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 where the source has brightened more than twenty-fold within less than two years. A broad-band 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 Gauss. VLBA observations at 43 GHz confirm this double structure and these sizes. Time scale 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 hotspots. Similar millimeter-peaked spectrum (MPS) sources could have escaped our attention because of their low flux density at typical survey frequencies and their strong variability.

Subject headings: Galaxies: active—Galaxies: individual: III Zw 2—Galaxies: jets—Galaxies: Seyfert—acceleration of particles—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; 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 NIR galaxy images (Taylor et al. 1996). The bolometric, optical-to-UV, luminosity for III Zw 2 was estimated to be $L_{\rm UV} \sim 10^{45}$ erg/sec (Falcke, Malkan, Biermann 1995; scaled to $H_0 = 75$ km/sec/Mpc as used here).

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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, four year long radio outburst which peaked around 1980. A more detailed radio lightcurve of this outburst was presented by Aller et al. (1985); the source showed a twenty-fold increase in radio flux density, rising from about 100 mJy at 8 GHz to over 2 Jy within four years. For comparison, the typical amplitude variability in Blazars like 3C279 is usually not much larger than a factor two or three. The source also shows optical (Lloyd 1984) and x-ray variability (timescale less than a day; Kaastra & Korte 1986; 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 et al. (1995; 1996a&b) 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. 1996a) which is significantly less than in typical blazars like 3C273 ($R \sim 2000$) 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 a Gigahertz-Peaked-Spectrum (GPS) or Compact-Steep-Spectrum (CSS) source which are considered to be predecessors of giant radio galaxies (O'Dea 1998); the structure as measured with VLBI and MERLIN is point-like (Falcke et al. 1996b; 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 towards the observer. Falcke et al. (1995 & 1996a) have identified a number of similar sources, named radio-intermediate quasars (RIQs), 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 and here report our first results.

2. Observations & Results

2.1. Radio lightcurves

III Zw 2 was re-entered 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 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 (MRRS; e.g. Teräsranta, H. et al. 1992) over more than ten years. The results are shown in Figure 1, where 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 slow-down of the flare. Its magnitude indicates the advent of a major outburst. A more detailed discussion of the lightcurves 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 100m telescope, the BIMA array, and the James-Clerk-Maxwell-Telescope (JCMT) to obtain a reliable and almost simultaneous broad-band 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 A-configuration on 1998 May 21 simultaneously in L (1.465 GHz) and P (350 MHz) band with a total integration time of 24 mins. 3C48 was used as the primary flux density calibrator and III Zw 2 was self-calibrated and mapped with AIPS. At 1.4 GHz we find flux densities of 44 mJy for the core and 8 mJy for an extended, lobe-like component $15''$ to the SW. A heavily tapered map reveals a possible bridge between core and lobe. The core also has a weak extension towards the west. The core and the lobe are also seen at 350 MHz where they are both point-like. 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 100m telescope on 1998 May 16 under very good weather conditions at 2.7, 4.9, 10.5, 14.6, 23, 32, & 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 & 24 with BIMA at 70 through 110 GHz and with JCMT at 150, 230, 350, & 666 GHz on 1998 May 27 & 28 using Uranus as 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 cm 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 towards 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 which becomes self-absorbed below 43 GHz and is optically thin at high frequencies. For such a blob where 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)

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

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 $\kappa_{\rm sync} = 2.9 \cdot 10^{-18} B_0^{4.25} \nu_9^{-3.25}\,{\rm cm}^{-1}$ and $\epsilon_{\rm sync} = 5.6 \cdot 10^{-20} B_0^{3.75} \nu_9^{-0.75}$, 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 AGN in quiescence. We derive a quiescent flux density level of $\sim$ 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 Fig. 2 as black dots, can be well fitted by a two-component model. If we ignore relativistic boosting for now (see Sec. 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 & $B = 0.5$ Gauss for the lower-frequency component and $d = 50$ μas & $B = 1.3$ Gauss 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 16 February 1998 at 43 and 15 GHz. We observed with a total bandwidth of 64 MHz for a full 8 hour scan, where we spent three quarter of the available observing time at 43 GHz and one quarter 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 3σ levels of 1.3 mJy 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$\pm$0.1 Jy consistent with the total flux density 1.7$\pm$0.1 Jy for the source from the monitoring data. An elliptical fit to the UV data gives a source size (FWHM) of 90 μas$\times$60 μas at PA -76°, yielding a brightness temperature of 3×10^{11}K. This elongated structure can also been seen in the super-resolved map with a circular beam of 0.1mas shown in Figure 3 (the nominal beam is 350$\times$130μas at PA $-7°$). The fitted spherical source size at 15 GHz is 100$\pm$50μas 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 non-zero closure-phases are well fit by a two-component model of a stronger core component (1$\pm$0.3 Jy, 50$\pm$15μas) and a weaker secondary component (0.6$\pm$0.3 Jy, 65$\pm$30μas) separated by 65$\pm$30μas at PA 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 the 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.

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 we actually measure with the VLBA.

3.2. Variability, cooling, and particle acceleration

Since the current outburst has begun in the beginning of 1997, the 22 GHz flux density of III Zw 2 has risen within $\sim$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 ten times lower (relative) amplitude. From the relation for the characteristic frequency $\nu_{\rm c}$ =34 GHz $(B/\mathrm{Gauss})(\gamma_{\rm e}/100)^2$ and with our magnetic field estimate of 1 Gauss we calculate that the typical electron Lorentz factor at 43 GHz is $\gamma_{\rm e} = 100$ and at our highest frequency 666 GHz is $\gamma_{\rm e} = 390$. The synchrotron cooling time scales $t_{\rm sync} = 7.7 \cdot 10^6$ sec $(B/\mathrm{Gauss})^{-2}(\gamma_{\rm e}/100)^{-1}$ 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 next section) it is likely that inverse Compton cooling of the relativistic electrons is important. This could lead to non-thermal optical and X-ray emission and could explain the variability in these wavebands 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&b) the flat quiescent spectrum measured in the past indicates a similarity to nuclear jets found in other AGN. This notion is strengthened by the slightly elongated structure found at VLBI scales, the faint extension of the core seen at a similar PA in the VLA map at 1.4 GHz, and the presence of a lobe-like feature 15$''$ to the SW. 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 time scale 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 sub-luminal jet speed or a strong shock in an initially relativistic jet with a speed $\gg 0.2c$ as proposed by Falcke et al. (1996a&b). 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 hotspots in radio galaxies or GPS/CSS sources. Such a scenario also would justify neglecting relativistic boosting in Sec. 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 hotspots on scales much smaller than the galaxy. Hence, one is tempted to call III Zw 2 a millimeter-peaked-spectrum (MPS) source, possibly containing ultra-compact hotspots 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 mm-VLBI experiments.

3.4. Conclusion

III Zw 2 remains a puzzle. Its radio core luminosity during outburst is very high ($\sim 4 \cdot 10^{43}$erg/sec 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 makes it look more like a Seyfert galaxy or radio-quiet quasar. An initially relativistic radio jet, strongly interacting with dense ISM at the sub-pc scale, thereby producing an intense shock (hotspot) 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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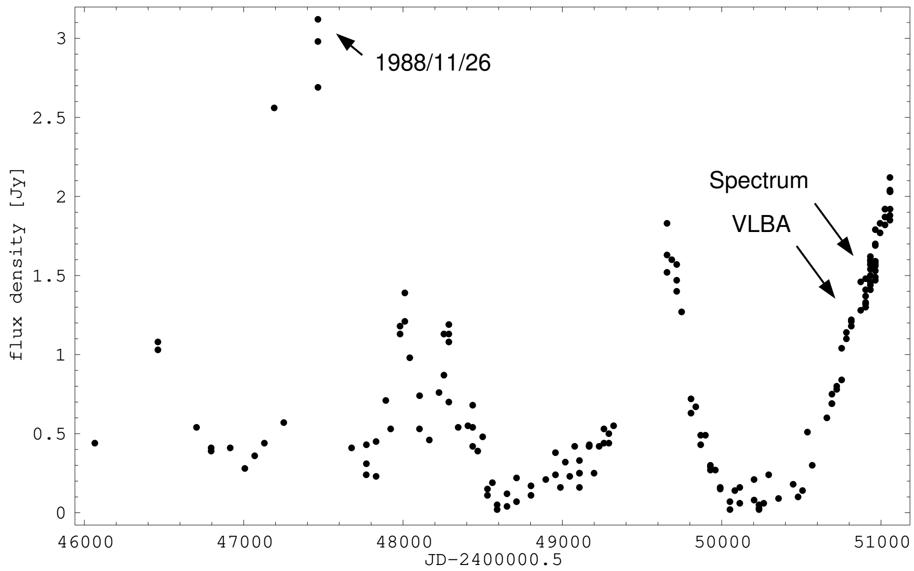
Fig. 1.— Long-term radio lightcurve of III Zw 2 at 22 GHz measured at Metsähovi.

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

Fig. 3.— VLBA map of III Zw 2 at 43 GHz convolved with a beam of 100μas. The gray dots represent the two-component model fitting the non-zero closure phases.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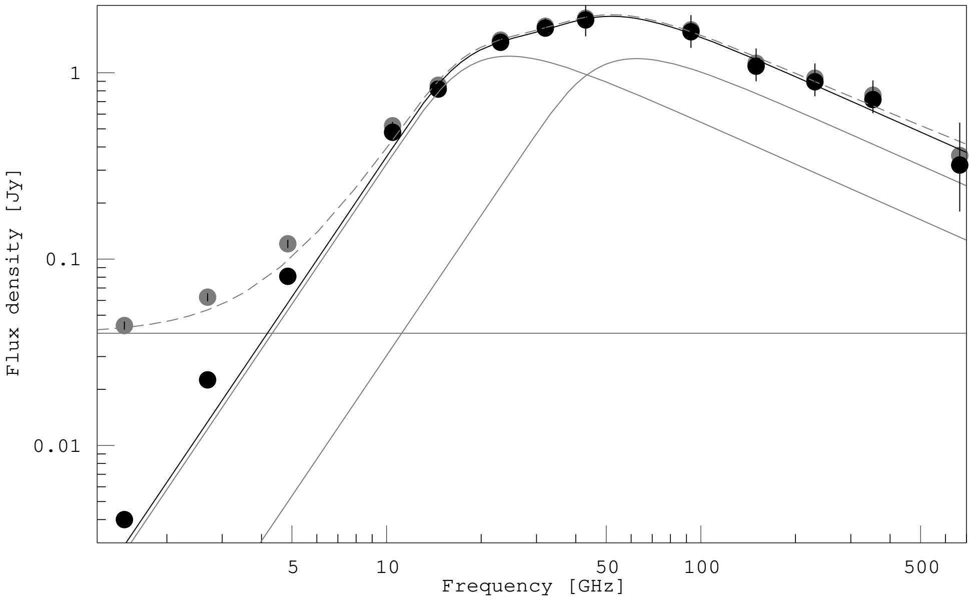
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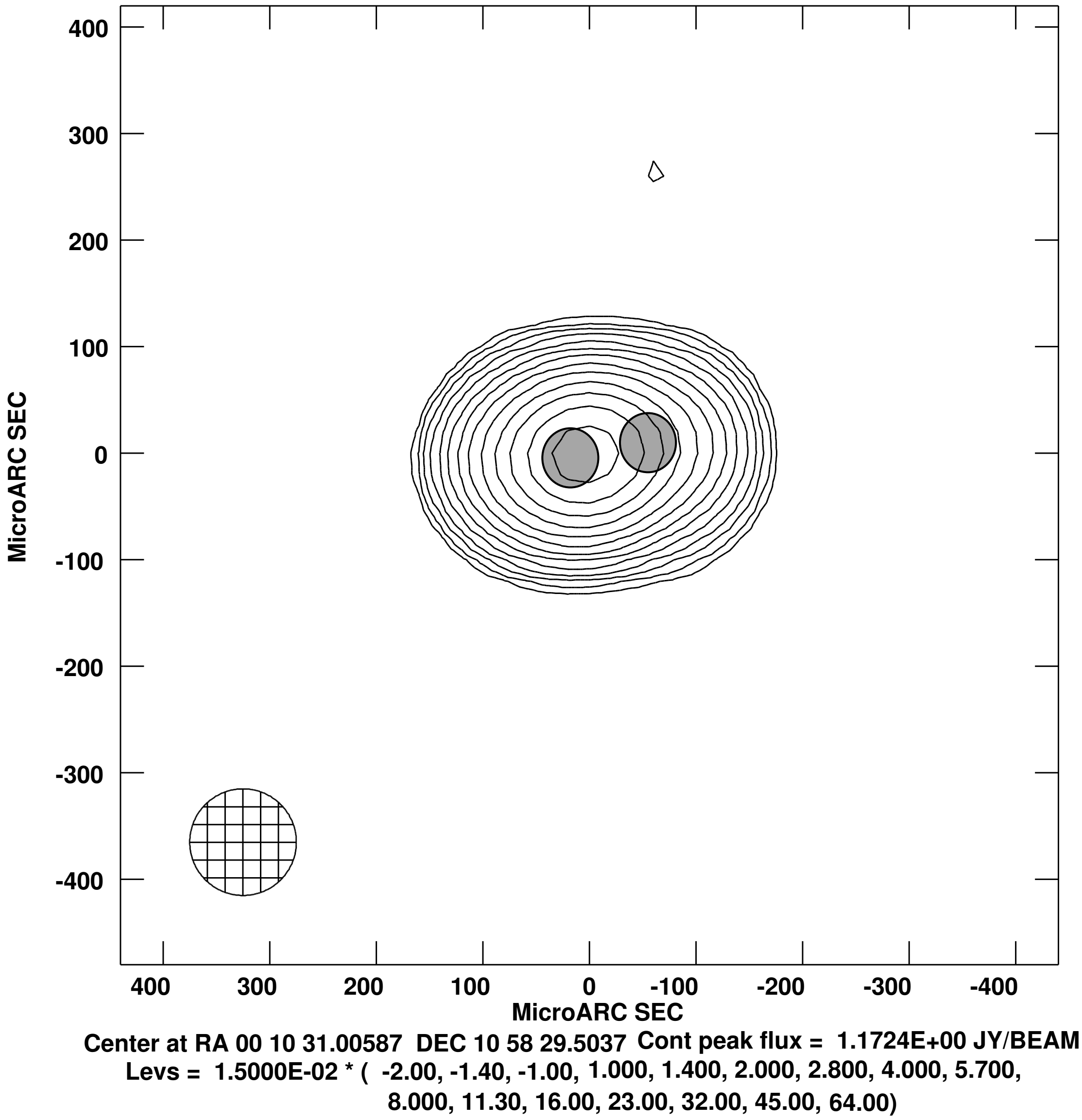
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8.000, 11.30, 16.00, 23.00, 32.00, 45.00, 64.00)