal galaxies might have been very optically thick during their early phases, if indeed most of their stars were formed in a giant starburst. Their SEDs would then have been similar to that of hyper-luminous IRAS galaxies. Mazzei & De Zotti (1996) showed that (sub)-mm observations of a number of high redshift radio galaxies supported this scenario. These models were exploited by Franceschini et al. (1994) to produce the first set of galaxy counts at optical and far-IR to sub-mm wavelengths and to predict the SED of the Cosmic IR Background (CIRB); a remarkable result was that the CIRB intensity might be as large as, or larger than, that of the optical background.

Up to that time, the optical quest for “normal” high-z (“primeval”) galaxies yielded a very meager return: only a handful of objects were discovered, mostly serendipitously or through absorption features in the spectra of distant quasars or gravitational lensing. The only effective method for finding high-z galaxies was optical identifications of radio sources, which are generally associated to early type galaxies.

A major breakthrough occurred roughly at the same time, thanks to the color selection technique targeting the Lyman discontinuity at 912 Å, developed by Steidel & Hamilton (1992, 1993). Follow-up spectroscopy with the Keck telescope confirmed the efficiency of this technique (Steidel et al. 1996) which led to the discovery of a widespread population of high-z galaxies.

Madau et al. (1996) applied the same technique to the multicolor images of the Hubble Deep Field to identify galaxies at $2.0 < z < 3.4$ ($U$ drop-outs) and at $3.5 < z < 4.5$ ($B$ drop-outs). They compared the luminosity density in HDF high-z galaxy samples to that found in low-z survey and interpreted these data in terms of evolution with redshift of the star-formation/metal-production rate. Although the results at high-z were presented as lower limits (because nearly all the corrections to be applied drive the derived star formation rates up) it was argued that they may be not far from the true values and that they are consistent with a peak in the metal production rate at $1 < z < 2$. There was a remarkable, at least qualitative, agreement between the metal production rate, $\dot{\rho}_Z(z)$, estimated in this way and the prediction of the cosmic chemical evolution models by Pei & Fall (1995), and the predictions of hierarchical CDM models (Baugh et al. 1998), all of which show a peak in the metal production rate at $z \sim 1–2$. On the other hand, their conclusions were affected by several large uncertainties due to (Ferguson et al. 2000; Somerville et al. 2001):

1. Selection criteria: the adopted color selection was extremely conservative and spectroscopic surveys (Steidel et al. 1996; Lowental et al. 1997) have identified at least a dozen $2 < z < 3.5$ galaxies that would have been missed.

2. Sampling of the luminosity function: Madau et al. (1996) simply summed up the observed fluxes of galaxies, although only the bright tail of the LF was sampled (Thompson et al. 2001).

3. Surface brightness corrections: for fixed luminosity and physical size, the surface brightness drops by about 1 mag between $z = 3$ and $z = 4$. This may produce a substantial underestimate of $\dot{\rho}_Z(z)$ at high $z$ (Ferguson 1998; Lanzetta et al. 1999).

4. Effects of dust: dust is ubiquitous in star-forming regions and relatively modest amounts of dust suffice to strongly attenuate the UV emission. Analysis of UV
spectral slopes yielded evidences of substantial dust extinction (Pettini et al. 1998; Meurer et al. 1997, 1999; Sawicki & Yee 1998; Steidel et al. 1999; Flores et al. 1999; Mobasher & Mazzari 2000). The derived upward corrections of the luminosity densities by Madau et al. (1996) range from factors of \( \sim 3 \) to more than 10, indicating that the correction based on optical/UV data is both large and very uncertain. Even more: very dusty galaxies, akin to ultra-luminous IRAS galaxies, that were present at high \( z \), would be largely unaccounted by these studies because they would be unlikely to be identified as Lyman-break galaxies.

All that boils down to the conclusion that the optical view of “primeval” galaxies is incomplete and biased. It must be complemented with far-IR/sub-mm observations.

Almost simultaneous with the discovery of LBGs was a second major breakthrough: the discovery of the Cosmic Infrared Background (Puget et al. 1996; Guiderdoni et al. 1997; Schlegel et al. 1998; Fixsen et al. 1998; Hauser et al. 1998; Lagache et al. 1999, 2000; Finkbeiner et al. 2000) at a level 10 times higher than the no-evolution predictions based on the IRAS local luminosity function of galaxies and twice as high as the Cosmic Optical Background obtained from the optical counts, implying that most of starlight emitted at early phases of galaxy evolution is actually reprocessed by dust (remember that in the local universe dust emission accounts for only \( \sim 30\% \) of the bolometric luminosity of galaxies). The CIRB SED turned out to be in remarkably good agreement with the models by Franceschini et al. (1994) whereby most of the star formation in spheroidal galaxies was enshrouded by dust. Thus, far-IR to sub-mm observations carry the most direct, minimally biased information on the cosmic star-formation/metal-production history.

Sub-mm observations have a particularly privileged role in the game: their uniquely strong, negative K-correction, due to the steep increase with frequency of dust emission in galaxies, coupled with the strong cosmological evolution demonstrated by ISO and SCUBA data (Elbaz et al. 1999; Smail et al. 1997; Hughes et al. 1998; Barger et al. 1999a,b; Eales et al. 1999) as well as by the CIRB intensity, greatly emphasizes high-redshift galaxies. Such observations therefore hold the key to understanding the formation and evolution of massive elliptical galaxies, a still controversial issue in cosmology.

2. Monolithic versus merging scenarios for the formation of spheroidal galaxies

Two quite different scenarios are still confronting each other. One scenario, motivated by hierarchical clustering Cold Dark Matter (CDM) cosmologies, predicts that most large galaxies arise from a series of merging events taking place over a major fraction of the cosmological time (Baugh et al. 1998; Kauffmann 1996).

The other scenario assumes instead that the bulk of the baryonic mass of the galaxy was assembled in gaseous form. Most stars formed in a single gigantic starburst, followed by essentially passive evolution, due to the ageing of stellar populations. This scheme is sometimes qualified as monolithic.

It is worth stressing that the monolithic scenario too can be consistent with the hierarchical gravitational instability picture for the structure formation. The difference
with the *merging* scenario is that large ellipticals formed most of their stars *in situ* as soon as the corresponding dark matter halos condensed out. In the *merging* scenario most stars are formed in smaller galaxies that subsequently merged and the merging events eventually triggered further bursts of star formation.

In the *merging* hypothesis, ellipticals would exhibit a broad range of colors and spectral properties, reflecting the variety of star formation histories, the bulk of stars having an intermediate age, and their number density should decrease with increasing redshift. On the contrary, in the *monolithic* scenario the number density should remain constant and the stars should be old and essentially coeval.

Several lines of observational evidence (the tightness of the fundamental plane for ellipticals in local clusters, the tight color-magnitude relation for ellipticals in clusters up to \( z \sim 1 \), the modest shift with increasing redshift in the zero-point of the fundamental plane, \( \text{Mg-}\sigma \), and color-magnitude relations for cluster ellipticals, the small zero-point offset between cluster and field ellipticals) converge in indicating that most stars in galactic spheroids are old (formed at \( z \gtrsim 2-3 \)) and essentially coeval (see Renzini & Cimatti 1999, Shade et al. 1999, and Kodama et al. 1999 for recent discussions).

It is, however, still controversial whether ellipticals were assembled to their present mass at a later epoch, compared to that of formation of their stars (see Renzini & Cimatti 1999, Ferguson et al. 2000, and references therein, and the recent work by Martini 2001 and Rodighiero et al. 2001). Good agreement was recently found by Daddi et al. (2000) between the observed surface density of Extremely Red Objects (EROs) in the widest field survey for such objects available, with that predicted by Pure Luminosity Evolution (PLE) models after applying the appropriate color and luminosity thresholds. Since there are indications that the bulk of EROs are passively evolving ellipticals, this result supports the view that most field ellipticals were fully assembled by \( z \sim 2.5 \).

### 3. The role of sub-mm surveys

Sub-mm data provide information on an earlier stage of formation of ellipticals than optical data do, i.e. on the stage when these galaxies were forming most of their stars. SCUBA surveys did in fact provide the most critical test for the *merging* scenario.[1]

A very comprehensive attempt to make detailed predictions for the observable properties of galaxies throughout the electromagnetic spectrum, at all redshifts, starting from an assumed initial spectrum of density fluctuations, was carried out by Granato et al. (2000). These authors combined the semi-analytical galaxy formation model of Cole et al. (2000; GALFORM) with the evolutionary spectro-photometric models including the effect of dust by Silva et al. (1998; GRASIL), to compute epoch-dependent galaxy luminosity functions from UV to sub-mm wavelengths.

GALFORM evolves the primordial density fluctuations and applies simplified analytical descriptions of the main physical processes of gas cooling and collapse, star for-

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[1] We will not deal here with the parameterized empirical approaches, evolving backwards in time the local luminosity functions at different wavelengths. Successful models of this kind were worked out by Franceschini et al. (1991), Franceschini (2000), Pearson & Rowan-Robinson (1996), Dwek et al. (1998), Blain et al. (1999), Tan et al. (1999), Rowan-Robinson (2001), Pearson et al. (2001), Takeuchi et al. (2001).
mation, feedback effect from supernovae, galaxy merging, chemical enrichment of stars and gas, and more, on top of a Monte Carlo description of the process of formation and merging of dark matter halos through hierarchical clustering.

GRASIL follows the evolution of stellar populations and absorption and emission by dust with a realistic 3D geometry, with a disk and a 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 evaluation of the dust temperature distribution at each point in the galaxy.

The models include both galaxies forming stars quiescently in disks, and starbursts triggered by galaxy mergers. They reproduce quite well a large number of observables, including the SEDs of normal spirals and starbursts from UV to sub-mm; their internal extinction properties and, in particular, the observed relationship between far-IR/UV luminosity ratio and the slope of the UV continuum and the observed starburst attenuation law (Calzetti et al. 2000) with the same dust mixture which reproduces the Milky Way extinction law; the local galaxy luminosity functions from UV to far-IR; the counts of galaxies in wavebands from UV to far-IR.

However, they fail by a factor ~10 to reproduce the sub-mm counts, which turn out to be the most critical test for semi-analytic approach.

In fact, analogous conclusions are reached by Devriendt & Guiderdoni (2000) who implemented a independent ab-initio models, building on earlier work by Guiderdoni et al. (1997, 1998) and exploiting the spectro-photometric evolution models, including dust, developed by Devriendt et al. (1999; STARDUST). To reproduce the 850 μm counts they are forced to introduce an ad-hoc population of heavily extinguished, massive galaxies with large star-formation rates at intermediate and high redshifts.

These difficulties, affecting even the best current recipes, may indicate that new ingredients need to be taken into account. A key new ingredient may be the mutual feedback between formation and evolution of spheroidal galaxies and of active nuclei residing at their centers.

4. Relationships between quasar and galaxy formation

In the past, evolutionary histories of quasars and of galaxies have been dealt with as essentially independent subjects. This was due to two main reasons. On one side, it was essentially impossible to have a synoptic view of the evolutionary history of the two populations, since the high redshift universe was almost exclusively the realm of quasars while the “local” universe (z < 1) was the realm of galaxies. On the other side, and perhaps more important, physical processes involved in the formation and evolution of both quasar and galaxies are of great complexity and therefore difficult to handle without the guidance of direct observational data.

The situation has drastically improved in the last years with the detection of ordinary and starburst galaxies up to z > 3 which has opened to direct investigation the early phases of galaxy evolution. There is now convincing evidence of substantial star-formation activity at least up to z ≃ 4 (Lagache et al. 1999; Steidel et al. 1999).

On the other hand, extensive data on the demography of super-massive black holes
(BH) in nearby galaxies has been accumulating, allowing to piece together an increasingly quantitative description of their mass function (Salucci et al. 1999) and of where (and possibly when) they formed. There is no evidence of quasar activity outside galaxies and deep imaging of bright quasar samples have revealed that their hosts are most likely elliptical galaxies (Hall & Green 1998; McLure et al. 1999; Schade et al. 2000).

As recognized by Haehnelt & Rees (1993), the epoch of quasar activity coincides with the time when the first potential wells form in the standard CDM scenario. In the same framework, Haehnelt et al. (1998) demonstrated that the luminosity function of actively star-forming galaxies at $z = 3$ and the B-band luminosity function of quasars at the same redshift can both be matched with the mass function of dark matter halos.

Suggestive similarities have been found between the history of the blue luminosity density produced by stars and quasars (Cavaliere & Vittorini 1998). The similarity persists and even strengthens when the history of star formation is compared with that of the global volume emissivity of Active Galactic Nuclei (Franceschini et al. 1999). The evolution of the luminosity density of extragalactic radio sources also appears to remarkably parallel that of the star formation rate (Dunlop 1998).

If quasars were in place roughly at the same time as galaxies, it is natural to expect that, given their high bolometric luminosities, they play an important role in the early evolution of galaxies (Silk & Rees 1998; Blandford 1999; Monaco et al. 2000): they may provide crucial feedback for limiting star formation, for arresting its growth, for inducing or inhibiting collapse of further density perturbations in the neighborhood and for ionizing the inter-galactic medium (Blandford 1999).

In turn, the fuelling of quasars is likely to be tightly related to galaxy evolution. Quasars are widely believed to be powered by accretion into a massive BHs. As discussed by Cavaliere & Vittorini (1998, 2000) the data on quasar evolution can be interpreted in terms of fuelling of BHs during the formation of the host galaxy while, at later times, accretion is rekindled by interactions of the host galaxy with companions.

It follows that a consistent evolutionary scenario must deal with the combined evolution of BHs and of their host galaxies. The link between the two classes of objects is given by the observed relationship between the BH mass and the mass (or, better, the velocity dispersion) of the host galaxy (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000). If this relationship was imprinted during the early phases of the evolution (Silk & Rees 1998; Fabian 1999), the formation rate of spheroids can be derived directly from the formation rate of quasars, which, in turn, can be inferred from the epoch-dependent luminosity function, now observationally determined (or at least estimated) up to $z = 4.5$ (Boyle et al. 2000; Fan et al. 2001), given the quasar lifetime, $\Delta t_Q$. The latter quantity can be determined from the condition of consistency with the present day mass function of spheroids (Salucci et al. 1999), giving $\Delta t_Q \simeq 4 \times 10^7$ yr, well within the range of current estimates yielding $\Delta t_Q \simeq 8 \times 10^6 - 10^8$ yr (Salucci et al. 1999; Martini & Weinberg 2001; Monaco et al. 2000).

In this framework, Granato et al. (2001) propose the following scenario:

- Once the effects of cooling and heating processes (the latter being mostly due to stellar feedback) are properly taken into account, the timescale for star formation within virialized dark matter (DM) halos turns out to be relatively short for mas-
sive spheroidal galaxies ($T_{\text{SF}} \sim 0.6$ Gyr for $M_{\text{DM}} \sim 5 \times 10^{12} M_\odot$), while in the case of less massive halos the feedback from supernovae (and/or from the active nucleus) slows down the star formation and can also expel a significant fraction of the gas. The canonical scheme implied by the hierarchical CDM scenario – small clumps collapse first – is therefore reversed when we consider baryons. During this phase, large spheroidal galaxies show up as luminous sub-mm sources, accounting for the $850 \mu$m counts.

- When the quasar luminosity reaches a high enough value, its action (ionization and heating of the gas), together with that of SN explosions, stops the star formation and eventually expels the residual gas. This naturally explains the observed correlation between BH and host spheroidal masses (Silk & Rees 1998; Fabian 1999). The same mechanism distributes in the IGM a substantial fraction of metals.

- A “quasar phase” follows, lasting $10^7$–$10^8$ yr.

- Intermediate- and low-mass spheroids have lower SFR’s and less extreme optical depths. They show up as LBGs.

- A long phase of passive evolution follows, galaxy spectra becoming rapidly red.

Determining the redshift distribution of SCUBA source is obviously of utmost importance, since it allows us to obtain a unbiased view of the star-formation history of the universe and potentially holds the key to understanding the formation and evolution of the most massive ellipticals. Unfortunately this is a very difficult job, due to the rather poor angular resolution of SCUBA and to the faintness of the optical counterparts, making the identification ambiguous in most cases. Of greatest importance are deep VLA maps of SCUBA fields which allow us to identify radio counterparts or place stringent limits on the radio flux of the sub-mm galaxies. The recent work on sub-mm to radio spectral indices (Carilli & Yun 1999, 2000) has provided us with a useful tool for estimating, or constraining, the redshifts. The redshift information derived in this manner can be compared with the spectroscopic redshifts for individual candidate optical counterparts to determine the reliability of proposed identifications.

In spite of the fact that only a handful of redshifts of sources detected in blank-field SCUBA surveys have been reliably measured, the results summarized in Dunlop (2001) indicate that most SCUBA sources are probably at $z > 2$, consistent with the scenario in which the peak AGN emission corresponds to, or even causes the termination of, major star-formation activity in giant spheroidal galaxies (Granato et al. 2001). Given that the optical emission of powerful quasars peaks at $z \simeq 2.5$, dust emission is expected to peak $\simeq 0.5$ Gyr earlier, i.e. at $z \simeq 3$ (Dunlop 2001).

Other important implications of this scenario concern clustering (Magliocchetti et al. 2001) and lensing properties of dusty spheroids (Perrotta et al. 2001b).

At early times, collapsed objects are likely to be in the highest peaks of the density field, since one needs a dense enough clump of baryons in order to start forming stars. Such high-$\sigma$ peaks are highly biased tracers of the underlying density field (Kaiser 1984; Bardeen et al. 1986; Mo & White 1996). The bias factor is strongly dependent on the mass of dark halos. Therefore, clustering measurements allow estimates of involved
masses. Although the samples of sub-mm galaxies are still too small to allow determinations of their clustering properties, large cell-to-cell fluctuations are seen, suggestive of strong clustering.

Gravitational lensing of extragalactic light by line of sight mass concentrations can strongly amplify fluxes of distant sources (Peacock 1982). Although the probability of strong lensing is very small, its distribution has a power-law tail \( p(A) \propto A^{-3} \) extending up to very large values \( (A_{\text{max}} \simeq 10^{-30} \text{ for extended sources; Perrotta et al. 2001a}) \). If counts decrease with increasing flux fast enough, the fraction of lensed sources at bright fluxes may be large. The special properties of the sub-mm counts make this spectral region ideally suited for detecting lensed sources. In fact, as noted above, this spectral region greatly emphasizes high-redshift sources (which have the highest probability of being gravitationally lensed) and yields very steep counts, thus maximizing the amplification bias (Peacock 1982; Turner et al. 1984). Thus, we expect that the fraction of gravitationally lensed galaxies is boosted in large area, relatively shallow surveys at sub-mm wavelengths (Blain 1996, 1998).

In the scenario by Granato et al. (2001) the bulk of star-formation in massive early-type galaxies occurred at \( z \geq 2 \) and was essentially completed at \( z \simeq 1 \). This translates into an essentially exponential turnover of the counts, reflecting the high-mass turnover of the mass (and of the associated luminosity) function of galactic halos in place at the relevant \( z \). While this extremely fast decline of the counts at bright fluxes may imply that unlensed forming spheroidal galaxies will not be detectable by large area, relatively shallow surveys such as those to be carried out by ESA’s PLANCK satellite, on the other hand, the amplification bias due to lensing is maximized. As a result, the counts of this population may be actually dominated, at the brightest flux levels, by highly magnified sources. This characteristic feature of the model by Granato et al. (2001) may help to discriminate between different scenarios, such as the one proposed by Rowan-Robinson (2001), predicting less steep counts, implying a much lower fraction of highly magnified, bright sources (Perrotta et al. 2001b).

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