LONG-TERM VARIABILITY OF 3C 273 AT 22 AND 44 GHz

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Received 30 October 1987; revised 25 April 1988

ABSTRACT

In this paper, we report observations of 3C 273 at 22 and 44 GHz during the past 7 yr. Between 1981 and 1984, the QSO was in a high-flux-density state at both frequencies, the intensity decreasing by a factor of 2 during 1985, reaching a minimum value in April 1986. The changes in the flux density were larger at 44 GHz and preceded the changes at 22 GHz. We identified the variability in 1983 with the millimeter and infrared outburst of February 1983, and were able to correlate the observed flux-density fluctuations with the appearance of the superluminal knots observed at 10.7 GHz with VLBI techniques.

I. INTRODUCTION

The study of the variability in the flux density of the radio source 3C 273 began in 1965 and continues up to the present time (Dent 1965; Allen *et al.* 1968; Medd *et al.* 1972; Dent and Kojoian 1972; Dent and Hobbs 1973; Dent *et al.* 1974; Dent and Kapitzky 1976; Altschuler and Wardle 1976; Andrew *et al.* 1978; Epstein *et al.* 1982).

Simultaneous observations at several frequencies have shown that the spectrum of 3C 273 is flat between 1.4 and 30 GHz, and that it steepens at higher frequencies, with the turning point somewhere between 30 and 90 GHz (Owen *et al.* 1978; O'Dell *et al.* 1978; Owen *et al.* 1980; Jones *et al.* 1981; Landau *et al.* 1983). However, the observed shape of the spectrum during a 10 yr period changed frequently, as was shown by Epstein *et al.* (1982) in their comparison between data at 90 GHz and at lower frequencies. Measurements of the flux density at 1 mm wavelength show large variability, not correlated with variability at lower frequencies in the same epoch (Elias *et al.* 1978; Kreysa *et al.* 1980; Jones *et al.* 1981; Ennis *et al.* 1982; Sherwood *et al.* 1983; Chini *et al.* 1984; Gear *et al.* 1984). Short-term variability (timescales of hours and days) was found at 22 GHz by Efanov *et al.* (1977), at 90 GHz by Landau *et al.* (1983), and at 300 GHz by Sherwood *et al.* (1983). An optical and infrared outburst was observed in 1983 (Robson *et al.* 1983; Sadun 1985). Further measurements in the infrared were reported by Roelling *et al.* (1986) and Robson *et al.* (1986). X-ray variability was observed by Marshall *et al.* (1981) and Besler *et al.* (1984).

Although it is generally accepted that the continuum radio emission from quasars is produced by synchrotron radiation of relativistic electrons, the geometry of the source and the process of acceleration and injection of the energetic particles are still not very well understood. VLBI observations at 2.3, 5, and 10.7 GHz show that the emission at these frequencies arises from several optically thin components or knots, which are separating from an unresolved optically thick core at apparently superluminal velocities (Cohen *et al.* 1971, 1983; Unwin *et al.* 1985; Cohen *et al.* 1987). The evolution of the knots was interpreted in terms of adiabatically expanding homogeneous sources in a relativistic jet which forms a small angle with the line of sight (Unwin *et al.* 1985). The evolution of the 1983 infrared outburst cannot be explained by such a simple model. Nonhomogeneous sources with special laws for the energetic-particle injection can reproduce the observations, although in such a model the number of free parameters is large (Marsher 1977; Gould 1979). Marsher and Gear (1985) obtained good

agreement with the observations using a model of a shock wave propagating in a relativistic jet. Other geometries have been proposed to confine the relativistic electrons, such as the expanding toroidal flux tube of Sturrock (1985). Several models of relativistic electrons in a plasma jet were studied; the jets could be propagating either nonrelativistically (Camezind and Courvoisier 1984) or relativistically (Konigl 1981; Marsher and Gear 1985).

In this paper, we report observations of 3C 273 at 22 GHz and 44 GHz during a 7 yr period. These frequencies have not been used for long-term variability studies except for a 2 yr period at the frequency of 24 GHz, reported by Haddock *et al.* (1987). At these frequencies, the atmospheric opacity is large and variable, and even with low-noise detectors and careful calibrations the uncertainty in the measurements can be as large as 10%.

II. OBSERVATIONS

The observations were made at the frequencies of 22 and 44 GHz with the 13.7 m radome enclosed Itapetinga radio telescope. The feed consisted of a rectangular horn, sensitive to the vertical component of the **E** vector. The half-power beamwidths were 4'2 and 2'1 at 22 and 44 GHz, respectively. The receiver was a *K* band mixer with a 1 GHz d.s.b., giving a system temperature (including sky temperature) of about 1000 K. The receiver was operated in the total-power mode. The observations consisted of scans through the source at constant elevation, with an amplitude in the sky of 60' at 22 GHz and 30' at 44 GHz. Each observation consisted, on the average, of 30 scans of 20 s duration, and was preceded by a calibration with a noise source and with a room-temperature load, to account for the effects of atmospheric absorption (Abraham *et al.* 1986). A baseline was subtracted from the data to eliminate the contribution of the sky temperature. Absolute flux calibration was obtained from observations of Virgo A, which has a flux density of 21.5 Jy at 22 GHz and 11.5 Jy at 44 GHz (Jansen *et al.* 1974). The planets Venus and Jupiter were also used as calibrators, especially at 44 GHz. The measurements reported here are generally the average of twelve 10 min observations (2 hr integration). The errors are the rms fluctuation of the 12 observations, and include the effects of changes in the atmospheric transmission and antenna-efficiency calibration.

III. RESULTS

The flux densities of 3C 273 at 22 and 44 GHz during the period 1980–1987 are presented in Fig. 1. In Table I we give

FIG. 1. Time behavior of 3C 273. Dots represent the 22 GHz data and stars the 44 GHz data. The lines joining the data points are included for visual purposes only. Error bars represent the rms fluctuation of the data.

the exact date, the flux density, and the rms error of the observations.

Between our first observation at 22 GHz in July 1980 (Abraham *et al.* 1982) and October 1981, the flux density increased by a factor of 1.7, and a program of systematic observations was started at that time. Whenever possible, observations at 44 GHz were also performed. The flux density of 3C 273 remained at a high level at both frequencies for the following 4 yr, presenting quasiperiodic fluctuations with amplitudes of approximately 15 Jy and timescales of about 1 yr. Although the observations at 44 GHz during the period were scarce and irregularly spaced, they seem to follow the same pattern as the 22 GHz data. The changes in the intensity were larger at 44 GHz. A continuous decrease in the flux density was observed, starting in December 1984 and ending in April 1986, when it reached its minimum value. Since then, 3C 273 has remained in a low-flux-density state, with fluctuations at both frequencies.

In Fig. 2, we present our 22 GHz observations for the period 1981–1983 together with the data at 24 GHz obtained by Haddock *et al.* (1987) and at 90 GHz reported by Baker (1983). The correlation between the data at 22 and 24 GHz is very good. The flux density at 22 GHz was systematically higher (approximately 5%) than the flux density at 24 GHz, probably due to the different methods used in each case for the determination of the atmospheric absorption and differences in the values adopted for the flux density of the standard sources. The 90 GHz data presented the same time behavior as the 22–24 GHz data, with a delay of about 4 months. The increase in the flux density in 1983 started earlier at higher frequencies. The amplitude of the variability was larger at 90 GHz (about 30 Jy) than at 22 GHz (about 15 Jy).

In Fig. 3, we present the spectra of 3C 273 between 5 and 10^3 GHz, at several epochs, with data obtained from the literature together with our data at 22 and 44 GHz. We observe that in most cases the amplitude of the changes in the flux density was larger at higher frequencies, as in the infrared outburst at the beginning of 1983, or the outburst at 1 mm observed at the end of 1980. The spectra at the beginning

TABLE I. Flux densities of 3C 273 at 22 and 44 GHz.

Date	S(22) (Jy)	S(22) (Jy)	S(44) (Jy)	S(44) (Jy)
20 Jul. 1980	25.0	0.6		
11 Oct. 1981	42.0	1.2		
25 Nov. 1981	40.8	0.8		
17 Dec. 1981	38.1	0.8		
13 Feb. 1982	35.1	2.4		
15 Mar. 1982	38.2	0.8		
18 Aug. 1982	45.7	1.0		
22 Aug. 1982			49.6	0.9
25 Sep. 1982	43.6	0.6	41.3	0.5
7 Nov. 1982	46.4	0.6		
12 May 1983	36.6	0.8		
10 Jul. 1983			43.2	1.0
12 Jul. 1983	42.5	0.6		
12 Oct. 1983	46.1	1.6	46.7	1.3
27 Nov. 1983	50.1	0.5	41.8	0.7
14 Mar. 1984	43.5	0.6		
18 Apr. 1984	42.3	0.9		
8 Jun. 1984	47.3	0.6		
28 Jun. 1984			44.9	1.6
12 Jul. 1984	46.4	0.9	46.6	0.8
16 Jul. 1984			50.2	2.7
26 Aug. 1984	46.4	0.7	42.3	1.5
21 Oct. 1984	44.6	0.8		
22 Oct. 1984			32.7	1.0
19 Dec. 1984	48.2	2.3	40.2	1.4
28 Mar. 1985	36.9	1.5		
27 Jul. 1985	35.6	1.1		
21 Aug. 1985	29.9	0.6		
16 Sep. 1985	29.1	0.6		
23 Sep. 1985	31.9	1.4		
17 Oct. 1985	24.7	1.0		
27 Oct. 1985	25.4	0.8		
21 Nov. 1985	25.5	0.9		
22 Jan. 1986	24.1	1.0		
27 Feb. 1986	22.8	0.4		
10 Apr. 1986	19.7	0.6		
18 Apr. 1986			13.9	2.4
28 May 1986	31.5	0.9	11.1	1.4
19 Jun. 1986	24.9	0.7		
20 Jun. 1986			13.4	0.2
22 Aug. 1986	22.0	1.1		
23 Aug. 1986			12.0	0.5
17 Sep. 1986	24.6	0.6		
28 Oct. 1986	25.0	1.0		
31 Oct. 1986			17.5	0.9
6 Dec. 1986	26.4	1.5	25.8	1.8
15 Feb. 1987			19.8	0.6
17 Feb. 1987	33.0	0.9		
9 Apr. 1987	30.5	0.5		
11 Apr. 1987			26.4	1.4
26 May 1987	29.2	0.8		
11 Jun. 1987			16.9	0.6
12 Jun. 1987	25.6	0.6		
5 Aug. 1987	24.8	0.5		
1 Sep. 1987	27.7	0.5		

of 1982 and during 1986 are very similar in shape. Between 22 and at least 300 GHz, the intensity in 1982 was higher by a factor of 2. In these epochs, the turnover in the spectra occurred at frequencies below 22 GHz.

IV. DISCUSSION

One of the principal questions that arises in the study of quasar emission is the correlation between variability at dif-

FIG. 2. Comparison between the 90 GHz data of Baker (1983) (dots in the upper part of the figure) and our 22 GHz data and the 24 GHz data of Haddock (1987) (large dots and squares in the lower part of the figure, respectively). Notice the difference in the scales for the 90 GHz and the 22–24 GHz data.

ferent frequencies. VLBI observations show that in 3C 273 the 10.7 GHz emission is the result of the superposition of several optically thin components, while the 22 GHz emission originates mostly in the core and maybe in some compact components, which are optically thick at 10.7 GHz (Unwin *et al.* 1985). It is possible, however, to relate our observations with the structures detected with VLBI at lower frequencies. First, we should note that the rate of occurrence of superluminal knots is about one per year (Unwin *et al.* 1985; Cohen *et al.* 1987), similar to the variability period shown by the 22 GHz data. The increase in the flux density at 22 GHz between 1980 and 1982 can be related to the doubling of the flux density of the core at 10.7 GHz between 1981.1 and 1982.1 (Unwin *et al.* 1985). The 1983 millimeter and infrared outburst reported by Robson *et al.* (1983) can be traced to the data at 22, 24, and 90 GHz presented in Fig. 2. In order to obtain a qualitative picture of the propagation

of the outburst at different frequencies, we shall adopt as the date of the beginning of the flare 1 February 1983 (Marsher and Gear 1985). We estimate that the maxima in the intensity at 90 and 22 GHz occurred 70 and 290 days later, respectively. These values are not very precise, since the spectra seemed to contain another component, with decreasing flux density during the evolution of the flare. For this reason, the amplitude of the flare could not be well determined either; 30 Jy for 90 GHz and 15 Jy for 22 GHz represent a lower limit. Marsher and Gear (1985) adopted amplitudes of 14 and 26 Jy for the frequencies of 370 and 300 GHz, respectively, based on an unperturbed spectrum of Clegg *et al.* (1983). We notice that the amplitude of the flare increased as the frequency of maximum intensity decreased at least up to the frequency of 90 GHz. This behavior was explained by Marsher and Gear (1985) in a model of shock waves propagating in a relativistic jet. When the Compton losses of the

FIG. 3. Spectra of 3C 273 at different epochs. The numbers beside each point represent the month of the observation. The 22 and 44 GHz data are from this paper. Data at other frequencies are from Ennis *et al.* (1982), Clegg *et al.* (1983), Barvainis (1984), Gear *et al.* (1984), and Robson (1986).

relativistic electrons dominate over synchrotron or radiative losses, it is possible to obtain the observed increase in flux density with a decrease in the frequency of the maximum. Between 90 and 22 GHz, the amplitude of the outburst decreased. The synchrotron losses probably dominated at that time. If we assume that the shock wave is propagating at a constant velocity, the radii of the shock would be $3.9h^{-1}$ pc and $7.5h^{-1}$ pc when the frequency of the maxima was 90 and 22 GHz, respectively. h is the Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. When synchrotron losses dominate, the frequency of maximum intensity is related to the radius of the shocked region by

$$\nu_m \propto R^x, \quad (1)$$

with

$$x = \frac{4(s+2) + 3a(s-1)}{3(s+5)}, \quad (2)$$

where s is obtained from the energy distribution of the relativistic electrons $N(E)$ given by

$$N(E) dE \propto E^{-s} dE \quad (3)$$

and a is related to the variation law of the magnetic field B by

$$B \propto R^{-a}. \quad (4)$$

s is related to the index α ($S \propto \nu^\alpha$) of the flaring component by

$$s = 1 - 2\alpha. \quad (5)$$

As mentioned before, we cannot separate with precision the spectrum of the flaring component, and therefore we do not know the value of α between 90 and 22 GHz.

The relation between the amplitude of the flare and the frequency of maximum intensity is given by

$$S_m \propto \nu_m^{-y}, \quad (6)$$

with

$$y = \frac{(2s-5)(2+3a)}{4(s+2) + 3a(s-1)}. \quad (7)$$

From the observations, we obtain $x = 1.4$ and $y = 0.33$, which give $s = 3.2$ for $a = 2$. The value found for a is larger than the one adopted by Marsher and Gear (1985), $a = 1$, indicating that if the model is correct the magnetic field should decrease faster with the distance to the center of the source.

Extrapolating this model, we found that when the frequency of the maximum in the spectrum is 10.7 GHz, the distance between the shock and the origin of the jet is $10h^{-1}$ pc. The shock wave reaches this point 266 days after the beginning of the outburst; that is, in October 1983. The intensity at that time was 14 Jy. The knot C7, first detected in 1984.1 at 10.7 GHz (Biretta *et al.* 1985), could be the result of the 1983 millimeter and infrared flare.

In the same way, we could follow the evolution of a component that had a maximum at 44 GHz around July 1984 and at 22 GHz in December of the same year. If we assume the same values of a and s as for the previous model, we conclude that the maximum intensity at 44 GHz occurred approximately 280 days after the beginning of the flare. Extrapolating to 10.7 GHz, the maximum in the spectrum would occur 160 days after the maximum at 22 GHz. The component C8 detected at 1985.6 (Cohen *et al.* 1987) could correspond to this source. A more detailed analysis between the data at 22 and 44 GHz and VLBI observations is not yet available. More frequent single-dish observations are needed, at closer frequencies, as well as systematic VLBI observations at 10.7 GHz and higher frequencies.

This work was partially supported by the Brazilian research agencies CNPq and FINEP.

REFERENCES

- Abraham, Z., Kaufmann, P., and Botti, L. C. L. (1982). *Astron. J.* **87**, 532.
 Abraham, Z., Botti, L. C. L., and Del Ciampo, L. (1986). *Rev. Mex. Astron.* **12**, 414.
 Allen, R. J., Barrett, A. H., and Crowther, P. P. (1968). *Astrophys. J.* **151**, 43.
 Altschuler, D. R., and Wardle, J. F. C. (1976). *Mem. R. Astron. Soc.* **82**, 1.
 Andrew, B. H., MacLeod, J. M., Harvey, G. A., and Medd, W. J. (1978). *Astron. J.* **83**, 863.
 Baker, D. C. (1983). In *VLBI and Compact Radio Sources*, IAU Symposium No. 110, edited by R. Fanti, K. Kellermann, and G. Setti (Reidel, Dordrecht), p. 31.
 Barvainis, R. E. (1984). Ph.D. thesis, University of Massachusetts.
 Bezler, M., Kendziorra, E., Staubert, R., Hasinger, G., Piesh, W., Reppin, C., Trumper, J., and Voges, W. (1984). *Astron. Astrophys.* **136**, 351.
 Biretta, J. A., Cohen, M. H., Hardebeck, N. E., Kaufmann, P., Abraham, Z., Peretto, A. A., Scalise, E., Jr., Schaal, R. E., and Silva, P. M. (1985). *Astrophys. J. Lett.* **292**, L5.
 Camezind, M., and Courvoisier, T. J.-L. (1984). *Astron. Astrophys.* **140**, 341.
 Chini, R., Kreysa, E., Mezger, P. G., and Gemund, H.-P. (1984). *Astron. Astrophys.* **137**, 117.
 Clegg, P. E., Gear, W. K., Ade, P. A. R., Robson, E. I., Smith, M. G., Nolt, I. G., Radostite, J. V., Glaccum, W., Harper, D. A., and Low, F. J. (1983). *Astrophys. J.* **273**, 58.
 Cohen, M. H., Cannon, W., Purcell, G. H., Shafer, D. B., Broderick, J. J., Kellermann, K. I., and Jauncey, D. L. (1971). *Astrophys. J.* **170**, 207.
 Cohen, M. H., Unwin, S. C., Lind, K. R., Moffet, A. T., Simon, R. S., Wilkinson, P. N., Spencer, R. E., Booth, R. S., Nicolson, G. D., Niell, A. E., and Young, L. E. (1983). *Astrophys. J.* **272**, 383.
 Cohen, M. H., Zensus, J. A., Biretta, J. A., Comoretto, G., Kaufmann, P., and Abraham, Z. (1987). *Astrophys. J. Lett.* **315**, L89.
 Dent, W. A. (1965). *Science* **148**, 1458.
 Dent, W. A., and Hobbs, R. W. (1973). *Astron. J.* **78**, 163.
 Dent, W. A., and Kapitzky, J. E. (1976). *Astron. J.* **81**, 1053.
 Dent, W. A., Kapitzky, J. E., and Kojan, G. (1974). *Astron. J.* **79**, 1232.
 Dent, W. A., and Kojan, G. (1972). *Astron. J.* **77**, 819.
 Efanov, V. A., Moiseev, I. G., Nesterov, N. S., and Shakhovskoy, N. M. (1977). *Nature* **269**, 493.
 Elias, J. H., Ennis, D. J., Gezari, D. Y., Hauser, M. G., Houck, J. R., Lo, K. Y., Matthews, K., Nadeau, D., Neugebauer, G., Werner, M. W., and Westerbrook, W. E. (1978). *Astrophys. J.* **220**, 25.
 Ennis, D. J., Neugebauer, G., and Werner, M. (1982). *Astrophys. J.* **262**, 451.
 Epstein, E. E., Fogarty, W., Mottmann, J., and Schneider, E. (1982). *Astron. J.* **83**, 863.
 Gear, W. K., Robson, E. I., Ade, P. A. R., Smith, M. G., Clegg, P. E., Cunningham, C. T., Griffin, M. J., Nolt, I. G., and Rodostitz, J. V. (1984). *Astrophys. J.* **280**, 102.
 Gould, R. J. (1979). *Astron. Astrophys.* **76**, 306.
 Haddock, T. F., Aller, H. D., and Aller, M. F. (1987). *Astron. J.* **93**, 1356.
 Janssen, M. A., Golden, L. M., and Welch, W. J. (1974). *Astron. Astrophys.* **33**, 373.
 Jones, T. W., Rudnick, L., Owen, F. N., Puschell, J. J., Ennis, D. J., and Werner, M. W. (1981). *Astrophys. J.* **243**, 97.

- Konigl, A. (1981). *Astrophys. J.* **243**, 700.
- Kreysa, E., Pauliny-Toth, I. I. K., Schultz, G. V., Sherwood, W. A., and Witzel, A. (1980). *Astrophys. J.* **240**, 117.
- Landau, R., Jones, T. W., Epstein, E. E., Neugebauer, G., Soifer, B. T., Werner, M. W., Puschell, J. J., and Balonek, T. J. (1983). *Astrophys. J.* **268**, 68.
- Marshall, N., Warwick, R. S., and Pounds, K. A. (1981). *Mon. Not. R. Astron. Soc.* **194**, 987.
- Marsher, A. P. (1979). *Astrophys. J.* **216**, 244.
- Marsher, A. P., and Gear, W. K. (1985). *Astrophys. J.* **298**, 114.
- Medd, W. F., Andrew, B. H., Harvey, G. A., and Locke, F. L. (1972). *Mem. R. Astron. Soc.* **77**, 109.
- O'Dell, S. L., Puschell, J. J., Stein, W. A., Owen, F., Porcas, R. W., Mufson, S., Moffet, T. J., and Ulrich, M.-H. (1978). *Astrophys. J.* **224**, 22.
- Owen, F. N., Porcas, R. W., Mufson, S. L., and Moffet, T. J. (1978). *Astron. J.* **83**, 685.
- Owen, F. N., Sprangler, S. R., and Cotton, W. D. (1980). *Astron. J.* **85**, 351.
- Robson, E. I., Gear, W. K., Clegg, P. E., Ade, P. A. R., Smith, M. G., Griffin, M. J., Nolt, I. G., Radostitz, J. U., and Howard, R. J. (1983). *Nature* **305**, 194.
- Robson, E. I., Gear, W. K., Brown, L. M. J., Courvoisier, T. J.-L., Smith, M. G., Griffin, M. J., and Blecha, A. (1986). *Nature* **232**, 134.
- Roelling, T. L., Becklin, E. E., Impey, C. D., and Werner, M. W. (1986). *Astrophys. J.* **304**, 646.
- Sadun, A. C. (1985). *Publ. Astron. Soc. Pac.* **97**, 395.
- Sherwood, W. A., Kreysa, E., Gemund, H.-P., and Bierman, P. (1983). *Astron. Astrophys.* **117**, L5.
- Sturrock, P. A. (1985). *Astrophys. J.* **293**, 52.
- Unwin, S. C., Cohen, M. H., Biretta, J. A., Pearson, T. J., Sielstad, G. A., Walker, R. G., Simon, R. S., and Lindfield, R. P. (1985). *Astrophys. J.* **289**, 109.

FIG. 1. Left-hand panels: Reproduction of the central part (128×128 pixels, 1 pixel = $0''.365$) of the CCD images of NGC 1172 and NGC 1199. Right-hand panels: dust lanes in the same two galaxies, extracted by modeling the bright bulges (see the text).

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