EXTREMELY RED AND DUSTY GALAXIES

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1. ABSTRACT

Preliminary results of a project aiming at unveiling the nature of the extremely red galaxies (ERGs) \(^1\) found in deep optical-NIR surveys are presented. Very little is known about these objects, the critical issue being whether they are old ellipticals at \(z>1\) or distant star-forming galaxies strongly reddened by dust extinction.

We expect to shed light onto the unknown nature of these galaxies by completing our three-step project: (1) the construction of two very deep optical/NIR surveys to select ERGs, (2) subsequent VLT/NIR spectroscopy; (3) observations in the submm-mm region with SCUBA at the JCMT and with MPIfRbolo at the IRAM 30m antenna.

2. INTRODUCTION

Optical and NIR deep surveys have recently boosted observational cosmology and allowed important advances in our understanding of young galaxies. It has been possible to detect star-forming objects at high redshifts and construct the star-formation rate (SFR) history of the universe converting

\(^1\)by extremely red galaxies hereafter we mean objects with colours \(R-K > 6\) and \(I-K > 5\)
the detected UV-optical or line rest-frame luminosities into a star formation rate (Madau et al. 1996; see also Calzetti, these Proceedings):

Several ways of inferring SFRs have been used:

- The star-formation rate (SFR) in Lyman-break galaxies deduced from their UV-rest frame luminosity is of the order of 4-50 $h^{-2}_{50} M_{\odot}/\text{yr}$ (Steidel et al. 1996; Madau et al. 1998).
- Lyman-α emitters present a comparable SFR obtained from their line luminosity of 1-10 $h^{-2}_{50} M_{\odot}/\text{yr}$ (Hu et al., 1998)
- OII ($\lambda 3727$) emitters have a SFR of 5-60 $h^{-2}_{50} M_{\odot}/\text{yr}$ (Cowie et al., 1996)
- because of a smaller bias against reddening higher values for SFR are inferred from H-α and H-β line luminosities: of 5-200 and 10-140 $h^{-2}_{50} M_{\odot}/\text{yr}$ respectively (Beckwith et al. 1998; Mannucci et al. 1998; Teplitz et al. 1998; Pettini et al. 1998).

When these results are combined together with those from galaxy surveys at $z \leq 1$ strong constraints on the comoving SFR are inferred (Madau et al., 1996). But a still debated question is the presence of the peak seen at $z \sim 1.5$, since surveys based only on UV-optical light are strongly biased towards dust-free objects.

Several arguments suggest that the population of high-$z$ galaxies detected so far may not represent the progenitors of all local galaxies and the consequent history of SFR may be strongly underestimated. The presence of other populations of objects is therefore very likely and may be advocated to explain the following.

- There is an absence of passively evolving ellipticals in deep surveys. Where are the associated protospheroids?
- There is a FIR-submm background detected by COBE, very likely due to the integrated emission of a so-far-hidden population of dusty galaxies (Puget et al. 1996; Hauser et al. 1998).
- ISO/SCUBA FIR/submm-mm surveys (Rowan Robinson et al. 1997; Kawara et al. 1997; Barger et al. 1998; Hughes et al. 1998; Smail, Ivison & Blain 1998; Eales et al.) are key to test the presence of these dusty objects and are indeed showing a large number of sub-mm luminous galaxies (at $850\mu m \sim 0.08-0.5$ objects arcmin$^{-2}$ with flux $>3$ mJy and 2 objects arcmin$^{-2}$ with $>1$mJy, Hughes et al. 1998). Is the detected dust obscuring a large fraction of the galaxy UV-luminosity?

*Maybe some/all of these dusty objects are already showing up in OPTICAL/NIR surveys.*
3. THE QUEST FOR ERGS

It is important to check whether the new very red galaxies showing up when we combine optical + NIR images represent part of the population of high-z dusty galaxies. These ERGs are missed by the traditional optical surveys because of their faintness at optical magnitudes and they do not show up in the surveys devoted to high-z galaxies such as those mentioned above. They are found thanks to the combination of deep optical and NIR images both in random fields and in those containing an AGN. Their surface density in the field at K<20 is of the order of 0.1-0.2 arcmin$^{-2}$ for R-K>6 or I-K>5 and of $\sim 0.01-0.05$ arcmin$^{-2}$ for R-K>7 or I-K>6 (Hu & Ridgway 1994; Cowie et al. 1996; Thompson et al. 1998; Barger et al. 1998) (for comparison the surface density of Lyman-break galaxies is 0.5 arcmin$^{-2}$ while that of QSOs with B<21.5 is $0.015$ arcmin$^{-2}$).

If resolved in ground-based and HST images ERGs usually show compact morphologies. They sometimes have asymmetric and distorted morphologies suggesting the presence of an interacting system or a tidal arm. Their faintness hampers the exploitation of Optical/NIR spectroscopy with 4m telescopes to obtain redshifts and to investigate their nature. So far the Keck 10m telescope has provided the only redshift available of one of these galaxies, HR10 (Dey et al., 1999).

The existence of a significant population of objects that is extremely red, moderately bright and at high redshifts is difficult to explain using the known properties of nearby galaxies. It is likely that ERGs form a heterogenous sample with observed properties alike not because of intrinsic similarity but only because of selection criteria. It is very unlikely that they are at very high redshifts (z>3), since this would require that these objects be exotic and very luminous. It is also unlikely that most of them lie at low redshifts since no population with the properties of ERGs is yet known to exist locally. Hints about their nature can be extracted from their extremely red colours and the likely explanations are actually twofold:

- Are they old L$_{\star}$ ellipticals at z>1? In this case their red colours are simply due to the passively evolving population of stars (Cohen et al., 1998).
- Are they strongly extincted starbursts or AGNs? In this case their UV-optical light is reddened by dust. Are they then similar to the sub-mm selected galaxies detected from SCUBA?

Even if they may not represent a large hidden population of galaxies in both scenarios they play an important role in understanding the integrated star-formation in the high-z population.
4. OUR ON-GOING PROJECTS

A multi-wavelength approach was then tackled to unveil the nature of these objects. Two surveys are presently being carried out to select two complete samples of ERGs: one in random fields and one around AGNs at \( z > 1.5 \). Their surface abundance will be inferred and targets for VLT spectroscopy will then be selected. The surveys make use of ESO ground-based (optical+NIR) and HST (WFPC2) data (see Pozzetti et al. 1998).

Meanwhile, a subsample of the selected ERGs will be observed at sub-mm and mm wavelengths using SCUBA+JCMT and MPIfRbolo+IRAM. The aim is to check whether thermal emission from dust in the ISM of these galaxies can be observed. The detection of the dust emission allows also to determine the FIR luminosity and to infer the SFR. These can be then compared with the sub-mm selected galaxies. An important outcome of this research will be then the inference of the ERGs contribution to the global star-formation history of the Universe and to the FIR/sub-mm background.

5. RESULTS OF OUR SUB-MM/MM INVESTIGATION: HR10

The ERG HR10 (the only one with redshift available) was independently detected with the IRAM 30m equipped with the MPIfRbolo and with the JCMT equipped with the SCUBA double arrays (Cimatti et al. 1998; see also Dey et al., 1999). The radio emission of this object is extremely weak in comparison with the millimetric flux \( \frac{S_{150\mu m}}{S_{1\text{mm}}} < 0.02 \); it is very likely therefore that the detected sub-mm/mm fluxes are not due to synchrotron emission but to thermal emission from a dusty medium. Combining these measurements with the ISO upper limit at 175 \( \mu \text{m} \) (Ivison et al., 1997) one can derive the dust properties. For a range of dust temperatures between 30 and 45 K the corresponding total dust mass lies in the range of \( 8-4 \times 10^8 \, h_{50}^{-2} \, M_\odot \) (for \( q_0=0.5 \) and a dust emissivity index \( \beta \) of 2). One must note, however, that although the thermal spectrum is not well constrained due to a lack of data in the Wien region, the uncertainty on the dust mass is not larger than a factor of 2. The total rest-frame far-IR luminosity in the range 10-2000 \( \mu \text{m} \) rest-frame is \( 2-2.5 \times 10^{12} \, h_{50}^{-2} \, L_\odot \). This luminosity places HR10 in the class of ultraluminous infrared galaxies and implies a SFR (adopting the relationship \( \text{SFR} \sim 10^{-10} L_{FIR} \) and assuming no AGN contribution) of \( \sim 200-500 \, h_{50}^{-2} \, M_\odot/\text{yr} \). It is worthwhile mentioning here that the SFR deduced from H\( \alpha \) emission was of \( 80 \, h_{50}^{-2} \, M_\odot/\text{yr} \) and from the UV continuum of only \( 1 \, h_{50}^{-2} \, M_\odot/\text{yr} \). SFR is then severely underestimated due to the strong dust extinction.

The nature of this galaxy will be further investigated via interferometric imaging of the 1.3mm continuum and CO line emission with the Plateau
de Bure IRAM interferometer.

6. FURTHER SUBMM-MM OBSERVATIONS

A sample of other 8 ERGs with $K < 20$ and $I-K > 6$ has been observed so far with SCUBA at the JCMT and with the IRAM 30m antenna, and other observations have been scheduled. The final data reduction is currently under way. For 4 ERGs we could reach the sensitivity required by our survey (rms $<2$ mJy at $850\mu m$), whereas the weather was not good enough to obtain deep data at $450\mu m$. A preliminary analysis suggests that we obtained three marginal detections at $850\mu m$ that need to be confirmed with deeper observations. We have also searched for the presence of a positive signal from the population of ERGs by coadding the data of the whole sample. The weighted average of the $850\mu m$ flux density of the entire sample provides a signal at $3\sigma$ level. One further object was detected both at $850$ and $1250\mu m$. Together with the detection of HR10, this hints that at least part of ERGs are dusty, even if not so extreme as HR10. These findings, however, still need to be confirmed and the final results will be presented in a forthcoming paper (Cimatti et al., in preparation).

It should be reminded here that the physical interpretation of the submm-mm observations is not severely hampered by the fact that the redshifts of the ERGs are unknown (with the exception of HR10). Thanks to the strong K-correction caused by the steep grey-body dust spectra, the expected flux at $\lambda_{obs} = 850\mu m$ of a dusty star-forming galaxy at $1 < z < 10$ is not a strong function of the redshift. Thus, since ERGs are expected to be at $z > 1$, a detection at $\lambda_{obs} = 850\mu m$ directly implies a large content of dust and high $L_{FIR}$ and SFR irrespective of the redshift (see also Hughes et al. 1998; Barger et al. 1998).

7. CONCLUSIONS

For at least one galaxy (HR10) a large amount of star formation is missing from a UV-only census. As such one could consider it as an observational proof of the predictions by models such as those by Zepf and Silk (1996), Franceschini et al (1998), Guiderdoni et al. (1998). One can argue that the space density of ERGs is not greatly different from those predicted by these models at these flux levels. For instance, Guiderdoni et al. (1998) predict a sky surface density of dusty galaxies at $175 \mu m$ of 0.05 arcmin$^{-2}$ similar to that of the extreme red galaxies. Sources in the redshift range 0.5-2.5, which contribute to the cosmic FIR background, should have fluxes at $200 \mu m$ (observed) in the range 10-100 mJy. For $T_d = 18-45$ K the expected observed flux of HR10 at this wavelength would be of 10-40 mJy. At this point
extrapolation from one object to the entire class is entirely speculative and a better statistics is required before carrying out any meaningful comparison.

HR10 can be fully considered a ULIRG since most of its energy is emitted in the FIR.

Caution must be used when extrapolating the star formation rates for UV-selected galaxies to the whole history of SF in the Universe. At least part of this occurs in highly extincted environment where UV and optical light cannot escape.

Objects like HR10 would be missed by optical imaging based on the continuum break or on strong emission lines, by IRAS and by traditional quasar surveys.

Our result demonstrate the powerful tool provided by the combination of deep optical/NIR imaging with sub-mm/mm observations.

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