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SUBMILLIMETER EMISSION FROM TYPE Ia SUPERNOVA HOST GALAXIES AT $z = 0.5$

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ABSTRACT

We present deep submillimeter observations of 17 galaxies at $z = 0.5$ that are hosts of a Type Ia supernova. Two galaxies are detected directly, and the sample is detected statistically with a mean 850 μm flux of 1.01 ± 0.33 mJy, which is 25%–135% higher than locally. We infer that the mean value of A_V in normal galaxies at $z = 0.5$ is comparable to or greater than the mean A_V in local normal galaxies, in agreement with galaxy chemical evolution models and indirect observational evidence. Scaling from the local value given by Rowan-Robinson gives a mean extinction at $z = 0.5$ of $\langle A_V \rangle = 0.56 \pm 0.17$. The dust in the brightest submillimeter object in our sample is best interpreted as normal "cirrus" dust similar to that seen locally. The detection rate of our sample suggests that some sources found in blank-field submillimeter surveys may not be high-redshift starbursts, but rather cirrus galaxies at moderate redshifts and with lower star formation rates. Finally, an increase in host dust extinction with increasing redshift may impact the cosmological results from distant supernova searches. This emphasizes the need to carefully monitor dust extinction when using Type Ia supernovae to measure the cosmological parameters.

Subject headings: cosmological parameters — galaxies: high-redshift — supernovae: general

1. INTRODUCTION

In recent years, deep surveys have found galaxies and QSOs at redshifts greater than 6, making it possible to trace the cosmic history of star formation and active galactic nucleus (AGN) activity from the epoch of reionization to the present day. In practice, however, achieving these goals is difficult, as translating observations of light from galaxies into measures of stellar content and formation histories is affected by the obscuring effects of dust. While dust obscuration is known to have a significant effect locally (e.g., Tresse & Maddox 1998), the role of dust at higher redshifts is even more important. Chemical evolution models (Calzetti & Heckman 1999; Pei, Fall, & Hauser 1999) predict that dust obscuration should peak at 2–3 times the current value at $1 < z < 2$, before slowly declining. Observationally, the importance of dust obscuration at high redshifts is exemplified by the very different cosmic star formation histories inferred from optical and infrared surveys. Infrared surveys produce star formation histories that rise more sharply from $z = 0$ to 1, and show a slower decline at higher redshifts than the star formation histories inferred from optical surveys (Lilly et al. 1996; Madau et al. 1996; Steidel et al. 1999; Rowan-Robinson et al. 1997; Hughes et al. 1998).

These surveys, however, do not examine extinction evolution in inactive galaxies. Blank-field infrared surveys are biased toward systems containing a dusty starburst or AGN, whereas Lyman break galaxies are selected by rest-frame UV flux, which may bias them toward having high rates of unobscured star formation. In this paper, we present preliminary results from a program to use deep submillimeter observations to investigate the evolution of submillimeter emission and dust opacity with redshift in what should be normal galaxies: the host galaxies of distant Type Ia supernovae (SNe Ia). Observations and data analysis are described in § 2, and results are presented in § 3. We discuss mean extinction levels and dust properties in § 4, and also mention some implications for deep submillimeter surveys and supernova cosmology. We assume $\Omega_0 = 1$, $\Omega_m = 0.3$, $\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1}.

2. OBSERVATIONS

The hosts of the SNe Ia discovered by the Supernova Cosmology Project (SCP; Perlmutter et al. 1999) and the High Redshift Supernova Search Team (HZT; Riess et al. 1998) are ideal targets for studying the evolution of dust opacity in normal galaxies: the galaxies have spectroscopic redshifts; the galaxies are selected independent of their apparent magnitudes, as the discovery is based on the supernova rather than the host; and SNe Ia come from evolved stellar populations. Furthermore, since the supernova spectrum must be disentangled from the host galaxy spectrum, none of the host galaxies contain the signature bright emission lines of a starburst or AGN (Riess et al. 1998; Perlmutter et al. 1999; A. Riess 2003, private communication; G. Aldering 2003, private communication).

We observed 17 host galaxies of supernovae discovered by the SCP and HZT. The only selection criteria were that the host galaxy redshifts should lie in a narrow interval around $z = 0.5$, so that the fluxes could be co-added without k-correcting to a common wavelength, and that the supernova in the host should be spectroscopically confirmed as a Type Ia. The host galaxies were observed at 450 and 850 μm using the Submillimeter Common User Bolometer Array (SCUBA) on the *James Clerk Maxwell Telescope* (*JCMT*). All observations were performed in photometry mode. The atmospheric conditions were of exceptional quality, with a mean 850 μm sky opacity of $\tau_{850} \sim 0.15$. We note the possibility that submillimeter flux from any of the objects in our sample could in principle arise from a chance-aligned high-redshift source; however, assuming a submillimeter source density from recent blank-field submillimeter surveys (Eales et al. 1999; Scott et al. 2002; Fox et al. 2002; Borys et al. 2003) and a conservative search radius of 2″ (the jiggle offset on photometry-mode observations with SCUBA) gives a probability that the flux from any one object in the sample comes from a chance-aligned submillimeter source of approximately 1 in 400. We therefore conclude that any submillimeter flux seen in our sample is most likely due to the target, rather than a background source. The data were reduced using the SCUBA User Reduction Facility (SURF) pipeline using standard methods.

For one host galaxy, that of SN 1997ey, we obtained *Hubble Space Telescope* (*HST*) imaging from the *HST* data archive. Observations were taken using the Space Telescope Imaging Spectrograph (STIS) using a clear filter. The data were reduced using the IRAF reduction package CALSTIS. The final image is presented in Figure 1.

3. RESULTS

The sample, their redshifts, and their submillimeter fluxes are presented in Table 1. One object (the host galaxy of SN 1997ey) is detected strongly at both 450 and 850 μm, one object (the host of SN 2000eh) is detected at 850 μm only, and the rest of the sample are undetected individually.

As our sample is randomly selected over a narrow redshift range, we can co-add the observed submillimeter fluxes to measure the mean submillimeter flux of normal galaxies at $z \sim 0.5$. We only consider the 850 μm fluxes, as the 450 μm calibration errors are large. The mean observed 850 μm flux for all 17 galaxies is 1.55 ± 0.31 mJy. The host galaxy of SN 1997ey, however, is significantly brighter than the others, and it is probable that this source is an outlier and the flux of this galaxy will bias the mean value significantly. Assuming that the "true" source flux distribution is a Gaussian, then the distribution of fluxes for the whole sample is consistent with a Gaussian at only the $\sim 5\ \sigma$ level, whereas excluding the host of SN 1997ey makes the distribution of fluxes consistent with a Gaussian at less than 2 σ and excluding any of the remaining sources does not make the fit statistically better. We therefore also quote the error-weighted mean flux of the 16 galaxies with the host of SN 1997ey excluded, which is 1.01 ± 0.33 mJy, and use this value in the following analysis.

4. DISCUSSION

We first review the origin of submillimeter flux from extragalactic sources and the relation between submillimeter flux and optical extinction. In many cases, submillimeter emission from extragalactic sources arises in starbursts: i.e., compact regions (less than 1 kpc across) containing $\sim 10^8\ M_\odot$ of dust heated by young massive stars forming at a rapid rate (greater than 50 $M_\odot$ yr^{-1}). Since submillimeter emission measures physical dust volume rather than the volume of space the dust is dispersed in, the same level of submillimeter emission can arise from a comparable mass of dust distributed in the disk of a galaxy heated by the general interstellar radiation field. This type of submillimeter emission, known as

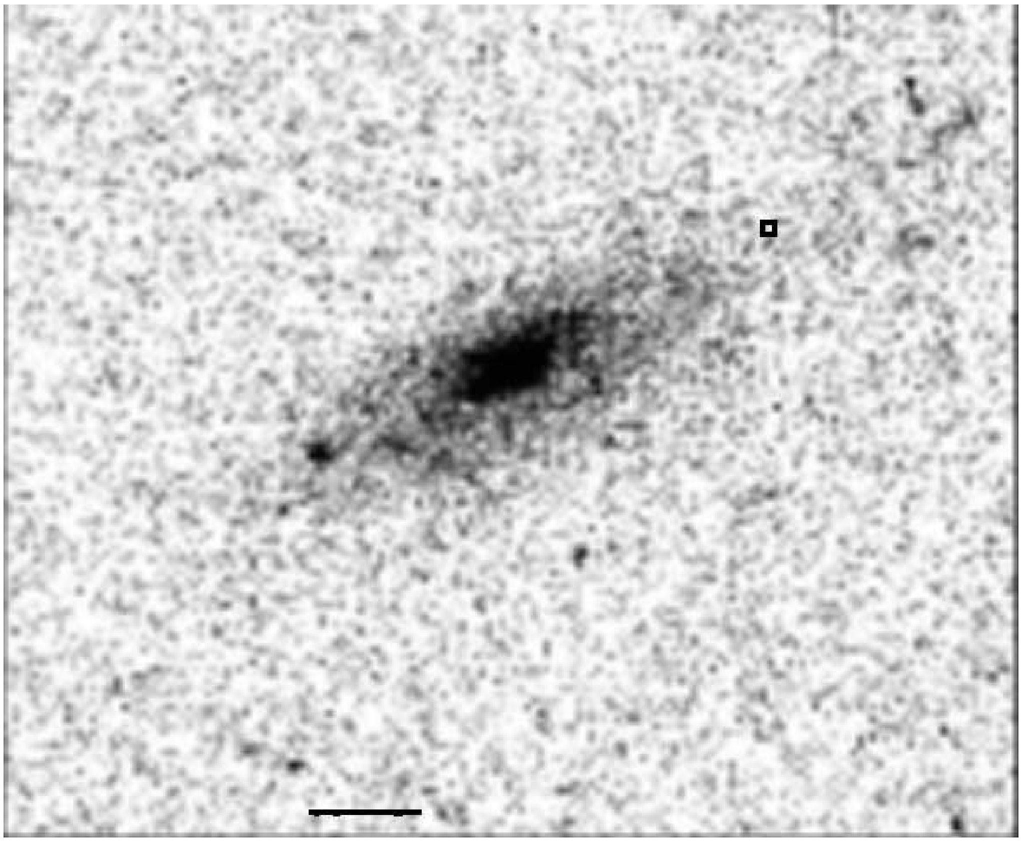

FIG. 1.—*HST* STIS image of the host galaxy of SN 1997ey, taken after the supernova had faded. The position of the supernova is marked with a square, and the bar at the bottom denotes 1″.

TABLE 1

Supernova Host Galaxies Observed at the *JCMT*

Host	Origin[a]	Redshift	S_{450}	σ_{450}	S_{850}	σ_{850}
SN 1994al	SCP	0.42	5.49	47.08	3.01	2.70
SN 1995aq	SCP	0.45	9.52	9.48	−1.33	1.49
SN 1995as	SCP	0.50	−6.10	5.20	−0.31	1.19
SN 1995ay	SCP	0.48	−4.10	4.13	0.87	1.17
SN 1995az	SCP	0.45	9.23	8.45	2.56	1.45
SN 1996cg	SCP	0.49	3.46	3.90	−1.11	1.04
SN 1997f	SCP	0.58	2.34	4.76	1.79	1.10
SN 1997l	SCP	0.55	−0.14	12.96	1.93	1.76
SN 1997em	SCP	0.46	0.24	6.45	−0.68	1.38
SN 1997ep	SCP	0.48	4.12	4.09	2.01	1.06
SN 1997ey	SCP	0.58	20.80	3.54	7.80	1.10
SN 1999fn	HZT	0.47	1.87	7.04	−0.12	1.28
SN 2000dz	HZT	0.50	−0.51	8.21	1.87	1.38
SN 2000ea	HZT	0.42	−10.90	13.80	2.45	2.02
SN 2000ee	HZT	0.47	1.96	4.63	1.23	1.06
SN 2000eg	HZT	0.54	5.92	4.20	1.29	1.16
SN 2000eh	HZT	0.49	5.18	6.65	4.61	1.53

Note.—Fluxes are quoted in the observed frame and are given in mJy. Errors are 1 σ.

[a] Groups responsible for discovering the supernova. SCP: Supernova Cosmology Project; HZT: High-Redshift Supernova Search Team.

"cirrus" emission, is seen locally in both Galactic sources (Casey 1991) and nearby galaxies (Bianchi, Davies, & Alton 1999; Dunne et al. 2000). Furthermore, there is evidence that cirrus emission may be important in blank-field submillimeter sources (Efstathiou & Rowan-Robinson 2003). As our targets contain an SNe Ia, which is known to come from evolved stellar populations, and because none of the targets contain optical signatures of starbursts or AGN, we are confident that any submillimeter flux from our targets will be cirrus emission.

The relation between cirrus submillimeter emission and optical extinction has been discussed by Hildebrand (1983), Casey (1991), and Bianchi et al. (1999). It turns out that the integrated submillimeter flux from a galaxy, with certain assumptions scales linearly with A_V. We summarize these arguments here. If the dust responsible for the submillimeter emission is also responsible for the optical extinction, then the ratio of the extinction efficiency in the V band to the emission efficiency in the submillimeter at some wavelength λ is equal to the ratio of the optical depths,

$$\frac{Q_{\mathrm{ext},V}}{Q_{\mathrm{em},\lambda}} = \frac{\tau_V}{\tau_\lambda}. \tag{1}$$

In the optically thin case, τ_λ can be written as

$$\tau_\lambda = \frac{I_\lambda}{B_\lambda T}, \tag{2}$$

where I_λ is the submillimeter intensity and T is the dust temperature. Solving for A_V gives (Bianchi et al. 1998)

$$A_V \propto \frac{Q_{\mathrm{UV}}}{Q_{\lambda_0}} \left(\frac{\lambda}{\lambda_0}\right)^\beta \frac{I_\lambda}{B_\lambda T} \tag{3}$$

where λ is the observed wavelength, λ_0 is a reference wavelength, and Q_{λ_0} is the extinction efficiency at the reference wavelength.

There are two important assumptions in this derivation that may affect our results. First, even though the fluxes lie within the Rayleigh-Jeans tail, the submillimeter flux still scales linearly with dust temperature, meaning that a mean increase in temperature could be responsible for increasing the submillimeter flux rather than an increase in optical extinction. However, even assuming pure luminosity evolution between the local universe and $z = 0.5$, the mean dust temperature will only increase as the one-fifth power of A_V (i.e., increasing with the mean surface brightness). Furthermore, the predicted rise in dust temperature between $z = 0$ and 0.5 from chemical evolution models (Pei et al. 1999) is probably on the order of 1 K or less, insufficient to produce a significant rise in submillimeter flux. Second, we turn to the gas-to-dust ratio. When using equation (3) to compare optical extinctions between different objects, it is assumed that the gas-to-dust ratio for both objects is the same. When comparing local galaxies to galaxies at $z = 0.5$, this criterion will not be satisfied; globally we expect significantly less star formation to have occurred by $z = 0.5$, which may lead to a higher mean gas-to-dust ratio there than locally. Based on indirect evidence (Pettini et al. 1999), we expect this rise to be no more than 10%–20% at $z = 0.5$, although at higher redshifts the change may be larger (Pei, Fall, & Bechtold 1991). As there is no published measure of the gas-to-dust ratio in normal galaxies at $z = 0.5$, we have assumed that the change from the local mean value is negligible.

4.1. *Dust Opacity Evolution in Normal Galaxies*

To establish if the mean submillimeter flux of our sample differs from the mean submillimeter flux of local normal (i.e., inactive) galaxies, we would like to compare to a local submillimeter survey of galaxies selected by optical flux. Currently, however, no such survey has been published. Therefore, to estimate the expected observed mean 850 μm flux at $z = 0.5$ from normal galaxies if there had been no evolution in dust opacity between the local universe and $z = 0.5$, we consider the local submillimeter survey of Dunne et al. (2000). We have redshifted the mean 850 μm flux from this survey to $z = 0.5$, with k-corrections derived using the cirrus models from Efstathiou & Rowan-Robinson (2003).

The resulting predicted observed 850 μm flux at $z = 0.5$ is 0.8 ± 0.1 mJy. This survey, however, is of galaxies from the *IRAS* Bright Galaxy Sample, which selects against galaxies with small dust masses and is composed of spiral, irregular, and interacting systems. The morphologies of the galaxies discovered by the supernova cosmology teams are known to be 70% spirals and irregulars, and 30% ellipticals (Farrah et al. 2002a; Sullivan et al. 2003). As our sample is randomly selected from the SNe Ia discovered by both the SCP and the HZT, it is reasonable to assume that the same morphological mix is present in our sample. In order to compare our value to the "no evolution" value, we must correct the no evolution value to reflect the morphological mix in our sample. If we assume that submillimeter emission from ellipticals is negligible, then this gives a predicted no evolution flux estimate, at $z = 0.5$, of 0.56 ± 0.1 mJy. The difference between our observed mean 850 μm flux of 1.01 ± 0.33 mJy (i.e., excluding the host of SN 1997ey) and this value implies a rise in submillimeter flux from normal galaxies at $z = 0.5$ in the range of 25%–135% (1 σ errors) more than local galaxies. Therefore, our results imply that submillimeter emission from normal galaxies at $z = 0.5$ is comparable to or higher than submillimeter emission from local normal galaxies.

We can use this mean submillimeter flux to estimate the mean value of A_V in spiral and irregular galaxies at $z = 0.5$. The most recent estimate of mean extinction levels in local *normal* galaxies (i.e., including only an optically thin cirrus component) is that of Rowan-Robinson (2003), who derives $E(B-V) = 0.1$, and therefore $\langle A_{V,\,\mathrm{local}} \rangle = 0.31$. Hence, we obtain $\langle A_{V,\,z=0.5} \rangle = 0.56 \pm 0.17$. This result is in good agreement with indirect observational evidence based on the star formation history of the universe (Lilly et al. 1996; Rowan-Robinson et al. 1997). It is also in agreement with both a model for the evolution in dust opacity with redshift (Calzetti & Heckman 1999), which predicts that the change in mean reddening between the local Universe and $z = 0.5$ will be $\Delta E(B-V) = 0.05$ with a corresponding increase in extinction of $A_V \sim 0.15$, and chemical evolution models (Pei et al. 1999), which model the evolution of gas and dust mass with redshift.

4.2. *Dust Properties in Spiral Galaxies at* $z = 0.5$

We now examine the dust properties in the host galaxy of SN 1997ey, which was detected at 450 and 850 μm. One possibility is that this galaxy harbors a dust-enshrouded starburst that produces the submillimeter flux; such a system would be unsuitable for examining the properties of dust in normal galaxies at $z = 0.5$. However, this is very unlikely for two reasons. First, as described earlier, none of the optical spectra of the other supernova host galaxies from either the SCP or the HZT, from which this galaxy is selected, show signs of an AGN or starburst. Second, the *HST* STIS image for this galaxy presented in Figure 1, taken after the supernova had faded, shows a disk galaxy with no signs of morphological disturbance, which are seen in local (Surace et al. 1998; Farrah et al. 2001; Bushouse et al. 2002) or high-redshift (Farrah et al. 2002b) starburst galaxies. We therefore conclude that the observed submillimeter flux comes from the host galaxy of SN 1997ey and that the host is a normal disk galaxy.

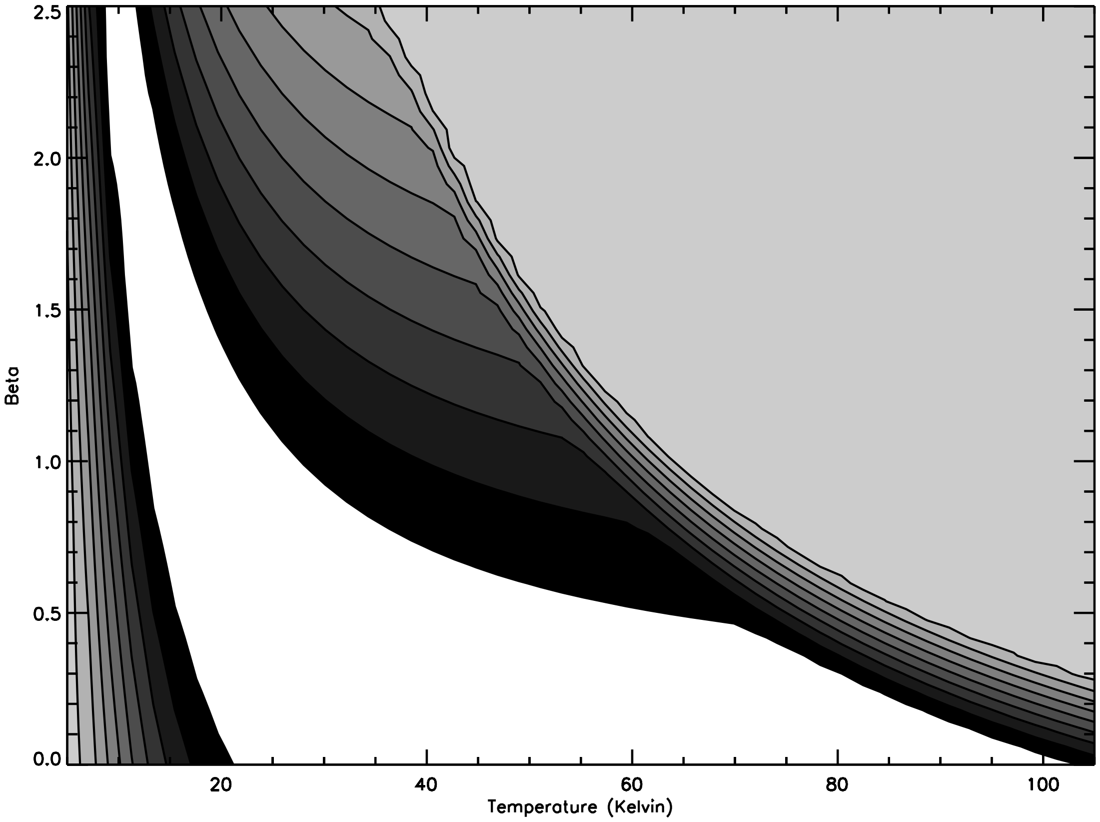

Fig. 2.—Reduced χ^2 distribution plot for the dust properties of the host galaxy of SN 1997ey. The white region shows the 3 σ confidence range for dust temperature and emissivity index. Each contour then represents a further 3 σ drop in confidence. Upper limits at 60 and 100 μm from *IRAS* were also used in constraining the distribution.

As submillimeter data exists at only two wavelengths, the properties of the dust in this galaxy are best estimated using a simple greybody formula. Figure 2 shows a reduced χ^2 distribution plot of β and T for the dust in the galaxy. Two particularly interesting cases are for $\beta \sim 2$, the cirrus or "Milky Way"-type dust solution, and for $\beta \sim 0$, the "gray" dust solution. While gray dust has previously been proposed to exist at high redshifts (Aguirre 1999), it is notable that, for $\beta \sim 2$, the dust temperature range is comparable to that seen locally and is consistent with the models of Pei et al. (1999). We therefore find no observational evidence that the dust at high redshift differs fundamentally in nature from the dust seen in the local Universe, and conclude that the dust in the host galaxy of SN 1997ey is normal cirrus dust.

4.3. *Normal Galaxies and Submillimeter Surveys*

The detection of one object in our sample with an 850 μm flux of ~8 mJy, highlights an alternative interpretation for the nature of some of the sources found in blank-field submillimeter surveys. We have observed 17 galaxies that have $B \sim 23$, and detected one of them at an 850 μm flux of ~8 mJy. There are approximately 3000 galaxies per deg^2 at this magnitude, so our detection rate is ~200 galaxies per deg^2. While statistics based upon one object are obviously not trustworthy, it is interesting that this detection rate agrees surprisingly well with the detection rate reported in previous blank-field submillimeter surveys to comparable depths (Scott et al. 2002; Fox et al. 2002), which found 19 objects to 8 mJy in 260 arcmin^2, or 270 per deg^2.

The nature of our source and the assumed nature of blank-field survey submillimeter sources are different. Blank-field survey submillimeter sources are generally thought to lie at $z > 1$ and to be galaxies undergoing extreme bursts of dust-shrouded star formation (Fox et al. 2002). The redshift, luminosity, and star formation rates are, however, in many cases estimated using only a limited set of photometric data. Our detection, which has a flux comparable to the sources found in these surveys, lies at $z = 0.58$ and, judging by the coldness of the dust and morphology of the galaxy, is forming stars at a more sedate rate. While some submillimeter sources now do have spectroscopic redshifts that put most of them at $z \geq 1$ (Lilly et al. 1999; Chapman et al. 2003), it is reasonable to infer that some of the submillimeter sources in blank-field surveys are at lower redshifts than previously thought and also have lower star formation rates. While the star formation rates in these sources will be high, they still need to be carefully accounted for in current and future submillimeter surveys to avoid overestimating the global history of star formation.

4.4. *Implications for Supernova Cosmology*

There is now strong, albeit indirect, evidence from observations of the cosmic microwave background (Jaffe et al. 2001; Spergel et al. 2003) and large-scale structure (Peacock et al. 2001) that the total density of the universe is dominated by dark energy. To determine the nature of dark energy, it is necessary to track its evolution with redshift directly, using a cosmological standard candle. Currently, the only method deployed to do this uses the luminosity distances of distant SNe Ia. The HZT and the SCP have performed surveys to find high-redshift supernovae, and both groups claim that dark energy dominates the total density of the universe, and that the expansion of the universe is currently accelerating (Riess et al. 1998; Perlmutter et al. 1999). The HZT have further claimed (Riess et al. 2001) to have found an earlier epoch of decelerating expansion, based on an apparent relative brightening of SNe Ia at $z > 1$ and that accelerating expansion commenced at $z \sim 1$. This relative brightening supports a real, "cosmological" influence on the supernova magnitudes, as alternative explanations (e.g., gray dust, or progenitor evolution) do not readily predict this relative brightening at $z > 1$.

These results are based upon the distant supernovae being $\Delta m = 0.40$ dimmer (with a flat universe prior) than if the expansion of the universe were decelerating. There are alternative interpretations that can in principle account for this dimming, one of these being host galaxy extinction. The issue of extinction toward distant SNe Ia has been examined in detail by both the SCP and the HZT by measuring the reddening of the supernova light curves, the SCP by comparing the rest-frame colors of their low- and high-redshift samples, and the HZT by fitting to the light curves via the multifilter light-curve shape (MLCS) method. The SCP find that the reddening of both their local and distant sample, after a small number of reddened supernovae are removed, have a small scatter with a mean value of close to zero. The HZT find that only a few of their distant supernovae are significantly reddened. An analysis of the color excesses derived from the supernova light curves as a function of host galaxy morphology by the SCP (Sullivan et al. 2003) also found only a modest difference in extinction between the SNe in ellipticals and SNe in spirals, with $E(B-V) = -0.03$ for the SNe in the ellipticals and $E(B-V) = 0.07$ for the SNe in spirals. Our result, a mean value of A_V in galaxies at $z = 0.5$ that is 25%–135% higher than for local galaxies, does not cast any doubt on the supernova teams' results, as this extinction level at $z = 0.5$ lies within 1.3 σ of the local value and is derived from the mean extinction in each galaxy rather than the line-of-sight extinction toward the supernovae. It does however highlight the need for caution, in general, when using supernovae as probes of the expanding universe, as our derived mean extinction, $A_V = 0.56 \pm 0.17$, implies a rise that is *at face value* comparable to the dimming ascribed to dark energy. Therefore, our result emphasizes the need to accurately monitor the extinction toward distant supernovae if they are to be used in measuring cosmological parameters.

5. SUMMARY

We have presented deep submillimeter observations of 17 SNe Ia supernova host galaxies at $z \sim 0.5$, from which we conclude the following:

1. The mean observed-frame submillimeter flux of the sample, excluding one bright object, is $S_{850} = 1.01 \pm 0.33$ mJy. Assuming that submillimeter flux scales linearly with optical extinction, then this implies a rise in optical extinctions in normal, inactive galaxies of 25%–135%, compared with local galaxies. Scaling from the local value of A_V given by Rowan-Robinson (2003) for optically thin cirrus emission gives $\langle A_{V,\, z=0.5} \rangle = 0.56 \pm 0.17$. This result is in good agreement with both chemical evolution models (Pei et al. 1999; Calzetti & Heckman 1999) and other, indirect observational evidence (Lilly et al. 1996; Rowan-Robinson et al. 1997). The temperature and emissivity of the dust in the brightest submillimeter object in our sample is comparable to the temperature and emissivity of dust in local galaxies.
2. The discovery of a moderate-redshift disk galaxy with a submillimeter flux comparable to the sources found in blank-field submillimeter surveys suggests that some of these blank-field sources may not be high-redshift starbursts, but

lower-redshift dusty disks. These sources must be carefully accounted for in current and future submillimeter surveys to avoid overestimating the global history of star formation.

3. Our results, when combined with previous work, infer a level of extinction in galaxies at $z = 0.5$ that could in principle produce a dimming that is comparable in size to the dimming ascribed to accelerated expansion, although the error on the value is large and the extinction level is the mean for the galaxy rather than the line-of-sight extinction toward the supernovae. This emphasizes the need to carefully monitor extinction levels toward distant supernovae if they are to be used to track the expansion rate history of the universe.

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