A COMPACT STARBURST CORE IN THE DUSTY LYMAN BREAK GALAXY WESTPHAL-MD111

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ABSTRACT

Using the IRAM Plateau de Bure Interferometer, we have searched for CO (3–2) emission from the dusty Lyman break galaxy Westphal-MD11 at $z = 2.98$. Our sensitive upper limit is surprisingly low relative to the system’s $850\,\mu m$ flux density and implies a far-IR/CO luminosity ratio as elevated as those seen in local ultraluminous mergers. We conclude that the observed dust emission must originate in a compact structure radiating near its blackbody limit and that a relatively modest molecular gas reservoir must be fueling an intense nuclear starburst (and/or deeply buried active nucleus) that may have been triggered by a major merger. In this regard, Westphal-MD11 contrasts strikingly with the lensed Lyman break galaxy MS 1512–cB58, which is being observed apparently midway through an extended episode of more quiescent disk star formation.

Subject headings: cosmology: observations — galaxies: ISM — galaxies: starburst

1. INTRODUCTION

Among $z \geq 2$ source populations, Lyman break galaxies (LBGs) dominate in sheer numbers of objects with spectroscopic redshifts (Steidel et al. 1999, 2003; Lehnert & Bremer 2003). As a result, they define a natural test set for galaxy evolution models (e.g., Baugh et al. 1998; Mo et al. 1999; Somerville et al. 2001). Different authors have reached different conclusions about the nature of star formation in LBGs. The population’s strong bias relative to the underlying dark matter fluctuations (Giavalisco et al. 1998; Adeleberger et al. 1998; Arnouts et al. 1999), at a level apparently correlated with rest-UV luminosity (Giavalisco & Dickinson 2001; Foucaud et al. 2003), argues that LBGs are forming spheroids at the centers of the most massive $z \sim 3$ halos. In contrast, a high close pair fraction suggests that the most massive halos host more than one LBG (Wechsler et al. 2001; Bullock et al. 2002), supporting scenarios in which LBG starbursts are brief and merger-driven (Lowenthal et al. 1997; Kolatt et al. 1999; Somerville et al. 2001). Because the star formation histories in these two pictures differ starkly, it is of great interest to establish observationally how LBG’s star formation rates, stellar population ages, stellar and gas masses, and dynamical timescales relate to each other. In particular, fully understanding star formation in LBGs requires characterizing the molecular gas from which their stars form; this motivates searches for CO line emission in at least a few representative systems.

The logical first target for such an effort was the gravitationally lensed system MS 1512–cB58 (hereafter cB58), the brightest LBG known. Baker et al. (2004, hereafter B04) succeeded in detecting cB58’s CO (3–2) emission after probing to greater depths than were reached by two previously published nondetections. As a second target, we chose Westphal-MD111 (hereafter WMD11), the dustiest LBG known. This $z = 2.98$ system was the strongest $850\,\mu m$ source in the Submillimeter Common-User Bolometer Array (SCUBA) survey of Chapman et al. (2000) and was revealed in high-resolution Hubble Space Telescope (HST) and Keck imaging to be a composite system including one extremely red object (ERO) component, two bluer ones, and a web of diffuse blue emission (Chapman et al. 2002). Since WMD11’s $S_{850}$ resembled that observed for cB58 (van der Werf et al. 2001), we reasoned that the two galaxies’ CO emission lines should also be comparably strong. Instead, we report an upper limit on WMD11’s CO (3–2) emission based on sensitive millimeter interferometry. This Letter assumes $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$ throughout.

2. DATA ACQUISITION AND REDUCTION

We observed WMD11 with the IRAM Plateau de Bure Interferometer (PdBI; Guilloteau et al. 1992) from 2003 April through September. The array included four to six 15 m diameter antennas; during our observations, these were arranged in variations on a compact D configuration with baselines ranging from 24 to 113 m. The 3 mm receiver on each antenna was tuned in single-sideband mode, giving typical system temperatures of 100–200 K in the lower sideband relative to the reference. To observe WMD11, we adopted as a pointing center the position $(a_2000=14^h18^m09^s76, \, \delta_2000=+52^\circ22'01.7')$ listed by Steidel et al. (2003) and used for the SCUBA observations of Chapman et al. (2000). For the $\nu_{1100} = 2.9816$ reported by Pettini et al. (2001), the CO (3–2) rotational transition is redshifted to 86.85 GHz. We deployed four correlator modules at this frequency, giving a total of 560 MHz ($1933\, km\, s^{-1}$) of contiguous bandwidth at 2.5 MHz ($8.6\, km\, s^{-1}$) resolution. Although we also tuned each antenna’s 1 mm receiver for simultaneous 242 GHz observations of thermal dust emission, the summer weather conditions caused prohibitively high phase noise and prevented us from using these data.

We calibrated the data using the CLIC routines in the GILDAS package (Guilloteau & Lucas 2000). Phase and amplitude variations within each track were removed by interleaving observations of the quasar J1419+543 (2$\sigma$ from WMD11 on the sky) every 30 minutes. Passband calibration used one of several bright quasars. The flux scale for each epoch was set by comparing J1419+543 with the passband calibrators and model sources CRL 618 and MWC 349, whose flux densities are regularly
monitored at the PdBI and IRAM 30 m. From the variance of multiple measurements, we estimate the accuracy of our final flux scale to be ∼15%. Before constructing ν tables from our calibrated data, we smoothed them to 5 MHz (i.e., 17.2 km s⁻¹) resolution. After editing for quality, we were left with the (on-source, six-telescope array) equivalent of 42 hr of data. We inverted the data cube without deconvolution using the IMAGR task in the NRAO AIPS package (van Moorsel et al. 1996). With natural weighting, the synthesized beam is 8.6 × 5.9″ at a position angle of 61°; the noise level per channel is 0.7 mJy beam⁻¹ across most of the bandpass before rising slightly at the high-velocity (low-frequency) end.

After we had already acquired the PdBI data, we learned (N. Reddy 2004, private communication) that a comprehensive registration of radio, optical, and X-ray sources in the Westphal field implies a true position for WMD11 some 2.5° northeast of its published coordinates (at α2000 = 14°18′09″78, δ2000 = +52°22′03″76). This offset implies—pointing errors aside—that for the 14.7 half-power beamwidth of SCUBA at 850 μm, the S₈₅₀ = 5.5 ± 1.4 mJy reported by Chapman et al. (2000) should translate to S₈₅₀ = 5.9 ± 1.4 mJy at the actual position of the LBG. The offset also means that any CO (3–2) emission from WMD11 should not lie at the PdBI phase center.

With cursory inspection showing no strong source, we searched for line emission by convolving the 17.2 km s⁻¹ cube with seven- and 16-channel boxcars. The resulting cubes have nearest neighbors by 10.4 km s⁻¹ and searched for companions within ∼10″ of the PdBI phase center (beyond this radius, a source would have to be unrealistically bright to have produced 5.5 mJy at the SCUBA pointing center). In each smoothed cube, the strongest candidate companion has less than 3.8σ significance, lies near a bowl of comparable (negative) significance, and lacks an optical counterpart when the pipeline-reduced HST imaging of Chapman et al. (2002) is reexamined. In most cases, the implied F_CO(3–2)/S₈₅₀ is even lower than 29 km s⁻¹ owing to the larger correction that must be made to S₈₅₀ for a “source” farther from the phase center. We do not view any of these candidates as real. It remains possible that a dusty companion lies close enough on the sky to WMD11 to yield a strong 850 μm detection but far enough away in velocity to escape our PdBI bandpass. However, this scenario is dismaying ad hoc, in that it diverts a high dust luminosity—at a level attained only by galaxy mergers in the local universe—from a system with a clear merger morphology.

It remains to explain how WMD11 can generate a large dust luminosity from a small reservoir of molecular gas. Exactly how much of a challenge this is depends on the value of the galaxy’s IR luminosity, which we can calculate from its 850 μm (~213.5 μm rest frame) flux density and the assumption of an opacity-weighted blackbody spectral energy distribution (SED),

\[ S_ν = B_ν(T_d, β, ν_0) = B_ν(T_d)[1 - \exp \{-ν(ν_0)^β\}] \]  

Here \( T_d \) is the dust temperature and \( ν_0 \) is the rest frequency at which the dust opacity is unity. We will (for now) neglect any contribution from hotter dust at wavelengths below the blackbody peak, making the frequency integral of this \( S_ν \), a conservative lower limit on \( L_ν \). Combined with our upper limit on CO (3–2) emission, a given choice of \( (T_d, β, ν_0) \) then gives us a conservative lower limit on the ratio \( L_ν/L_CO(3–2) \). For a particular \( T_d \) however, this ratio also has a firm upper limit. In the molecular interstellar medium of normal galaxies, a CO emission line will be optically thick at some brightness temperature \( T_b \) (less than the gas kinetic temperature \( T_{kin} \) as a result of subthermal excitation), while dust with \( T_d > T_b \) produces far-IR continuum emission that is optically thin. As density and column density increase, \( L_CO \) will rise as the CO transition is thermalized (i.e., \( T_d \rightarrow T_{kin} \)), but \( L_ν \) will rise much more dramatically as the dust emission becomes optically thick. The upper limit on \( L_ν/L_CO \) is reached when both dust and gas are

\[ \frac{S_ν(T_d, β, ν_0)}{S_ν(T_d, β, ν_0)} = B_ν(T_d)[1 - \exp \{-ν(ν_0)^β\}] \]  

This gives a conservative upper limit to the velocity width of CO (3–2) emission from WMD11: the data of Murphy et al. (2001) imply a mean |ν_CO/ν_0| = 1.1, while the data of Armus et al. (1989) for a smaller ULIRG sample give |ν_CO/ν_0| = 0.9. We would posit that the dust emission seen by Chapman et al. (2000) comes from a highly obscured companion or background galaxy rather than from WMD11 itself. Small et al. (2002) show the surface density of SMGs with \( S_{ν>5} \geq 5 \) mJy to be \( 800 \pm 50 \) deg⁻²; we might then expect the original survey of 16 LBG fields by Chapman et al. (2000) to have turned up 0.3–1 sources in this brightness regime at random. While such odds are not negligible, WMD11’s unusually red \( R - K \) color (Shapley et al. 2001), together with the systematic dependence of 1.2 mm flux density on this color in a larger LBG sample (A. Baker et al. 2004, in preparation), suggests that some association of the 850 μm source with the rest-UV/optical counterpart is reasonable.
radiating as blackbodies with \( T_d = T_b \). Solomon et al. (1997) have shown that this “blackbody [upper] limit” is

\[
\frac{L_{\text{IR}}}{L_{\odot}} \left( \frac{L_{\text{CO}}}{\text{K km s}^{-1} \text{ pc}^{-2}} \right)^{-1} \leq 231 \left( \frac{T_d}{50 \text{ K}} \right)^3 \left( \frac{\Delta \nu_{\text{CO}}}{300 \text{ km s}^{-1}} \right)^{-1}
\]

and that local ULIRGs fall only a factor of \( \sim 3 \) below it.

For WMD11, the observed 850 \( \mu \text{m} \) flux density and upper limit(s) on CO (3–2) emission are only compatible with the upper limit on \( L_{\text{IR}}/L_{\text{CO}} \) imposed by equation (2) for a severely limited range of SEDs. For \( \Delta \nu_{\text{CO}} = 121 \) (276) \text{ km s}^{-1}, dust temperatures \( T_d \leq 60 \) (60) K are excluded at once because the blackbody limit they impose is simply too stringent. More generally, we require a quite small value of \( \nu_c \) for any choice of \( T_d \) and \( \beta \) if we are to suppress \( L_{\text{IR}} \) relative to \( L_{\text{CO}} \). Figure 1 shows the dependence of \( c/\nu_c \) as a function of \( T_d \), \( \beta \), and \( \Delta \nu_{\text{CO}} \) if WMD11 exactly satisfies the blackbody limit. For \( \Delta \nu_{\text{CO}} = 121 \) \text{ km s}^{-1}, \( T_d \leq 60 \) K and \( \beta \geq 1.5 \) will produce dust emission that is optically thick at rest wavelengths \( \lesssim 213.5 \) \( \mu \text{m} \).

Given that local ULIRGs do not themselves reach equality in equation (2), this conclusion should hold robustly for most plausible \((T_d, \beta)\). For \( \Delta \nu_{\text{CO}} = 276 \) \text{ km s}^{-1}, dust emission at rest wavelength 213.5 \( \mu \text{m} \) will be optically thick for any SED.

If WMD11’s observed 850 \( \mu \text{m} \) emission is indeed optically thick, we can estimate the characteristic size of the emitting region (assuming a spherical geometry) as

\[
R_d = 303 \left( \frac{L_{\text{IR}}}{10^{12} L_{\odot}} \right)^{0.5} \left( \frac{T_d}{50 \text{ K}} \right)^{-2} \text{ pc}
\]

For a fiducial \((T_d, \beta, \nu_c) = (70 \text{ K}, 1.5, 1 \text{ THz})\), WMD11’s \( S_{850} \) translates to \( L_{\text{IR}} = (6.0 \pm 1.4) \times 10^{12} h_{0.5}^2 L_{\odot} \) and thus to a radius \( R_d \approx 380 h_{0.7}^{-1} \text{ pc} \). Assuming \( T_d = 40 \) and 90 K yields \( R_d \approx 610 \) and 320 \( h_{0.7}^{-1} \text{ pc} \), respectively (although recall that \( T_d \leq 60 \) K is incompatible with \( \Delta \nu_{\text{CO}} \approx 276 \text{ km s}^{-1} \)). Such radii are comparable to the sizes of molecular gas disks in local ULIRGs (Downes & Solomon 1998; Bryant & Scoville 1999). Indeed, the same logic works in reverse: Solomon et al. (1997) point to the compact molecular gas structures in ULIRGs as evidence for high optical depths, which they use in turn to explain these systems’ high \( L_{\text{IR}}/L_{\text{CO}} \) ratios.

Our conclusion that the dust source in WMD11 is both optically thick to long rest wavelengths and spatially compact is independent of whether its \( L_{\text{IR}} \) is powered by star formation or accretion. Given the lack of evidence for an active galactic nucleus (AGN) in either optical spectroscopy or radio continuum mapping of WMD11 (Chapman et al. 2002), a compact starburst seems more likely. However, the cautionary example of the \( z = 3.09 \) Ly\( \alpha \) nebula detected at 850 \( \mu \text{m} \) by Chapman et al. (2001), for which accretion remains one of the few plausible sources of ionizing photons (Chapman et al. 2004), suggests a deeply embedded AGN should not be excluded for WMD11 either.

4. LBGs have diverse modes of star formation

Given WMD11’s morphological resemblance to an early-stage galaxy merger and its large IR luminosity, we estimate its molecular gas mass using the \( M_{\text{gas}}/L_{\text{CO}} \) conversion factor appropriate for local ULIRGs. Downes & Solomon (1998) suggest that this should be lower than the Galactic value and \( \approx 0.8 M_{\odot} \text{ (K km s}^{-1} \text{ pc}^{-2})^{-1} \), which for \( \Delta \nu_{\text{CO}} = 121 \) (276) \text{ km s}^{-1} gives WMD11 a molecular gas mass of \( \lesssim 3.9 (5.9) \times 10^9 h_{0.7}^2 M_{\odot} \) (including helium) that could plausibly have originated in a single progenitor spiral (Helfer et al. 2003). WMD11’s ERO component may be the remnant of a second, older spheroid progenitor: Chapman et al. (2002) note that if all of its redness (\( R_{177} - K_s = 6.15 \)) is attributed to extinction, the system’s total 850 \( \mu \text{m} \) flux density would be overpredicted by a substantial factor.

To estimate WMD11’s star formation rate, we calculate its total (8–1000 \( \mu \text{m} \) \( L_{\text{IR}} \)) by smoothly grafting a short-wavelength power law \( S_{\nu} \propto \nu^{-0.7} \) (Blain et al. 2002) onto the fiducial SED used in § 3. This step properly includes emission from hotter dust. For \( \Delta \nu_{\text{CO}} = 121 \text{ km s}^{-1} \), we begin with \( T_d = 50 \) K and obtain \( L_{\text{IR}} = (4.0 \pm 0.9) \times 10^{12} h_{0.7}^2 L_{\odot} \), which for a 1–100 \( M_{\odot} \) Salpeter (1955) initial mass function (IMF) corresponds to a star formation rate of \( 330 \pm 80 h_{0.7}^2 M_{\odot} \text{ yr}^{-1} \) (Kennicutt 1998). For \( \Delta \nu_{\text{CO}} = 276 \text{ km s}^{-1} \), we must adopt a higher \( T_d = 70 \) K, which gives \( L_{\text{IR}} = (8.5 \pm 2.0) \times 10^{12} h_{0.7}^2 L_{\odot} \) and a star formation rate (710 \pm 170) \( h_{0.7}^2 M_{\odot} \text{ yr}^{-1} \). Pettini et al. (2001) estimate (for the same IMF) that the star formation rate in WMD11 is \( 8 h_{0.7}^2 M_{\odot} \text{ yr}^{-1} \) from H\( \beta \) line and rest-UV continuum fluxes before correction of either for extinction. In hindsight, the agreement between those estimates does not point to a low global dust obscuration but to a complex geometry in which blue star-forming patches are scattered about the periphery of a dusty starburst core. Such configurations are also seen locally: local ULIRGs can have quite blue UV colors that conceal their true degree of obscuration (Goldader et al. 2002), while the most massive molecular gas concentrations and intense star formation can occur off the optically bright nuclei in nearby mergers like the Antennae (Vigroux et al. 1996; Wilson et al. 2000).

The ratio of the molecular gas mass and star formation rate in WMD11 nominally limits the gas exhaustion timescale to a short \( t_{\text{gas}} \lesssim 10 \) Myr, modulo large uncertainties in SED and \( \Delta \nu_{\text{CO}} \). An instructive contrast can be drawn with cB85, which is forming stars according to a Schmidt (1959) law with a much longer \( t_{\text{gas}} \sim 240 \) Myr comparable to its most likely age for past star formation (B04). Differing modes of star formation
in these two LBGs naturally explain why we are apparently catching WMD11 closer to the endpoint of its evolution than cB58. In a major merger, gas from the progenitor galaxies will be rapidly dumped into the system’s center of mass or ejected through tidal tails (from which infall and ensuing star formation will be slow). Since the central starburst will shut off abruptly as soon as the central gas concentration has been consumed or expelled by a wind, we might expect that if WMD11 is a major merger, we should indeed be catching it near the end of a brief burst. For more quiescent star formation in a disk, an extended H i reservoir would be capable of refilling a molecular gas reservoir at smaller radii. We would therefore expect that LBGs like cB58, in which star formation has a less violent trigger, would tend to be observed in the middle of a star formation episode without a sharply defined end. With this new evidence that LBGs can have quite different modes of star formation, it is clear that understanding the distribution of such modes across the full LBG population will be important in constraining these systems’ contributions to the cosmic histories of star formation and mass assembly.

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