On the detectability of the Sunyaev–Zel’dovich effect of massive young galaxies

Daniel Rosa-González,1,2* Roberto Terlevich,1,3 Elena Terlevich,1† Amancio Friaça4 and Enrique Gaztañaga5

1INAOE, Luis Enrique Erro 1, Tonantzintla, Puebla 72840, Mexico
2Astrophysics Group, Blackett Laboratory, Imperial College, Prince Consort Road, London SW7 2BW
3Institute of Astronomy, Madingley Road, Cambridge CB3 0HA
4Instituto Astronômico e Geofísico, USP, R. do Matao 1226, Cidade Universitaria, 05508-900, São Paulo, SP, Brazil
5Institut d’Estudis Espacials de Catalunya, Edifici Nexus, Gran Capita 2-4, desp. 201, 08034 Barcelona, Spain

Accepted 2003 November 4. Received 2003 October 29; in original form 2003 May 8

ABSTRACT

The Sunyaev–Zel’dovich (SZ) effect, expected to be associated with massive star formation activity produced during the formation of the most luminous bulges of normal galaxies, is discussed. Using 1D chemohydrodynamical models for spheroidal galaxy evolution, we show that, during the early epochs of galaxy evolution, the gas in massive events of star formation may reach temperatures and densities high enough to produce values of the Comptonization parameter \( y \) comparable to those present in galaxy clusters.

In this scenario, we discuss the possibility of detection of the SZ signature in high-redshift star-forming galaxies with the next generation of millimetre telescopes capable of arcsec resolution and equipped with high-sensitivity detectors. We show how millimetre colour–colour diagrams or diagnostic diagrams could be used to distinguish between the dust emission and the SZ effect, and suggest the use of simultaneous multifrequency observations to improve the chances of detecting the SZ effect.

Key words: galaxies: evolution – cosmic microwave background – radio continuum: galaxies.

1 INTRODUCTION

The Sunyaev–Zel’dovich (SZ) effect (Sunyaev & Zel’dovich 1972) is produced when the cosmic microwave background (CMB) photons from the Rayleigh–Jeans region, due to interaction with fast electrons, move to the Wien tail of the CMB spectrum, thus producing a unique spectral signature. This signature shows an increase with respect to the mean CMB brightness of the observed intensity for wavelengths shorter than 1.34 mm and a decrease for wavelengths longer than 1.34 mm. This is known as the thermal SZ effect. Another component is the kinetic SZ effect, due to the interaction with CMB photons of plasma moving coherently with respect to the reference frame where the CMB is isotropic (e.g. Rephaeli 1995; Birkinshaw 1999; Church, Jaffe & Knox 2001).

The SZ effect constitutes a powerful tool to study the physical properties of the intercluster gas, and, when combined with X-ray observations, also to estimate cosmological constants such as the Hubble constant \( H_0 \), the current mass density of the Universe \( \Omega_M \) or the cosmological constant \( \Lambda \) (e.g. Majumdar 2001; Diego et al. 2002; Levine, Schulz & White 2002; Reese et al. 2002; Majumdar & Mohr 2003).

It is understood that in clusters the thermal SZ effect due to the interaction of CMB photons with electrons with temperatures around \( 10^8 \) K dominates over the kinetic SZ effect. This fact is evidenced by combining observations at 1 mm, where the thermal effect is close to the maximum, at 1.4 mm, where it is almost zero and the kinetic SZ effect can be marginally detected, and at 2 mm, where the thermal SZ has its minimum and is negative (e.g. Lamarre et al. 1998; Mauskopf et al. 2000).

The advent of a new generation of millimetre telescopes (LMT/GTM or ALMA, described in Section 3) that combine relatively high angular resolution with high sensitivity will allow astronomers to explore the possibility of detecting the SZ effect in volumes much smaller than that of a cluster of galaxies. Would it be possible for these new instruments to detect the SZ effect in individual galaxies? Natarajan & Sigurdsson (1999), Rosa-González et al. (2000, 2001), Majumdar, Nath & Chiba (2001) and Rosa-González (2002) have indeed explored the detectability of the SZ effect in individual galaxies.

Natarajan & Sigurdsson (1999) studied the SZ effect due to galactic outflows powered by the mechanical energy provided by the accretion of matter on to the central supermassive black hole in...
quasars (QSOs). Majumdar et al. (2001) proposed the evolution of supernova-driven galactic winds during the early stages of evolution of a normal galaxy, as the cause of the distortion of the CMB radiation due to the kinetic SZ effect. A similar model was originally proposed by Tegmark, Silk & Evrard (1993) to explain the absence of absorption lines in the observed spectra of high-redshift quasars (Gunn–Peterson effect, Gunn & Peterson 1965). The explosion model assumes an initial energy input that is equal to 2 per cent of the total luminosity generated in the supernova (SN) explosions during about $5 \times 10^7$ yr. The range of galaxy masses covered by this model goes from $5 \times 10^7$ to $10^{11} M_{\odot}$, Rosa-González et al. (2001, 2002) and Rosa-González (2002) discussed the possibility of observing the SZ effect in the centre of young giant spheroidal galaxies. They include in the calculations both the thermal and the kinetic SZ effect.

In the accepted galaxy formation scenario described by the hierarchical model (e.g. Navarro, Frenk & White 1995), massive galaxies form after merging with smaller systems that have been formed in a previous epoch. However, there is observational evidence that a significant number of $L^*$ galaxies exist at redshift of about 5 and beyond (Hu, Cowie & McMahon 1998; Stanway, Bunker & McMahon 2003). Jimenez et al. (1999) discussed the possibility of the existence of massive elliptical galaxies at high redshift, contrary to early predictions of the hierarchical models of galaxy formation. The study of massive galaxies at high redshift that could be detected through the unique SZ signature could be used to constrain the different galaxy formation scenarios.

The SZ effect due to young galaxies together with radio sources (Holder 2002) and dusty galaxies (Blain, Ivison & Smail 1998; Blain 1998) are potential sources of noise in sensitive studies of SZ clusters and upcoming measurements of the CMB fluctuations (e.g. FIRST, Planck). Therefore, their characteristic emission and physical scale must be quantified. In this paper we explore in detail the possibility of detecting the SZ effect in young galaxies undergoing a massive star formation event. We discuss the confusion due to dust emission and suggest a diagnostic to segregate between dust emission and SZ effect distortions.

### 1.1 Thermal SZ effect

The SZ effect describes the brightness change of the CMB due to inverse Compton scattering by hot electrons (Sunyaev & Zel’dovich 1972). The change in intensity between the unaffected CMB radiation and the radiation that goes through the hot gas can be expressed by the integral

$$\Delta I = \frac{2h}{c^2} \int_{-\infty}^{+\infty} ds P(x) \left[ \frac{v_0^2}{\exp(hv_0/kT_{\text{rad}})} - \frac{v^2}{\exp(hv/kT_{\text{rad}})} \right],$$

where $hv_0$ is the energy of the CMB photons, $hv$ is the energy of the photons that come out from the cluster, $s = \log(v/v_0)$, $\tau_x$ is the optical depth for scattering and $P(x)$ is the probability that an incident photon with energy $hv_0$ becomes a photon with energy $hv$ (Birkhawsh 1999).

The integral in equation (1) can be calculated by using the non-relativistic expression given by the Kompaneets (1957) approximation,

$$\Delta I(x) = h(x)\tau_x I_0,$$

where the distortion of the photon spectrum $h(x)$ is defined by

$$h(x) = \frac{e^x}{(e^x - 1)^2} \left( x \coth \frac{x}{2} - 4 \right).$$

$x = hv/kT_{\text{rad}}$ is the dimensionless frequency, with $T_{\text{rad}} = 2.728$ the temperature of the CMB,

$$I_0 = \frac{2h}{c^2} \left( \frac{k_B T_{\text{rad}}}{h} \right)^3$$

and the Comptonization parameter $y$ is defined by the integral of the electron pressure along the line of sight,

$$y = \sigma_T \int d\ln n_e \frac{k_B T_e}{m_e c^2}.$$
gas. In this way, we can calculate the $y$ profiles, which are used to estimate the flux collected by a given beam size at a given frequency.

In the FT98 model, a single massive dark halo hosts baryonic gas that falls towards the centre of the dark halo and will subsequently form stars. The dark halo is given by a static mass density distribution $\rho_{\text{h}}(r) = \rho_{\text{h}0}[1 + (r/r_{\text{h}})^2]^{-1}$, where $\rho_{\text{h}0}$ is the halo central density and $r_{\text{h}}$ is the halo core radius. The gas and the stars exchange mass through star formation and stellar mass losses (supernovae, planetary nebulae and stellar winds). Both the stellar distribution and the dark halo are truncated at a common tidal radius $r_t$. The system, assumed to be spherical, is subdivided into several spherical zones and the hydrodynamical evolution of its interstellar medium (ISM) is calculated. The equations of chemical evolution for each zone are then solved, taking into account the gas flow, and the evolution of the chemical abundances is obtained. A total of $\approx 100$ star generations are stored during 13 Gyr for chemical evolution calculations. We assume that, at a given radius $r$ and time $t$, the specific star formation rate $\dot{\rho}(r,t)$ follows a power-law function of gas density ($\rho$): $\dot{\rho}(r,t) = v(\rho/\rho_0)^{1/2}$, where $\rho_0$ is the initial average gas density inside $r_0$ and $v$ is the normalization of the star formation law. We include inhibition of star formation for expanding gas [$V \cdot u > 0$] or when the density is too low and therefore the cooling is inefficient [i.e., for a cooling time $t_{\text{cool}} = (3/2) k_B T / \mu m_H \Lambda(T)$ $\rho$ longer than the dynamical time $t_{\text{dyn}} = (3\pi/16 \rho_g)^{1/2}$, where $\mu$ is the mean molecular weight and $M_H$ is the hydrogen mass] by multiplying $\dot{\rho}$ as defined above by the inhibition factors $[1 + \beta_{\text{cool}} \text{max}(0, V \cdot u)]^{-1}$ and $[1 + \beta_{\text{cool}} t_{\text{cool}}/t_{\text{dyn}}]^{-1}$. A characteristic of these models is that several episodes of inflow and outflow occur simultaneously at different radii. The chemodynamical model for spheroids was used to investigate the relation between young elliptical galaxies and QSO activity (FT98), the absence of passively evolving elliptical galaxies in deep surveys (Jimenez et al. 1999), Lyman break galaxies (Friačh & Terlevich 1999), blue core spheroids (Friačh & Terlevich 2001), the coupled spheroid and black hole formation (Archibald et al. 2002), and the link between damped Lyman $\alpha$ systems (DLAs) and dwarf galaxies (Lanfranchi & Friačh 2003).

The models are parametrized according to the (initial) baryonic mass inside the tidal radius, $M_0 = M_{\text{g}} + M_{\text{s}}$ (where $M_{\text{g}}$ is the baryonic Galaxy mass, $M_{\text{s}}$ is the gas mass and $M_{\text{s}}$ is the stellar mass), $r_t$, and the ratio of the halo to the (initial) luminous mass, $M_{\text{h}}/M_0$. We have investigated a grid of runs with $M_0$ between $10^{11}$ and $5 \times 10^{12} M_\odot$, and $r_t$ in the range 2.5–15 kpc (see FT98). We set $r_t = 28r_0$ and $M_{\text{s}}/M_0 = 5$. The latter value is compatible with the recent WMAP results where the baryon density $\Omega_m = 0.047 \pm 0.006$ and the matter density $\Omega_M = 0.29 \pm 0.07$ (Spergel et al. 2003). Smaller (larger) values of the ratio of dark matter to baryonic mass do not significantly alter the observed fluxes, but as a result of the shallower (deeper) potential well, the galactic winds will appear earlier (later). For example, in the model with $M_0 = 10^{12} M_\odot$, the galactic wind occurs at 1.51, 1.55 and 1.67 Gyr, for $M_{\text{s}}/M_0 = 3, 5$ and 7.5 respectively.

The chemical evolution is driven by the stellar winds, planetary nebulae and SN phase that produce the enrichment of the ISM. A new generation of stars form in the more metal-rich medium. We do not assume the instantaneous recycling approximation for the chemical enrichment, but instead take into account the delays for gas restoring from the stars due to the main-sequence lifetimes. Instantaneous mixing with the ISM is assumed for the stellar ejecta.

We use metallicity-dependent yields for Type II and Ia supernovae (SNII, SNIIa) and intermediate-mass stars (IMS): the SNII yields from Woosley & Weaver (1995), for metallicities $Z/Z_\odot = 0, 10^{-4}, 10^{-2}, 10^{-1}$ and 1; the SNIIa yields from Iwamoto et al. (1999) – their models W7 and W70 (progenitor metallicity $Z = Z_\odot$ and $Z = 0$, respectively); and the yields for IMS (0.8–8 $M_\odot$), with initial $Z = 0.001, 0.004, 0.008$, 0.02 and 0.4, from van de Hoek & Groenewegen (1997) – their variable $\eta_{\text{IMB}}$ case. For more details of the nucleosynthesis prescriptions, see FT98. The models start with an entirely gaseous protogalaxy with primordial chemical abundances ($Y = 0.24, Z = 0$).

In the FT98 models there is self-consistency of the hydrodynamics, chemical evolution and atomic physics, since the cooling

---

**Figure 1.** The kinetic SZ effect (solid and dot-dashed lines) signature is compared to the thermal SZ effect (dashed line) for the case where the kinetic effect is half of the thermal one. The two cases of the kinetic SZ effect correspond to gas moving away from (dot-dashed line) and towards (solid line) the observer.

**Figure 2.** Electron density and temperature profiles for the model of baryonic mass $2 \times 10^{12} M_\odot$. The various lines correspond to different times: 20 Myr for the solid line, 600 Myr for the dotted line, 1 Gyr for the dashed line, 4 Gyr for the dot-dashed line and 11 Gyr for the triple dot-dashed line.

© 2004 RAS, MNRAS 348, 669–678
function is evaluated based on the actual chemical abundances obtained from the chemodynamical modelling. For the sake of simplicity, our cooling function is a function only of the abundances of O and Fe, which are the main coolants for $T > 10^5$ K. In the calculation of the cooling function, the abundances of elements other than Fe and O have been scaled to the O abundance as

$$n_i = n_{i,\odot} + (n_i,\odot - n_{i,\odot})n_{\alpha}/n_{\alpha,\odot},$$

where $n_i$ is the ISM abundance by number of the element $i$, $n_{i,\odot}$ its primordial abundance and $n_{i,\odot}$ its solar abundance [the photospheric values of Holweger (2001) for N and O, and the meteoritic values of Grevesse & Sauval (1998) for the other elements].

It is important to note that the FT98 models describe the evolution of isolated galaxies and do not take into account effects such as mergers that play an important role in structure formation within hierarchical galaxy formation models. However, the FT98 models can be considered as a description of the evolution of the hot gas after a major star-forming event produced by interaction or merger. In addition, while the present chemodynamical model accounts for complex flow patterns, with inflow in some regions and outflow in other regions, the model does not take into account asymmetric fluxes arising from the assumed spherical symmetry. Despite the limitations due to the spherical symmetry, the detailed predictions of this model are useful because of the good radial resolution of the galaxy, the realistic treatment of star formation, and the proper calculation of the chemical evolution of the gas and stars. The FT98 model represents a complementary tool to the semi-analytic models of galaxy formation, which currently adopt very simplified recipes of star formation but with coarser space resolution (e.g. Somerville & Primack 1999; Benson et al. 2001).

An important aspect relevant to the present calculation is that the models provide an estimate of the size of the hot gas region. This is central for deriving the expected flux because the effective $y$ parameter (which is the average of the $y$ parameters within a given beam size, Section 2.1) depends strongly on the size of the telescope beam.

### 2.1 The SZ effect in massive young galaxies

The FT98 models predict that the hot gas in massive star-forming regions with ages between $10^8$ and $10^9$ yr can reach temperatures exceeding $10^7$ K and densities higher than $1 \text{ cm}^{-3}$ within a radius of a few kiloparsecs. These temperatures and densities imply values of the Comptonization parameter $y$ larger than $10^{-4}$. The maximum temperatures of the gas in the models ($\sim 1 \text{ keV}$) are well below the relativistic limit ($\sim 500 \text{ keV}$), and therefore we use the non-relativistic approximation (e.g. Birkinshaw 1999) to estimate the SZ effect (equation 2). Notice that the central $y$ parameter is calculated for a region of a few hundred parsecs across. Only in this region is the $y$ parameter comparable to those observed in galaxy clusters.

Fig. 3 shows the variation of the thermal parameter ($y_{\text{th}}$) with radius. At the beginning of the calculations (the $t = 20$ Myr lines in Figs 2 and 3), the gas has not yet settled in the potential well of the galaxy and its density is low and temperature is cold everywhere (the model initial conditions assume gas at $T = 10^4$ K), and as a consequence $y$ is very small. As the model evolves, the gas falls towards the centre and is compressed, giving rise to shocks that rapidly heat the gas in the core to approximately the virial temperature of the system ($T \sim 10^7$ K). Then, highly efficient star formation occurs throughout the galaxy and a young stellar population is rapidly built up. Following the initial violent burst of star formation, the first SNII appear and heat the ISM. Star formation is vigorous and intense during the first $\sim 0.5$ Gyr, when nearly half of the stellar population is formed. In Figs 2 and 3, we see that at $t = 0.6$ Gyr there is enough gas at temperatures around $T = 10^7$ K to maintain values of $y$ close to $10^{-4}$ in the central kiloparsecs. At 1 Gyr since the start of the calculations, the star formation gas has consumed most of the gas and SNII (and SNIa) heating is past its maximum. Although the gas temperature is higher than before, its density has dropped along most of the galaxy, resulting in a significant decrease of $y$. As the galaxy evolves, the star formation rate decreases, and the main heating source of the ISM is provided by SNIa. Eventually, the thermal energy of the gas is enough to overcome the escape velocity, and the remaining gas is expelled from the galaxy by galactic winds. At this point, the primary burst of star formation ceases. The curves at $t = 4$ and 11 Gyr illustrate the post-galactic wind stage, when the gas temperature is high, but the low density implies a low $y$.

The $y$ parameter is smaller in the external layers where the pressure is lower, and therefore the resulting $y$ parameter averaged within the telescope beam is expected to be lower than the central one. This effect can be quantified by an effective $y$ parameter ($y_{\text{eff}}$) defined as the average of the $y$ parameter in the different shells weighted by the corresponding projected area and convolved with the telescope beam profile:

$$y_{\text{eff}} = \left( \frac{1}{\theta^2} \int y \, d\theta \right) * B(\theta),$$

where $\theta$ is the size of the telescope beam and $B(\theta)$ is the telescope beam profile. In reality, the telescope beam will cover a variable fraction of the galaxy, depending on its intrinsic size, its redshift and the adopted cosmology (Fig. 4). In order to translate physical sizes to angular sizes, we adopted a cosmological model given by $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$ and $h = 0.7$.

To illustrate the effect of beam dilution, we show in Fig. 5 the change of $y_{\text{eff}}$ with respect to the beam angle for models at 400 Myr. The results are similar for different times. The behaviour of $y_{\text{eff}}$ can be analysed in three separate cases, according to the beam size, as follows.

(i) **Small beam:** $y_{\text{eff}}$ increases as $\theta^2$, where $\theta$ is the size of the beam. In this case the beam size is smaller than the first radius of the model at the given time, so the value of $y$ increases until the telescope beam reaches the inner radius of the model galaxy.
The SZ effect of massive young galaxies

(ii) Medium beam: for beam angles similar to the inner radius, the model obtains the maximum value of $\gamma$, which corresponds to the central one ($\gamma_c$). The integrated pressure in the external layer is lower than in the inner ones; hence increasing the beam size produces a slight decrease of $\gamma_{\text{eff}}$.

(iii) Large beam: when the size of the beam is larger than the region where the values of $\gamma$ are significant, the averaged $\gamma$ goes down as $\theta^{-2}$. Notice that for the most massive galaxy (baryonic mass $5 \times 10^{12} M_\odot$) the fast decline is reached after an angle of about 10 arcsec but for the low-mass galaxies the fast decline starts when the angle is about 1 arcsec.

Fig. 6 shows that, for the massive galaxies, the Comptonization parameter reaches values higher than $3 \times 10^{-5}$. In the case of quasar outflows, Natarajan & Sigurdsson (1999) estimated a value for the Comptonization parameter of about $5 \times 10^{-5}$. Similar values of the Comptonization parameter were estimated for the case of early galactic winds (Majumdar et al. 2001). However, the dilution effect produces a significant decrease of the $\gamma$ parameter and consequently a smaller expected flux (Fig. 6). Using the output of the models, we obtained the effective $\gamma$ parameter as a function of time and beam angle. The behaviour of the central $\gamma$ and the effective $\gamma$ parameter for the case of a beam of 5 arcsec is plotted in Fig. 6. The central $\gamma$ parameters have maxima between $150 \times 10^6$ and $10^9$ yr, independently of the baryonic mass of the galaxy. The maximum values go from $2 \times 10^{-4}$ for galaxies with baryonic masses of $5 \times 10^{12}$ and $2 \times 10^{12} M_\odot$, down to $3 \times 10^{-5}$ for galaxies with baryonic masses of $10^{11} M_\odot$. The effective $\gamma$ within an angle of 5 arcsec is about 10 times lower than the central one (Fig. 6). The given times in Figs 6, 7 and 9 correspond to galaxies that started to collapse at redshift 50. Within these initial conditions, the maximum SZ amplitude is reached at redshifts between 12 and 5.

2.2 The kinetic SZ effect in young galaxies

There are two processes that could produce a significant kinetic SZ effect in young galaxies. One is the infall of the primordial gas to the centre of the galaxy and the other is the outflow produced by SN explosions and winds from massive young stars.

The calculations of the thermal SZ effect presented in the previous section are for a spherical galaxy (the models by FT98 on which the
cold with temperatures of about 104 K favouring the kinetic effect of gas to the centre of the galaxy. During this epoch the gas is relatively low density, the implied kinetic SZ effect would be much less than the thermal effect. The central region of the galaxy the thermal effect dominates due to the high temperatures and densities, and as a result the central parameter is higher than the kinetic component.

In this gross approximation, the kinetic effect is dominant at early phases of the galaxy evolution (less than 0.5 Gyr) due to the infall of gas to the centre of the galaxy. During this epoch the gas is relatively cold with temperatures of about 10^4 K favouring the kinetic effect over the thermal one. During this early phase the SZ kinetic effect could be several times higher than the thermal effect (Fig. 7). In the central region of the galaxy the thermal effect dominates due to the high temperatures and densities, and as a result the central parameter is higher than the kinetic component.

Notice, however, that an assumption of extremely asymmetric infall is probably less justified than that of asymmetric wind. However, when the galactic wind is operating (t > 1 Gyr), because of its low density, the implied kinetic SZ effect would be much less than the thermal SZ effect. Moreover, at these late times, the galaxy is far from the time of maximum SZ effect (t ~ 0.5 Gyr).

3 TELESCOPES AND DETECTORS

There are a few future millimetre and sub-millimetre facilities that may be capable of detecting the SZ effect produced by individual galaxies.

One is the Atacama Large Millimeter Array (ALMA), a project led by institutions of Europe, Japan and North America. ALMA will be an array of 64 antennas of 12 m in diameter getting baselines up to 10 km. It is expected that ALMA will cover the wavelength range from 8 mm to 350 µm (Blain 2001). It will be situated in the Atacama desert in Chile.

Another one is the Large Millimeter Telescope (LMT/GTM), a binational project between UMASS (USA) and INAOE (Mexico), with a single dish antenna of 50 m diameter. It will be situated on the Cerro la Negra in México. In the case of observations of the continuum, which is the case for the SZ effect, the LMT/GTM will be equipped with BOLOCAM, a sensitive wide-field camera that will operate between 3 and 1 mm. At 1 mm on the LMT/GTM, BOLOCAM will have a projected pixel size of 5 arcsec, three times smaller than SCUBA on the James Clerk Maxwell Telescope observing at 850 µm (Holland et al. 1998).

We have also included the characteristics of the Green Bank Telescope (GBT), a 100-m single dish, which is planned to be able to work at 3 mm in the next few years (Dicker, private communication).

The mapping speed is defined as the ratio between the field of view (FOV) and the square of the sensitivity. High mapping speed is necessary to complete surveys covering big portions of the sky and to detect the fainter sources. Table 1 shows the sensitivity, FOV and mapping speed for the different telescopes. The sensitivity of BOLOCAM in the LMT/GTM is estimated from Glenn et al. (1998). The sensitivity and FOV of ALMA are from Blain (2001). Notice that ALMA is not designed to perform wide-area surveys (so it does not have an associated mapping speed). We are interested in the detection of the SZ effect in young massive galaxies that at high redshift may have a few arcsec in size and an estimated flux of several µJy (see Section 2.1). Table 1 shows that it may be possible to detect them with the next generation of millimetre teleopes.

4 THE EFFECT OF DUST EMISSION

Dust emission is a dominant component in the observed multifrequency spectrum of galaxies over a wide range of redshifts. Given the small signal associated with the SZ of individual galaxies, dust emission will probably dominate the millimetre spectrum, making it difficult to detect the SZ signature. At high redshift the peak of the dust emission (~100 µm) moves to submillimetre and millimetre wavelengths (e.g. Rowan-Robinson et al. 1997; Hughes et al. 1998), i.e. over the region where the SZ effect has its maximum.

We estimated the relative amplitude of the flux due to the SZ effect and that due to the dust by comparing the millimetre flux due to dust emission in M82, a well-known star-forming galaxy, with the expected flux due to the SZ effect. M82 is a nearby (~3.2 Mpc) starburst galaxy with an infrared luminosity of L(8–1000 µm) = 3 x 10^{10} L⊙, which represents 84 per cent of the total galaxy luminosity (Telesco 1988). Hughes, Gear & Robson (1994) showed that the spectral distribution of energy in the sub-mm range of M82 is well fitted by a greybody law with a temperature of 48 K and an emissivity index of 1.3.

The dust emission is

\[ F_\nu = M_{\text{dust}} k^{\text{rest}}_{\nu} B(\nu, z) \left( \frac{1 + z}{z} \right), \]

where \( z \) is the redshift of the source, \( k^{\text{rest}}_{\nu} \) is the rest-frequency mass absorption coefficient (e.g. Rowan-Robinson 1986), \( B(\nu, z) \) is the rest-frequency value of the Planck function for dust at temperature \( T \), \( D_L \) is the luminosity distance and \( M_{\text{dust}} \) is the total mass of dust (Hughes, Dunlop & Rawlings 1997). For the rest-frequency mass absorption coefficient \( k^{\text{rest}}_{\nu} \) we adopted the value of 0.15 m² kg⁻¹ as suggested by Hughes et al. (1997). The dependence of \( k_d \) with wavelength is given by \( k_d \propto \lambda^{-\beta} \), where \( \beta \) is the emissivity index of the dust grains.

Observations of galaxies with different sources of heating indicate an average dust grain temperature of about 50 K (e.g. Chini et al. 1989a; Chini, Kreysa & Biermann 1989b; Hughes et al. 1993;
about 108 M\(_\odot\) (2000) with equation (9), we estimate for Arp 220 a dust mass of 3 \(\times 10^7\) \(\odot\). The whole galaxy will have a lower metal content or less evolved than M82. The dust content of M82 does not change with time, and therefore the infrared luminosity of about \(2 \times 10^{12} L_\odot\) is brighter than M82 (Arp 220-like luminosity, Fig. 8) to the extreme case of an ultraluminous infrared galaxy (ULIRG) with an emissivity index of 1.2. A value of 2 \(\times 10^7\) \(\odot\) for the dust mass is given by Dunne et al. (2000) assuming a dust temperature of 42.2 K and an emissivity index of 1.5 given by Hughes et al. (1994). In what follows we assume a dust temperature of 50 K and \(\beta = 1.5\). The dashed lines are the expected flux for a galaxy 100 times more luminous than M82. The lower dashed line corresponds to fluxes at 2 mm and the upper dashed line to fluxes at 1 mm.

Galaxies such as M82 have an expected flux at 1 mm of about 20 \(\mu\)Jy for redshifts between 1 and 2 at 5 \(\mu\)Jy for observations at 2 mm (100 times higher for the case of an Arp 220-like galaxy). Notice that these values are similar to the maximum values of the fluxes due to SZ emission for massive galaxies with baryonic masses higher than \(10^{11}\) \(\odot\) (Fig. 7). The estimate of total fluxes due to dust does not take into account the relative size of the galaxy since the SZ flux plotted in Fig. 7 corresponds only to the flux estimated inside a beam size of 5 arcsec. At high redshift (\(z > 3\)) the whole galaxy will fill the 5 arcsec beam, but probably will be resolved by interferometric observations. The other fact is that the dust content of M82 does not change with time, and therefore the fluxes in Fig. 8 can be considered upper limits for galaxies with lower metal content or less evolved than M82.

| Telescopes and diameter | Camera | Wavelength (mm) | Angular resolution (arcsec) | Sensitivity (mJy Hz\(^{-1/2}\)) | FOV (arcmin\(^2\)) | Mapping speed (arcmin\(^2\) h\(^{-1}\) mJy\(^{-2}\)) |
|------------------------|--------|----------------|-----------------------------|-----------------------------|------------------|-----------------------------|
| JCMT (15 m)            | SCUBA  | 0.85           | 15                          | 90                          | 2                | 0.9                         |
| GBT (100 m)            | 3 mm camera | 3.00       | 8                           | 0.2                         | 0.3              | 27000                       |
| LMT/GTM (50 m)         | BOLOCAM| 1.2            | 6                           | 2                           | 2                | 1800                        |
| ALMA (<10 km)          | –      | 1.30           | 0.03                        | 0.46                        | 0.16             | –                           |

**Figure 8.** The solid lines are the expected flux for M82 at 2 mm (lower solid line) and at 1 mm (upper solid line), assuming a dust temperature of 50 K and \(\beta = 1.5\). The dashed lines are the expected flux for a galaxy 100 times more luminous than M82. The lower dashed line corresponds to fluxes at 2 mm and the upper dashed line to fluxes at 1 mm.

### 5 DIFFERENTIAL MAPPING AND THE MILLIMETRE COLOUR–COLOUR DIAGRAM

The particular spectral signature of the SZ effect, i.e. a positive maximum at about 800 \(\mu\)m and a negative minimum at around 2 mm plus its non-dependence on redshift, can be used to maximize its detection against the dust emission from the same source.

Using the fact that at 2 mm the SZ has a negative value, the difference between the flux at 1 mm and the flux at 2 mm (Fig. 9) is almost twice the signal given by the individual values (Fig. 7). Notice that subtracting the signal at 1 mm from the signal at 2 mm will also cause a decrease in the flux due to sources dominated by dust emission, therefore producing a map biased to SZ sources. Source confusion due to dust emission should also be reduced. This differential mapping method will also help in removing the sky signal, as at these low resolutions the atmospheric emissions at 1 mm and 2 mm are correlated. In a single observation with a wide-area camera, the sky signal is removed by using the fact that some of the pixels are viewing the blank sky. Subtracting the time average level of these blank pixels can increase the signal-to-noise ratio by a factor of 3. This is possible because the source structure is constant in time while the sky varies over the array on time-scales of several seconds (Holland et al. 1998). The use of simultaneous measurements at different wavelengths allows one to reduce the sky noise due to a better sampling of the fast sky fluctuations. Also it is possible to separate different components of the image (i.e. detector noise, sky, astrophysical signal) without assuming any atmospheric spectrum.
by solving a set of coupling equations and obtaining a model of the sky brightness distribution (Mauskopf et al., in preparation).

To distinguish between galaxies that are dominated by dust emission and galaxies that are dominated by the SZ effect, we have explored the use of millimetre colour–colour diagnostic diagrams.

Let us consider the emission of an object composed by the thermal SZ effect with a fixed Comptonization parameter of $10^{-4}$ plus a greybody. The amplitude of the greybody emission is given by changing $R$, which is the ratio between the maximum of the greybody emission and the maximum of the SZ emission (Fig. 10).

Fig. 11 represents the plane $I(2 \text{ mm})/I(1 \text{ mm})$ versus $I(3 \text{ mm})/I(1 \text{ mm})$ given by the ratios between the intensities at the given wavelengths. The intensity of the SZ effect is fixed by adopting a $y$ parameter of $10^{-4}$. The dust emission is given by a greybody with temperature of 50 K and an emissivity of $\beta = 1.5$. The amplitude of the dust emission is calculated by varying $R$ ($R = 0.1, 1.0, 5.0, 10, 20$). The error bars were estimated by fixing the values of $R$ and redshift but allowing the temperature to vary between 35 and 65 K and the emissivity parameter between 1 and 2.

Fig. 11 allows us to examine the behaviour of the millimetre colours for different redshift ranges:

(i) **Low-redshift galaxies** ($z \lesssim 1$): In this case the peak of the greybody is far away from the millimetre range where the signal due to the SZ is dominant (between 1 and 3 mm). For $R = 0.1$ we obtain almost the (negative) pure SZ colour [$I(2 \text{ mm})/I(1 \text{ mm}) = -0.72, I(3 \text{ mm})/I(1 \text{ mm}) = -0.68$]. For higher values of $R$ the Rayleigh–Jeans tail of the greybody radiation starts to contaminate the SZ spectra, producing a shift towards the top right of the $I(2 \text{ mm})/I(1 \text{ mm})$ versus $I(3 \text{ mm})/I(1 \text{ mm})$ plane, but for these redshifts the displacement is modest.

(ii) **Intermediate-redshift galaxies** ($2 \lesssim z \lesssim 5$): This case is similar to the previous one but the greybody emission on top of the SZ is
more important, producing a larger displacement of the points to the top right corner of the diagram, while the millimetre colours remain negative.

(iii) High-redshift galaxies \((z > 5)\): In this case the Rayleigh–Jeans part of the greybody emission has covered the SZ effect emission at 2 mm, producing in some cases positive \(I(2 \text{ mm})/I(1 \text{ mm})\) and \(I(3 \text{ mm})/I(1 \text{ mm})\) ratios.

Fig. 11 indicates that all points in the bottom left part of the diagram have a dominant SZ component. This diagnostic seems valid up to a redshift of several. The accuracy or reliability of the diagnostic will clearly depend on the size of the error bars, which in turn depend on the amplitude of the signal and the sensitivity of the telescope. All in all it seems that the new facilities would permit one to start the exploration of at least the largest star-forming systems at \(z < 12\) even if they show moderate dust emission. Within the estimated error bars, sources dominated by the SZ effect fall clearly in the distinct quarter of the diagram where both the 2 mm-to-1 mm and 3 mm-to-1 mm intensity ratios are negative. This result is very robust in the sense that sources dominated by the SZ are going to be separated from the dust emission independently of redshift. The confusion is higher for high-redshift galaxies with dust emission comparable to the SZ emission.

The diagnostic diagram presented in Fig. 11 would be partially covered by future deep surveys at millimetre wavelengths, showing high-redshift sources dominated either by dust or by SZ emission. Because of the expected delay between the burst event and the production of metals and dust, our diagnostic diagram can potentially be used to constrain the sources and time-scales for dust and metal production in the early Universe (Morgan & Edmunds 2003).

To advance further in the study of the evolution of the SZ and dust emission in a self-consistent manner, to check in more detail the possibility of observing the SZ through individual galaxies with the next generation of millimetre telescopes, and to estimate the contribution of SZ sources to the background radiation, we will present in a forthcoming paper a set of simulated millimetre maps including sources dominated by SZ and those dominated by dust emission (with different clustering properties) plus a comparison of our predictions on the SZ background with those made by Aghanim, Balland & Silk (2000) based on the SZ due to black hole-seeded protogalaxies.

6 CONCLUSIONS

In this paper we have explored the possibility that the central Comp-tonization parameter in young spheroidal galaxies or galaxies undergoing a massive star-forming event may reach values comparable to those observed in galaxy clusters. However, as a result of the poor angular resolution–sensitivity combination of present-day millimetre facilities, the detection of the SZ effect in individual galaxies may only be possible with the next generation of millimetre telescopes with high angular resolution and high sensitivity (e.g. GM/T/LMT or ALMA) and then probably only in the most massive systems capable of producing a 800 \(\mu\)Jy flux of more than a few \(\mu\)Jy for periods of time of several hundred megayears.

We have included instrumental noise in our calculations, but neglected the noise contribution caused by high-redshift millimetre background point sources (e.g. Blain 1998; Hughes et al. 1998). The confusion due to unresolved sources depends on the actual details (i.e. resolution) of the observation, the (unknown) emission radial profile of these sources and the extrapolation of the number counts to fainter fluxes. Blain et al. (2002) give an estimation of the confusion limit of about 10 \(\mu\)Jy for the case of observations at 1 mm and a beam size of 5 arcsec. This value is comparable to the expected SZ flux of galaxies with baryonic masses of \(2 \times 10^{12}\) \(M_\odot\) and an age of \(\sim 3 \times 10^8\) yr (Fig. 7). Confusion will be a major problem when combining independent observations at different frequencies, but its effect will be greatly reduced using instruments that simultaneously observe at three selected frequencies.

A major difficulty in the detection of the SZ effect in an individual galaxy will be its confusion with the dust emission originating in the same star formation event. To solve the dust contamination problem, we suggest exploiting the particular spectral signature of the SZ spectrum and maximizing its segregation from dust emission by using simultaneous multifrequency observations or differential detection at 1, 2 and 3 mm. In the diagnostic diagram presented in Fig. 11, there is a wide region centred at \(I(2 \text{ mm})/I(1 \text{ mm}) = -0.3\) and \(I(3 \text{ mm})/I(1 \text{ mm}) = -0.3\) where the thermal SZ emission can be clearly separated from the dust emission over a wide range of redshifts.

Owing to its particular spectrum, the detection of the SZ signature in individual galaxies and the discrimination between sources dominated by the SZ effect and sources dominated by dust emission would be enhanced by the use of differential mapping systems that simultaneously observe at three selected frequencies (Section 3). Additional advantages of such systems will be the lowering of the minimum detected flux due to a better sampling of the time-correlated atmospheric fluctuations (i.e. reducing the sky noise) and the relative absence of source confusion generated by dust-emitting sources.

The new generation of millimetre cameras, such as SCUBA-2\(^1\) or SPEED\(^2\) – which will have the capability of observing simultaneously in more than one band – should be ideal to detect compact and faint SZ sources.

ACKNOWLEDGMENTS

DRG gratefully acknowledges financial support from CONACYT, the Mexican Research Council, as part of ET Research Grant No 32186-E. At present DRG is supported by POE, a European Research Training Network. Discussions with David Hughes, Richard Ellis, Manolis Plionis and Guillermo Tenorio-Tagle, together with useful suggestions from an anonymous referee, greatly improved this work.

REFERENCES

Aghanim N., Balland C., Silk J., 2000, A&A, 357, 1
Archibald E. N., Jimenez R., Dunlop J. S., Friaça A. C. S., McLure R. J., Hughes D. H., 2002, MNRAS, 336, 353
Benson A. J., Frenk C. S., Baugh C. M., Cole S., Lacey C. G., 2001, MNRAS, 327, 1041
Birkinshaw M., 1999, Phys. Rep., 310, 97
Blain A., 1998, MNRAS, 297, 502
Blain A., 2001, in Wootten A., ed., ASP Conf. Ser. Vol. 235, Science With the Atacama Large Millimeter Array (ALMA). Astron. Soc. Pac., San Francisco, p. 261
Blain A. W., Ivison R. J., Smail I., 1998, MNRAS, 296, 29
Blain A. W., Smail I., Ivison R. J., Knell J.-P., Frayer D. T., 2002, Phys. Rep., 369, 111
Chini R., Kirzegel E., Kreyesa E., Gemenudd H., 1989a, A&A, 216, L5

\(^1\) http://www.roe.ac.uk/ate/projects/scuba_two/

\(^2\) http://www.astro.umass.edu/~fcrao/instrumentation/
