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Non-thermal mm-continuum emission from the radio galaxy B2 0902+343, and non-detection of CO(4–3)

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Abstract. We detected the 2.9-mm nonthermal continuum emission from the z = 3.4 radio galaxy B2 0902+343 at a level of 4.2 ± 0.6 mJy with the IRAM interferometer. The millimeter continuum source is unresolved with our 2.4″ beam, and its position agrees with the unresolved nuclear component on centimeter-wavelength VLA maps. There is no evidence for any excess due to dust emission above the non-thermal continuum spectrum to a limit of 0.6 mJy, corresponding to an upper limit of 2×10^7 $M_\odot$ on the mass of 60 K dust. The interferometer data show no evidence for any CO(4–3) line in the range z = 3.396–3.402, to 2 mJy in 100 km s^{-1} channels. A search with the IRAM 30 m telescope for CO(4–3) in the same redshift range also gave a non-detection to 2 mJy. This limit is one-tenth the peak CO(3–2) line intensity of IRAS 10214+4724, and is about the line flux expected from ultraluminous IR galaxies at z = 3.4.

Key words: galaxies: individual: (B2 0902+343) – galaxies: interstellar matter – galaxies: nuclei – cosmology: observations – radio lines: galaxies – readio continuum: galaxies

1. Introduction

In the past two years, the radio galaxy B2 0902+343 at z = 3.40 has been searched for redshifted CO at several millimeter observatories. This interest was spawned by suggestions that high-z radio galaxies might have large amounts of gas, by the detection of H I absorption (Uson et al. Cornwell 1991; Briggs et al. 1993), by the recognition of the galaxy's blue spectral energy distribution and the detection of strong Lyman alpha and [O III] emission (Eisenhardt & Dickinson 1992; Eales & Rawlings 1993; Eales et al. 1993), as well as C IV and He II emission (Martín-Mirones et al. 1995). While the blue spectral energy distribution is consistent with B2 0902+343 being a young galaxy, the strong Lyman alpha and [O III] emission from active galaxies can arise from an AGN, or a starburst, or both.

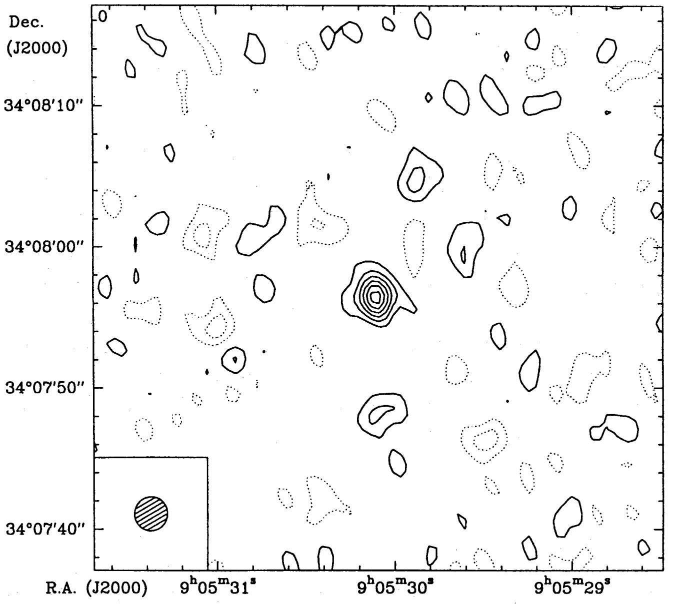

Fig. 1. Map of continuum emission from B2 0902+343 at 105 GHz. The half-power size of the 2.4″ × 2.3" beam is shown at lower left. Contour interval is 0.5 mJy = 1.7 σ. The zero contour is omitted

We report here high-sensitivity interferometer observations at 3 mm that show the galaxy has no molecular gas that is easily detectable with the current generation of millimeter telescopes. The central region of the galaxy may thus be relatively free of dust and molecular gas, thereby allowing its radio jets and non-thermal UV photons to escape to great distances.

2. Observations

The observations were made with the IRAM interferometer on Plateau de Bure, France in November 1994. The four 15 m antennas were used in two configurations giving a total of 12 baselines ranging from 24 to 288 m, and a synthesized beam of 2.4″ × 2.3″. The SIS receivers were tuned to optimize lower

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Table 1. Observations of B2 0902+343 with the IRAM interferometer

Continuum :		
mm-continuum position (J2000; $\pm 0.2''$)	$09^h05^m30.11^s$	$+34°07'56.5''$
mm-continuum position (1950)	$09^h02^m24.78^s$	$+34°19'57.2''$
VLA cm component N position (B1950)	$09^h02^m24.80^s$	$+34°19'56.8''$
mm position minus VLA	$\Delta\alpha = -0.2''$,	$\Delta\delta = +0.4''$
mm-continuum size (FWHM)	$< 0.4''$	
105 GHz continuum flux density	4.2 ± 0.6 mJy	
mm spectral index ($S \sim \nu^{\alpha}$)	-0.3 ± 0.1	
1.3 mm dust excess above nonthermal flux	< 0.6 mJy	
Mass of dust at $T_d = 60$ K	$< 2 \times 10^7$ $M_{\odot}$	
Line search:		
CO(4–3) frequencies searched	104762 ± 250 MHz	
CO(4–3) redshifts searched	3.396 to 3.402	
CO(4–3) peak flux	< 2 mJy	
CO(4–3) flux, $S\,\Delta V$, over 200 km s^{-1}	< 0.4 Jy km s^{-1}	
CO luminosity, $L'_{\rm CO}$(obs)	$< 4 \times 10^9$ K km s^{-1} pc^2	
H$_2$ mass, if $L'_{\rm CO}(4\text{–}3) = L'_{\rm CO}(1\text{–}0)$	$< 2 \times 10^{10}$ $M_{\odot}$	

Notes: VLA position from Carilli (1995); $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$; luminosity distance, $D_L = (1+z)^2\, D_A = 18.4$ Gpc ($1'' = 4.6$ kpc).

sideband operation, and had typical receiver temperatures of 70 to 90 K SSB at 105 GHz. Typical system temperatures, in T_{a*} units, were 165 to 250 K SSB. The spectral line correlator covered 1430 km s^{-1}, centered on 104.762 GHz ($z = 3.40085$ for CO(4–3)). We smoothed the line data to various resolutions from 50 to 290 km s^{-1}. Amplitudes and phases were calibrated with the 4.2 Jy source 0923+32, whose flux was measured with the IRAM 30 m telescope in September – December 1994. The r.m.s. noise was 0.32 mJy in the 500 MHz wide continuum map, 0.8 mJy in 290 km s^{-1} channel maps, and 1.25 mJy in 100 km s^{-1} channel maps.

3. The radio continuum source

The broad band 105 GHz map (Fig. 1) shows a continuum source that is unresolved with the 2.4″ beam. Fits to the interferometer visibilities gave a size $< 0.4''$. The source has a flux density of 4.2 ± 0.6 mJy in agreement with the 105 GHz value of 4.8 ± 0.3 mJy measured by Yun & Scoville (1995) with a beam of $5.4'' \times 4.5''$. The position of the continuum source (Table 1) is the same as the nucleus of the galaxy detected at centimeter wavelengths (Carilli 1995). The 0.4″ (2σ) difference in Dec. between the mm position and the VLA cm-wave position is not significant, given the weakness of the source at 105 GHz.

The radio spectrum of B2 0932+343 (Fig. 2) shows that only the nucleus (component N of Carilli et al. 1994) contributes at millimeter wavelengths. The measured mm and cm fluxes fit a power law with a non-thermal spectral index -0.3 ± 0.1. The flux at 105 GHz and that measured by Chini & Krügel (1994) at 230 GHz both fall right on the flat power-law spectrum of component N's non-thermal radio emission, so there is no evidence for any thermal emission by dust. From the spectrum (Fig. 2), we estimate the upper limit on the thermal dust flux at 230 GHz to be 0.6 mJy. We assume the dust emitting in the rest-frame sub-mm region is optically thin and at a temperature of 60 K, as in the ultraluminous IR galaxies (Solomon et al. 1996). We also assume the dust absorption coefficient κ_d at 1012 GHz (= $(1+z) \times 230$ GHz) is 7.7 cm^2 per gram of *dust*, where we have scaled $\kappa_d \propto \nu^2$ from the values of Krügel & Chini (1994; their Sect. 4.1.1). With these assumptions, the dust flux limit of 0.6 mJy corresponds to an upper limit on the dust mass[1] of 2×10^7 $M_{\odot}$.

4. CO searches

Figure 3 shows the 290 km s^{-1} channel maps from the interferometer in the central 40″ region of the galaxy, after the 4.2 mJy continuum source has been subtracted. Figure 4 shows interferometer spectra with 100 km s^{-1} resolution, on and off the position of the continuum source. Within the noise, there is no evidence for any CO line above the continuum, in either the 100 km s^{-1} spectra or the 290 km s^{-1} channel maps. At the position of the continuum source, a conservative upper limit to a line with 150–200 km s^{-1} linewidth is 2 mJy, or an integrated line flux < 0.4 Jy km s^{-1} over 200 km s^{-1}.

B2 0902+343 was also searched for the CO(4–3) line with the IRAM 30 m telescope on Pico Veleta, near Granada, Spain, in June, August, and December 1994. We searched for redshifted CO(4–3) over a 500 MHz band centered at 104.780 GHz, corresponding to $z = 3.399$, close to the redshifts of the rest-frame UV/ optical lines and the H I. No line was detected (Fig. 5). After smoothing to a resolution of 90 km s^{-1}, the 2σ limit on the peak line flux was 2 mJy, as at the interferometer. The source was also searched for the CO(5–4) line at 130.970 GHz, and

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[1] We use $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ throughout this paper.

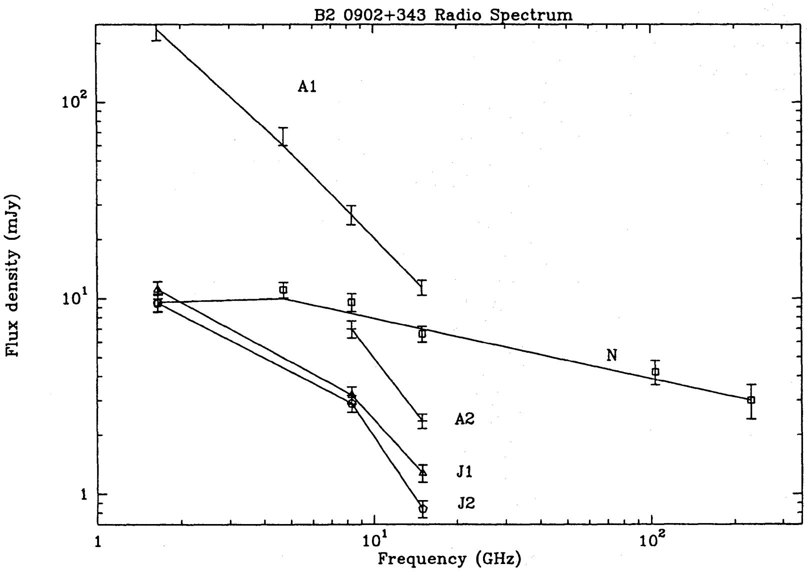

Fig. 2. Radio continuum spectra of components in B2 0902+343, after the nomenclature of Carilli et al. (1994). The mm continuum measurements at 105 GHz are from this paper and from Yun & Scoville (1995) and the measurements at 230 GHz are from Chini and Krügel (1994). All other points are from Carilli et al. (1994) and Carilli (1995)

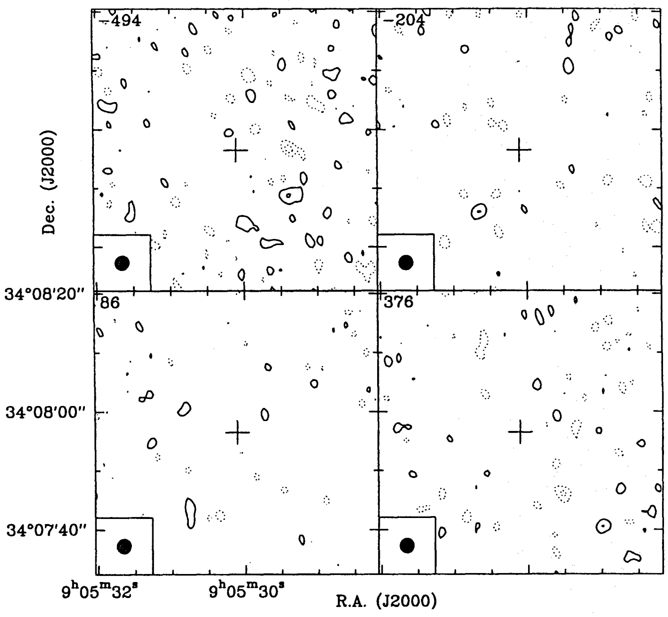

Fig. 3. Channel maps at 2.4″ × 2.3″ resolution. The cross marks the position of the 4.2 mJy continuum source, which has been subtracted from the original maps. The channels are 290 km s^{-1} wide, centered on the velocities indicated in the upper left of each box, which are Doppler velocities calculated relative to 104.82 GHz. The 2.4″ beam is indicated at the lower left of each box. The contour interval is 1.5 mJy; the zero contour is omitted. The r.m.s. noise is 0.8 mJy. The data show only noise, with no evidence for CO(4–3) line emission

the CO(8–7) line at 209.548 GHz. The searches at the 30 m telescope are described in detail by Evans et al. (1996).

The upper limits on CO emission derived at both the IRAM interferometer and the 30 m telescope correspond to an upper limit on the CO luminosity of 4 × 10^9 K km s^{-1} pc^2, which is about two to three times lower than some other low redshift ultraluminous IR galaxies (see the survey by Solomon et al. 1996). It is about one-tenth the apparent CO(3–2), (4–3), and (6–5) luminosity of IRAS F10214+4724, before correction for gravitational lensing. If the radio galaxy B2 0902+343 had the same excitation of CO(4–3) relative to CO(1–0) as in IRAS F10214+4724, then the corresponding limit on the mass of molecular gas is 2 × 10^{10} $M_\odot$. The upper limits are consistent with the CO luminosities and molecular masses derived for nearby radio galaxies by Mazzarella et al. (1993) which are 2 to > 10 times less than the CO luminosity of Arp 220 — *in the CO(1–0) line*. In the CO(4–3), (5–4), and (8–7) lines searched here, the nearby radio galaxies are probably even weaker relative to Arp 220, since they probably do not have the strong nuclear concentration (300 pc) and high CO mean brightness temperature (> 30 K) of the Arp 220 CO emission. Hence our CO detection limits mean that the high-z radio galaxy B2 0902+343 is not any richer in molecular gas than low-z radio galaxies, or gas-rich normal galaxies. The near-nuclear environment in radio galaxies is probably less dense than in some other AGNs such as Seyfert 1's, allowing two forms of energy to escape from the nuclear region to great distances: the AGN's radio jets and the AGN's hard, non-thermal, ionizing radiation.

5. The mm-continuum source and the Lyα and [O III] emission

As in other radio galaxies, the nucleus' flat, −0.3 power law spectrum probably steepens in the mid-IR (observed frame) to the −1.3 power-law typical of AGN optical/UV continuum radiation. At z = 3.4, this familiar power law spectrum would yield a νL_ν spectral energy distribution peaking near 30 μm (observed frame) with a power of 3 × 10^{11} $L_\odot$. Shortward of the rest-frame Lyman edge at 912 Å, the −1.3 power law spectrum would still contain 1 × 10^{11} $L_\odot$. The rest-frame UV power would be 1 × 10^{14} $L_\odot$ if there is no mid-IR break in the non-thermal spectrum.

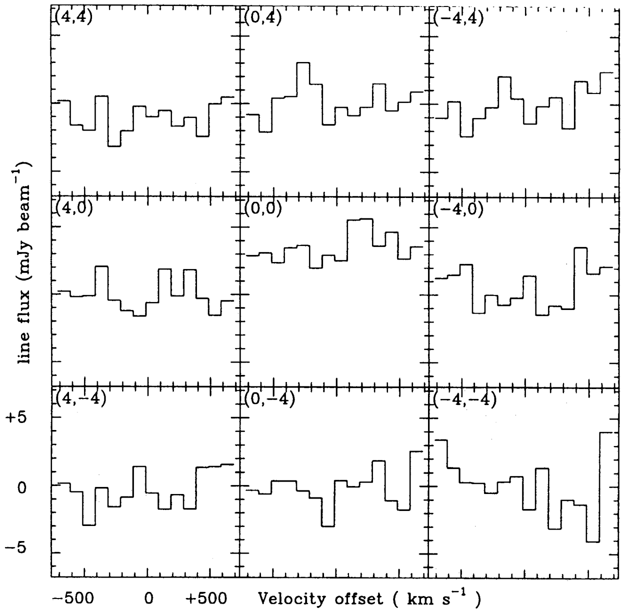

Fig. 4. Interferometer spectra at 100 km s^{-1} resolution at grid points separated by 4″, with the central point centered on the B2 0902+343 continuum source. The position offsets (arcsec) are indicated in parentheses in the upper left corner of each box. The beam is 2.4″. Velocity offsets are relative to 104.762 GHz The central box shows a 4 mJy offset above the zero level due to the continuum source. The r.m.s. noise in the spectra is 1.2 mJy

It is interesting to compare this power available in non-thermal ionizing continuum photons with the power radiated in optical lines. The strong Lyα emission (Eisenhardt & Dickinson 1992) is extended over 5″, or 23 kpc around the galaxy, with two peaks aligned E-W. The Lyα flux in the E and W peaks on the images by Eisenhardt & Dickinson is 6×10^{-19} W m^{-2}, corresponding to a rest-frame Lyα luminosity of 1×10^9 L$_\odot$. It is thus remarkable that the mm continuum spectrum of the nucleus (Fig. 2), extrapolated to UV wavelengths, has 10^2 to 10^5 more luminosity in ionizing photons than is observed in Lyα photons re-emitted by the extended ionized halo. Hence, rather than star formation, the ultimate source of the halo ionization may be the high-energy extension of the nuclear component's mm/cm synchrotron spectrum.

How could such a bright nuclear source escape detection on optical or IR images? The observations (e.g., Lilly 1988) set a limit on the 4000 Å flux from the radio nucleus of $\sim 0.5\,\mu$Jy. This is about the flux predicted by extrapolating from the millimeter flux with a −0.3 power law that changes to −1.3 in the mid-IR. If, on our line of sight, there is in the radio galaxy an extinction A_V (rest frame) of 1 or 2 mag, it would be easy to mask the nucleus. Hence at optical wavelengths, a modest extinction can hide the powerhouse of the galaxy. At centimeter wavelengths, the nuclear radio emission is insignificant compared to the steep-spectrum, non-thermal radio lobes. Only in the millimeter region does the non-thermal nucleus emerge as the dominant source.

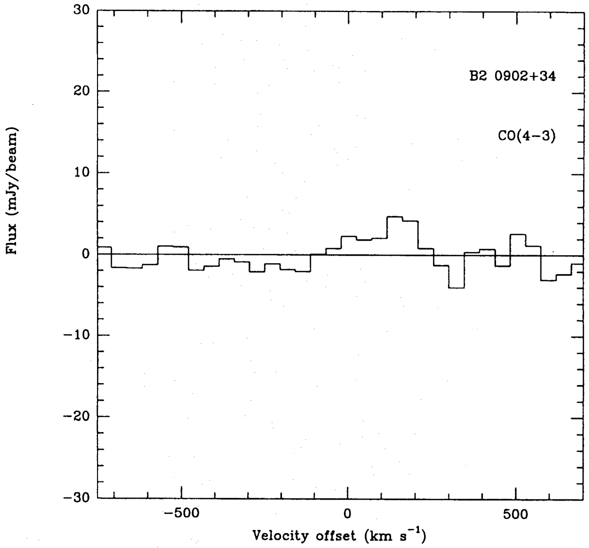

Fig. 5. Spectrum taken at 104.8 GHz at the 30 m telescope. This negative result provides a limit of 3 mJy on any CO(4–3) line from B2 0902+343

6. Conclusions

1. At 105 GHz, the millimeter continuum flux of B2 0902+343 is 4.2 ± 0.6 mJy.
2. The mm continuum source coincides with the centimeter wavelength component N — the nucleus or the base of the non-thermal radio jet.
3. The 105 GHz continuum source size is $< 0.4''$. Identification of the mm source with the cm-band component N suggests its true size is $< 0.05''$ ($<$ 230 pc), as on the VLA maps by Carilli et al. (1994) and Carilli (1995).
4. There is no evidence for any thermal emission by dust. The flux detected by Chini & Krügel (1994) at 1.3 mm is also synchrotron radiation, not thermal dust emission. The mass of any thermal dust radiating at 60 K is $< 2 \times 10^7$ M$_\odot$.
5. There is no CO(4–3) line in the redshift range 3.396 to 3.402, to a level of 2 mJy in channels 290 km s^{-1}wide. The limit on the CO luminosity is one-tenth the apparent CO luminosity of IRAS 10214+4724, and one-half to one-third that of the stronger ultraluminous IR galaxies. That is, in their present state, the IRAM telescopes could in principle detect the strongest known ultraluminous IR galaxies out to $z = 3.5$.
6. Extrapolation of the non-thermal millimeter radio flux to the rest-frame ultraviolet provides more than enough ionizing photons to account for the extended ionized halo seen in Lyα and [O III]. The non-detection of molecular gas or thermal dust emission at millimeter wavelengths may be consistent with a gas-poor environment around the AGN, that allows both radio jets and UV synchrotron photons to escape.

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