A SHOCK-INDUCED PAIR OF SUPERBUBBLES IN THE HIGH-REDSHIFT POWERFUL RADIO GALAXY MRC 0406−244

Yoshiaki Taniguchi,1 Yoichi Ohyama, Takashi Murayama,2 Michitoshi Yoshida,4 Nobunari Kashikawa,5 Masanori Iye,5 Kento Aoki,6 Toshiyuki Sasaki,3 George Kosugi,3 Tadafumi Takata,3 Yoshihiko Saito,7 Koji S. Kawarata,5 Kazuhiro Sekiguchi,9 Kichi Okita,3 Yasuhiro Shimizu,4 Motoko Inata,5 Noboru Ebizuka,7 Tomohiko Ozawa,8 Yasushi Yadamaru,4 Hiroko Taguchi,9 Yasuhiro Shiroya,2 Shingo Nishiura,2,10 Hiroshi Sudou,2 Tohru Nagao,2 Saeko Noda,2 Yohei Koyama,2 Yuko Kakazu,2,11 Masaru Aki,2 Shinobu S. Fujita,2 and Rie R. Kobayashi1

Received 2001 May 29; accepted 2001 August 7; published 2001 August 23

ABSTRACT

We present new optical spectroscopy of the high-redshift powerful radio galaxy MRC 0406−244 at redshift of 2.429. We find that the two extensions toward the northwest and southeast probed in the rest-frame ultraviolet image are heated mainly by the nonthermal continuum of the active galactic nucleus. However, each extension shows a shell-like morphology, suggesting that they are a pair of superbubbles induced by the superwind activity rather than by the interaction between the radio jet and the ambient gas clouds. If this is the case, the intense starburst responsible for the formation of superbubbles could occur \( \sim 1 \times 10^7 \) yr ago. On the other hand, the age of the radio jets may be on the order of \( \sim 10^6 \) yr, being much shorter than the starburst age. Therefore, the two events, i.e., the starburst and the radio jet activities, are independent phenomena. However, their directions of the expanding motions could be governed by the rotational motion of the gaseous component in the host galaxy. This idea appears to explain the alignment effect of MRC 0406−244.

Subject headings: galaxies: active — galaxies: individual (MRC 0406−244) — galaxies: starburst — radio continuum: galaxies

1. INTRODUCTION

Since high-redshift (\( z \)) powerful radio galaxies (HzPRGs) provide us a unique opportunity to investigate the formation and evolution of both galaxies and active galactic nuclei (AGNs), follow-up investigations have been made intensively for these past two decades (Chambers, Miley, & van Breugel 1990; Eales & Rawlings 1993, 1996; Röttgering et al. 1995; Best, Longair, & Röttgering 1996; see for a review McCarthy 1993). One of important problems related to HzPRGs is the so-called alignment effect; there is the strong correlation between the position angles (P.A.’s) of the radio axis and the rest-frame optical and ultraviolet continua for PRGs at redshifts above \( \sim 0.6 \) (Chambers, Miley, & van Breugel 1987; McCarthy et al. 1987; see also Djorgovski et al. 1987). The origin of this alignment effect has been in debate (e.g., McCarthy 1993), and there are two favorable ideas. One is the jet-induced star formation in which the UV continuum emission is considered to arise from massive stars formed in the shocked region (e.g., Chambers et al. 1987; McCarthy et al. 1987; Rees 1989; Begelman & Cioffi 1989; Daly 1990). The kinematics and ionization state of HzPRGs often suggest the importance of the shock heating (e.g., Best, Röttgering, & Longair 2000; De Breuk et al. 2000). An alternative idea is the scattering of an anisotropic continuum radiation from a central engine of AGNs (Tadhunter, Fosbury, & di Serego Alighieri 1988; Fabian 1988; di Serego Alighieri et al. 1989; Scarrott, Rolph, & Tadhunter 1990; Cimatti et al. 1994). The strong linear polarization in the rest-frame UV continua has been considered as strong evidence for this idea (e.g., Cimatti et al. 1998 and references therein).

Among the HzPRGs with evidence for the alignment effect, MRC 0406−244 has been investigated in detail (McCarty, Elston, & Eisenhardt 1992; Eales & Rawlings 1993, 1996; Rush et al. 1997). This radio galaxy was discovered in the MRC/1 Jy radio source survey and identified as an HzPRG at \( z = 2.429 \) (McCarthy et al. 1991; McCarthy, Baum, & Spinrad 1996). It shows core and double-lobe structures in radio, and the rest-frame UV line and continuum emission are spatially extended along the radio axis, forming an elongated S, or figure-eight–shaped structure with some knots (Rush et al. 1997). Rush et al. (1997) investigated the origin of the aligned continuum based on their multiwavelength imaging analyses of MRC 0406−244. They found that the scattering by dust in tidal features, which could be made by a putative merger between galaxies, is favored to explain the optical depth of each knot. However, McCarthy (1999) suggested that the morphological appearance of the extended nebula around MRC 0406−244 seen in redshifted H\( \beta \) and [O iii] lines looks like a pair of superbubbles (see also Pentericci et al. 2001), which is the galactic-scale outflow driven by the collective effect of a large number of super-
nova explosions of massive stars formed in a starburst (Chevalier & Clegg 1985; Tomisaka & Ikeuchi 1988; see for a review Heckman, Armus, & Miley 1990). In order to examine the possibility that the UV morphology may alternatively be interpreted as a pair of superbubbles, we have made optical spectroscopy using the Subaru 8.2 m telescope. In this Letter, we show our new results and discuss the origin of the rest-frame UV and optical morphology of MRC 0406–244. Following Rush et al. (1997), we adopt a Hubble constant $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and a deceleration parameter $q_0 = 0.1$ throughout this Letter. In this cosmology, 1" corresponds to $\approx 10$ kpc at $z = 2.429$.

2. OBSERVATIONS

Observations were made with the Faint Object Camera and Spectrograph (FOCAS; Kashikawa et al. 2000) on the Subaru 8.2 m telescope (Kaifu 1998) during a commissioning run of the FOCAS on 2001 February 18. The seeing condition was 0"7. In order to observe both line and continuum emission properties of MRC 0406–244, we set the 0"8 wide slit along the major axis of the radio structure (PA $= 128^\circ$; e.g., Rush et al. 1997). The 300B grating together with a Y47 filter allows us to obtain an optical spectrum between 4700 and 9000 Å with a spectroscopic resolution of 11.3 Å (the instrumental FWHM). The pixel resolution is 0"3 (3 pixel binning) $\times$ 5.65 Å (4 pixel binning). The exposure time was 1800 s. After subtracting the bias image in a standard manner, flat-fielding and the optical distortion corrections were applied with the special software developed by the FOCAS team (Yoshida et al. 2000). Wavelength calibration and the flux calibration were made with a standard manner using IRAF.

3. RESULTS

In Figure 1d, we show our CCD spectrum of MRC 0406–244 where the three strong emission lines, C IV $\lambda 1549$, He II $\lambda 1640$, and C III$\lambda 1909$, are clearly seen;12 these lines are simply denoted as C IV, He II, and C III. Although this galaxy exhibits a strong Ly$\alpha$ emission line (McCarthy et al. 1996; Rush et al. 1997), our spectrum does not cover its restshifted wavelength. All these lines are clearly extended over 2" in both the northwest and southeast directions. The continuum emission is found within the nuclear region of less than 1", although Rush et al. (1997) detected the extended continuum emission over $\sim$2" on their high-resolution Hubble Space Telescope images. A spectrum of the red galaxy northwest of MRC 0406–244 is also recorded. However, its redshift is unknown since it does not have any strong emission lines in the observed wavelength coverage. In the left-hand panels, we present the spatial variations of emission-line velocities (Fig. 1a), FWHMs of the emission lines corrected for the instrumental resolution (Fig. 1b), and the emission-line ratios of C IV/He II, C III/He II, and C IV/C III (Fig. 1c). In all of the panels, the continuum peak at $\lambda 6404$ Å is set to be the origin.

The kinematical structure of the emission-line nebula is complicated across the region. The velocity difference between the northwest and southeast sides amounts to $\sim 1500$ km s$^{-1}$ for the velocity curve probed by the C IV emission. All emission lines are blueshifted at most off-nuclear regions ($\geq 1"$) comparing to the velocity around the nucleus. It is noted that the velocity curves do not show a simple symmetric structure around the nucleus. McCarthy et al. (1996) and Pentericci et al. (2001) found another emission-line component with $\sim 1000$ km s$^{-1}$ with respect to the systemic velocity by Ly$\alpha$ emission. Our observations show that this component cannot be probed by the three emission lines studied here. The C IV velocity field is more blueshifted with respect to that of both C III and He II at off-nuclear regions. The line widths of both C IV and C III emission are as wide as $\sim 400$ km s$^{-1}$ in FWHM at off-nuclear regions, which is too broad to be explained by the thermal motion of star-forming nebulae within the disk. The nuclear region shows a narrower line width ($\sim 300$ km s$^{-1}$) in C IV. On the other hand, the line width of He II shows the different trend; i.e., the FWHM of He II is wider around the nucleus ($\sim 500$ km s$^{-1}$). All these properties cannot be interpreted by a typical galactic rotation of the host galaxy. It is noted that the different behavior of the C IV line from those of the other emission lines may be attributed to the large optical depth effect because the C IV emission line is a resonance line.

The three emission-line ratios (C IV/He II, C III/He II, and C IV/C III) are very useful to examine excitation mechanisms of the ionized gas (photoionization by massive stars or AGNs, or shock-heating) in high-z objects (e.g., Allen, Dopita, & Tsvetanov 1998; De Breuck et al. 2000).13 We find that the relative intensity of C IV increases with increasing radial distance (see Fig. 1c). This stronger C IV emission at large radial distance cannot be understood in terms of photoionization by massive

12 Another weak emission line, O III$\lambda 1663$, is also seen in our spectrogram. The O III/He II ratio is $\sim 0.1$, 0.08, and 0.2–0.3 at l" southeast, the nucleus, and l" northwest, respectively. We do not discuss this emission line in more detail in this Letter.

13 It is noted that He II $\lambda 1640$ values in the shock + precursor models of Allen et al. (1998) are underestimated by a factor of 1–6; see De Breuck et al. (2000).
stars since the ionization potential of the line (64.5 eV) is too high to be ionized by the ionizing radiation from massive stars. In order to understand the excitation mechanism more clearly, we present UV emission-line diagnostics in Figure 2: the top left panel shows C iv/He ii versus C iv/C iii, the bottom left panel shows C iv/He ii versus C iv/C iii, and the bottom right panel shows C iv/He ii versus C iii/He ii. The observed data points are shown together with model results of both AGN photoionization (Sutherland, Bicknell, & Dopita 1993) and shock heating (Dopita & Sutherland 1996); see, for the parameters adopted in the models, the top right panel of Figure 2.

In all the diagrams, we find that both the nuclear region and the inner regions within $r < 2^{20}$ (i.e., $r < 20$ kpc) can be understood in terms of the AGN photoionization with the ionization parameter from $\log U \sim -2.5$ to $-2$. It is interesting to note that the ionization parameter increases with increasing radial distance. Since the ionizing photon density should decrease with the $r^{-2}$ law, it is necessary to invoke that the nucleon density could decrease as proportional to $r^a$ with $a < -2$. An alternative idea may be that the shock heating is more dominated in the outer regions.

In particular, the large departure from the prediction of AGN photoionization can be seen in the outermost part of the southeast nebula. There seem to be two possible explanations for this departure. One is the metallicity effect because the strengths of both C iv and C iii emission lines become larger with decreasing carbon abundance (e.g., Vernet et al. 2001). In order to explain the observed sudden change, it is necessary to assume that the carbon abundance decreases suddenly by a factor of 2.5 in the outer regions. This value seems not surprising because some HzPRGs show evidence for such metal-poor ionized gas (Villar-Martín, Tadhunter, & Clark 1997; De Breuck et al. 2000; Overzier et al. 2001; Vernet et al. 2001). Another idea may be the shock heating. As shown in Figure 2, the southeast emission-line component tends to favor the shock model with the shock velocity of $v_{\text{shock}} \sim 200$ km s$^{-1}$. This inferred shock velocity appears consistent with the observed FWHM of the southeast nebula; see Figure 1b. Although it seems hard to judge which is the case for the outer part of the southeast nebula of MRC 0406−244, the shock heating may contribute in part to the ionization.

4. DISCUSSION

4.1. Origin of the Figure-Eight-shaped Nebulae

Our new optical spectroscopy has shown that the spatially extended nebulae seen in both the northwest and southeast directions are mainly ionized by AGN photoionization, although the southeast nebula shows possible evidence for shock heating. If we infer that the southeast nebula contains metal-poor (i.e., $Z/Z_\odot \sim -0.4$) gas photoionized by the AGN nonthermal continuum, it is necessary to assume that the metallicity of the ionized gas shows the sudden change at $r \sim 20$ kpc. This sudden change may be interpreted as gas clouds being swept up by the superwind activity interacting with the ambient halo gas at this radius. If we regard that the figure-eight-shaped morphology of the southeast and northwest nebulae is attributed to wound tidal features (Rush et al. 1997), it seems hard to explain the sudden change in metallicity. It is therefore considered that the figure-eight-shaped morphology can be interpreted as the relic of a pair of superbubbles.

The origin of UV continuum of the figure-eight-shaped structure is not clear. Since the majority of the ionization can be attributed to the AGN photoionization, massive stars could not be the major UV continuum source. Stars later than B-type stars could contribute to the UV continuum if they were made in the shock-heated gas clouds. An alternative idea is the scattering of an anisotropic continuum radiation from a central engine of AGNs (e.g., Cimatti et al. 1998 and references therein). However, no spectropolarimetry has yet been done for MRC 0406−244, and thus we cannot conclude which is the case. It will be important to carry out optical spectropolarimetry to investigate this issue in future.

4.2. The Origin of the Alignment Effect of MRC 0406−244

Here we consider a possible origin of the alignment effect of MRC 0406−244. We attribute the figure-eight-shaped morphology of this galaxy to a pair of superbubbles. Since MRC 0406−244 is associated with a bright host galaxy (i.e., $M_r \sim -29$ or $M_r \sim -25$), the host galaxy may be a typical massive galaxy with a mass of $M_\odot \sim 10^{12} M_\odot$. If this is the case, it takes $7 \times 10^8$ yr to the onset of the superbubble from the host galaxy potential (Arimoto & Yoshii 1987). This age appears consistent with that estimated by Eales & Rawlings (1993; see also McCarthy et al. 1992).

On the other hand, the age of the radio jet ($t_{\text{jet}}$) in MRC 0406−244 is much shorter than the above timescale because the projected distances of the northwest and southeast radio lobes, 54.5 and 29.5 kpc, gives nominally $t_{\text{jet}} \sim 2 \times 10^4$ yr and $\sim 1 \times 10^4$ yr, respectively, given the jet velocity of $v_{\text{jet}} \sim 0.1c$ (e.g., Alexander & Leahy 1987). Therefore, it seems reasonable to consider that the radio jet activity is an independent phenomenon from the starburst and the subsequent superwind activity. This seems to make sense because the onset of the radio jet activity needs the presence of a supermassive black hole and the gas accretion onto it (e.g., Rees 1984), both of which are different from the starburst activity.

Here a question arises as to why the radio jet axis is aligned to the superwind direction since the radio jet activity and the starburst/superwind activity are different physical processes
and their timescales are also significantly different. The superwind could blow as a bipolar wind, which is often observed in many superwind galaxies in the local universe (see Heckman et al. 1990), since it is likely that the gas in the host galaxy is distributed with a disklike configuration even for the young host galaxy of MRC 0406−244. On the other hand, the radio jet is expelled to the two directions perpendicular to the accretion plasma disk. Therefore, we can explain the alignment effect if the accretion disk is nearly coplanar to the host disk. Another example to which this scenario is applicable may be LRG 0329−0134 at z ∼ 1 (Taniguchi & Murayama 2001). Since high-redshift superwinds could contribute to the chemical enrichment of the intergalactic medium (e.g., Heckman et al. 1990; Taniguchi & Shioyi 2001), it will be important to investigate HzPRGs systematically.

We would like to thank the staff of the Subaru Telescope office. We also thank Fumihide Iwamuro and Carlos De Breuck for useful discussions on HzPRGs and the referee, Patrick McCarthy, for useful comments and suggestions. This work was financially supported in part by the Ministry of Education, Science, and Culture (grants 10044052 and 10304013).

4.3. Other Implications

MRC 0406−244 tells us that the intense starburst and subsequent superwind activity may be important even in HzPRGs. In particular, the formation of shell-like structures driven by the superwind activity gives rise to some important implications. For example, if low-mass stars are also formed in blobs, the blobs could evolve either to globular clusters (Taniguchi, Trentham, & Ikeuchi 1999) or to dwarf galaxies (e.g., Mori, Yoshii, & Nomoto 1999). Another example of such superwind/superbubble-driven formation of shell-like structures may be B3 0731+438 at z = 2.43 studied by Motohara et al. (2000), which also shows the alignment effect with the biconical nebula.

REFERENCES

Alexander, P. A., & Leahy, P. J. 1987, MNRAS, 225, 1
Allen, M. G., Dopita, M. A., & Tsvetanov, Z. I. 1998, ApJ, 493, 571
Arimoto, N., & Yoshii, Y. 1987, A&A, 173, 23
Begelman, M. C., & Cioffe, D. 1989, ApJ, 345, L21
Best, P. N., Longair, M. S., & Röttgering, H. J. A. 1996, MNRAS, 280, L9
Best, P. N., Röttgering, H. J. A., & Longair, M. S. 2000, MNRAS, 311, 23
Chambers, K. C., Miley, G. K., & van Breugel, W. J. M. 1987, Nature, 329, 604
———. 1990, ApJ, 363, 21
Chevalier, R. A., & Clegg, A. W. 1985, Nature, 317, 44
Cimatti, A., di Serego Alighieri, S., Field, G. B., & Fosbury, R. A. E. 1994, ApJ, 422, 562
Cimatti, A., di Serego Alighieri, S., Vernet, J., Cohen, M., & Fosbury, R. A. E. 1998, ApJ, 499, L21
Daly, R. A. 1990, ApJ, 355, 416
De Breuck, C., Röttgering, H., Miley, G., & van Breugel, W., & Best, P. 2000, A&A, 362, 519
di Serego Alighieri, S., Fosbury, R. A. E., Tadhunter, C. N., & Quinn, P. J. 1989, Nature, 341, 307
Djorgovski, S., Spinrad, H., Pedelty, J. A., Rudnick, L., & Stockton, A. 1987, AJ, 93, 1307
Dopita, M. A., & Sutherland, R. S. 1996, ApJS, 102, 161
Eales, S. A., & Rawlings, S. 1993, ApJ, 411, 67
———. 1996, ApJ, 460, 68
Fabian, A. C. 1988, in Cooling Flows in Clusters and Galaxies, ed. A. C. Fabian (NATO ASI Ser. C, 229; Dordrecht: Kluwer), 315
Heckman, T. M., Armus, L., & Miley, G. K. 1990, ApJS, 74, 833
Kaifu, N. 1998, Proc. SPIE, 3352, 14
Kashikawa, N., et al. 2000, Proc. SPIE, 4008, 104
McCarthy, P. J. 1993, A&A&A, 31, 639
———. 1999, in IAU Symp. 186, Galaxy Interactions at Low and High Redshift, ed. J. E. Barnes & D. B. Sanders (Dordrecht: Kluwer), 321
McCarthy, P. J., Baum, S. A., & Spinrad, H. 1996, ApJS, 106, 281
McCarthy, P. J., Elston, R., & Eisenhardt, P. 1992, ApJ, 387, L29
McCarthy, P. J., van Breugel, W. J. M., Kapahi, V. K., & Subrahmanya, C. R. 1991, ApJ, 102, 522
McCarthey, P. J., van Breugel, W. J. M., Spinrad, H., & Djorgovski, S. G. 1987, ApJ, 321, L29
Mori, M., Yoshii, Y., & Nomoto, K. 1999, ApJ, 511, 585
Motohara, K., et al. 2000, PASJ, 52, 33
Overzier, R. A., Röttgering, H. J. A., Kurk, J. D., & De Breuck, C. 2001, A&A, 367, L5
Pentericci, L., McCarthy, P. J., Röttgering, H. J. A., Miley, G. K., van Breugel, W. J. M., & Fosbury, R. 2001, ApJS, 135, 63
Rees, M. J. 1984, ARA&A, 22, 471
———. 1989, MNRAS, 239, 1P
Röttgering, H. J. A., Miley, G. K., Chambers, K. C., & Macchetto, F. 1995, A&AS, 114, 51
Rush, B., McCarthy, P. J., Athreya, R. M., & Persson, S. E. 1997, ApJ, 484, 163
Scarrott, S. M., Rolph, C. D., & Tadhunter, C. N. 1999, MNRAS, 243, 5P
Sutherland, R. S., Bicknell, G. V., & Dopita, M. A. 1993, ApJ, 414, 510
Tadhunter, C. N., Fosbury, R. A. E., & di Serego Alighieri, S. 1998, in BL Lac Objects, ed. L. Marashi, T. Maccaro, & M. H. Ulrich (Berlin: Springer), 79
Taniguchi, Y., & Murayama, T. 2001, ApJ, 547, L13
Taniguchi, Y., & Shioyi, Y. 2001, ApJ, 547, 146
Taniguchi, Y., Trentham, N., & Ikeuchi, S. 1999, ApJ, 526, L13
Tomisaka, K., & Ikeuchi, S. 1988, ApJ, 330, 562
Vernet, J., Fosbury, R. A. E., Villar-Martín, M., Cohen, M. H., Cimatti, A., di Serego Alighieri, S., & Goodrich, R. W. 2001, A&A, 370, 407
Villar-Martín, M., Tadhunter, C., & Clark, N. 1997, A&A, 323, 21
Yoshida, M., et al. 2000, Proc. SPIE, 4009, 240