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THE RADIO-TO-SUBMILLIMETER SPECTRAL INDEX AS A REDSHIFT INDICATOR

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ABSTRACT

We present models of the 1.4 to 350 GHz spectral index $\alpha_{1.4}^{350}$ for starburst galaxies as a function of redshift. The models include a semianalytic formulation, based on the well-quantified radio–to–far-infrared correlation for low-redshift star-forming galaxies, and an empirical formulation, based on the observed spectrum of the starburst galaxies M82 and Arp 220. We compare the models to the observed values of $\alpha_{1.4}^{350}$ for starburst galaxies at low and high redshift. We find reasonable agreement between the models and the observations and, in particular, that an observed spectral index of $\alpha_{1.4}^{350} \geq +0.5$ indicates that the target source is likely to be at high redshift, $z \geq 1$. The evolution of $\alpha_{1.4}^{350}$ with redshift is mainly due to the very steep rise in the Raleigh-Jeans portion of the thermal dust spectrum shifting into the 350 GHz band with increasing redshift. We also discuss situations in which this relationship could be violated. We then apply our models to examine the putative identifications of submillimeter sources in the Hubble Deep Field and conclude that the submillimeter sources reported by Hughes et al. are likely to be at high redshifts, $z \geq 1.5$.

Subject headings: galaxies: distances and redshifts — galaxies: evolution — galaxies: starburst — infrared: galaxies — radio continuum: galaxies

1. INTRODUCTION

Detecting submillimeter continuum emission from objects at $z \geq 2$ has revolutionized our understanding of galaxies at high redshift (Hughes et al. 1998; Ivison et al. 1998; Smail, Ivison, & Blain 1997; Eales et al. 1999; Barger et al. 1998). The emission is thought to be thermal emission from warm dust, with implied dust masses $\geq 10^8\ M_\odot$. A number of these submillimeter sources have also been detected in CO emission with implied molecular gas masses $\geq 10^{10}\ M_\odot$ (Brown & Vanden Bout 1991; Barvainis et al. 1994; Ohta et al. 1996; Omont et al. 1996b; Guilloteau et al. 1997; Frayer et al. 1998). The large reservoirs of warm gas and dust in these systems have led to the hypothesis that these are starburst galaxies, with massive star formation rates $\geq 100\ M_\odot\ \mathrm{yr}^{-1}$ (Hughes & Dunlop 1998). In some cases, there may be an associated active galactic nucleus (AGN), leading to questions about the dominant dust-heating mechanism—star formation, AGNs, or both (Sanders & Mirabel 1996; Downes & Solomon 1998; Smith et al. 1997)?

A well-studied phenomenon in nearby star-forming galaxies is the radio–to–far-IR correlation, i.e., the tight correlation found between the radio continuum emission and the thermal dust emission (Condon 1992; Helou & Bicay 1993). The radio continuum emission is thought to be synchrotron radiation from relativistic electrons spiraling in interstellar magnetic fields. The standard explanation for the radio–to–far-IR correlation involves relativistic electrons accelerated in supernova remnant shocks and dust heated by the interstellar radiation field. Both quantities are then functions of the massive star formation rate (Condon 1992; Cram et al. 1998; Yun, Reddy, & Condon 1999; Gruppioni, Mignal, & Zamorani 1999), although the detailed physical processes giving rise to the tight correlation remain enigmatic. If the radio–to–far-IR correlation is independent of redshift, then the sharp rise in the Raleigh-Jeans portion of the thermal dust spectrum shifting into the 350 GHz band with increasing redshift implies that the observed spectral index between radio and submillimeter frequencies should evolve strongly with redshift (Hughes et al. 1999).

In this Letter, we explore the possibility of using the radio-to-submillimeter spectral index as a redshift indicator for star-forming galaxies. Models of the expected spectral index between 1.4 and 350 GHz (850 μm), $\alpha_{1.4}^{350}$, are presented based on the standard relationships derived for nearby star-forming galaxies and on the observed spectra of two "canonical" starburst galaxies, M82 and Arp 220. We present a simple analytic expression relating redshift to $\alpha_{1.4}^{350}$, and we compare the models to the observed values of $\alpha_{1.4}^{350}$ for starburst galaxies at low and high redshift. We find reasonable agreement between the models and the observations and, in particular, that an observed spectral index of $\alpha_{1.4}^{350} \geq +0.5$ indicates that the target source is likely to be at high redshift, $z \geq 1$. We discuss possible "confusing" mechanisms that could complicate the analysis, such as radio emission driven by an AGN, dust heated solely by a radio-quiet AGN, and free-free absorption at low radio frequencies. We then apply our models to examine the putative identifications of submillimeter sources in the Hubble Deep Field (HDF).

2. ANALYSIS

Condon (1992) presents semianalytic, linear relationships between the massive star formation rate and the radio and far-IR emission from active star-forming galaxies. We have used these relationships to derive a simple relationship between redshift and $\alpha_{1.4}^{350}$ by making a simplifying assumption that the source spectrum can be characterized by two power-law spectra, one at low frequencies (observing frequency ≤ 30 GHz) with a spectral index α_{radio} and one at high frequencies (observing frequency between 230 and 850 GHz) with index α_{submm}. We define spectral index in terms of frequency ν and the observed flux density S_ν as $S_\nu \propto \nu^\alpha$. Equation (21) in Condon (1992), relating radio synchrotron luminosity to massive star formation rate, can be written in terms of observed flux density as

$$S_{\mathrm{radio}} = 4 \times 10^{28} \left[\frac{(1+z)^{1+\alpha_{\mathrm{radio}}}}{4\pi D_L^2}\right] \left[\frac{\nu_{\mathrm{radio}}}{1.4\ \mathrm{GHz}}\right]^{\alpha_{\mathrm{radio}}} \times \mathrm{SFR\ ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}}, \quad (1)$$

where S_{radio} is the observed radio flux density due to synchrotron

emission, $\nu_{\rm radio}$ is the observing frequency in GHz, D_L is the source luminosity distance in cm, and SFR is the star formation rate for stars with masses $\geq 5\ M_\odot$, in units of $M_\odot\ {\rm yr}^{-1}$. The equation relating submillimter emission from warm dust to massive star formation rate can be derived using Condon's equation (26), assuming a spectrum of the form observed for nearby active star-forming galaxies such as M82:

$$S_{\rm submm} = 1 \times 10^{28} \left[\frac{(1+z)^{1+\alpha_{\rm submm}}}{4\pi D_L^2}\right] \left[\frac{\nu_{\rm submm}}{350\ {\rm GHz}}\right]^{\alpha_{\rm submm}} \times {\rm SFR\ ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}}, \quad (2)$$

where $S_{\rm submm}$ is the submillimeter flux density due to thermal dust emission, and $\nu_{\rm submm}$ is the observing frequency. We use $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ where required.

Taking the ratio of these two expressions, it is straightforward to show that the spectral index between 1.4 and 350 GHz, $\alpha_{1.4}^{350}$, behaves as a function of redshift z as

$$\alpha_{1.4}^{350} = -0.24 - [0.42 \times (\alpha_{\rm radio} - \alpha_{\rm submm}) \times \log(1+z)]. \quad (3)$$

This relationship is plotted in Figure 1. For $\alpha_{\rm radio}$, we adopt the standard value in Condon (1992) of -0.8. For $\alpha_{\rm submm}$, we use values of $+3.0$ (*solid curve*) and $+3.5$ (*short-dashed curve*). Note that the observed spectral indices between 270 and 850 GHz for M82 and Arp 220 are $+3.4$ and $+3.0$, respectively.

We have also derived values of $\alpha_{1.4}^{350}$ as a function of redshift for two canonical starburst galaxies, M82 and Arp 220. These two galaxies have well-sampled spectra over the entire frequency range from the radio into the optical (Klein, Wielebinski, & Morsi 1988; Scoville et al. 1991). The $\alpha_{1.4}^{350}$ models were derived by fitting accurate polynomials to the observed data from 1.4 to 22 GHz and from 230 to 20,000 GHz. These results are shown in Figure 1 as a dotted curve for M82 and a long-dashed curve for Arp 220.

The empirical models for M82 and Arp 220 differ from the simplified two power-law models in two important ways. First, the observed spectral indices at zero redshift are typically higher for the empirical models relative to the two power-law model. This difference is most likely due to a low-frequency flattening at 1.4 GHz due to free-free absorption in the denser H II regions in the galaxies (Condon 1992). For instance, the observed spectral index for M82 between 1.4 and 5 GHz is -0.58, while the spectral index between 5 and 10.7 GHz is -0.72 (Klein et al. 1988). Second, the two power-law model diverges at large redshift, while the empirical models flatten and eventually turn over at $z > 7$. This effect is due to the fact that the thermal spectra peak around 3000 GHz (100 μm) for a dust temperature of 30 K. An observed frequency of 350 GHz corresponds to a rest-frame frequency of 3000 GHz at $z = 7.5$; hence, at higher redshift the spectrum has gone "over the top" of the thermal peak.

Plotted in Figure 1 are values of $\alpha_{1.4}^{350}$ for galaxies detected at 350 and 1.4 GHz. The submillimeter data for the low-redshift galaxies are from a survey of nearby active star-forming galaxies using the James Clerk Maxwell Telescope (JCMT) (Hughes, Gear, & Robson 1990; Rigopoulou, Lawrence, & Rowan-Robinson 1996), while the submillimeter data for the $z > 1$ sources are from Rowan-Robinson et al. (1993), Isaak et al. (1994), Barvainis et al. (1995), Omont et al. (1996a), Dey et al. (1999), Cimatti et al. (1998), Ivison et al. (1998, 1999),

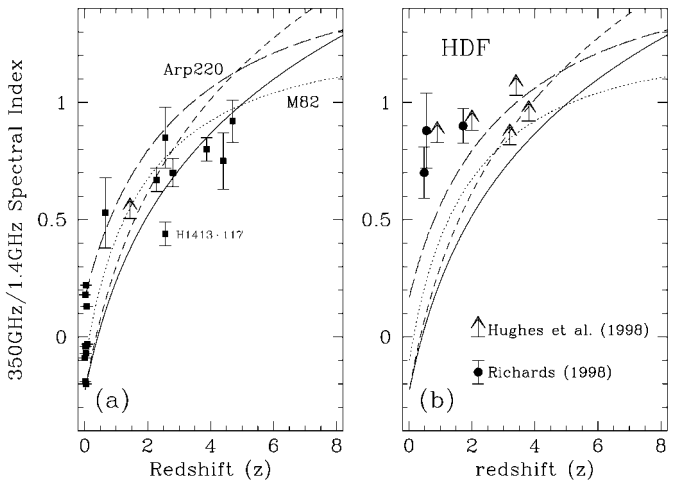

FIG. 1.—(*a*) Two power-law models (eq. [3]) for the 1.4–350 GHz spectral index $\alpha_{1.4}^{350}$ for star-forming galaxies as a function of redshift are shown with a solid curve ($\alpha_{\rm submm} = +3.0$) and a short-dashed curve ($\alpha_{\rm submm} = +3.5$). The assumed radio spectral index is -0.8. The dotted and long-dashed curves show the expected values of $\alpha_{1.4}^{350}$ vs. redshift based on the observed spectra of the star-forming galaxies M82 and Arp 220, respectively. Also plotted in filled squares are the submillimeter data for the low-redshift galaxies from a survey of nearby active star-forming galaxies using the JCMT (Hughes et al. 1990; Rigopoulou et al. 1996), and the submillimeter data for the $z > 1$ sources are from Rowan-Robinson et al. (1993), Isaak et al. (1994), Barvainis et al. (1995), Omont et al. (1996a), Eales et al. 1999, Ivison et al. (1998, 1999), Lewis et al. (1998), and Kawabe et al. (1998). The 3 σ lower limit is shown for the $z = 1.44$ galaxy HR 10 (Dey et al. 1999). All of the radio data are from the Very Large Array. (*b*) The curves are the same as in panel *a*. The data points are the putative identifications of the five submillimeter sources detected in the Hubble Deep Field by Hughes et al. (1998; 3 σ lower limits) and by Richards (1999; *filled circles*). Our modeling suggests that the submillimeter sources are likely to be at a high redshift ($z \geq 1.5$).

Lewis et al. (1998), Eales et al. (1999), and Kawabe et al. (1998). All of the radio data are from the Very Large Array (VLA) (see also Fomalont et al. 1991). Overall, the models appear to define (within the errors) the range in observed values of $\alpha_{1.4}^{350}$ as a function of redshift. In particular, the galaxies at $z > 1.5$ have $\alpha_{1.4}^{350}$ values $\geq +0.5$, while the low-redshift galaxies have $\alpha_{1.4}^{350}$ values $\leq +0.2$.

The scatter in the data for low-redshift galaxies is, again, due in part to variations in free-free absorption at 1.4 GHz between sources. In the more extreme cases, the implied (mean) free-free optical depths are ≥ 1 at 1.4 GHz, implying emission measures $\geq 6 \times 10^6\ (T_K/10^4)^{3/2}$ for the starburst regions (Taylor et al. 1999). Note that this phenomenon is relevant only for low-z galaxies since the low-frequency turnover rapidly shifts out of the 1.4 GHz band with increasing redshift.

The scatter in the data at high redshift may be due, in part, to contamination of the radio emission by an active nucleus. The frequency of radio AGNs among an IR-selected galaxy sample is about 10% for galaxies with $L_{\rm FIR} \geq 10^{11}\ L_\odot$ (Yun et al. 1999). Radio AGN emission will cause the observed value of $\alpha_{1.4}^{350}$ to fall below the values predicted for star-forming galaxies. One clear example of this in Figure 1*a* is the Cloverleaf quasar, H1413+117 at $z = 2.56$ (Barvainis et al. 1995), which has a rest-frame radio continuum luminosity of 1.3×10^{32} ergs s^{-1} Hz^{-1} at 1.4 GHz, allowing for a magnification factor of 7.6 by gravitational lensing. Even corrected for lensing, the implied star formation rate is unreasonably high ($3300\ M_\odot\ {\rm yr}^{-1}$ using eq. [21] of Condon 1992), and the expected 350 GHz flux density is 230 mJy. The observed 350 GHz flux density is a factor of 5 lower. It is likely that H1413+117 is a Fanaroff-

Riley class I ("FR I" = low-luminosity) radio galaxy, with a radio luminosity 2 times larger than M87. One method for separating AGN-driven radio emission from starburst-driven radio emission is subarcsecond imaging in the radio and submillimeter to look for spatial coincidence of the radio and submillimeter emission. Note that we have not included the submillimeter detections of high-redshift Fanaroff-Riley class II (high-luminosity) radio galaxies in this study, such as 4C 41.17 at $z = 3.8$ and 1435+635 at $z = 4.25$ (Hughes & Dunlop 1998). The extreme radio powers of these objects (1000 × M87) imply $\alpha_{1.4}^{350} \leq -0.5$, which is off the bottom of Figure 1, and they can be unambiguously recognized as such.

A third possible uncertainty in Figure 1 can arise due to gravitational lensing. A number of the high-redshift sources are known to be gravitationally lensed (Barvainis 1998; Blain 1998). If the radio continuum and submillimeter emission are roughly co-spatial, as would be the case for a starburst galaxy, then gravitational lensing will not affect the $\alpha_{1.4}^{350}$ values. However, if the radio emission is distributed differently than the submillimeter emission, as could occur for a radio-loud AGN, then differential magnification by a lens could lead to significant variations in the observed $\alpha_{1.4}^{350}$.

The general agreement between the models and the data in Figure 1 arises mainly from the very sharply rising submillimeter spectrum of thermal dust emission ($\alpha_{\rm submm} \geq +3$). This sharp rise in the submillimeter spectrum, coupled with the large "lever arm" in frequency between 1.4 and 350 GHz, can mitigate the uncertainties in the radio spectrum, such as free-free absorption, or even low-luminosity radio AGN emission (Schmitt et al. 1997). A submillimeter frequency of 350 GHz is a good choice for this study, since it is close to the minimum on the Raleigh-Jeans part of the thermal dust spectrum for low-z galaxies (Condon 1992), for which the value of $\alpha_{1.4}^{350}$ should be close to zero, and it does not reach the peak in the dust emission spectrum until $z \approx 7$ (see above), where $\alpha_{1.4}^{350} \geq 1$. Since the strength of the method lies in the steep rise in the dust spectrum, van der Werf et al. (1999) have recently performed an analogous analysis using the optical–to–far-IR spectral index as a redshift indicator. One problem that occurs in the optical is confusion. A typical submillimeter error box of 3″ has a 50% chance of containing a "random" optical galaxy at the limit of the HDF ($I_{814} \leq 29$; Williams et al. 1996), while at 1.4 GHz the probability is only 1% for finding a ≥10 μJy source in the error box (Langston et al. 1990).

3. DISCUSSION

Figure 1 can be considered in two ways. The first is as a redshift indicator for star-forming galaxies. In this regard, the most important conclusion that can be reached from Figure 1 is that a value of $\alpha_{1.4}^{350} \geq +0.5$ indicates that the source is likely to be at high redshift, $z \geq 1$.

One possible mechanism that could lead to larger $\alpha_{1.4}^{350}$ values for starburst galaxies than predicted by the models based on the radio–to–far-IR correlation would be to "quench" the radio continuum emission associated with star formation through inverse Compton losses off the microwave background radiation field. However, this mechanism is likely to become important only at very high redshift ($z \geq 6$). The energy density in the microwave background increases as $(1 + z)^4$, which, at $z = 6$, corresponds to the energy density in a magnetic field of about 100 μG—comparable to the expected interstellar magnetic fields in starburst nuclei (Condon et al. 1991; Carilli, Wrobel, & Ulvestad 1998). The lifetime for a relativistic particle radiating at a rest frequency of 10 GHz (= 1.4 GHz observed frequency) is then 0.5 Myr.

Contamination of the radio continuum emission by a low-luminosity radio AGN could lead to an ambiguity for values of $\alpha_{1.4}^{350} \leq +0.2$, such that the source is either a starburst galaxy at low redshift or a radio-loud AGN at higher redshift. The amount of contamination by radio-loud AGNs in a given galaxy sample will depend on the relative cosmic density of active star-forming galaxies versus radio-loud AGNs and on the flux density limits of the observations. Assuming that sensitive observations can be made of galaxies with star formation rates of order 10 $M_\odot$ yr^{-1} out to high redshift (see below), then the expected contamination by FRI-class radio galaxies should be ≤30%, based on galaxy populations at low redshift (Yun et al. 1999; Osterbrock 1989; Hammer et al. 1995; Richards et al. 1998). Of course, this fraction could change with redshift (Gruppioni et al. 1999).

The second use for Figure 1 is as an "AGN indicator." Given a value of $\alpha_{1.4}^{350}$ and an independent estimate of the source spectral redshift, if the source lies well below the curves in Figure 1, then it is likely that the source has a radio-loud AGN component. Again, H1413+117 is a good example of this. Theoretically, a source can appear well above the curves in Figure 1 if the dust-heating mechanism is entirely due to a radio-quiet AGN. Thus far, no examples of this latter type have been found, but current limits on a few sources cannot preclude such a situation.

We can apply the analysis in Figure 1 to address the identification of the submillimeter sources detected in the HDF by Hughes et al. (1998). Because there are of order 10 optical galaxies within a given SCUBA beam at 350 GHz (FWHM = 15″), unique identification of the submillimeter sources is difficult from the astrometry alone. Hughes et al. have argued that the submillimeter sources are at $z \geq 1$ based on the submillimeter spectral shape. Using the deep radio imaging data from the VLA, Richards (1999) has argued that there is a 6″ offset between the submillimeter frame with respect to the radio and optical frame and that the sources HD F850.3 and HD F850.4 could be identified with bright optical galaxies at $z \sim 0.5$ instead. As shown in Figure 1*b*, however, the derived radio-to-submillimeter spectral index for the three proposed identifications by Richards (*filled circles*) are much too large to be consistent with their redshifts. Reversing the argument, the maximum expected 350 GHz fluxes for the two bright $z \sim 0.5$ radio sources are 0.21 and 0.44 mJy, factors of 14 and 5.2 too small compared to the observed values.

Conversely, if the SCUBA astrometric accuracy is better than 6″, only upper limits exist for the 1.4 GHz radio flux (3 σ = 23 μJy). The resulting *lower* limits to $\alpha_{1.4}^{350}$ for the five HDF submillimeter sources are shown in Figure 1*b* using the redshifts estimated by Hughes et al. The derived $\alpha_{1.4}^{350}$ is larger than +0.8 in all five cases, and therefore these sources are likely to be located at $z \geq 1.5$, more in line with the approximate redshifts estimated for the sources based solely on the submillimeter spectral indices by Hughes et al. (1998). Further, the brightest submillimeter source HDF 850.1 has $\alpha_{1.4}^{350} > +1.0$, larger than any previously detected submillimeter source (see Fig. 1*a*), suggesting $z \geq 3$. For comparison, the $z = 4.7$ QSO BR 1202−0725 has $\alpha_{1.4}^{350} = +0.92$.

Recent infrared, submillimeter, and radio observations suggest that optical studies of galaxies at high redshift may miss a significant population of massive star-forming galaxies due to dust obscuration and that the cosmic star formation rate may be a factor 3 or more larger at $z \geq 1$ than estimated from optical

studies (Flores et al. 1999; Hughes et al. 1998). Sensitive submillimeter observations using bolometer arrays and sensitive radio observations using the VLA are typically limited to sources with flux densities $\geq$1 mJy at 350 GHz and $\geq$40 μJy at 1.4 GHz (Richards et al. 1998), corresponding to sources with star formation rates $\geq$100 $M_{\odot}$ yr^{-1} at $z \approx 2$. The large millimeter array currently being designed for the high desert in Chile will have a 350 GHz sensitivity of about 10 μJy in 1 hr. This will be easily adequate to detect galaxies with star formation rates of order 10 $M_{\odot}$ yr^{-1} at $z = 3$ (Brown 1996), for which the expected flux density at 350 GHz is 100 μJy. Likewise, the upgraded VLA will have sub-microjansky sensitivity at 1.4 and 2.3 GHz for full-synthesis observations. This should be adequate to image these same galaxies, for which the expected flux density at 1.4 GHz is a few microjanskys, with subarcsecond resolution. Hence, in the near future we should be able to extend radio and submillimeter studies of star formation to "normal" galaxies at substantial look-back times.

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