Near-infrared surveys have revealed a substantial population of enigmatic faint galaxies with extremely red optical-to-near-infrared colours and with a sky surface density comparable to that of faint quasars [1]. There are two scenarios for these extreme colours: (i) these distant galaxies have formed virtually all their stars at very high redshifts and, due to the absence of recently formed stars, the colours are extremely red [2] and (ii) these distant galaxies contain large amounts of dust, severely reddening the rest-frame UV–optical spectrum. HR10 (z = 1.44, [1, 3]) is considered the archetype of the extremely red galaxies. Here we report the detection of the continuum emission from HR10 at 850μm and at 1250μm, demonstrating that HR10 is a very dusty galaxy undergoing a major episode of star formation. Our result provides a clear example of a high-redshift galaxy where the star formation rate inferred from the ultraviolet luminosity would be underestimated by a factor up to 1000, and shows that great caution should be used to infer
the global star formation history of the Universe from optical observations only.

The current knowledge of the global star formation activity in the Universe is mostly based on the UV continuum luminosity of high-z galaxies [4]. However, a crucial phase in the evolution of a galaxy might be a vigorous starburst producing copious amounts of luminous stars. In this stage, most of the UV stellar radiation would be absorbed by the dust grains and re-emitted in the far-infrared (FIR), making the galaxy dark at UV and optical wavelengths. A cosmic background has been first detected at $\lambda_{\text{obs}} \sim 200 \mu m - 2 \text{mm}$ [3] and then interpreted by [3]. In addition, a cosmic background at $140 \mu m$ and $240 \mu m$ has been recently found by [7]. The presence of such a background suggests the existence of a population of distant dusty galaxies. Several models predict the number of dusty galaxies at high-z [8, 9, 10, 6]. However, the presently known dusty galaxies at $z > 1$ are limited to a handful of extremely rare objects such as radio galaxies, quasars and IRAS-selected luminous galaxies ([11, 12] and references therein), and the existence of a general field population of dusty galaxies has not been established yet. Recent surveys for field galaxies found faint ($R > 24$) and very red objects with colours typically in the range of $7 < R - K < 8$ [1, 13]. Their sky surface density, $\approx 0.01-0.02$ arcmin$^{-2}$ at $K \leq 20$ [1, 13], is comparable to that of faint quasars [1], but about one order of magnitude less than that of field galaxies with $z > 3$ [14].

In order to test if a fraction of these galaxies have these extremely red colours because of strong dust reddening, we started a programme aimed at detecting their (sub)-mm dust thermal emission. Our first target was HR10, one of the reddest galaxies known to date, with $I = 24.9$, $R - K \sim 8$, $I - K = 6.5$ [1] and the only with a measured redshift ($z = 1.44$ [3]). Its UV-optical spectral energy distribution (SED) suggested the presence of dust reddening [3, 13]. HR10 was observed and detected with the Institut de Radioastronomie Millimétrique (IRAM) 30m antenna at $1250 \mu m$ as well as with
the James Clerk Maxwell Telescope (JCMT)\footnote{The JCMT is operated by the Joint Astronomy Centre on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organisation for Scientific Research, and the National Research Council of Canada} 15m telescope at 850\(\mu\)m in March and September 1997 respectively. The details of the observations and data reduction can be found in the legend of Figure 1. Throughout the paper we assume \(H_0 = 50\) kms\(^{-1}\) Mpc\(^{-1}\), \(q_0 = 0.5\), and we define \(h_{50} = H_0/50\).

Figure 1 shows the SED of HR10. Synchrotron radiation emission as the source of the sub-mm fluxes can be ruled out because the radio fluxes\footnote{\cite{3,16}} constrain the extrapolated synchrotron flux at 1250\(\mu\)m to be \(<0.34\) mJy, more than an order of magnitude less than the observed one. We therefore interpret the continuum emission observed at 850\(\mu\)m and 1250\(\mu\)m as due to thermal dust emission. Using the ISO upper limit at 175\(\mu\)m\footnote{\cite{17}}, and for dust emissivity indices \(\beta = 1 - 2\)\footnote{\cite{18}}, the temperature is found to be in a range \(18 < T_d < 45\) K. These temperatures fall into the range of those of active and star-forming galaxies (\cite{19,12,11} and references therein). The total dust mass can be estimated as \cite{20}: \(M_d = S_{\nu_{\text{obs}}}D_L^2/[((1 + z)\kappa_d(\nu_{\text{rest}})B(\nu_{\text{rest}},T_d)]\), where \(\nu_{\text{obs}}\) and \(\nu_{\text{rest}}\) are, respectively, the observed and rest-frame frequencies, \(S_{\nu_{\text{obs}}}\) is the observed flux density at \(\nu_{\text{obs}}\), \(D_L\) is the luminosity distance, \(B\) is the black-body Planck function, \(T_d\) is the dust temperature and \(\kappa_d = 0.67(\nu_{\text{rest}}/250\text{GHz})^\beta\text{ cm}^2\text{ g}^{-1}\) is the adopted mass absorption coefficient\footnote{\cite{11}}. In the two extreme cases considered in Figure 1, the total dust mass is \(M_d = 7.3 \times 10^8\) \(h_{50}^{-2}\) M\(_\odot\) and \(M_d = 3.3 \times 10^9\) \(h_{50}^{-2}\) M\(_\odot\) for \(T_d=45\) K and \(T_d=18\) K respectively. The dust mass increases or decreases of a factor of about 2 if \(\beta=1\) or \(\beta=2\) respectively. If we assume \(M_{H_2}/M_d=100\)\footnote{\cite{21}}, the mass of molecular hydrogen is of the order of \(M_{H_2} \approx 10^{11}\) \(h_{50}^{-2}\) M\(_\odot\). The total FIR luminosity is estimated by integrating the grey-body curves in the range \(\lambda_{\text{rest}} = 10\) - \(2000\)\(\mu\)m, \(L_{FIR,\text{rest}} = 4\pi D_L^2(1 + z)^2 \int S_{\nu_{\text{obs}}} d\nu\), where \(D_L\) is the luminosity distance and \(S_{\nu_{\text{obs}}}\) is the flux density. We find that \(L_{FIR,\text{rest}} = 3.8 \times 10^{12}\) \(h_{50}^{-2}\) L\(_\odot\) and \(L_{FIR,\text{rest}} = 7 \times 10^{13}\) \(h_{50}^{-2}\) L\(_\odot\).\footnote{\cite{3,10,11}}
1.5 \times 10^{13} \, h_{50}^{-2} \, L_\odot$ for $T_d=18$ K and $T_d=45$ K respectively.

At low redshifts, HR10 is comparable to the ultra-luminous infrared galaxies (ULIGs) which are dusty systems with $L_{FIR} > 10^{12} \, L_\odot$ and typically $T_d \sim 30$-60 K \cite{12}, but with dust masses $M_d \sim 10^{7-8} \, M_\odot$ lower than those inferred for HR10 (\cite{12} and references therein). At high redshifts, HR10 can be compared to $IRAS$10214+4724, an ULIG at $z = 2.286$ \cite{22} whose properties are severely affected by gravitational lensing. If the correction for lensing magnification is taken into account ($\approx 30 \times$ in the infrared \cite{23}), $IRAS$10214+4724 has $L_{FIR} = 4.4 \times 10^{12} \, h_{50}^{-2} \, L_\odot$ and $M_d = 1.1 \times 10^8 \, h_{50}^{-2} \, M_\odot$ comparable to those of HR10, but it has a warmer dust temperature ($40 < T_d < 80$ K, \cite{12, 11} and references therein). The warmer dust could be due to the additional source of UV radiation provided by the hidden quasar present in the nucleus of $IRAS$10214+4724 \cite{24}.

If we apply the relation between the star formation rate and the $FIR$ luminosity: 

$$SFR = \Psi 10^{-10} L_{FIR}/L_\odot \, M_\odot \, yr^{-1},$$

where $\Psi = 0.8 - 2.1$ (\cite{25} and references therein), and we adopt $\Psi = 1.5$, we derive $SFR \sim 570 - 2250 \, h_{50}^{-2} \, M_\odot \, yr^{-1}$, which is larger than the typical $SFRs$ of low-$z$ ULIGs ($\approx 10 - 100 \, M_\odot \, yr^{-1}$ \cite{12}), but comparable to that of $IRAS$10214+4724 ($\approx 660 \, M_\odot \, yr^{-1}$ \cite{11}). If HR10 contains an obscured AGN heating the dust, then only a fraction of $L_{FIR}$ can be ascribed to star formation. The $H\alpha$ line detected in a very low resolution spectrum of HR10 \cite{3} has a signal-to-noise ratio insufficient to establish the presence of a broad component of this line, which would imply that the nucleus of the quasar is not severely obscured. However, the $K$-band morphology of HR10 is spiral-like and not strongly nucleated, and it does not support the presence of a directly visible quasar nucleus.

Due to the steep rise of the grey-body dust spectra towards $\lambda_{rest} \sim 100 - 200 \mu$m, the observations at longer wavelengths make the sub-mm and mm flux (at a fixed
observed $\lambda$) of a dusty galaxy roughly constant for approximately $1 < z < 10$. For instance, we moved HR10 to three different redshifts ($z = 0.7, 2.2, 3.3$) and we computed how its properties would change accordingly adopting $\beta = 1.5$ and an optically thin grey-body: $S_\nu \propto \nu^\beta B_\nu(T)$. We find that the inferred dust temperature would increase from approximately 15-20 K at $z = 0.7$ to 45-50 K at $z = 3.3$. $L_{\text{FIR}}$ and $M_d$ would be $\sim 0.1, 7.25 \times 10^{13} \ h_{50}^{-2} \ L_\odot$ and $\sim 30, 10, 5.6 \times 10^8 \ h_{50}^{-2} \ M_\odot$ for $z = 0.7$ ($T_d = 18$ K), $z = 2.2$ ($T_d = 35$ K), and $z = 3.3$ ($T_d = 45$ K) respectively. The main implication is that a galaxy with observed (sub)-mm properties as those of HR10 would be classified a dusty ultra-luminous infrared galaxy in a wide range of redshifts.

The discovery of dust associated with HR10 has several implications. First of all, it sheds light on the nature of this galaxy, demonstrating that HR10 is a very dusty star-forming galaxy where, similarly to low-$z$ ULIGs, most of the energy is emitted in the far-infrared. The second implication is generally related to the problem of estimating the star formation rate in distant galaxies. The global history of the star formation in the Universe is presently inferred mostly by the continuum UV luminosity of optically-selected high-$z$ galaxies, from which the derived SFRs are in the range of 4-25 $h_{50}^{-2} \ M_\odot \ yr^{-1}$. However, such estimates can be severely hampered by the presence of dust extinction which modifies the shape and reduces the flux of the UV spectra. Observations of low-redshift galaxies have also pointed out the limits of the UV–blue light as a SFR estimator (see for instance and references therein). HR10 allow us to see an extreme example of this problem applied to a high-$z$ system. In fact, the H$\alpha$ luminosity of HR10 would imply a $SFR \sim 80h_{50}^{-2} \ M_\odot \ yr^{-1}$, whereas the luminosity of the UV continuum at 2800 Å would suggest $SFR \sim 1h_{50}^{-2} \ M_\odot \ yr^{-1}$, both at least one order of magnitude less than the $SFR$ suggested by the $FIR$ luminosity. In this regard, our results show that the global star formation history of the Universe can be fully traced only if the effects of dust are taken into account. Objects like HR10 would
have not been found by neither optical imaging surveys based on the Lyman-continuum break \[14\] or on strong emission lines, nor by IRAS surveys, nor by traditional quasar surveys. Instead, our results demonstrate that the combination of optical and near-IR deep imaging, coupled with (sub)-mm observations, is an efficient method to find dusty galaxies at high-z. Recent deep SCUBA imaging suggests indeed the presence of a population of faint sub-mm sources \[28\].

The observations of HR10 suggest that the star formation in distant objects occurs with different modes, and that the most vigorous episodes of star formation probably arise in dusty environments as predicted by several models \[9, 10, 27\]. However, our data cannot tell us if HR10 is forming its first generation of stars, or if the starburst is occurring in an already formed system. Nevertheless, in both cases we are witnessing a major episode of star formation: if the burst lasts about \(10^7\) years (a typical time scale for a starburst \[12\]), the total mass of gas converted into stars is of the order of \(10^{10}\) \(M_\odot\), which is approximately 10% of the total mass of a present-day massive galaxy.

Finally, we find relevant to note that the observed properties of HR10 fit into the predictions of \[6\] that the sources at \(z \sim 0.5 - 2.5\) which contribute to the cosmic \(FIR - mm\) background should have fluxes around 10-100 mJy at \(\lambda_{\text{obs}} = 200\mu m\). For \(18 \leq T_d \leq 45\) K, the expected flux of HR10 at \(\lambda_{\text{obs}} = 200\mu m\) is in the range of 10-40 mJy. Moreover, we also note that the sky surface density of dusty galaxies at \(\lambda_{\text{obs}} = 175\mu m\) predicted by \[8\] (\(\approx 0.05\) arcmin\(^{-2}\)) is within a factor of five similar to that of the extremely red galaxies \[1, 13\]. Future observations will provide clues on what fraction of the extremely red galaxies contributes to the \(FIR - mm\) background.

References
[1] Hu, E.M., Ridgway, S.E. Two extremely red galaxies. *Astron. J.* 107, 1303-1306 (1994).

[2] Dunlop, J. *et al.* A 3.5-Gyr-old galaxy at redshift 1.55. *Nature* 381, 581 (1996).

[3] Graham, J.R. & Dey, A. The redshift of an extremely red object and the nature of the very red galaxy population. *Astrophys.J.* 471, 720-725 (1996).

[4] Madau, P., Pozzetti, L., Dickinson, M. The star formation history of field galaxies. *Astrophys.J.* in press (1998).

[5] Puget, J.L. *et al.* Tentative detection of a cosmic far-infrared background with COBE. *Astron. Astrophys.* 308, L5-L8 (1996).

[6] Guiderdoni, B. *et al.* The optically dark side of galaxy formation *Nature* 390,257-259 (1997).

[7] Schlegel, D.J., Finkbeiner, D.P., Davis, M. Maps of Dust IR Emission for Use in Estimation of Reddening and CMBR Foregrounds *Astrophys.J.* in press (1998).

[8] Blain, A.W, & Longair, M.S. Millimetre background radiation and galaxy formation. *Mon.Not.R.Astron.Soc.* 265, L21-L24 (1993).

[9] Franceschini, A., Mazzei, P., Danese, L., & De Zotti, G. Luminosity evolution and dust effects in distant galaxies: implications for the observability of the early evolutionary phases. *Astrophys.J.* 427,140-154 (1994).

[10] Zepf, S.E., Silk, J. On the effects of bursts of massive star formation during the evolution of elliptical galaxies. *Astrophys.J.* 466,114-121 (1996).

[11] Hughes, D.H., Dunlop, J.S., Rawlings, S. High-redshift radio galaxies and quasars at submillimetre wavelengths: assessing their evolutionary status. *Mon.Not.R.Astron.Soc.* 289, 766-782 (1997).
[12] Sanders, D.B., Mirabel, I.F. Luminous infrared galaxies. *Ann. Rev. Astron. Astrophys.* 34, 749-782 (1996).

[13] Thompson, D., Beckwith, S.V.W. in *The Young Universe: Galaxy Formation and Evolution at Intermediate and High Redshift* (eds. D’Odorico, S., Fontana, A. & Giallongo, E.), in press, (A.S.P. Conference Series) (1998).

[14] Steidel, C.C. *et al.* Spectroscopic confirmation of a population of normal star-forming galaxies at redshifts $z > 3$. *Astrophys.J.* 462, L17 (1996).

[15] Cimatti, A., Bianchi, S., Ferrara, A., Giovanardi, C. On the dust extinction in high-z galaxies and the case of extremely red objects. *Mon.Not.R.Astron.Soc.* 290, L43-L49 (1997).

[16] Jones, M.E. *et al.* Detection of a cosmic microwave background decrement toward the $z = 3.8$ quasar pair PC 1643+4631A,B. *Astrophys.J.* 479, L1-L3 (1997).

[17] Ivison, R.J., Archibald, E.N., Dey, A., Graham, J.R. in *The Far-Infrared and Submillimetre Universe* (ed. Wilson, A.), (ESA vol. SP-401, ESA Publications Division, ESTEC, Noordwijk, the Netherlands) p.281-284 (1998).

[18] Whittet D.C.B. 1992, *Dust in the galactic environment*, Institute for Physics Publishing, Bristol.

[19] Andreani, P., Franceschini, A. 1.25-mm observations of a complete sample of *IRAS* galaxies. II. Dust properties. *Mon.Not.R.Astron.Soc.* 283, 85-100 (1997).

[20] Hildebrand, R.H. The determination of cloud masses and dust characteristics from submillimetre thermal emission. *Q.Jl.R. Astr.Soc.* 24, 267-282 (1983).
[21] Solomon, P.M., Downes, D., Radford, S.J.E., Barrett, J.W. The molecular interstellar medium in ultraluminous infrared galaxies. *Astrophys.J.* 478, 144-161 (1997).

[22] Rowan-Robinson, M. *et al.* The ultraviolet-to-radio continuum of the ultraluminous galaxy *IRAS* F10214 + 4724. *Mon.Not.R.Astron.Soc.* 261, 513-521 (1993).

[23] Eisenhardt, P.R. *et al.* Hubble Space Telescope Observations of the Luminous *IRAS* Source FSC 10214+4724: A Gravitationally Lensed Infrared Quasar *Astrophys.J.* 461, 72 (1996).

[24] Goodrich, R.W. *et al.* FSC 10214+4724: a gravitationally lensed, hidden QSO. *Astrophys.J.* 456, L9 (1996).

[25] Rowan-Robinson, M. *et al.* Observations of the Hubble Deep Field with the Infrared Space Observatory - V. Spectral energy distributions, starburst models and star formations history. *Mon.Not.R.Astron.Soc.* 289, 490-496 (1997).

[26] Gallagher, J.S. III, Hunter, D.A. *Star formation in galaxies* (ed. Lonsdale-Persson, C.J.), (NASA: Pasadena CP-2466) p.167-177 (1987).

[27] Zepf, S.E. Formation of elliptical galaxies at moderate redshifts. *Nature* 390, 377-379 (1997).

[28] Smail, I., Ivison, R.J., Blain, A.W. A deep sub-millimeter survey of lensing clusters: a new window on galaxy formation and evolution. *Astrophys.J.* in press (1997).

[29] Kreyesa, E., *Proc. Int. Symp. on Photon Detectors for Space Instrumentation* (ed. Guyenne, T.D.), (ESA/ESTEC Publications) (1993).
Acknowledgments. We are grateful to Sofia Randich, David Hughes, Rob Ivison, Matt Lehner and Jo Baker for useful discussions, to Esther Hu for checking the astrometry of HR10 and for helpful suggestions. We also thank the three anonymous referees for their useful and constructive comments.

Figure Caption

Figure 1: Filled circles: fluxes of HR10 taken from [1, 3, 17, 16] and this work. The IRAS $3\sigma$ upper limits at $\lambda_{\text{obs}} = 12, 25, 60, 100\,\mu\text{m}$ were derived from co-added survey data with the SCANPI procedure available at IPAC (Infrared Processing & Analysis Center). The curves show two extreme cases of grey-bodies consistent with the data. Dashed curve: optically thin grey-body, $S_\nu \propto \nu^\beta B_\nu(T)$, with $\beta = 1.5$ and $T_d = 18$ K. Continuous curve: grey-body optically thin at $\nu < \nu_0 = 750$ GHz, $S_\nu \propto B_\nu(T)\{1 - \exp[-(\nu/\nu_0)^\beta]\}$ [11], with $\beta = 1.5$ and $T_d = 45$ K. HR10 was observed for 64 minutes (on source) with the MPIfR 19-channel bolometer [29] (12.50 $\mu$m, 11\arcsec (FWHM) beam, 32\arcsec chop throw, zenith opacity 0.09-0.3). Flux calibration was achieved using Uranus as primary calibrator and Mars and pointing quasars as secondary ones. The mean atmospheric level was found averaging the measurements of 16 channels and subtracted from the central pixel, which targeted HR10. The final flux at 1250$\mu$m is $4.9 \pm 0.7$ mJy. The simultaneous observations at 450 and 850$\mu$m were made with the SCUBA bolometer array (Robson et al., in preparation) at the JCMT in photometry mode (108 minutes on source, zenith opacity 0.3 at 850$\mu$m). The sky background was removed from the flatfielded and despiked data by subtracting the average signal from 5 neighbour bolometers (containing no source signal). The data were calibrated using photometry and beam maps of Mars and Uranus. The flux at 850$\mu$m and 450$\mu$m resulted to be $8.7 \pm 1.6$ mJy and $< 180$ mJy ($3\sigma$) respectively. The $1\sigma$ error bars of the 850$\mu$m and 1250$\mu$m flux densities indicate the statistical uncertainties, whereas the uncertainty on the absolute flux calibration is estimated to be $\sim 15$-20$\%$ both in the
IRAM and SCUBA data.
