GALAXY EVOLUTION WITH ALMA

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Abstract

The submillimeter and millimeter domains are privileged for the exploration of galaxies at high redshift, because of the negative K-correction: the peak of the dust emission at 60-100 microns is red-shifted in these domains. Already blind surveys in blank fields with today instrumentation have discovered in the continuum of the order of one object per square arcmin, with large limitations due to confusion. In the molecular lines, the K-correction is not so favorable, and it has been until now difficult to detect the objects, except when they are starbursting monsters, or gravitationally lensed (about a dozen galaxies have been detected). ALMA will bring more than one order of magnitude improvement, and will not be affected by confusion. Normal star-forming objects will be detected, and in particular those enshrouded in dust, so the instrument will be complementary to the optical ones, such as NGST or ELTs.

1 Introduction

The formation and evolution of galaxies is one of the main drivers for the large millimeter array ALMA. This is essentially due to three arguments:

• it is now well established that there is a large increase in the frequency and efficiency of starbursts at high redshift; there is almost a factor 10 increase from $z = 0$ to $z = 1$ in the star formation rate

• the most active starbursts are the most obscured by dust; this is well observed at $z = 0$, the young stars are still embedded in their molecular clouds. At high redshifts, the intense starbursts will almost radiate all their energy through heated dust. The star formation rate can be highly under-estimated at optical wavelengths. The far-infrared to optical luminosity ratio is observed to vary considerably, between 0.1 and 1000, and is a good indicator of starbursts

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Fig. 1. SED for a typical starforming galaxy in the radio and far-infrared, for various redshifts $z = 0.1, 1, 3, 6, 10, 30, 60$ ($H_0 = 75 \text{km/s/Mpc}, q_0 = 0.5$). The synchrotron spectrum on the right side is a power-law of slope -0.7, and left the emission from dust is modelled by PAHs, very small grains and big grains, as in Désert et al. (1990) to fit the Milky Way data. It has been assumed here that the dust properties are the same as in our Galaxy, and that the power of the starburst is the same at any redshift.

- the millimeter and sub-millimeter domain are favored by the negative K-correction: the maximum of dust emission, that occurs around $100\mu m$ progressively enters in the millimeter domain (at 0.3mm for $z = 2$). The spectral energy distribution (SED) is particularly steep in this region, since we are in the Rayleigh-Jeans domain, where the Planck function is $B(\nu) \propto \nu^2$, and the optical depth is $\tau \propto \nu^\beta$, with $\beta \sim 1.5-2$. The emission therefore varies as $4 \sim \nu^4$ (cf figure 1).

2 Present and future surveys at high $z$

The present blank field surveys, carried out with JCMT-SCUBA or IRAM-MAMBO at 0.85 -1.2 mm (Smail et al 1997, Barger et al 1998, Carilli et al 2000) have been quite successful, and find about 1-2 sources/ arcmin$^2$ above a flux of 1 mJy. The log(N)-log(S) source counts diagram has been prolonged at low fluxes due to amplification by gravitational lens effect, through clusters of galaxies.

The main problem encountered by present surveys is the identification of sources, which has revealed quite difficult. This is related to the low spatial resolution (of the order of 15$''$), which is also source of confusion. The next spa-
tial instruments, (such as SIRTF, Herschel) will also suffer from confusion, while ALMA will solve the problem. Another way to identify sources is to obtain the redshifts through molecular millimetric lines, and this will be possible with wide-band receivers, such as those considered for the “redshift machines” on LMT, GBT, ALMA...

The results of present submm surveys allow to estimate the star formation rate as a function of redshift, and in particular to determine how much this rate is underestimated by optical surveys. After many controversies and debates, the extinction correction to apply to visible/UV data is converging towards a factor about 3 (e.g. Genzel & Cesarsky 2000), and the star formation rate is slightly decreasing at high redshift after a maximum at $z = 2$. This estimation is also compatible with the constraints of the Cosmic Infrared Background (CIB) (Puget et al 1996, Hauser et al 1998).

A large fraction of the energy produced in starburst is reprocessed by dust, the sub-mm sources represent already a large fraction of the CIB (between 10 and 60%). But the question arises as to determine the relative contribution of AGN and starburst in dust heating. The fact that the sources responsible for the X-ray background are not the same as those for the CIB (Severgnini et al. 2000) does not exclude the possibility that the latter are mainly heated by obscured AGN (Barger et al 2001).

ALMA will not suffer confusion, because of its high spatial resolution (better than 0.1", see Table 1). Its high sensitivity will allow to detect more normal (non-ULIRG) objects, such as the Lyman-Break Galaxies (Steidel et al 1996, Adelsberger & Steidel 2000). Their frequency is of the order of 150/arcmin$^2$ for $z=2.5-3.5$, and this will allow the detection of about 100 times more submm sources than today. In the millimeter domain, it is also likely that different objects will be seen than in the optical, due to extinction (see Melchior, this conference).

### Table 1. Panorama of large (>200m$^2$) mm and sub-mm instruments

| Name          | Area  | $\lambda_{min}$ | $\theta$ (") |
|---------------|-------|-----------------|--------------|
| IRAM-30m      | 707   | 1mm             | 10           |
| IRAM-PdB (6x15m) | 1060  | 1mm             | 0.5          |
| NRO-45m       | 1590  | 1.3mm           | 8            |
| NRO (6x10m)   | 509   | 1.3mm           | 0.5          |
| OVRO (6x10m)  | 509   | 1.3mm           | 0.5          |
| BIMA (10x6m)  | 282   | 1.3mm           | 0.5          |
| CARMA         | 791   | 1.3mm           | 0.5          |
| SMA (7x6m)    | 200   | 0.3mm           | 0.1          |
| GBT-100m      | 7854  | 2.6mm           | 7            |
| LMT-50m       | 1963  | 1mm             | 6            |
| ALMA (64x12m) | 7238  | 3-0.3mm         | 0.1-0.01     |
| EVLA (35x25m) | 17200 | 6mm             | 0.004        |
Fig. 2. Predicted flux for an homogeneous cloud model at $T_h = 50$K, $n_{H_2} = 10^3$ cm$^{-3}$ and $N_{CO} = 3 \times 10^{20}$ cm$^{-2}$, for various redshifts $z = 0.1, 1, 2, 3, 5, 10, 20, 30,$ and $q_0 = 0.5$. The flux is predicted for the first CO lines of the rotational ladder, materialised each by a circle (they are joined by a line only to guide the eye). The same power has been assumed for the starburst at all redshift, and $T_d^{6} - T_{bg}^{6}$ is conserved (cf Combes et al. 1999).

The present submm source counts have been compared to theoretical expectations, in particular to semi-analytical models, based on the hierarchical scenario for galaxy formation. Observations help to constrain the numerous free parameters and to refine the scenarios. Two strategies are possible:

– either all parameters are fixed according to "realistic" laws or assumptions (Granato & Silva 2001)
– or the best fit is searched for, with a restricted number of parameters (Blain 2000).

In particular the models deduce the evolution as a function of redshift of the energy released by the baryons through mergers. The result is that mergers are much more efficient for star formation in the past, which could be explained by the larger gas fraction, and the smaller dynamical time.

To better determine the molecular gas mass fraction, and therefore the efficiency of star formation, ALMA is necessary to detect the CO lines in high-z galaxies. The detection of CO lines is also favored by the fact that the high J lines have larger fluxes, and once redshifted, they enter the submm and mm domain, but the K-correction is not negative, and it is more difficult to detect the lines than the continuum at high redshift. The prediction of the CO lines flux depends
Fig. 3. Predicted flux as a function of redshift for the same model as in figure 2, displayed now for each of the CO lines separately; this shows that the high-J lines are not much helpful after J=4.

Due to the abundance of starbursts at high z, it is likely that most galaxies will reveal dense and hot molecular gas, and be easily detected from high J lines. However, it is not necessary to go at very high frequency since the maximum flux is already reached at J=4-5 (see figure 3 and e.g. Papadopoulos & Ivison 2001).

3 Molecular component, chemistry and dynamics in galaxies

Other important issues where ALMA will make a breakthrough are:

- molecular line absorptions: many more continuum sources will be detected in the mm and submm with the enhanced sensitivity of ALMA; probing high column density along the line of sight of remote quasars will allow tackling the fate of baryons as a function of z, high redshift chemistry, etc... (Combes & Wiklind 1999)

- the detection of individual molecular clouds in many nearby galaxies will allow, through application of the virial theorem, a more accurate determination of the ill-known CO/H$_2$ conversion factor
• the detection of CO at large distance from the center in nearby galaxies, and
  the exploration of the outer parts of galaxies
• dynamics of galaxy centers with high resolution, CO as only tracer where HI
  is deficient (nuclear bars and spirals), and relation with AGN
• detection of the molecular torus, expected in AGN unification theory
• dwarf galaxies, and molecular gas outside galaxies (tidal dwarfs, star forma-
  tion complexes...)

4 Conclusions

ALMA will bring considerable progress in the understanding of the molecular com-
ponent and star formation efficiency in nearby galaxies. One of the main driver is
 to open the window on the formation of galaxies: the star formation history, the
 efficiency as a function of z to make stars and energy from baryons in mergers,
 the history of gas enrichment, the scenario for bulge and disk formation, etc.. The
 submm and mm domains are a necessary complement of other wavelength
 studies, in particular the visible domain, since starbursting galaxies suffer significant
 obscuration.

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