High Sensitivity Array Observations of the $z = 4.4$ QSO BRI 1335–0417

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ABSTRACT

We present sensitive phase-referenced VLBI results on the radio continuum emission from the $z = 4.4$ QSO BRI 1335–0417. The observations were carried out at 1.4 GHz using the High Sensitivity Array (HSA). Our sensitive VLBI image at 189×113 mas (1.25×0.75 kpc) resolution shows continuum emission in BRI 1335–0417 with a total flux density of 208 ± 46 μJy, consistent with the flux density measured with the VLA. The size of the source at FWHM is 255×138 mas (1.7×0.9 kpc) and the derived intrinsic brightness temperature is $\sim 3.5 \times 10^4$ K. No continuum emission is detected at the full VLBI resolution (32×7 mas, 211×46 pc), with a 4σ point source upper limit of 34 μJy beam^{-1}, or an upper limit to the intrinsic brightness temperature of 5.6×10^5 K. The highest angular resolution with at least a 4.5σ detection of the radio continuum emission is 53×27 mas (0.35×0.18 kpc). At this resolution, the image shows a continuum feature in BRI 1335–0417 with a size of 64×35 mas (0.42×0.23 kpc) at FWHM, and intrinsic brightness temperature of $\sim 2\times10^5$ K. The extent of the observed continuum sources at 1.4 GHz and the derived brightness temperatures show that the radio emission (and thus presumably the far-infrared emission) in BRI 1335–0417 is powered by a major starburst, with a massive star formation rate of order a few thousand $M_\odot$ yr^{-1}. Moreover, the absence of any compact high-brightness temperature source suggests that there is no radio-loud AGN in this $z = 4.4$ QSO.

Subject headings: galaxies: individual (BRI 1335–0417) — galaxies: active — galaxies: high-redshift — radio continuum: galaxies — techniques: interferometric

1. INTRODUCTION

Optical surveys such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) and the Digitized Palomar Sky Survey (Djorgovski et al. 1999) have revealed large samples of quasi-stellar objects out to $z \sim 6$. Studies by Fan et al. (2002) and Fan et al. (2006) have shown that at such a high redshift we are approaching the epoch of reionization, the edge of the "dark ages", when the first stars and massive black holes were formed.

Observations of high redshift QSOs at mm and sub-mm wavelengths have shown that a significant fraction ($\sim$ 30%) of the sources are strong emitters of far-infrared (FIR) radiation, which is thermal emission from warm dust. These sources have luminosities $L_{\rm FIR} > 10^{12}$ $L_\odot$, and molecular gas masses greater than 10^{10} $M_\odot$ (Solomon & Vanden Bout 2005; Riechers et al. 2006). Moreover, the large reservoirs of warm gas and dust in these objects have led to the hypothesis that these are starburst galaxies with massive star formation rates on the order of 1000 $M_\odot$ yr^{-1} (Bertoldi et al. 2003; Beelen et al. 2006; Carilli et al. 2004; Walter et al. 2003).

An important question regarding these high-z QSOs is whether the dust heating mechanism is dominated by a central AGN, or starburst activity in the QSO host galaxies. The high resolution of Very Long Baseline Interferometry (VLBI) observations permits a detailed look at the physical structures in the most distant cosmic sources. Also, sensitive VLBI continuum observations can be used to determine the nature of the energy source(s) in these galaxies at radio frequencies.

To date, several high redshift QSOs have been imaged at milliarcsecond resolution (Frey et al. 1997, 2003; Momjian et al. 2004; Beelen et al. 2004; Momjian et al. 2005). These are the highest resolution studies of such distant QSOs by far. In this paper, we present sensitive VLBI observations of the $z = 4.4$ QSO BRI 1335–0417.

The source BRI 1335–0417, which has an optical redshift of 4.396 ± 0.026, was identified in the Automatic Plate Measuring (APM) survey (Irwin et al. 1991; Storrie-Lombardi et al. 1996). This QSO is the second brightest source at millimeter wavelengths with redshifts $z > 4$, with the brightest being the $z = 4.7$ QSO BRI 1202–0725 (Omont et al. 1996). The implied FIR luminosity of BRI 1335–0417 is $L_{\rm FIR} = 3.1 \times 10^{13}\ L_{\odot}$. Thus far, there is no evidence for multiple imaging in BRI 1335–0417 due to strong gravitational lensing (Carilli et al. 1999).

The optical spectrum of the QSO BRI 1335–0417 shows a strong absorption by Lyα and metal lines at the source redshift (Storrie-Lombardi et al. 1996). Its CO $(5-4)$ line emission was detected at $z = 4.4074 \pm 0.0015$ (Guilloteau et al. 1997). The CO $(2-1)$ emission studies on this source by Carilli et al. (1999) suggested optically thick emission from warm (> 30 K) molecular gas. The derived total molecular gas mass is $M_{\rm H2} = (1.5 \pm 0.3) \times 10^{11}\ M_{\odot}$, making BRI 1335–0417 one of the most massive molecular gas reservoirs known at high redshifts.

The source BRI 1335–0417 is also detected in the radio continuum at 1.4 and 4.9 GHz with the Very Large Array (VLA) in C-configuration, with flux densities of 220 ± 43 and $76 \pm 11\ \mu$Jy, respectively (Carilli et al. 1999; Yun et al. 2000). The source appears unresolved at the resolution of these VLA observations, which is on the order of several arcseconds.

Throughout this paper, we assume a flat cosmological model with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 71$ km s^{-1} Mpc^{-1}. In this model, at the distance of BRI 1335–0417, 1 milliarcsecond (mas) corresponds to 6.6 pc.

2. OBSERVATIONS AND DATA REDUCTION

The VLBI observations of BRI 1335–0417 were carried out at 1.4 GHz on 2005 December 31 and 2006 January 7, using the High Sensitivity Array (HSA), which included the Very Long Baseline Array (VLBA), the phased Very Large Array (VLA), and the Green Bank Telescope (GBT) of the NRAO[1]. Four adjacent 8 MHz baseband channel pairs were used in the observations, both with right and left-hand circular polarizations, and sampled at two bits. The data were correlated at the VLBA correlator in Socorro, NM, with 2 s correlator integration time. The total observing time was 14 hr. In these observations, the shortest baseline is between the phased VLA and the VLBA antenna in Pie Town, NM, which is

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52 km. This short-spacing limit filters out all spatial structure larger than about $0.''42$. Table 1 summarizes the parameters of these observations.

The observations employed nodding-style phase referencing, using the calibrator J1335–0511 ($S_{1.4\ \mathrm{GHz}} = 0.4$ Jy), with a cycle time of 4 min, 3 min on the target source and 1 min on the calibrator. A number of test cycles were also included to monitor the coherence of the phase referencing. These tests involved switching between two calibrators, the phase calibrator J1335–0511 and the phase-check calibrator J1332–0509 ($S_{1.4\ \mathrm{GHz}} = 0.3$ Jy), using a similar cycle time to that used for the target source.

The accuracy of the phase calibrator position is important in phase-referencing observations (Walker 1999), as this determines the accuracy of the absolute position of the target source and any associated components. Phase referencing, as used here, is known to preserve absolute astrometric positions to better than $\pm 0.''01$ (Fomalont 1999).

Data reduction and analysis were performed using the Astronomical Image Processing System (AIPS) and Astronomical Information Processing System (AIPS++) of the NRAO. After applying *a priori* flagging, amplitude calibration was performed using measurements of the antenna gain and system temperature for each station. Ionospheric corrections were applied using the AIPS task "TECOR". The phase calibrator J1335–0511 was self-calibrated in both phase and amplitude and imaged in an iterative cycle.

Images of the phase-check calibrator, J1332–0509, were deconvolved using two different approaches: (a) by applying the phase and the amplitude self-calibration solutions of the phase reference source J1335–0511 (Figure 1*a*), and (b) by self calibrating J1332–0509 itself, in both phase and amplitude (Figure 1*b*). The peak surface brightness ratio of the final images from the two approaches gives a measure of the effect of residual phase errors after phase referencing (i.e. 'the coherence' due to phase referencing). At all times, the coherence was found to be better than 98%.

The self-calibration solutions of the phase calibrator, J1335–0511, were applied on the target source, BRI 1335–0417, which was then deconvolved and imaged at various spatial resolutions by tapering the visibility data.

3. RESULTS & ANALYSIS

Imaging the target source at the full resolution of the VLBI array, which is 32×7 mas (211×46 pc, PA$=-7°$), achieved an rms noise level of 8.5 μJy beam^{-1}, but did not reveal any continuum component in the field of BRI 1335–0417. This indicates the absence of any compact radio continuum emission with flux densities of $\geq 4\sigma \simeq 34$ μJy beam^{-1}, which in turn implies an upper limit to the intrinsic brightness temperature (corresponding to a rest frequency of ∼8 GHz) of 5.6×10^5 K for any compact radio source in BRI 1335–0417. Our coherence tests during these observations using two VLBI calibrators show that the lack of a strong point source in BRI 1335–0417 at the full resolution of the array cannot be due to the phase referencing procedure. The 4σ flux limit reported above is almost an order of magnitude lower than the flux measured by the VLA (220 ± 43 μJy) at 1.4 GHz (Carilli et al. 1999). This immediately implies that more than ∼80% of the radio continuum emission in BRI 1335–0417 is extended and not confined to the central AGN.

In the following, we will assess if our HSA observations can recover the flux seen by the VLA. To do so, we applied a two-dimensional Gaussian taper falling to 30% at 1 Mλ to the visibility data in both the u- and v-directions. This gives a beam size of 189×113 mas (1.25×0.75 kpc, P. A.$= -48°$), and the resulting image is shown in Figure 2. The rms noise level in this naturally weighted image is 28 μJy beam^{-1}. The peak flux density of the detected continuum source is 126 ± 28 μJy beam^{-1}, and the total flux density is 208 ± 46 μJy, which agrees well with the flux density measured with the VLA at 1.4 GHz (Carilli et al. 1999). The size of the source at full width half maximum (FWHM) is 255×138 mas (1.7×0.9 kpc), and the derived intrinsic brightness temperature is $(3.6 \pm 0.9) \times 10^4$ K.

Figure 3 shows the continuum emission in BRI 1335–0417 at the highest angular resolutions for which there is at least 4.5σ detection ($\sigma = 19$ μJy beam^{-1}). This corresponds to a resolution of 53×27 mas (0.35×0.18 kpc) in position angle $-6°$. This image was obtained by applying a two-dimensional Gaussian taper falling to 30% at 5 Mλ in both the u- and v-directions of the visibility data. The peak flux density of the continuum source detected at this resolution is 87 ± 19 μJy beam^{-1}, and the total flux density is 131 ± 30 μJy. The size of the source is 64×35 mas (0.42×0.23 kpc) at FWHM, and its intrinsic brightness temperature is $(2.2 \pm 0.5) \times 10^5$ K. The results obtained at this resolution imply that about two thirds of the total radio emission emerges from the central ∼0.3 kpc of BRI 1335–0417, and, likewise, one third arises from more extended scales (∼1.3 kpc).

4. DISCUSSION

We have detected 1.4 GHz emission from BRI 1335–00417 (corresponding to a rest frame frequency of ∼8 GHz) using the HSA. At a moderate resolution (189×113 mas; Figure 2) the intrinsic brightness temperature value of the detected continuum structure is $\sim 3.5 \times 10^4$ K. The measured flux density at this resolution is consistent with the VLA flux density of this source (Carilli et al. 1999). This implies that the radio continuum emission at 1.4 GHz is confined to the extent of the structure seen in the VLBI image (Figure 2), which is 1.7×0.9 kpc at FWHM. Furthermore, the highest resolution image with continuum detection (Figure 3) shows that almost two thirds of the total radio continuum emission at 1.4 GHz is arising from the central $\sim$0.3 kpc.

At the full resolution of our array (32×7 mas), the radio emission from BRI 1335–0417 is resolved out and does not show any single dominant source of very high brightness temperature ($< 5.6 \times 10^5$ K). This is in contrast to the results obtained by Momjian et al. (2004) on a sample of three high-z radio-loud quasars which were imaged with the VLBA, namely J1053-0016 ($z = 4.29$), J1235-0003 ($z = 4.69$), and J0913+5919 ($z = 5.11$). In each of these $z > 4$ quasars, a radio-loud AGN dominates the emission at 1.4 GHz on a few mas size scale, with intrinsic brightness temperatures in excess of 10^9 K.

Condon et al. (1991) have derived an empirical upper limit to the brightness temperature for nuclear starbursts of $\sim 10^5$ K at 8 GHz (our rest frequency), while typical radio-loud AGN have brightness temperatures exceeding this value by at least two orders of magnitude. These authors also present a possible physical model for this limit involving a mixed non-thermal and thermal radio emitting (and absorbing) plasma, constrained by the radio-to-FIR correlation for star-forming galaxies.

For BRI 1335–0417, the derived intrinsic brightness temperatures from our VLBI observations are typical of starburst galaxies. Also, the linear extent of the radio continuum emission region in BRI 1335–0417 is typical of local starburst powered Ultra-Luminous IR galaxies (ULIRGs; Sanders & Mirabel 1996), such as Arp 220, Mrk 273, and IRAS 17208–0014 (Smith et al. 1998; Carilli & Taylor 2000; Momjian et al. 2003).

Another argument in favor of a massive starburst origin for the radio continuum emission from BRI 1335–0417 is that this source follows the radio-FIR correlation for star forming galaxies, although the massive star formation rate is extreme, of order a few thousand $M_\odot$ yr^{-1} (Carilli et al. 1999).

The physical characteristics of the QSO BRI 1335–0417 are similar to two other high-z luminous IR sources; the brightest mm source in the Omont et al. (2003) sample of QSOs with redshifts between $1.8 < z < 2.8$, namely J1409+5628 at $z = 2.58$, and the brightest mm source in the Omont et al. (1996) sample of QSOs at redshifts $z > 4$, namely BRI 1202–0725 at $z = 4.7$. High angular resolution observations of J1409+5628 and BRI 1202–0725 at 1.4 GHz (Beelen et al. 2004; Carilli et al. 2002) showed that the radio continuum emission in these optically very bright QSOs is dominated by extreme nuclear starbursts, with massive star formation rates on the order of 10^3 $M_\odot$ yr^{-1}. Moreover, sensitive, tapered VLBI images of BRI 1202–0725 at 1.4 GHz (Momjian et al. 2005) revealed the starburst regions in each of its two components that are separated by $4''$, with sizes and brightness temperatures comparable to that seen in BRI 1335–0417.

The measured 1.4 GHz radio flux density in BRI 1335–0417 is consistent with extreme nuclear starburst activity, with the radio continuum being the sum of supernovae (SNe), supernova remnants, and residual relativistic electrons in the interstellar medium, as shown in the model presented by Condon et al. (1991). However, detecting individual SNe at $z = 4.4$ is unlikely. Smith et al. (1998) reported the detection of several luminous radio SNe in the prototype ULIRG Arp 220 with flux densities between 0.2 and 1.17 mJy and angular sizes on the order of 0.25 mas. At the distance of BRI 1335–0417, the flux densities of such luminous radio SNe would be between $(0.8 - 4.5) \times 10^{-3}$ μJy. These values are three to four orders of magnitude lower that the rms noise levels achieved in our VLBI observations.

5. ACKNOWLEDGMENTS

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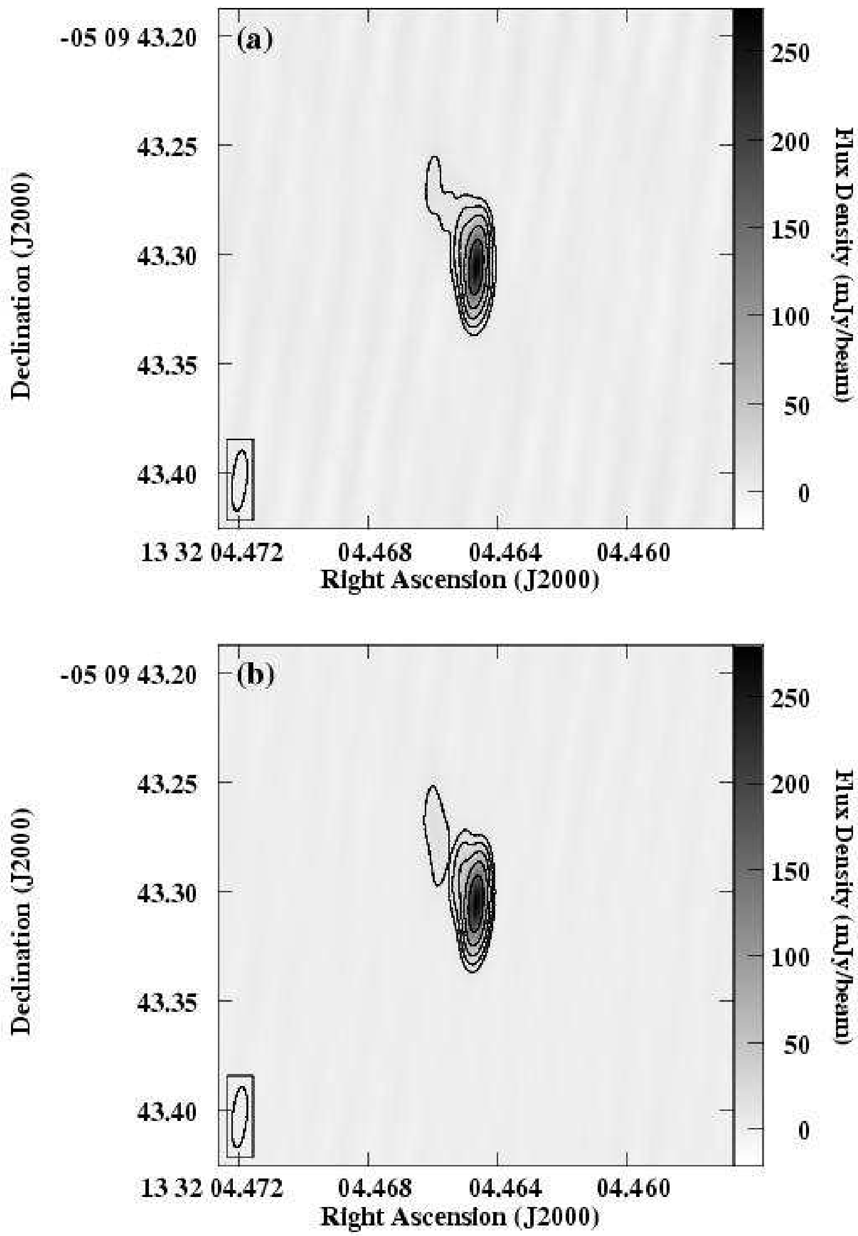

Fig. 1.— Continuum images of the phase-check calibrator J1332–0509 at 1.4 GHz: a) obtained by applying the phase and the amplitude self-calibration solutions of the phase reference source J1335–0511, b) obtained by self calibrating J1332–0509 itself, in both phase and amplitude. The restoring beam size in both images is 27.9×6.5 mas in position angle $-5°$. The contour levels are at -3, 3, 6, 12, 24, 48 times the rms noise level in the phase-referenced image (top), which is 3.2 mJy beam^{-1}. The gray-scale range is indicated by the step wedge at the right side of each image.

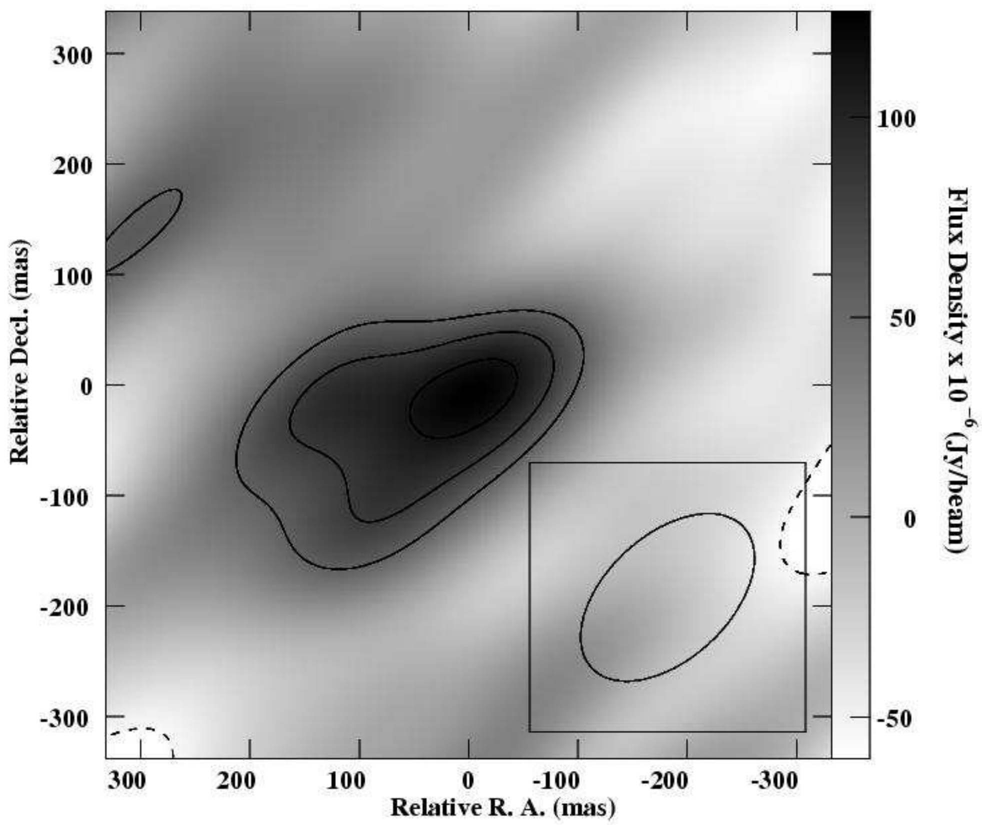

Fig. 2.— Naturally weighted 1.4 GHz continuum image of BRI 1335–0417 at 189×113 mas resolution (P. A.=$-48°$). The peak flux density is 126 μJy beam^{-1}, and the contour levels are at -2, 2, 3, 4 times the rms noise level, which is 28 μJy beam^{-1}. The gray-scale range is indicated by the step wedge at the right side of the image. The reference point (0, 0) is α(J2000.0) = $13^{\rm h}38^{\rm m}03\overset{\rm s}{.}4034$, δ(J2000.0) = $-04°32'35\overset{''}{.}271$. A two dimensional Gaussian taper falling to 30% at 1 Mλ was applied.

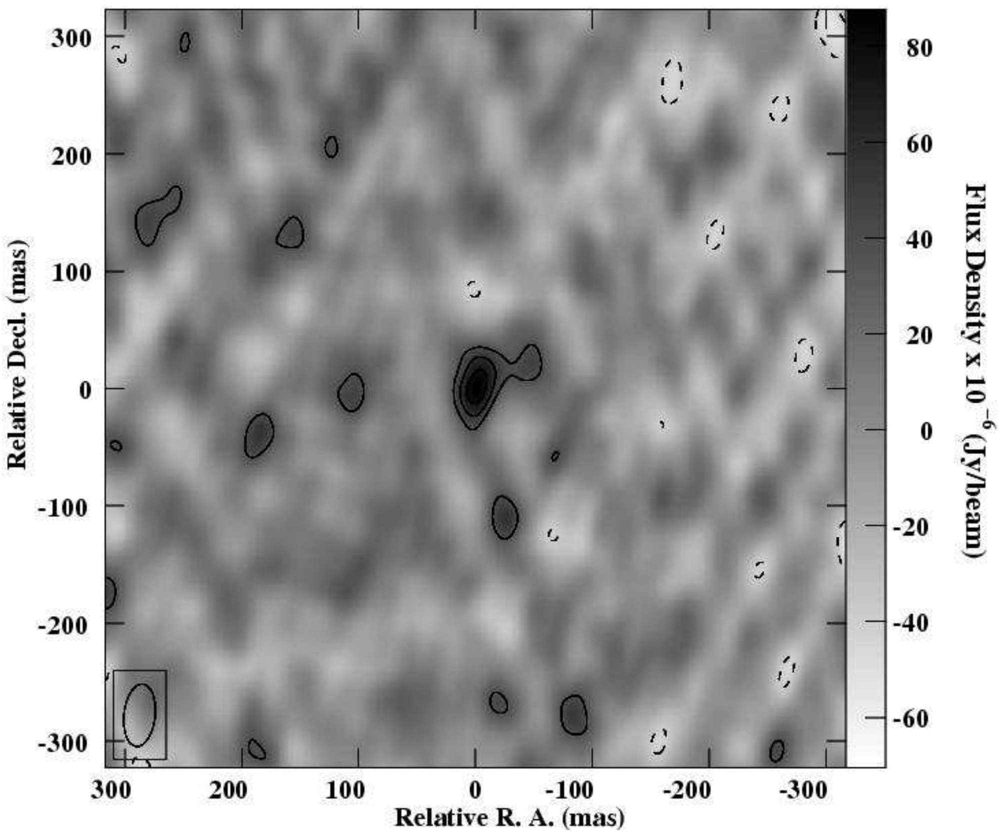

Fig. 3.— Naturally weighted 1.4 GHz continuum image of BRI 1335–0417 at 53 × 27 mas resolution (P. A.=−6°). The peak flux density is 87 μJy beam^{-1}, and the contour levels are at −2, 2, 3, 4 times the rms noise level, which is 19 μJy beam^{-1}. The gray-scale range is indicated by the step wedge at the right side of the image. The reference point (0, 0) is α(J2000.0) = $13^{\rm h}38^{\rm m}03\overset{\rm s}{.}4034$, δ(J2000.0) = $-04°32'35\overset{''}{.}271$. A two dimensional Gaussian taper falling to 30% at 5 Mλ was applied.

Table 1. PARAMETERS OF THE VLBI OBSERVATIONS OF BRI 1335–0417

Parameters	Values
Observing Dates	2005 Dec. 31 & 2006 Jan. 7
Total observing time (hr)	14
Phase calibrator	J1335–0511
Phase-referencing cycle time (min)	4
Frequency (GHz)	1.4
Total bandwidth (MHz)	32