DUST, GAS, AND THE EVOLUTIONARY STATUS OF THE RADIO GALAXY 8C 1435+635 AT $z = 4.25$

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ABSTRACT

We present the results of new rest-frame far-IR observations of the $z = 4.25$ radio galaxy 8C 1435+635, which not only confirm that it contains an enormous quantity of dust (as first inferred from its millimeter-wave detection by Ivison in 1995), but also allow the first meaningful constraints to be placed on the mass of this dust and associated gas. The new measurements consist of (1) clear detections of submillimeter continuum emission at $\lambda_{obs} = 450$ and 850 μm obtained with the new submillimeter bolometer array, SCUBA, on the James Clerk Maxwell Telescope, (2) continuum upper limits at $\lambda_{obs} = 350$, 750, and 175 μm obtained with SCUBA and the PHT far-IR camera aboard the *Infrared Space Observatory*, and (3) a sensitive upper limit on the CO (4–3) line flux obtained with the IRAM 30 m Millimeter Radio Telescope. The resulting rest-frame 33–238 μm continuum coverage allows us to deduce that 2×10^8 $M_{\odot}$ of dust at a temperature of 40 ± 5 K is responsible for the observed millimeter/submillimeter emission. Using our CO upper limit, which constrains M_{H_2}/M_d to less than 950, we go on to calculate robust limits on the total gas reserves (H$_2$ + H I), which are thereby constrained to between 4×10^{10} and 1.2×10^{12} $M_{\odot}$. The submillimeter properties of 8C 1435+635 are thus strikingly similar to those of the $z = 3.80$ radio galaxy 4C 41.17, the only other high-redshift galaxy detected to date at submillimeter wavelengths whose properties appear *not* to be exaggerated by gravitational lensing. The inferred gas masses of both objects are sufficiently large to suggest that the formative starbursts of massive elliptical galaxies are still in progress at $z \simeq 4$. Observations of complete samples of radio galaxies spanning a range of redshifts and radio luminosities will be required to determine whether the spectacular far-IR properties of 8C 1435+635 and 4C 41.17 are primarily due to their extreme redshifts or to their extreme radio luminosities.

Subject headings: galaxies: individual (8C 1435+635) — galaxies: ISM — galaxies: photometry — infrared: galaxies

1. INTRODUCTION

Systematic redshift surveys out to $z \simeq 1$ and the discovery of Lyman-limit galaxies at $z \simeq 3$ have allowed considerable progress to be made in understanding the star formation history of some bright, present-day galaxies, and suggest that global star formation activity in our universe peaked at around $z \simeq 2$ (e.g., Lilly et al. 1995; Pei & Fall 1995; Madau et al. 1996; see also Smail, Ivison, & Blain 1997). However, these same optical surveys appear to confirm that the properties of massive elliptical galaxies are little changed by $z \simeq 1$, consistent with the picture that most of the stars in massive ellipticals were formed in a relatively short-lived, intense starburst at high redshift (e.g.,

Dunlop et al. 1996). If, as has been suggested by a number of authors (e.g., Zepf & Silk 1996), this initial starburst is biased toward the formation of significant quantities of high-mass stars (and hence dust), then a massive elliptical in the throes of formation would be expected to emit copious quantities of far-IR radiation. When viewed at high redshift, such an object would therefore be expected to be a strong submillimeter source. Consequently, it has long been anticipated that the formation and evolution of elliptical galaxies will be one of the key cosmological issues that can be best addressed through the introduction of deep submillimeter imaging.

Despite the success of the optical surveys described above in sampling the universe out to $z \simeq 3$ and the exciting potential of deep submillimeter surveys to probe the high-redshift universe, the study of radio galaxies remains arguably the best method to trace the cosmological evolution of

massive elliptical galaxies. This is because selection on the basis of strong extended radio emission guarantees the following:

1. The host galaxy is a giant elliptical or the progenitor thereof (Matthews, Morgan, & Schmidt 1964; Lilly & Longair 1984), a key advantage over optical/IR surveys where one is forced to resort to circumstantial evidence, such as comoving number densities, to help make an educated guess as to the most appropriate low-redshift counterpart for a given high-redshift source.

2. Highly efficient selection of high-redshift galaxies, the properties of which should not be significantly biased by gravitational lensing (in contrast, for example, to optically selected quasars that are selected primarily on the basis of their strong, compact emission).

These considerations suggest that steep-spectrum radio galaxies are currently the targets of choice to trace the cosmological evolution of dust and gas (and hence star formation activity) in massive elliptical galaxies. Furthermore, such reasoning has already received a considerable observational boost as a result of the successful millimeter/submillimeter detections of first 4C 41.17 (Dunlop et al. 1994; Chini & Krügel 1994) and then 8C 1435+635 (Ivison 1995).

The most useful physical parameter that can be extracted from such observations is the *mass* of dust, and hence the amount of gas, that remains to be converted into stars at the epoch of observation. However, as discussed in detail by Hughes, Dunlop, & Rawlings (1997), to obtain a reliable estimate of the dust and gas masses in high-redshift objects requires that the uncertainty in dust temperature be minimized through obtaining millimeter–far-IR measurements that extend to significantly shorter wavelengths than the Rayleigh-Jeans tail, preferably straddling the rest-frame far-IR emission peak. Furthermore, it is helpful (through observations of CO lines) to confirm that gas/dust ratios in such high-redshift sources are at least consistent with those seen in low-redshift galaxies, before daring to extrapolate from the dust mass to the total mass of gas available for future star formation.

In this paper we address both these issues through a concerted program of new millimeter/submillimeter/far-IR observations of the $z = 4.25$ radio galaxy 8C 1435+635. Such a program has only been made possible through the advent of new, highly sensitive facilities, in particular the newly commissioned submillimeter bolometer array, SCUBA, on the James Clerk Maxwell Telescope (JCMT),[2] and the PHT far-IR camera aboard the *Infrared Space Observatory* (*ISO*). Together these facilities offer the opportunity of moving millimeter/far-IR studies of high-redshift objects from the pioneering world of bare detections to the reliable extraction of meaningful physical parameters.

The organization of this paper is as follows:

1. We describe our existing and new millimeter to far-IR measurements of 8C 1435+635, which prove beyond doubt that the far-IR emission from this galaxy is produced by dust.

2. We use these data to derive new constraints on the dust and inferred gas mass in this galaxy.

3. We then discuss the implications of our results for the evolutionary status of 8C 1435+635, compare its properties with those of 4C 41.17, and conclude with a brief discussion of the implications of this work for the evolution and formation of massive ellipticals in general.

Unless otherwise stated, we assume $q_0 = 0.5$ and $H_0 = 50$ km s^{-1} Mpc^{-1} throughout; the impact on our conclusions of adopting a lower value for q_0 is specifically addressed in § 4.

2. OBSERVATIONS

2.1. 8C 1435+635; Existing Data

The existence of a large mass of dust in 8C 1435+635 was first inferred as a result of its detection at $\lambda_{obs} = 1250$ μm ($S_{1250} = 2.57 \pm 0.42$ mJy) by Ivison (1995). At the time of this observation, 8C 1435+635 (4C 63.20) was the most distant known radio galaxy, with a redshift $z = 4.25$ corresponding to a look-back time of around 92% of the age of the universe. Its prodigious radio luminosity ($P_{1.5 \text{ GHz}} = 5.4 \times 10^{27}$ W Hz^{-1} sr^{-1}; Lacy et al. 1994) allied with a surprisingly weak Lyman-α line ($L_{Ly\alpha} = 5.5 \times 10^{36}$ W; Spinrad, Dey, & Graham 1995) made 8C 1435+635 a natural target for observers in the submillimeter/millimeter regime where reservoirs of dusty molecular gas betraying the galaxy's initial brief burst of star formation might be seen.

A further attraction of this source as a potential target for millimeter/submillimeter observations arises from the fact that, like 4C 41.17 (Dunlop et al. 1994), 8C 1435+635 is an ultrasteep spectrum (USS) radio source in which extrapolation of its radio spectrum leads to an expected synchrotron contribution of less than 0.01 mJy at $\lambda_{obs} \simeq 1$ mm. For this reason, the 1250 μm emission observed by Ivison (1995) was difficult to explain as arising from anything other than thermal radiation from dust. Nevertheless, it is worth reemphasizing that this one data point was insufficient to conclusively exclude some previously undetected high-frequency synchrotron component from being responsible for the rest-frame far-IR emission.

2.2. Measurements with SCUBA on JCMT

Data were obtained during the period 1997 April–June using the 0.1 K, submillimeter common-user bolometer array (SCUBA; Gear et al. 1998). SCUBA has two arrays of bolometric detectors that are operated at 0.1 K to achieve sky background-limited performance on the telescope. The long-wavelength (LW) array operates at 750 and 850 μm and has 37 pixels, each having a diffraction-limited beam of diameter 14″ at 850 μm. The short-wavelength (SW) array has 91 pixels and operates at 350 and 450 μm with beamwidths of 7″.5. Both arrays have a 2′.3 instantaneous field of view, and by means of a dichroic beam splitter, one can observe two submillimeter wavelengths simultaneously (e.g., 350 + 750 or 450 + 850 μm).

Photometry of pointlike sources (i.e., those that are unresolved) is performed using the central pixels of each array, which are aligned to within an arcsecond of each other. Experience has shown that, for good to moderate seeing conditions, the best photometric accuracy is achieved by averaging the source signal over a slightly larger area than the beam. This is achieved by "jiggling" the secondary

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mirror in a filled-square, 9 point pattern, with a 2″ offset between points. The integration time at each point in a jiggle is 1 s, so the pattern takes 9 s to complete. During the jiggle, the secondary mirror was chopped azimuthally by 60″ at 7 Hz. After the first 9 s jiggle, the telescope was nodded to the reference position (subsequently every 18 s).

Data at 450 and 850 μm were obtained during 1997 June 12 UT; measurements at 350, 450, 750, and 850 μm taken during the commissioning of SCUBA in the period 1997 April–May were also used. In total, 280 minutes were spent on source at 450 and 850 μm and 100 minutes at 350 and 750 μm.

Skydips were performed before, during, and after the target measurements. On 1997 June 12, the atmospheric zenith opacities at 450 and 850 μm were very stable, 0.66 and 0.16, respectively; during the commissioning nights, the zenith opacity was in the range 1.65–1.96 at 350 μm, 0.78–1.05 at 450 μm, 0.51–0.70 at 750 μm, and 0.16–0.21 at 850 μm. The air mass of 8C 1435+635 was between 1.38 and 1.58. Telescope pointing accuracy was checked regularly using 1308+326, Arp 220 and 1418+546, and the largest pointing correction after two slews was 2″9. All data were calibrated against Mars.

Data reduction consisted of taking the measurements from the central bolometer, rejecting spikes, and averaging over 18 s. Data from the adjacent bolometers were treated in a similar manner. Figure 1 shows that the scatter in values measured by the central bolometer is repeated in the average of the adjacent detectors. The signal detected by all the bolometers is clearly dominated by spatially correlated sky emission.

We experimented with several methods of removing the residual sky background, using means and medians of 1 to n rings of " residual sky background " pixels ($n = 1, 2, 3$ at 850 μm). These schemes all gave consistent results. Removing the sky in this way reduced the effective noise-equivalent flux density from 140 to 95 mJy Hz$^{-1/2}$, which is in excellent agreement with our photon noise-based models, suggesting that we have removed the effects of excess sky noise entirely. Figure 2 shows data co-added over the course of several nights, where the standard error integrates down with time
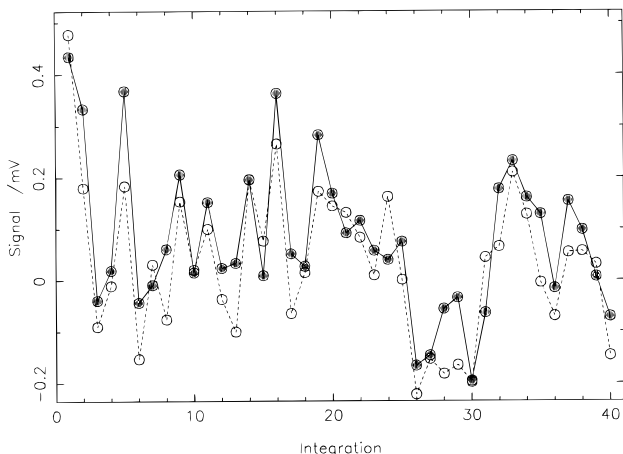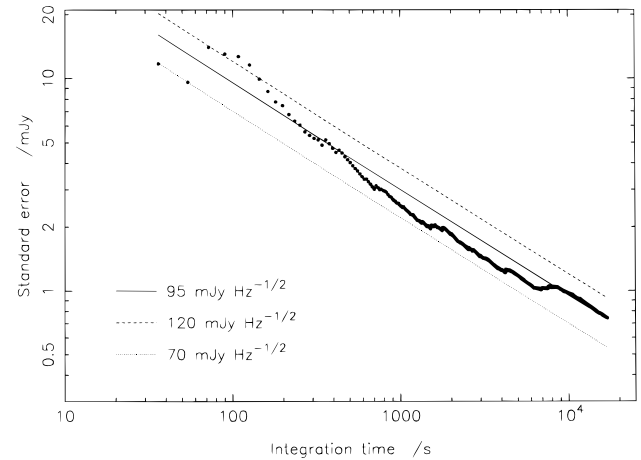

FIG. 2.—Evolution with time of the standard error in 850 μm flux density as measured with SCUBA. The solid line shows the error falling as $95(t/s)^{-1/2}$ mJy, and the data conform to this ideal.

as $95(t/s)^{-1/2}$ mJy during a period of 17,000 s. The measured flux densities are reported in Table 1.

2.3. Mapping at 175 μm with ISO

On 1997 April 13, during orbit 514 of *ISO*[3] (Kessler et al. 1996), we used the far-IR camera PHT (Lemke et al. 1996) to obtain an oversampled map centered on 8C 1435+635. We used the C200 camera (a 2×2 stressed Ge:Ga array with 90″ pixels) and a broadband filter centered at 175 μm to perform a 4×3 raster with 46″ grid spacings. We integrated for 57 s at each point in the grid, and the major axis of the 4′6 × 5′4 map was at a position angle of 108°. The C200 raster was preceded and followed by 32 s calibration scans of an internal photometric standard.

The data were reduced using the PHT Interactive Analysis[4] package (PIA V6.0e), and an upper limit is reported in Table 1. Corrections were made for detector nonlinearity, etc., and the data were extensively deglitched. Data quality was good with consistent calibration scans. Our maps were made using the best available flat-fielding algorithms and calibration information, but forthcoming PIA software may be able to improve upon our reduction.

2.4. CO Measurements from the IRAM 30 m MRT

The galaxy 8C 1435+635 was observed during 1996 August 17–18 using the IRAM 30 m MRT. Two 512 MHz filter banks were used as backends for the 3MM1 and 3MM2 receivers; the central frequency for each receiver was

FIG. 1.—Central SCUBA bolometer signal at 850 μm (*filled symbols*) and the average signal of the adjacent six bolometers (*open symbols*) over the course of 40 18 s integrations during 1997 May 2, clearly showing that the signal is dominated by spatially correlated sky emission. A similar trend was seen at 450 μm.

TABLE 1

PHOTOMETRY OF 8C 1435+635 USING JCMT AND *ISO*

Detector	UT Date 1997	Wavelength (μm)	Flux Density (mJy)
PHT	April 13	175	3 σ < 40.1
SCUBA......	May 12–13	350	3 σ < 87.0
SCUBA......	April–June	450	23.6 ± 6.4
SCUBA......	May 12–13	750	8.74 ± 3.31[a]
SCUBA......	April–June	850	7.77 ± 0.76

[a] 2.64 σ marginal detection; 3 σ < 18.7 mJy.

87.784 GHz, giving coverage over the range $4.237 < z < 4.267$ for the CO (4–3) rotational transition (1700 km s^{-1} of velocity coverage). The 25″ beam was nutated by 120″ in azimuth at a rate of 0.5 Hz, with the telescope position switching by the same distance every 30 s to alternate the signal and reference beams. Altogether, exclusive of overheads, 13.3 hr were spent on source. The atmospheric zenith opacity was normally around 0.1 and T_{sys} was ∼250 and ∼190 K for 3MM1 and 3MM2.

The CLASS reduction package was used to calibrate the spectra on the T_{MB} scale (where 1 K = 4.7 Jy), then to co-add and bin the data into 24 MHz channels (80 km s^{-1}). We found that the noise level in our co-added spectrum decreased steadily with time. The final noise level was 0.3 mK (in line with theoretical expectations). For a Gaussian line profile of width 300 km s^{-1}, we derive a CO line luminosity of 3 $\sigma < 5 \times 10^{10}$ K km s^{-1} pc^2, or, for $M(H_2)/L'_{CO} = 4$ $M_\odot$ (K km s^{-1} pc^2)$^{-1}$ (Evans et al. 1996), $M(H_2, 3\sigma) < 2 \times 10^{11}$ $M_\odot$.

3. RESULTS

The spectral energy distribution (SED) of 8C 1435+635 is shown in Figure 3. A search for CO (1–0) using the Very Large Array (van Ojik et al. 1997) extended the frequency coverage of the radio regime to 22 GHz and shows that the radio spectral index continues to be as steep and negative at 22 GHz as it is between 4.9 and 15 GHz.

Assuming that there is no flatter, high-frequency component, the nonthermal contribution at the wavelengths of SCUBA's submillimeter filters is less than 0.01 mJy. This indicates that we can safely interpret the millimeter to far-IR regime in isolation, and it is immediately clear that this portion of the SED is dominated by emission from dust.

3.1. Dust Properties

Hughes et al. (1997) have shown that the uncertainties in calculating the mass of dust responsible for the thermal,
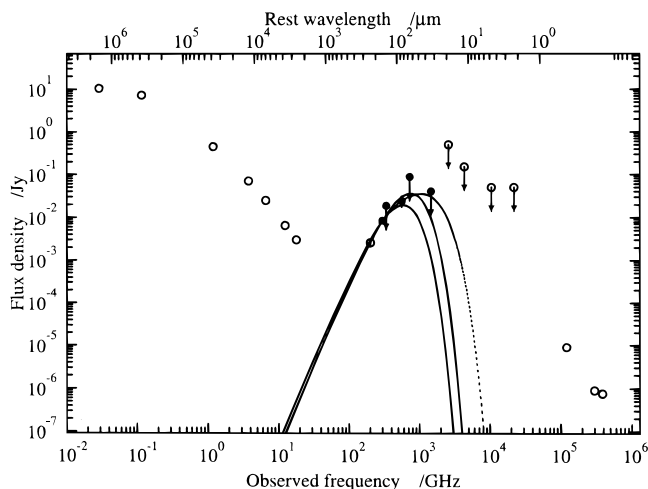
submillimeter emission in high-redshift radio galaxies are the following:

1. Our limited knowledge of the rest-frame mass absorption coefficient k_d and its dependence on frequency
2. The dust temperature, T_d, which has rarely been constrained to better than ±20 K for any high-redshift system, even assuming optically thin dust.
3. The elusive values of H_0 and q_0.

Unfortunately, these problems are sometimes coupled. For example, Hughes et al. (1993) noted that there is a trade-off between T_d and the critical frequency at which the dust becomes optically thick; models with dust that becomes optically thick in the far-IR can support higher temperatures than models with dust that remains optically thin into the mid- or near-IR regimes. This dichotomy is difficult to resolve, even with an SED that is sampled on both the Rayleigh-Jeans and Wien portions of the curve.

Here, we adopt an average value of 0.15 m^2 kg^{-1} for k_d at 800 μm, with $k_d \propto v^\beta$, where β, the frequency dependence of the dust grain emissivity, is +2.0 (the best-fit value). It matters little if we adopt $\beta = +2.0$ or $\beta = +1.5$, though the latter value is difficult to reconcile with the observed spectral index. In both cases our mass estimates are directly comparable to those presented elsewhere (see, e.g., Hughes et al. 1997; Cimatti et al. 1998). To adopt $\beta = +1.5$ would raise our dust temperature estimate by around 10 K, but the dust mass remains within 20% of that deduced for $\beta = +2.0$.

To estimate T_d, we have assumed that the dust is optically thin. Isothermal fits to the data then suggest that $T_d = 40 \pm 5$ K and $\beta = +2.0$ (see Fig. 3). If the true far-IR opacity is significant, for example, if the dust becomes optically thick at 200 μm (as is possibly the case for Arp 220; Emerson et al. 1984), then we could contrive a fit to the data that supports $T_d = 110$ K without compromising the 175 or 450 μm data. Having adopted average dust parameters qualified the validity of our fits and explained the possible sources of error, a dust mass estimate of 2×10^8 $M_\odot$ then follows from equation (2) of Hughes et al. (1997).

Although absolute measurements of dust masses are prone to large errors, if one wants to investigate galactic evolution by comparing the dust masses of high-redshift and low-redshift galaxies (using dust mass as a "galactic clock"; Eales & Edmunds 1996), some of the sources of error are removed. Uncertainties in both H_0 and the mass absorption coefficient are irrelevant as long as the same values are used at low and high redshift. Our dust mass estimate for 8C 1435+635 is much larger than the highest dust mass derived for local spirals by Eales & Edmunds (1996): a factor of 3 if $q_0 = 0.5$ and a factor of 10 if $q_0 = 0$ (local ellipticals have, of course, even lower dust masses). This immediately shows that 8C 1435+635 is nothing like the galaxies in the local universe.

Table 2 lists the CO luminosities and dust masses of 8C 1435+635 and the other high-redshift systems that have been observed to date in CO line and submillimeter continuum. The ratios of CO luminosity to dust mass are quite similar to those of low-redshift galaxies. In the literature this is often claimed as evidence that the gas/dust ratio is the same at high redshifts as at low redshifts. This is not necessarily correct. The metallicity of a galaxy will be a strong function of cosmic time (Edmunds 1990), and so the hydrogen/CO ratio and the hydrogen/dust ratio will undoubtedly change with time (a possibility that we con-

FIG. 3.—SED of 8C 1435+635. *Filled circles*: new data (*filled circles*); *open circles*; older data from Hales et al. 1990, Rees 1990, Lacy et al. 1994, Spinrad et al. 1995, Ivison 1995, Carilli et al. 1997, and van Ojik et al. 1997. Two modified blackbodies (*solid lines*) represent dust at 35 and 45 K ($\beta = +2.0$)—the most extreme temperatures commensurate with the 450 μm flux density for optically thin, isothermal dust. Another modified blackbody (*dotted line*) represents a 110 K, isothermal dust component (also $\beta = +2.0$), still commensurate with the 175–1250 μm SED, but becoming optically thick at 200 μm, demonstrating that the dust properties remain poorly constrained.

TABLE 2

GAS AND DUST PARAMETERS FOR HIGH-REDSHIFT SYSTEMS

Object	L'_{CO} (10^9 K km s^{-1} pc^2)	M_{H_2} (10^9 $M_\odot$)	L_{FIR} (10^{12} $L_\odot$)	M_d (10^6 $M_\odot$)
FSC 10214+4724......	55	25	4.4	105
BR 1202−0725	72	330	65	1530
H1413+117	24	41	11	240
53W002[a]	42	170	12	280
4C 41.17	<65	<310	25	580
8C 1435+635	<50	<200	10	215

NOTE.—Consistent use of $q_0 = 0.5$; $H_0 = 50$ km s^{-1} Mpc^{-1}; Gaussian lines of width 300 km s^{-1}; lensing factors, H1413+117 ($\times 11$); FSC 10214+4724 ($\times 20$). See Ivison et al. 1996, Scoville et al. 1995, 1997, Ohta et al. 1996, and Barvainis et al. 1997.

[a] Marginal submillimeter detection (Hughes et al. 1997).

sider further when estimating the gas mass in § 3.3). The constancy of the gas/dust ratio actually tells us that the ratio of the fraction of metals going into CO to the fraction of metals being bound up in dust is not changing with cosmic time. Although this may not seem a strong statement, it is reassuring that the physics of the interstellar medium (at least in this respect) does not appear to be changing over a large fraction of the age of the universe.

3.2. *Instantaneous Star Formation Rate (SFR)*

The far-IR luminosity, L_{FIR}, suggested by dust with the properties described in § 3.1 is 1.0×10^{13} $L_\odot$. For dust that becomes optically thick in the far-IR, L_{FIR} rises to 2.7×10^{13} $L_\odot$.

If we assume that the energy reemitted by the dust is initially supplied by massive stars rather than by the AGN (the naiveté of this argument is discussed in the following section), L_{FIR} can be used directly to infer the instantaneous SFR. The far-IR luminosity implied by our data suggests a SFR of 2000–5400 $M_\odot$ yr^{-1}, the kind of spectacular burst that could, if sustained, produce 10^{12} $M_\odot$ of stars in less than 0.5 Gyr. This assumes a Salpeter initial mass function spanning 1.6–100 $M_\odot$, i.e., limited to O, B, and A stars. Reducing the lower limit to 0.1 $M_\odot$ *increases* the implied SFR by a factor of 3 (Thronson & Telesco 1986).

In the absence of AGN heating, the ratio of L_{FIR} to L'_{CO} provides some idea of the efficiency with which the available molecular gas is converted into stars. For 8C 1435+635, we find a value greater than 200 $L_\odot$ (K km s^{-1} pc^2)$^{-1}$, higher than that for ultraluminous *IRAS* galaxies (~ 85); indeed, only quasars such as BR 1202−0725 and H1413+117 (450−900) and the radio galaxy 4C 41.17 (>400) rival the efficiency with which 8C 1435+635 apparently converts its gas into stars. Without exception these systems host active nuclei that may well indicate that what we are viewing is related to AGN activity rather than to the birth of their stellar populations.

3.3. *The Gas Mass*

An estimate of SFR, as derived above from the far-IR luminosity, is inevitably of dubious value in an active object such as 8C 1435+635 simply because it is hard to distinguish whether the dust is heated primarily by the AGN or by young massive stars. However, the issue of the heating source is itself arguably of little importance because even if the dust heating could be reliably attributed to young massive stars, an estimate of the instantaneous SFR (however reliable) does not allow one to distinguish between a violent, short-lived starburst and a more sus-

tained burst of star formation in which a significant fraction of the galaxy's eventual stellar mass might be converted into stars.

In practice, therefore, the most useful indicator of the evolutionary status of 8C 1435+635 is an estimate of the mass of gas that, at the epoch of observation, has yet to be processed into stars. A massive reservoir of gas would suggest that the galaxy is extremely young (present-day ellipticals have a large ratio of stellar mass to molecular gas mass, where the latter is typically less than 10^8 $M_\odot$; e.g., Wiklind, Combes, & Henkel 1995; Lees et al. 1991). With the information gleaned from our continuum and spectral line measurements, both of which are the deepest to date, we should be able to discuss the gas mass with more confidence than is usually the case.

Nevertheless, extrapolating from a dust mass to the total mass of baryons in a galaxy that are *not* already locked up in stars at the epoch of observation generally involves three, often rather uncertain, steps. First a value has to be measured or adopted for the ratio of molecular CO gas to dust. Second, a value has to be assumed for the ratio of molecular hydrogen to CO (expected to be a function of galactic metallicity and hence age). Third, to the total mass of H_2 must be added the mass of atomic hydrogen through the adoption of a ratio of H I/H_2. To quantify the combined effect of uncertainties in these three steps, we have chosen to calculate what can safely be regarded as rather robust lower and upper limits to the total baryonic gas mass of 8C 1435+635 by first adopting the highest reasonable values for *all three* relevant ratios, and then adopting the lowest reasonable values.

3.3.1. *Upper Limit on Total Baryonic Gas Mass*

The highest reasonable value for the ratio of CO to dust in 8C 1435+635 is constrained by our own failure to detect CO emission. Using the normal Galactic calibration of L'_{CO}/M_{H_2}, our nondetection corresponds to a molecular gas/dust ratio of $M_{H_2}/M_d < 950$. This limit seems entirely consistent with observations of other high-redshift galaxies where CO has actually been detected; observations of the lensed quasars BR 1202−0725, FSC 10214+4724, and H1413+117 (Ohta et al. 1996; Omont et al. 1996; Scoville et al. 1995; Barvainis et al. 1997) and the $z = 2.39$ radio galaxy 53W002 (Scoville et al. 1997; Hughes et al. 1997) yield values in the range $M_{H_2}/M_d = 170$–600, after correcting to our adopted cosmology (see Table 2).

We must then ask how reasonable it is to apply the Galactic calibration to a galaxy at $z > 4$, particularly since metallicity is expected to increase with age in most reason-

able models of the chemical evolution of galaxies. It is at present impossible to test this directly, but we can gain some confidence that the ratio of M_{H_2}/M_d in 8C 1435+635 is indeed very unlikely to significantly exceed 1000 from observations of Lyman α absorbers. Studies of damped Lyman-α absorption systems suggest $M_{H_2}/M_d = 400$–2000 (Fall, Pei, & McMahon 1989; Wolfe 1993), and we can be confident that 8C 1435+635 is a more highly evolved system than damped Lyman absorbers, the supposed progenitors of disk galaxies, since 8C 1435+635 is already more luminous than an L^* galaxy in starlight. We therefore adopt $M_{H_2}/M_d = 1000$, and hence $M_{H_2} = 2 \times 10^{11}$ $M_\odot$ as an upper limit to the molecular gas mass of 8C 1435+635. We thus simply sidestep the issue of whether this gas mass arises from a CO luminosity close to our limit coupled with a near-Galactic calibration, or whether the CO luminosity is much lower and a low-metallicity calibration might apply.

Last, to produce an upper limit on total baryonic gas mass, we must adopt a generous value for the ratio M_{HI}/M_{H_2}. Barvainis et al. (1997) found $M_{HI}/M_{H_2} \sim 4$ for H1413+117, although this may have been affected by differential lensing; Andreani, Casoli, & Mirabel (1995) found $M_{HI}/M_{H_2} \sim 2$ for *IRAS* galaxies; Wiklind et al. (1995) found $M_{HI}/M_{H_2} \sim 5$ for far-IR selected elliptical galaxies, whereas Lees et al. (1991) found $M_{HI}/M_{H_2} = 1.0 \pm 0.9$). For our present purpose we therefore adopt the largest of these values ($M_{HI}/M_{H_2} \sim 5$) and hence arrive at a robust upper limit of $M_g = 1.2 \times 10^{12}$ $M_\odot$ for 8C 1435+635 within our adopted cosmology (the effect of varying cosmology is discussed in § 4).

3.3.2. *Lower Limit on Total Baryonic Gas Mass*

We now proceed, in an analogous way, to calculate a highly conservative value for the total gas mass in 8C 1435+635. Models of galactic evolution suggest that metallicity should increase with time, and that the gas/dust ratio should decrease accordingly (Edmunds 1990). If we take the gas/dust ratio appropriate for present-day galaxies, we should therefore obtain a firm lower limit for the true gas content of 8C 1435+635.

Estimates of the gas/dust ratio in the local universe range from $100-150$ for the Milky Way to ~ 1080 for some nearby galaxies (usually where only the warm dust has been sampled; Devereux & Young 1990). So we adopt $M_{H_2}/M_d = 100$ (accepting the Galactic calibration for $L'_{CO}/M(H_2)$ to deduce $M_{H_2} = 2 \times 10^{10}$ $M_\odot$ as an firm lower limit to the molecular gas mass of 8C 1435+635.

Finally, we apply the lowest of the reported values for M_{HI}/M_{H_2} discussed above (i.e., $M_{HI}/M_{H_2} = 1$) to arrive at a robust lower limit of $M_{gas} = 4 \times 10^{10}$ $M_\odot$ for 8C 1435+635 within our adopted cosmology.

4. DISCUSSION: 8C 1435+635 AND 4C 41.17: PRIMEVAL ELLIPTICALS OR VIOLENT MERGERS?

What then can we conclude from our basic result that 8C 1435+635 contains between 4×10^{10} and 1.2×10^{12} $M_\odot$ of material, which has yet to be turned into stars at the epoch of observation corresponding to $z \simeq 4$? One important and *model-independent* point is that our new observations have largely served to confirm the similarity between the submillimeter properties of 8C 1435+635 and 4C 41.17, despite differences between their optical morphologies, surface brightnesses, colors, and spectra. The fact that

these two objects, both at $z \simeq 4$ and both with comparably extreme radio luminosities, should both appear to contain a few times 10^{11} $M_\odot$ of gas must be telling us something rather basic.

In simple terms, the extreme far-IR luminosities and dust and gas masses of these two sources must either be a result of their extreme redshift or associated in some way with their extreme radio luminosities. Observations of larger samples of sources spanning a range in redshift and in radio luminosity will be required to answer this question, but it is interesting to consider briefly the implications of either option.

If these extreme submillimeter properties are primarily due to redshift, this would imply that all massive ellipticals at $z \simeq 4$ could still be in the process of forming a significant fraction of their eventual stellar populations. Indeed, if it is assumed that the present-day counterpart of 8C 1435+635 is a very massive elliptical galaxy with a stellar mass of $\sim 10^{12}$ $M_\odot$, the upper end of our derived range of gas masses is consistent with a picture in which, at the epoch of observation, 8C 1435+635 has yet to form the *vast majority* of its eventual stellar population. This possibility gains further credence from the fact that our derived dust mass has arguably been minimized to a certain extent by the assumption of an Einstein–de Sitter universe. In a low-density universe, the derived masses increase by up to a factor of 4, in which case even our lower limit on the gas mass rises to 2×10^{11} $M_\odot$, thus making it difficult to argue against the conclusion that 8C 1435+635 is rather young. Would such a conclusion be consistent with the recent discovery that the dominant stellar population in at least some (and arguably all) radio galaxies is already more than 3 Gyr old by $z \simeq 1.5$ (Dunlop et al. 1996; Spinrad et al. 1997)? The answer is yes, and indeed there is an interesting (if somewhat frustrating) degeneracy at work here: reducing q_0 to the point where it is hard to escape the conclusion that 8C 1435+635 and 4C 41.17 contain an entire galaxy's worth of gas also stretches the cosmological timescale, allowing 3 Gyr to elapse between $z = 4$ and 1.5, in which case the epoch of spectacular submillimeter emission from young elliptical galaxies would indeed be expected to correspond to $z \geq 4$.

If our derived lower limit on the gas mass of 4×10^{10} $M_\odot$ is in fact closer to the truth, then we would seem to be forced back toward the conclusion that we are witnessing either (1) the tail end of the formation process of massive ellipticals or (2) a new injection of gas/dust from an interaction which we see heated by the AGN or by a violent interaction-induced starburst in what could be an otherwise well-evolved underlying galaxy whose stars were formed at still higher redshift. The latter option seems completely plausible because, while the ages of radio sources and their host galaxies appear to be completely decoupled (differing by two orders of magnitude at the present day), the fact that global radio-source activity seems to trace the cosmic star formation history of the universe (Dunlop 1997) suggests that both radio sources and starbursts are fueled in a fundamentally similar way, perhaps through galaxy-galaxy interactions. In this context it would perhaps not be too surprising if the massive fuel supplies required to power the ultraluminous radio sources 8C 1435+635 and 4C 41.17 also inevitably resulted in an associated massive burst of star formation activity. Of course in a hierarchical picture of galaxy formation, the distinction between a massive merger

and the final stages of galaxy formation might be viewed as rather artificial.

5. CONCLUSION

While uncertainties beyond the scope of this work (e.g., the value of q_0 and the metallicity of high-redshift radio galaxies) mean that the precise interpretation of the large mass of dust residing in 8C 1435+635 remains ambiguous, we have demonstrated the power of SCUBA to constrain the properties of dust in galaxies at $z > 4$. The radio galaxies 8C 1435+635 and 4C 41.17 are undeniably extreme objects, but their very similar dust and gas masses mean that they can certainly serve as useful benchmarks for future submillimeter studies of high-redshift galaxies. Thus, while at present we cannot determine whether the spectacular far-IR properties of 8C 1435+635 and 4C 41.17 are primarily due to their extreme redshifts or to their extreme radio luminosities, the quality of our SCUBA data provides encouragement that submillimeter observations of complete samples of radio galaxies, spanning a range of redshifts and radio luminosities, should be able to settle this issue in the near future. Perhaps most exciting of all, our observations of 8C 1435+635 serve to reemphasize that if most massive ellipticals do indeed form in comparably spectacular starbursts, such objects will be easily detected by the first submillimeter surveys of blank fields, even out to $z \simeq 10$.

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