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A MAJOR RADIO OUTBURST IN III Zw 2 WITH AN EXTREMELY INVERTED, MILLIMETER-PEAKED SPECTRUM

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ABSTRACT

III Zw 2 is a spiral galaxy with an optical spectrum and faint extended radio structure typical of a Seyfert galaxy, but also with an extremely variable, blazar-like radio core. We have now discovered a new radio flare in which the source has brightened more than 20-fold within less than 2 yr. A broadband radio spectrum between 1.4 and 666 GHz shows a textbook-like synchrotron spectrum peaking at 43 GHz, with a self-absorbed synchrotron spectral index $+2.5$ at frequencies below 43 GHz and an optically thin spectral index -0.75 at frequencies above 43 GHz. The outburst spectrum can be well fitted by two homogenous, spherical components with equipartition sizes of 0.1 and 0.2 pc at 43 and 15 GHz and with magnetic fields of 0.4 and 1 G. VLBA observations at 43 GHz confirm this double structure and these sizes. Timescale arguments suggest that the emitting regions are shocks which are continuously accelerating particles. This could be explained by a frustrated jet scenario with very compact hot spots. Similar millimeter-peaked spectrum sources could have escaped our attention because of their low flux density at typical survey frequencies and their strong variability.

Subject headings: acceleration of particles — galaxies: active — galaxies: individual (III Zw 2) — galaxies: jets — galaxies: Seyfert — quasars: general

1. INTRODUCTION

III Zw 2 (PG 0007+106, Mrk 1501, $z = 0.089$) is an active galaxy with very unusual radio properties and extreme variability. The source was discovered by Zwicky (1967) and initially classified as a Seyfert galaxy (e.g., Arp 1968; Khachikian & Weedman 1974; Osterbrock 1977), but was later also included in the PG quasar sample (Schmidt & Green 1983). The galaxy was classified as a probable spiral by Hutchings et al. (1982), which was later confirmed by fitting model isophotes to near-IR galaxy images (Taylor et al. 1996). The bolometric, optical-to-UV luminosity for III Zw 2 was estimated to be $L_{\rm UV} \sim 10^{45}$ ergs s^{-1} (Falcke, Malkan, & Biermann 1995; scaled to $H_0 = 75$ km s^{-1} Mpc^{-1} as used here).

The most intriguing property of III Zw 2, however, is its extreme variability at radio and other wavelengths. Schnopper et al. (1978) described the onset of a huge, 4 yr long radio outburst which peaked around 1980. A more detailed radio light curve of this outburst was presented by Aller et al. (1985); the source showed a 20-fold increase in radio flux density, rising from about 100 mJy at 8 GHz to over 2 Jy within 4 yr. For comparison, the typical amplitude variability in blazars like 3C 279 is usually not much larger than a factor of 2 or 3. The source also shows optical (Lloyd 1984) and X-ray variability (timescale less than 1 day; Kaastra & de Korte 1988; Pounds 1986).

Such a pattern of variability is usually associated with BL Lac objects and blazars, which are thought to be associated with radio galaxies within the unified scheme (e.g., Urry & Padovani 1995). However, as Falcke and coworkers (Falcke 1995; Falcke, Sherwood, & Patnaik 1996b; Falcke, Patnaik, & Sherwood 1996a) have pointed out, III Zw 2 clearly does not fit into these categories. Its time-averaged radio-to-optical flux density ratio R is of the order 200 (Falcke et al. 1996b), which is significantly less than in typical blazars like 3C 273 ($R \sim 2000$) and other flat-spectrum radio quasars. Its extended radio flux density from parsec to kiloparsec scales consists of only a weak 8 mJy component at 1.4 GHz (Unger et al. 1987) and hence cannot be associated with a typical radio galaxy. Radio spectrum and interferometer observations also rule out gigahertz-peaked spectrum (GPS) or compact steep spectrum (CSS) sources, which are considered to be predecessors of giant radio galaxies (O'Dea 1998); the structure as measured with VLBI and MERLIN is pointlike (Falcke et al. 1996a; Kellermann et al. 1998).

The shape and luminosity of the extended radio emission and the host galaxy type are rather typical for a Seyfert galaxy, and it has therefore been suggested that III Zw 2 could be a "weak blazar" in a Seyfert galaxy or radio-quiet quasar, i.e., an intrinsically radio-weak yet relativistic jet pointing toward the observer. Falcke et al. (1995, 1996b) have identified a number of similar sources, named radio-intermediate quasars, which might indeed form such a class of weak blazars.

To test this hypothesis, we have started to watch III Zw 2 more carefully. In the beginning of 1998, it became clear that III Zw 2 would show another major outburst, and we launched a number of observational projects to study the radio evolution of this outburst. Here we report our first results.

2. OBSERVATIONS AND RESULTS

2.1. *Radio Light Curves*

III Zw 2 was reentered into the radio-flux monitoring program at Michigan (Aller et al. 1985) in 1997 May (observations previously ceased at the end of 1995) and thereafter was observed every few days at 4.8, 8, and 14.5 GHz. The 15 GHz flux density rose linearly since then, while the 8 and 4.8 GHz

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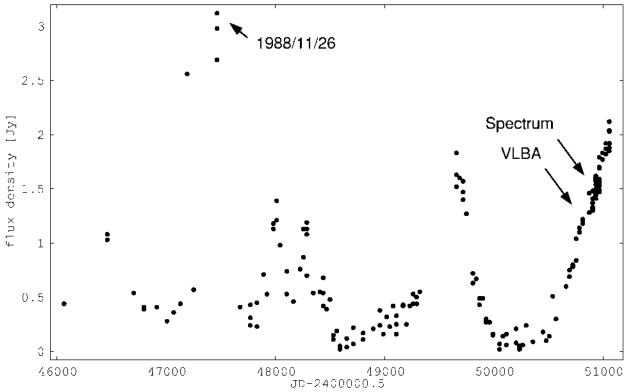

FIG. 1.—Long-term radio light curve of III Zw 2 at 22 GHz, measured at Metsähovi.

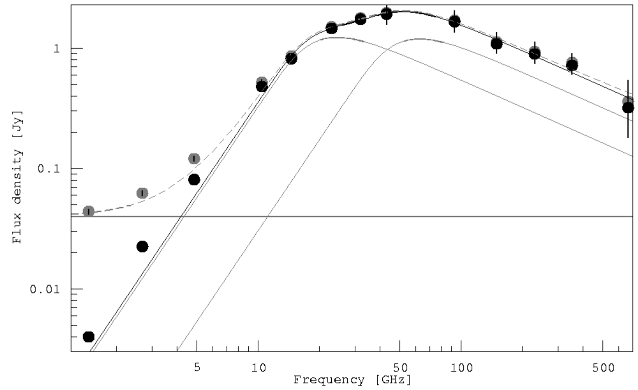

FIG. 2.—Broadband radio spectrum of III Zw 2. Gray dots show the flux densities measured between 1998 May 16 and May 28, and black dots show the outburst spectrum with the quiescent level of 40 mJy subtracted. The two short-dashed lines and the vertical line represent the three fitted components (quiescent level and two self-absorbed synchrotron components), the solid line is the resulting fit to the outburst spectrum (self-absorbed synchrotron components only), and the long-dashed line represents the fit to the total observed spectrum.

flux density levels remained low, indicating an inverted spectrum. In addition, III Zw 2 was also monitored at 22 and 37 GHz at the Metsähovi Radio Research Station (e.g., Teräsranta et al. 1992) over more than 10 yr. The results are shown in Figure 1, in which we have plotted the radio light curve at 22 GHz up until 1998 September. The most recent rise of the flux density is very obvious without any sign of a slowdown of the flare. Its magnitude indicates the advent of a major outburst. A more detailed discussion of the light curves will be given in a later paper.

2.2. *Radio Spectrum*

In addition to the available monitoring data, we used the Very Large Array (VLA), the Effelsberg 100 m telescope, the BIMA array, and the James Clerk Maxwell Telescope (JCMT) to obtain a reliable and almost simultaneous broadband radio spectrum of III Zw 2 extending over two and a half decades in frequency from 1.4 to 660 GHz.

The VLA observations were made in the A configuration on 1998 May 21 simultaneously in L (1.465 GHz) and P (350 MHz) bands with a total integration time of 24 minutes. The source 3C 48 was used as the primary flux density calibrator, and III Zw 2 was self-calibrated and mapped with the Astronomical Image Processing System (AIPS). At 1.4 GHz, we find flux densities of 44 mJy for the core and 8 mJy for an extended, lobelike component 15″ to the southwest. A heavily tapered map reveals a possible bridge between core and lobe. The core also has a weak extension toward the west. The core and the lobe are also seen at 350 MHz, where they are both pointlike. Because the amplitudes of the interferometer data at 350 MHz were corrupted by interference, an absolute flux estimate was not possible. Nevertheless, we can infer from the data that the lobe-to-core ratio at 350 MHz is 0.5, consistent with a flat core and a steep lobe spectrum [e.g., for a typical, yet at this stage completely arbitrary, spectral index of $\alpha = -1$ ($S_\nu \propto \nu^\alpha$) for the lobe, we would get a core flux density of roughly 65 mJy].

III Zw 2 was observed with the Effelsberg 100 m telescope on 1998 May 16 under very good weather conditions at 2.7, 4.9, 10.5, 14.6, 23, 32, and 43 GHz with cross scans (e.g., Kraus 1997). NGC 7027 was used as primary flux density calibrator (Ott et al. 1994). If we make a linear fit with time to the available monitoring data at 15 and 22 GHz, the predicted flux densities for this day differ from the Effelsberg fluxes by only 1.3% and 2.5%, respectively. High-frequency data for III Zw 2 were obtained on 1998 May 20 and 24 with BIMA at 70–110 GHz and with JCMT at 150, 230, 350, and 666 GHz on 1998 May 27 and 28 using Uranus as the flux density calibrator.

The measured flux densities at the various frequencies are plotted in Figure 2 with gray dots. The spectrum is highly inverted at centimeter wavelengths, with a spectral index as high as $\alpha = +1.9 \pm 0.1$ between 4.8 and 10.5. The spectral turnover is around 43 GHz. Some flattening of the spectrum can be seen toward lower frequencies. At frequencies above 43 GHz, the spectrum becomes steep with a spectral index around $\alpha = -0.75 \pm 0.15$.

2.3. *Spectral Fitting*

With the available broad frequency coverage, we are able to decompose the spectrum into its various components. The spectral shape is clearly indicative of an almost homogenous, spherical synchrotron source that becomes self-absorbed below 43 GHz and is optically thin at high frequencies. For such a blob for which S_ν is the observed flux density, D is the distance from the observer, d is the diameter of the blob, and $\kappa_{\rm sync}$ and $\epsilon_{\rm sync}$ are the synchrotron absorption and emission coefficients, the observed spectrum will be given by a simple radiative transfer equation (e.g., Rybicki & Lightman 1979):

$$S_\nu = \frac{d^2}{4D^2}\frac{\epsilon_{\rm sync}}{\kappa_{\rm sync}}\left[1 + e^{-d\kappa_{\rm sync}d}\left(\frac{d\kappa_{\rm sync}}{6} - 1\right)\right]. \qquad (1)$$

For a pitch-angle averaged power-law distribution of electrons with index $p = 2.5$ (between electron Lorentz factors $\gamma_{\rm min} = 1$ and $\gamma_{\rm max} = 10^4$), which is in equipartition with the magnetic field, we obtain $\kappa_{\rm sync} = 2.9 \times 10^{-18} B_0^{4.25} \nu_9^{-3.25}$ cm^{-1} and $\epsilon_{\rm sync} = 5.6 \times 10^{-20} B_0^{3.75} \nu_9^{-0.75}$, where ν_9 is the frequency in GHz and B_0 is the magnetic field in gauss.

In addition to this synchrotron-spectrum, we have to take into account the quiescent spectrum of III Zw 2 on which the outburst spectrum is superposed and which most likely leads to the flattening of the spectrum at lower frequencies. For simplicity, we assume a flat spectrum ($\alpha = 0$). This is indicated by earlier post-flare data and is quite typical for central cores in active galactic nuclei (AGNs) in quiescence. We derive a quiescent flux density level of ∼40 mJy, from satisfying the requirement that the outburst spectrum in the self-absorbed part continues as a power law after subtraction of the quiescent spectrum. This quiescent flux density is consistent with the 350 MHz data and earlier VLA flux observations at 8 GHz in 1992 October by Browne et al. (1998) near a flux density minimum of III Zw 2.

The pure outburst spectrum after subtraction, shown in Figure 2 (*black dots*), can be well fitted by a two-component model. If we ignore relativistic boosting for now (see § 3.3), least-squares fitting of the synchrotron spectrum (Fig. 2, *solid line*) then provides an estimate for the diameters and magnetic fields involved. We find with our equipartition assumption $d = 120$ μas and $B = 0.5$ G for the lower frequency component and $d = 50$ μas and $B = 1.3$ G for the higher frequency component. We note that inclusion of relativistic boosting with typical Lorentz factors of a few would only change these numbers by a factor of a few.

2.4. *VLBA Observations*

Following the onset of the outburst, we activated a VLBA target-of-opportunity program to monitor the structural evolution of the source. A first-epoch observation was made on 1998 February 16 at 43 and 15 GHz. We observed with a total bandwidth of 64 MHz for a full 8 hr scan, where we spent three-quarters of the available observing time at 43 GHz and one-quarter of it at 15 GHz. We reduced the data using the software packages AIPS and DIFMAP (Shepherd, Pearson, & Taylor 1994). Fringes were detected in the III Zw 2 data on all baselines. We calibrated the gains using system temperature information and applied atmospheric opacity corrections. The amplitude gains for the stations at Brewster, North Liberty, and Pie Town were ignored for the absolute amplitude calibration.

The data were then self-calibrated and mapped. For naturally weighted maps, we obtained dynamic ranges of 2000:1 at 43 GHz and 5000:1 at 15 GHz. Down to respective 3 σ levels of 1.3 and 0.4 mJy, no additional components besides the central core were detected. The core itself is resolved at 43 GHz, where the visibilities drop to one-third at 1200 Mλ. It is only marginally resolved at 15 GHz. At 43 GHz, we find a total flux density of 1.6 ± 0.1 Jy, consistent with the total flux density 1.7 ± 0.1 Jy for the source from the monitoring data. An elliptical fit to the UV data gives a source size (FWHM) of 90 μas × 60 μas at P.A. $= -76°$, yielding a brightness temperature of 3×10^{11} K. This elongated structure can also been seen in the superresolved map with a circular beam of 0.1 mas shown in Figure 3 (the nominal beam is 350 × 130 μas at P.A. $= -7°$). The fitted spherical source size at 15 GHz is 100 ± 50 μas for a total flux density of 0.7 Jy, giving a brightness temperature of 5×10^{11} K.

The closure phases at long baselines for the 43 GHz data show a significant deviation from zero, indicating an asymmetric structure. The nonzero closure phases are well fit by a two-component model of a stronger core component (1 ± 0.3 Jy, 50 ± 15 μas) and a weaker secondary component (0.6 ± 0.3 Jy, 65 ± 30 μas) separated by 65 ± 30 μas at P.A. $= 75° \pm 10°$.

3. SUMMARY AND DISCUSSION

3.1. *Self-absorbed Synchrotron Spectra*

Because the current outburst spectrum of III Zw 2 dominates almost the entire radio flux density, we have a unique opportunity to study the spectrum and evolution of such a flare over a wide frequency range with low resolution. In typical AGN radio flares, the spectrum is much more confused by multiple components so that VLBI techniques have to be used to separate them, providing only very small frequency coverage because of the frequency-dependent resolution of the telescopes and resulting blending of the components.

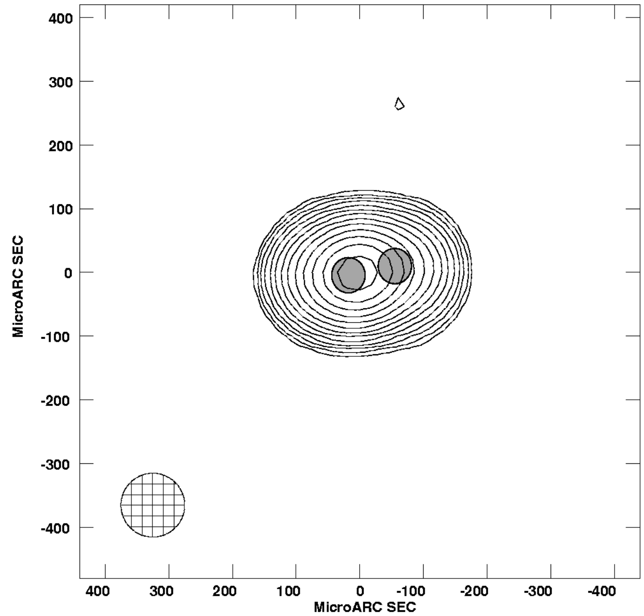

FIG. 3.—VLBA map of III Zw 2 at 43 GHz convolved with a beam of 100 μas. The gray dots represent the two-component model fitting the nonzero closure phases. The center is at RA = $00^h10^m31\overset{s}{.}00587$, decl. = $10°58'29\overset{''}{.}5037$; peak flux equals 1.17 Jy beam^{-1}. The levels are 15 mJy × (−2, −1.4, −1, 1, 1.4, 2, 2.8, 4, 5.7, 8, 11.3, 16, 23, 32, 45, 64).

Hence, our first-epoch spectrum for III Zw 2 already provides a nice confirmation of very basic synchrotron theory, giving a spectrum with a textbook-like shape for the outburst component: starting in the optically thick regime with a spectral index approaching its maximal value of $\alpha = +2.5$, it turns over into the optically thin regime with the typical spectral index of $\alpha = -0.75$. Moreover, the diameters we obtain from the spectral fitting assuming equipartition are consistent with those that we actually measure with the VLBA.

3.2. *Variability, Cooling, and Particle Acceleration*

Since the current outburst began in the beginning of 1997, the 22 GHz flux density of III Zw 2 has risen within ~600 days by at least a factor of 20. Even compared to blazars, this variability amplitude is extreme; for example, the dramatic millimeter flare in NRAO 530 (Bower et al. 1997) had an almost 10 times lower (relative) amplitude. From the relation for the characteristic frequency $\nu_c = 34$ GHz $(B/\mathrm{gauss})(\gamma_e/100)^2$ and with our magnetic field estimate of 1 G, we calculate that the typical electron Lorentz factor at 43 GHz is $\gamma_e = 100$ and at our highest frequency, 666 GHz, is $\gamma_e = 390$. The synchrotron cooling timescales $t_{\mathrm{sync}} = 7.7 \times 10^6$ s $(B/\mathrm{gauss})^{-2}(\gamma_e/100)^{-1}$ at these energies are only 50 and 14 days, respectively, and hence are much shorter than the duration of the current outburst. This directly implies that the region of enhanced emission must also be a region of very efficient in situ particle acceleration.

Since the measured brightness temperature is very close to the Compton limit (a few times 10^{11} K; Readhead 1994) and if relativistic boosting can be ignored (see § 3.3), it is likely that inverse Compton cooling of the relativistic electrons is important. This could lead to nonthermal optical and X-ray emission and could explain the variability in these wave bands as seen in earlier outbursts.

3.3. *Jet Nature and Expansion Velocity*

Another interesting question, of course, is what the nature of this core actually is. As speculated in Falcke et al. (1996a, 1996b), the flat quiescent spectrum measured in the past indicates a similarity to nuclear jets found in other AGNs. This notion is strengthened by the slightly elongated structure found at VLBI scales, the faint extension of the core seen at a similar position angle in the VLA map at 1.4 GHz, and the presence of a lobelike feature 15″ to the southwest. In flux density and morphology, the latter is rather typical for lobes associated with Seyfert jets (e.g., Mrk 34 or Mrk 573; Falcke, Wilson, & Simpson 1998).

Assuming that one or both components were ejected at or before the onset of the flare, we can calculate an upper limit to the expansion velocity of the system. Using the duration of the outburst (600 days) as the timescale and the component separation (0.1 pc) of the components at 43 GHz as the size scale, we calculate a characteristic velocity, i.e., expansion velocity, of $\lesssim 0.2c$. This could either mean a subluminal jet speed or a strong shock in an initially relativistic jet with a speed $\gg 0.2c$ as proposed by Falcke et al. (1996a, 1996b). The relativistic shock scenario seems to be more likely since we have already shown above that particle acceleration is actually taking place. In fact, the shocks could be similar to hot spots in radio galaxies or GPS/CSS sources. Such a scenario also would justify neglecting relativistic boosting in § 2.3.

The highly inverted spectrum of III Zw 2 at GHz frequencies points into a similar direction. We know that such spectral shapes at lower frequencies mainly originate from CSS and GPS sources, where the spectrum is dominated by jets and hot spots on scales much smaller than the galaxy. Hence, one is tempted to call III Zw 2 a millimeter-peaked spectrum (MPS) source, possibly containing ultracompact hot spots and operating on very short timescales compared even to GPS sources. If other, similar MPS sources exist, they might have easily escaped current low-frequency radio surveys and could become important targets for millimeter VLBI experiments.

3.4. *Conclusion*

III Zw 2 remains a puzzle. Its radio core luminosity during outburst is very high ($\sim 4 \times 10^{43}$ ergs s^{-1} at 350 GHz, which is comparable to the radio luminosity of Cygnus A), yet it is apparently located in a spiral galaxy. Moreover, its quiescent flux density and extended structure make it look more like a Seyfert galaxy or radio-quiet quasar. An initially relativistic radio jet—strongly interacting with dense interstellar matter at the subparsec scale, thereby producing an intense shock (hot spot) and slowing down the jet considerably—could be a possible explanation. Because of the simplicity of the source and its very low quiescent level, monitoring of the spectral and structural evolution of the outburst will help to test this or other scenarios and may teach us something about the general nature of radio flares, their expansion speeds, and their connection to particle acceleration. To achieve this, additional monitoring of this outburst at optical and X-ray wavelengths would be highly desirable.

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