Dust temperature and the submillimeter–radio flux density ratio as a redshift indicator

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Abstract. It is difficult to identify the distant galaxies selected in existing submillimeter (submm)-wave surveys, because their positional accuracy is only several arcseconds. Currently, centimeter-wave VLA observations are required in order to determine sub-arcsec positions, and so to make reliable optical identifications. Carilli & Yun (1999) pointed out that the ratio of the radio and submm-wave flux densities provides a redshift indicator for dusty star-forming galaxies, when compared with the tight correlation observed between the far-infrared (FIR) and radio flux densities for low-redshift galaxies. This method provides a useful, albeit imprecise, indication of the distance to a submm-selected galaxy. However, because the degeneracy between the effects of increasing the redshift of a galaxy and decreasing its dust temperature is not broken, it does not provide an unequivocal redshift estimate.

1. Introduction

The intensity of synchrotron radio emission from shock-heated electrons in star-forming galaxies is known to be correlated tightly with their FIR emission from dust grains heated by the interstellar radiation field (see the review by Condon 1992). This FIR–radio correlation arises because both radiation processes are connected with the rate of ongoing high-mass star formation activity in a galaxy. The correlation links the flux densities of a galaxy in both the 60- and 100-\(\mu\)m IRAS passbands and at a frequency of 1.4 GHz in the radio waveband. A reasonable pair of template spectral energy distributions (SEDs), which describe dusty galaxies at the relevant frequencies are shown in Fig. 1, and compared with observations of the luminous dusty galaxy Arp 220. This SED, galaxy evolution models taken from the same paper and the FIR–radio correlation can be combined to predict the faint counts of radio galaxies. The predicted count of galaxies brighter than 10 \(\mu\)Jy at 8.4 GHz is 0.8 arcmin\(^{-2}\), in agreement with the observed value of 1.0 \(\pm\) 0.1 arcmin\(^{-2}\) (Partridge et al. 1997).

The slope of the SED changes abruptly at a wavelength of about 3 mm, at which the dominant contribution to the SED changes from synchrotron emission to thermal dust radiation. Because the FIR–radio correlation links the flux densities on either side of this spectral break, it could be exploited to indicate the redshift of the galaxy (Carilli & Yun 1999). Carilli & Yun calculated that the radio–submm flux density ratio of a distant dusty galaxy, which lies on the
Figure 1. The template SEDs used to describe dusty galaxies by Guiderdoni et al. (1998) and Blain et al. (1999b). The dashed line is normalized to match the FIR–radio correlation (Condon 1992). At long wavelengths, the SED is dominated by synchrotron radio emission with a spectral index $\alpha_{\text{radio}} \simeq -0.8$. At short wavelengths the SED is dominated by the thermal radiation from dust grains with an emissivity index $\beta = 1.5$ and a temperature $T = 38$ K. The observed SED of Arp 220 is also shown. Guiderdoni et al.’s template includes MIR spectral features (see Xu et al. 1998).

FIR–radio correlation, should be

$$\frac{S_{1.4\text{GHz}}}{S_{850\mu\text{m}}} = 3.763(1 + z)^{1.007(\alpha_{\text{radio}}-\alpha_{\text{submm}})},$$

as a function of redshift $z$. $\alpha_{\text{radio}}$ and $\alpha_{\text{submm}}$ are the spectral indices of the SED, $S_{\nu} \propto \nu^{\alpha}$, in the radio and submm wavebands. Typically, $\alpha_{\text{radio}} \simeq -0.8$ and $\alpha_{\text{submm}} \simeq 3.0$ to 3.5. $\alpha_{\text{submm}}$ is the sum of the Rayleigh-Jeans spectral index ($\alpha = 2$) and $\beta$, the spectral index in the dust emissivity function $\epsilon_{\nu} \propto \nu^{\beta}$.

Carilli & Yun (1999) also derived empirical flux density–redshift relations from the SEDs of Arp 220 and M82. The spread of the redshift values that correspond to a fixed flux density ratio across their four models corresponds to an uncertainty $\Delta z \simeq 0.5$.

The sensitive 850-µm SCUBA camera at the JCMT (Holland et al. 1999) has been used to detect high-redshift dusty galaxies (see Blain et al. 1999a and references within). These are probably the high-redshift counterparts to the low-redshift ultraluminous infrared galaxies (ULIRGs), and so their SEDs might also be expected to follow the FIR–radio correlation. In this case, the ratios of their radio and submm-wave flux densities could be substituted into equation (1) to indicate their redshifts.
Table 1. Spectroscopic ($z_{\text{spec}}$) and radio-submm redshifts for dusty galaxies calculated using the formula of Carilli & Yun (1999). The predicted redshifts $z_{3.0}$ and $z_{3.5}$ are presented assuming $\alpha_{\text{submm}}$ values of 3.0 and 3.5 respectively.

| Name              | $z_{\text{spec}}$ | $z_{3.0}$ | $z_{3.5}$ | Reference          |
|-------------------|-------------------|-----------|-----------|--------------------|
| SMM J02399-0136   | 2.80              | 2.9 ± 0.3 | 2.3 ± 0.3 | Frayer et al. (1998) |
| SMM J14011+0252   | 2.57              | 3.8 ± 0.4 | 3.3 ± 0.4 | Frayer et al. (1999) |
| BR 1202-0725      | 4.69              | 3.9 ± 0.5 | 3.1 ± 0.4 | Kawabe et al. (1999) |
| IRAS F10214+4724  | 2.29              | 2.8 ± 0.2 | 2.2 ± 0.3 | Rowan-Robinson et al. (1993) |
| Arp 220           | 0.02              | 1.1 ± 0.1 | 1.0 ± 0.1 |                    |

The observed radio and submm-wave flux densities of five dusty galaxies are used to predict their redshifts in Table 1. This technique provides a coarse indication of the redshift of these five galaxies, which all lie at spectroscopic redshifts within the bounds of the range of predictions made by Carilli & Yun’s four models. What are the systematic effects that limit the reliability of the inferred redshifts?

2. The FIR–radio correlation at high redshifts

The FIR–radio correlation is based on observations of a range of low-redshift galaxies; low- and high-luminosity spiral galaxies, irregular star-forming dwarf galaxies and ULIRGs. One factor that could modify the general properties of the SEDs of high-redshift dusty galaxies is the $(1 + z)$ increase in the temperature of the cosmic microwave background (CMB) from its value at $z = 0$. However, unless the dust temperature $T \leq 20$ K this is unlikely to have a significant effect on the SED if $z \leq 5$. The details are discussed in more detail by Blain (1999a).

The increasing temperature of the CMB has another effect. Above a certain redshift the energy density in the CMB exceeds that in the magnetic field in the interstellar medium (ISM) of the observed galaxy. Synchrotron radio emission will thus be suppressed due to the cooling of relativistic electrons by inverse Compton scattering of CMB photons. Carilli & Yun (1999) estimate that this will typically occur for ULIRGs at $z \geq 6$, and at $z \geq 3$ for the lesser magnetic fields in the ISM of the Milky Way. This effect is not included in the results presented here; however, this potential deficit in the radio flux density from high-redshift galaxies should be borne in mind.

3. Uncertainties

Galaxies with a range of different dust temperatures $T$ lie on the FIR–radio correlation. This is because the FIR flux densities involved in the correlation are at wavelengths close to the peak of the SED of a typical dusty galaxy. Hence, shifting the position of the peak of the SED, by changing $T$, makes little difference to the integrated FIR luminosity and thus to the FIR–radio flux density ratio. However, in the submm waveband, the effect of modifying either the dust temperature $T$ or the emissivity index $\beta$ is much greater, as shown
Fig. 2. Examples of SEDs defined by different values of the $z = 0$ dust temperature $T$ and dust emissivity index $\beta$, all normalised to the same flux density at 60 $\mu$m. The SEDs are very different in the submm waveband, but very similar in both the FIR and radio wavebands.

by the five different model SEDs in Fig. 2. Three different dust temperatures $T = 20, 40$ and 60 K are included, each with an emissivity index $\beta = 1.5$. In addition, the SED is calculated for a $T = 40$ K model with $\beta = 1.0$ and 2.0.

The predicted forms of the submm–radio flux density ratio as a function of redshift for all five template SEDs are shown in Fig. 3(a). The results of Carilli & Yun (1999), calculated using equation (1), are also shown for comparison. Carilli & Yun’s equation provides a good description of the 1.4-GHz:850-$\mu$m flux density ratio if $T \geq 60$ K. However, because the positions of the curves in Fig. 3(a) are quite different if $T \leq 60$ K, the redshift that would be assigned to a cooler galaxy using the 1.4-GHz:850-$\mu$m flux density ratio alone is uncertain. This is true even if the FIR–radio correlation is assumed to be free from any intrinsic scatter, and if any additional contribution to the radio flux density from an active galactic nucleus (AGN) is neglected. The intrinsic scatter in the FIR–radio correlation is about 0.2 dex, and so because the power-law index of the lines in Fig. 3(a) is about $-2$ at $z \sim 2$, an additional 0.1 dex ($\approx 25$ per cent) uncertainty would be expected. See Carilli & Yun (1999) for a discussion of the effects of any AGN component, which should lead to a conservatively low redshift estimate.

It is interesting to replot the curves in Fig. 3(a) as a function of the combined redshift–dust temperature parameter $(1 + z)/T$. This is the quantity that is constrained by measuring the position of the peak of the thermal dust emission component of the SED by combining observations in the FIR and mid-infrared (MIR) wavebands. The results are shown in Fig. 3(b). Because the radio flux density is produced by a non-thermal emission mechanism, a measurement of the radio–submm flux density ratio might be expected to break the degeneracy
Figure 3. Left (a): the 1.4-GHz:850-µm flux density ratios expected for the five model SEDs shown in Fig. 2 as a function of redshift \( z \). A considerable range of redshifts could be deduced from a measurement of this ratio if the temperature \( T \) or emissivity index \( \beta \) of the dust in the galaxy being observed was uncertain. The curves from Carilli & Yun (1999) are plotted assuming \( \alpha_{\text{radio}} = -0.8 \). Carilli & Yun stressed that a ratio greater than 0.1 is likely to indicate \( z < 1 \), while a ratio less than \( 10^{-2} \) is likely to indicate \( z > 2 \). Right (b): the same ratio plotted as a function of \((1+z)/T\), showing that it is difficult to break the degeneracy between \( z \) and \( T \) using joint radio–submm measurements.

between temperature and redshift. However, because the differences between the curves in Fig. 3(b) are not much greater than the scatter in the FIR–radio correlation, the degeneracy remains.

4. Other redshift indicators

The ‘redshifted dust temperature’ of a galaxy, \( T/(1+z) \), can be determined by measuring the frequency of the peak of the FIR dust component of the SED (see Figs 1 and 2), but \( z \) and \( T \) cannot be determined independently. Locating the peak frequency requires both long and short wavelength observations: see Blain (1999b) and Hines (1999) elsewhere in this volume.

Spectral features produced by emission from polycyclic aromatic hydrocarbon molecules and atomic fine-structure lines in the restframe MIR waveband (see Fig. 1) could be exploited to obtain photometric redshifts for distant galaxies (Xu et al. 1998). At shorter wavelengths, the prospects for obtaining photometric redshifts using the 3–10 µm SIRTF IRAC camera have been discussed recently by Simpson & Eisenhardt (1999). Photometric redshifts deduced from these features will not be subject to the \( T-z \) degeneracy.

The identification of an optical counterpart to a submm-selected galaxy usually requires a radio observation and a great deal of observing time (see for example Ivison et al. 1998). The optical magnitudes and colours of heavily-obscured submm-luminous galaxies are expected to extend over wide ranges, and
so the derivation of redshift information from broad-band optical photometry will probably require careful individual analysis of each submm-selected galaxy. Photometry and spectroscopy of likely optical counterparts to submm-selected galaxies (Smail et al. 1998; Barger et al. 1999) indicate that the ratios of 850-µm and optical I-band flux densities are scattered by about an order of magnitude across the sample.

5. Conclusions

Radio observations of submm-selected galaxies are crucial in order to make reliable optical identifications. The ratio of the radio and mm/submm-wave flux densities also provides information about the redshift of the galaxy (Carilli & Yun 1999). However, the temperature and emissivity of dust in distant galaxies has a very significant effect on the ratio of the submm-wave and radio flux densities, and so for reasonable values of the dust emissivity and temperature, this ratio cannot be used to break the degeneracy between the dust temperature and redshift of a distant dusty galaxy.

Acknowledgments. I thank Chris Carilli, Kate Isaak, Rob Ivison, Richard McMahon, Kate Quirk and Min Yun for helpful comments, and OCIW for support at this meeting.

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