Modelling the millimetre–infrared flaring behaviour of the quasar 1253−055 (3C 279)

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ABSTRACT
The infrared through millimetre light curve of 3C 279 is investigated for the period of 1986 until mid-1994, during which time several flares were observed. A quiescent spectrum (identified with emission from an underlying jet) is presented. Both the near-IR and 375–150 GHz regimes are shown to be well described by power laws, with no evidence for any thermal contribution in the IR. Successful isolation of the flaring component by subtraction of a base level is found to be difficult. Dividing each individual flare into two regimes corresponding to before and after maximum flux, we find strong linear correlations between log 90 GHz flux and 22–90 GHz spectral slope. Furthermore, the gradient of the linear correlation steepens as the flare decays after maximum. This trend is observed for several successive flares, and can be successfully explained in terms of evolution of the flare according to the the shocked-jet model of Marscher & Gear (1985).

Key words: quasars: individual: 3C 279 – radio continuum: galaxies – radiation mechanisms: non-thermal – galaxies: jets

1 INTRODUCTION

The object 1253−055 (3C 279) is a member of that class of active galactic nucleii (AGN) known as blazars, comprising BL Lacertae objects and optically violently variable (OVV) quasars (see Bregman 1990 for a review). 3C 279 is a member of the latter group, and exhibits those properties evinced by sources typical of the blazar phenomenon: strongly variable radio to optical polarization (e.g. Hughes, Aller & Aller 1991, Wills et al. 1992, Nartallo-Garcia et al., in preparation), significant flux variability (e.g. Webb et al. 1990, Edelson 1992, Stevens et al. 1994 [hereafter BLZ5]), and a flat or slowly declining radio spectrum (e.g. Brown et al. 1989a, Gear et al. 1994). In addition it is a strong superluminal radio source (Unwin et al. 1989) and has shown highly variable emission at energies in excess of 1 GeV (Kniffen et al. 1993).

In a previous paper (BLZ5) we presented light curves for our complete sample of sources from K-band in the near-infrared to 22 GHz, including a representative spread of frequencies around the transition from optically thin to thick emission (375, 270, 230, 150 GHz). The flaring behaviour was analysed in the context of the shocked-jet model of Marscher & Gear (1985); hereafter MG85. In this model the individual flares evolve through three distinct phases, depending on the dominant energy loss mechanism. In the initial growth phase Compton energy losses predominate and the synchrotron self-absorption turn-over frequency decreases whilst the turn-over flux increases. The second (synchrotron or plateau) phase occurs when synchrotron losses dominate. In this phase the turn-over flux is roughly constant whilst the turn-over frequency decreases. Finally the flare reaches the adiabatic or decay phase when both the turn-over flux and frequency decrease. The appearance of the light curve for any given frequency depends on whether the observing frequency lies on the rise, plateau or decay phase. Flare maximum is attained simultaneously at observing frequencies above the transition from Compton to synchrotron phase; the amplitude of the flare increases with decreasing frequency. Below this transition, flare maximum occurs when the turn-over passes the observing frequency; lags between maxima correspond to the time taken for the turn-over to evolve to longer wavelengths. It was found that, for a number of sources (3C 279 included), the delays between flare maxima at different frequencies and the amplitudes of the flares at those frequencies were roughly in agreement with the above picture. However, spectral deconvolution of the flaring emission from any underlying component is necessary to confirm the details of the model described above,

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Figure 1. Light curves for 3C 279.

and furthermore to provide necessary information which can lead to refinement of the model. The aim of this paper is to look at ways in which the data presented in BLZ5 can be used to aid development of shocked-jet models.

2 OBSERVATIONS

This paper analyses substantially the same data as was presented in BLZ5, and the observations are discussed in detail in that paper (see also Robson et al. 1993). To summarize, the bulk of the 150–375 GHz data were obtained at the James Clerk Maxwell Telescope, Mauna Kea, using the UKT14 bolometer (Duncan et al. 1990). Additional 230 and 150 GHz data, as well as all the 90 GHz observations, were obtained from the IRAM 30-m telescope at Pico Valeta (see Steppe et al. 1993 for instrument and reduction details), and from the SEST, La Silla (see Booth et al. 1989). The 37 and 22 GHz data came from the Metsähovi Radio Research Station, Kylmälä (Teräsranta et al. 1992). The infrared observations were obtained mostly at the United Kingdom Infrared Telescope (UKIRT), Mauna Kea, or at the ESO 2.2-m telescope, Chile (see Litchfield, Robson & Stevens 1994 and references therein for data and reduction details).

3 RESULTS

3.1 Overview of data

The light curves for 3C 279 from the beginning of 1986 until mid 1994 are presented in Fig. 1. The K-band is shown as being representative of the near-IR; the full 1.25–10.0 μm data set is tabulated in Litchfield et al. 1994.

The key features of the behaviour of the source can be summarized as follows. There was a major flare in 1988 which was well covered at IR frequencies and at 37, 22 GHz, but largely under-sampled elsewhere. Subsequent flares were well sampled at all frequencies except the near-IR. Between mid 1989 and early 1990 there was a period of low flux, followed by a large flare, the onset of which began in early 1990. This flare has the appearance of being two flares occurring in rapid succession: the flare of early 1990 is seen to reach a maximum in late June at 150 and 90 GHz, and then to decline slightly before rapidly rising to a maximum in late 1990/early 1991. At 90 and 37 GHz the rise is clearly broken into two regions of markedly different gradient: the rate of change of flux increases sharply in the latter part of 1990. This indicates the onset of a new flare at this time, since the onset of a flare is seen to be much more rapid than the subsequent decay (Robson et al. 1993).

The flare decreased through 1991 at all frequencies except for 22 GHz. This decline was reversed in late 1991 with a further small peak followed by a decline to a level concordant with quiescence (at JCMT frequencies) in mid 1992. For frequencies below 150 GHz the low level achieved in 1992 was much higher than the quiescent level. This indicates the slower decay time-scales of flares at lower frequencies which is a feature of the MG85 model. Further small flares occurred in 1993 and 1994. It should be noted that, at lower frequencies (particularly 22 GHz) the individual features have merged into a broader but shallower hump, and the light curve at 22 GHz is markedly different in shape to the light curves at higher frequencies.

The behaviour is thus seen to be complex, particularly after 1990, when a number of flares, probably about 5, occur over the space of 4 years. These can be readily distinguished at higher frequencies, but merge together in the radio regime as a result of the increased time constant.

3.2 Quiescent spectrum

Investigations of flaring behaviour of blazars tend to concentrate on modelling epochs when the flux is significantly raised above some base level. This base level can be identified with the emission from some underlying jet along which shocks (identified with the flares) are propagating (MG85), and is generally assumed to be quasi-steady in that it is much less variable than the flares which are superimposed upon it (but see van der Walt 1993). In a previous paper (Robson et al. 1993) we were able to identify, for 3C 273, an extended period of low flux with this quiescent emission (henceforth we use the word quiescent to refer to the underlying jet).

It can be seen from Fig. 1 that during the periods 1986–1994 the nearest thing to a quiescent state occurred in 1989–1990 which separated the two large flares of 1988 and 1991. During this period the flux was largely stable at 375 and 270 GHz, somewhat noisy at 230 GHz, and declining slightly at 150 GHz. We bin the data over some arbitrarily selected period and adopt the weighted mean of the data in the bin as the average quiescent flux. This procedure can be used for both the sub-mm and IR regions. The monitoring in the infrared during this time was rather sparse and also rather noisy (indicating a fair amount of activity in the source, even during a low state. This is reflected in the noise at 230 and 150 GHz.) This activity is to be contrasted with the extended period of low flux seen in the infrared during 1983–early 1986 (Gear et al. 1985, 1986; Brown et al. 1989a). The flux levels during 1983–1986 are typically within 1 mJy of the lowest flux levels seen in 1990, and for this reason it is probably justified to use the low values taken from Brown et al. (1989a) to estimate the infrared flux during our nominal quiescent period.

In summary, the IR data were binned from 1983 January 11 to 1986 February 24, whilst the 375–150 GHz data were binned from 1989 June 20 to 1990 April 7. For the 90–22 GHz data, selected periods were used when the flux seemed to have attained its lowest level (1986 January 17 to 1986 April 8). The resulting quiescent spectrum is shown in Fig. 2. The spectral index, α (defined as $F_\nu \propto \nu^\alpha$ where F_ν is the flux and ν frequency) is calculated for the millimetre (150–375 GHz) and near-IR by a weighted χ^2 fit. The mm index is found to be -0.35 ± 0.02 whilst the near IR has a slope of -1.68 ± 0.03. An indication of the quality of the fit is given by the parameter, q, which is required to be above some tolerance level. q is defined as the probability of chance occurrence, and the tolerance level is taken as 0.01 (Press et al. 1992). Fig. 2 indicates that both fits are acceptable and the millimetre fit particularly so. It is to be noted that, in contrast with the case of 3C 273 (Robson et al. 1993) there appears to be no excess thermal emission over the non-thermal IR power law (the upper limit to the 10.0 μm flux is entirely consistent with the extrapolated near-IR

Figure 2. Quiescent spectrum for 3C 279. See text for details.

Table 1. The quiescent flux density values. Errors are given by the figures in the brackets.

Frequency	Flux (Uncertainty) (mJy)
J	1.82 (0.03)
H	3.05 (0.05)
K	4.66 (0.09)
L	10.3 (0.3)
N	< 75
(GHz)	(Jy)
300	4.01 (0.40)
375	4.70 (0.06)
270	5.23 (0.08)
230	5.51 (0.08)
150	6.45 (0.10)
90	7.42 (0.37)
37	8.32 (0.18)
22	8.55 (0.15)

power law. It is therefore to be assumed that the relative contribution of dust to synchrotron emission in the near- to mid-IR is much less in 3C 279 than in 3C 273. The values assumed for the quiescent flux are given in Table 1.

4 SPECTRAL EVOLUTION

There are two distinct approaches to investigating the spectral behaviour of a blazar in the course of flaring. The first is to examine a sequence of complete spectra (log flux vs. log frequency) and to compare some features (e.g. turn-over, maximum flux) of successive spectra with the predictions of a given model. The second approach, investigation of the dependence of spectral index on flux, will be attempted in section 5.

Previous theoretical discussions have in part assumed that the flare emission can be described as being from a homogeneous self-absorbed synchrotron emitting slab (see MG85, Valtaoja et al. 1988). To check this assumption, and to compare the observations directly with existing models, we need to be able to separate the underlying flux from the flare component. In previous work this has been done by subtraction of an identified quiescent flux value from the total observed flux (MG85, Robson et al. 1993; see also Stevens et al. 1995). In this section we show a sequence of 'snapshot' spectra and discuss the evolution in terms of existing models.

Fig. 3 shows a sequence of spectra. The requirement for inclusion was complete, simultaneous 375–150 GHz coverage. The 90–22 GHz data were linearly interpolated from adjacent points. The spectra are a composite of flare flux and underlying flux, and so homogeneous slab curves will be generally poor fits to the spectra.

Some trends in turn-over frequency and peak flux are

Figure to go here.

Figure 3. Sequence of spectra for 3C 279.

Figure continued.

Figure 3 – *continued*

Figure 3 – *continued*

Figure 4. Quiescent flux subtracted spectra for 3C 279.

discernible. The first two panels of Fig. 3 show a decay of an old flare at 90 GHz with the clear propagation of peak flux to lower frequencies. At the beginning of 1990 the flux increases at higher frequencies and the peak flux is at about 90 GHz. In 1991 a propagation of the peak to lower frequencies is seen, followed by increased emission at 90 GHz after which the process repeats. This behaviour occurs throughout the observing epochs. The rise of flux at higher frequencies precedes the propagation to 37 and 22 GHz (similar behaviour was seen for 3C 273 in Robson et al. 1993). It should be noted that, in general, a power-law description of the 375–150 GHz data is appropriate. However, direct interpretation of the evolution of the flare in terms of e.g. the model of MG85 (by superposition of a synchrotron spectrum onto a

Figure 5. Pre-flare subtracted spectra for 3C 279.

quasi-steady underlying component) is not possible unless we can isolate the flaring component directly. We discuss methods of achieving this below.

In common with the approach of MG85, Valtoaja et al. (1988), and Robson et al. (1993) we can identify the underlying flux with the quiescent flux (Table 1) and subtract this from the total flux in order to isolate the flare flux. Note that we require that each data point remains at least a 3σ detection after subtraction. Examples are shown in Fig. 4, where we have fitted each spectrum with a homogeneous synchrotron slab spectrum with variable turn-over flux, frequency and optically thin slope. It is clear that the resulting spectra are not usually well described by emission from a homogeneous synchrotron slab.

There are a number of reasons why this should be so. That we fail to obtain the homogeneous synchrotron form for the flare spectrum may question, for example, the homogeneity of the emitting region. Inhomogeneities will tend to flatten the spectrum at frequencies below the turn-over, but will not make a significant difference to the peak flux and frequency. The assumption of homogeneity is reasonable during the early stages when the shock is thin.

In van der Walt (1993), detailed calculations were presented which showed that for an adiabatic, expanding shock, the emission from the unshocked jet is variable, and can be substantially less than the quiescent levels. This leads to an underestimate of the flaring component when it is calculated by subtraction. However, the shock in the MG85 shock model is thin in comparison with that assumed by van der Walt (1993), the dominant loss mechanisms being Compton and synchrotron cooling. We can assume, therefore, that the unshocked jet emission is reasonably constant during the lifetime of the shock, at least for frequencies $\gtrsim 90$ GHz.

In a recent paper, Sincell & Krolik (1994) have suggested that induced Compton scattering of photons by medium energy relativistic electrons may provide a dominant opacity mechanism in compact radio sources. This would result in a number of modifications to the output emission, and in particular would produce a flattening of the optically thick (longer wavelength) end of the spectrum. This could contribute to the appearance of the quiescent spectrum, but it is less certain that the shocked emission would be modified to any great extent. Induced Compton scattering is expected to be important if $\sigma_{\rm T} N_{\rm c} k T_{\rm b}/m_{\rm e}c^2 > 1$ (Sincell & Krolik 1994), where $T_{\rm b}$ is the brightness temperature and $N_{\rm c}$ is the column density of the scattering electrons. Setting $T_{\rm b}$ to be 2×10^{11} K (Sincell & Krolik 1994), we have $N_{\rm c} \gtrsim 5\times10^{22}$ cm^{-2} for induced Compton scattering to be important. The relative thinness of the shocked region (of order 10^{-3} pc during the early stages, e.g. MG85, but c.f. Valtoaja & Teräsranta 1994) suggests that this inequality may not be satisfied for plausible values of the electron number density, a quantity which is highly sensitive to the model parameters (not least the lower limit to the electron energy distribution.) The issue is uncertain, but optically thick spectral indices of ~ 2.5 have been found for 0420−014 (Stevens et al. 1995) and 3C 345 (Stevens et al., in preparation) which indicates that induced Compton scattering cannot at least be important for all blazars.

A further likely problem is the long term persistence of slowly decaying flares which add to the flux at lower frequencies. Inspection of the light curves of Fig. 1 shows that neither the 22 GHz nor the 37 GHz emission decays to a stable base level. Consequently, the quiescent fluxes shown in Fig. 2 correspond to the lowest flux values seen in Fig. 1. We cannot know if these correspond to anything more than local minima. Thus, any single observation will generally consist of the sum of the quiescent flux, flux from the (most recent) flare (which we are seeking to isolate), and flux from an unidentified number of residual, decaying flares. These additional components may be resolved by VLBI, if available, (but not easily at $\nu \gtrsim 90$ GHz). The point is that subtraction of the lowest available flux epoch (Table 1) will not remove these residual components. The net result is an overestimate of the flaring flux at 37, 22 GHz. This is particularly important for post 1992 when the activity of the source increased dramatically. In particular, the excess flux at these low frequencies can obscure the turn-over and thus hinder comparison with theory.

We suggest the following procedure to compensate for these additional components. Instead of subtracting the quiescent spectrum, we can identify a pre-flare component (i.e. a spectrum from a time immediately before the flare was seen at higher frequencies). This will be largely identical to the quiescent spectrum for the 150–375 GHz emission, but significantly above the quiescent levels between 22 and 90 GHz. If we assume that the rate of increase of the flare flux is greater than the rate of decrease of the flux of the previous components, then, at least in the early stages, the pre-flare spectrum will be a reasonable approximation to a steady underlying component. It should then be possible to isolate the flare by subtraction of the pre-flare spectrum.

Fig. 5 shows the results of subtracting selected pre-flare spectra. The fitted optically thin slopes lie from −0.62 to −0.94, with a mean of −0.75. These values are steeper than the quiescent slope of ~ -0.4, perhaps indicative of radiation losses. The first panel of Fig. 5 shows a spectrum from early 1989. This corresponds to a time after the large but under-sampled flare of 1988, and during the decay of the subsequent smaller event of early 1989 (but before our notional quiescent epoch of section 3.2). As the light curves in the millimetre are so patchy before about 1989, the pre-flare which has been subtracted is from 1990 January 17. This has similar flux levels and better spectral coverage than the actual pre-flare epochs of early 1988. The remaining panels have had the pre-flare of 1993 January 19 subtracted. We note that this procedure works best for large amplitude flares (to minimize the effects of noise), and that this problem is more acute when subtracting a pre-flare spectrum which has a higher flux than the quiescent spectrum.

The best homogeneous synchrotron curve in Fig. 5 was obtained for an early flare which was relatively isolated, that is, surrounded by epochs of quiescent flux (above 90 GHz). For these flares, residual 22 and 37 GHz emission was successfully removed by subtraction of a pre-flare. After 1992, an epoch of densely packed flaring occurred, and subtraction of the pre-flare is less effective at isolating the flaring emission during these times. The 22 GHz point tends to be too high, and the spectra can be better fitted with power-laws broken at 90 GHz (although the reduction in χ^2 is marginal). It should be noted, however, that the excess of the 22 GHz point over the synchrotron curve is in all cases less than about 1.5 Jy. If the flaring flux is overestimated because we neglect to remove additional components, but underestimated because the quiescent flux is too high, then an excess of ~ 1 Jy at 22 GHz over the expected synchrotron form means the magnitudes of the two effects must be nearly equal. This is not impossible, (but rather coincidental) and suggests that the both effects are rather small.

5 VARIATIONS IN SPECTRAL INDEX

We now consider the variation of spectral index in the IR, sub-mm and radio regimes. Straight line fits to data points may mask any inherent curvature of the frequency regime fitted but enable spectral trends to be more easily identified.

5.1 Infrared spectral variations

Fig. 6 shows log J-band flux against near-IR spectral slope calculated from a weighted fit to all the simultaneous J–L$'$ flux values from 1986 January onwards. The errors in the ordinate are typically of the order of the symbol size and so are not shown for clarity. The relative paucity of quiescent points means that low flux level trends are difficult to identify (c.f. Robson et al. 1993). However, a Spearman rank-order correlation test indicates a > 99.99 per cent confidence level of a correlation in the sense of flatter slope at higher flux. These results are in agreement with those of Gear, Robson & Brown (1986), Brown et al. (1989b) for well sampled sources such as OJ 287, and are interpreted as an injection of high energy electrons with a subsequent rapid decay due to energy losses causing an abrupt steepening of the spectrum. Note that, in Brown et al. (1989b), 3C 279 itself showed no evidence for a correlation as discussed above. It is probable that this was due to the low number of data points available, and more importantly to the fact that 3C 279 was in quiescence at the time. This agrees with the interpretation of the effect as a phenomenon associated with flaring.

Figure 6. Near-IR spectral index against log J-band flux.

Figure 7. Millimetre spectral index against log 270 GHz flux.

5.2 375–150 GHz spectral variations

In BLZ5 it was found that there was no strong tendency for the millimetre–sub-mm spectral index to either steepen or flatten with increasing flux. We repeat this result here for a slightly enlarged data set (see Fig. 7). The spectral index shown here is again a weighted least-squares (χ^2) fit to simultaneous 375–150 GHz data points; fits below a certain tolerance threshold ($q = 0.01$) were ignored. A Spearman rank-order test shows no evidence of a correlation between flux and spectral slope (the confidence level for such a correlation is only ~ 15 per cent), in agreement with the findings of BLZ5. Other sources exhibiting strong flaring behaviour (e.g. 3C 345, 3C 273, 0235+164, see BLZ5) show a strong correlation of flattening spectral slope with increased flux. This has been variously explained as an effect of the passage of the self-absorption turn-over through the viewing window, or again as the effect of radiative losses upon a flatter, recently injected electron population. If the former is correct, and if 3C 279 has a particularly low frequency turn-over when flaring, then we would expect any correlation to be weak. However, analysis of the flares in BLZ5 revealed that the absorption turn-overs of other sources (e.g. 0235+164) are at even lower frequencies, which argues against this interpretation. In the latter case, it might be possible that such radiation losses are not as important for 3C 279. However, we suggest that undersampling of the large flare is the most probable explanation for the absence of any strong correlation. We note from Fig. 7 that the maximum 270 GHz flux used was around 14 Jy; the flare was fairly undersampled above this flux level in terms of the simultaneous 375–150 GHz flux measurements necessary for calculation of the spectral slope. It may be, therefore, that the expected trend has been masked by the relatively low flux data used in Fig. 7. Further data at high flaring epochs are needed to settle this point.

5.3 22–90 GHz spectral variations

The temporal lag between flux maxima is seen to become measurable between frequencies below 90 GHz, and it is at these frequencies that the flare amplitudes begin to plateau off or decline, in agreement with the model of MG85 (see BLZ5). We now contrast the spectral behaviour of 3C 279 in the optically thin (millimetre) regime with its optically thick behaviour.

Fig. 8 shows log 90 GHz flux against the two-point (straight-line) 22–90 GHz spectral index for 3C 279 from November 1989 onwards. The data train has been divided into sections corresponding to the rise and fall of individual flares at 90 GHz (panels a–c; see Table 2). Since the two sets of observations were not simultaneous, linear interpolation was performed on the better sampled of the two data sets, namely that for 22 GHz. Flares are distinguished on the basis of clear changes of gradient (usually the onset of the new flare is marked by a steepening of the rate of change of flux); flares are sub-divided with the point of maximum flux being assigned to the rise phase. The exceptions are for the flare starting late 1989 (the decay of which was obscured by the fast rise of the following flare), and the rise of the flare of late 1993 which was treated as one with the fall of the previous flare due to the lack of data points. Fig. 8 shows that, for each section, there is a clear linear correlation between log 90 GHz flux and spectral index. The lines are given by straight line fits to the data taking into account the errors in both flux and spectral index (e.g. Press et al. 1992).

We note that i) the slopes ($d\alpha/d\log S_{90} \equiv \alpha'$) of each of the fitted straight lines are roughly the same, ranging from 1 to 2; and ii) the decay portion of each flare has a significantly steeper slope than the rise part. We attempt to provide a theoretical basis for these results in the next section.

6 DISCUSSION

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Figure 8. 22–90 GHz spectral index against log 90 GHz flux. Linear fits to the rise (circles) and fall (squares) of each flare are shown.

Table 2. Slopes of the linear fit to each division of the data train shown in Fig. 8.

Panel	Dates	Flare	α' (σ)
(a)	1989 Oct 31–1990 Aug 15	Rise	1.72 (0.14)
(b)	1990 Aug 27–1990 Dec 31	Rise	1.34 (0.24)
(b)	1991 Jan 11–1991 May 29	Fall	1.99 (0.28)
(c)	1992 Dec 30–1993 May 01	Rise	1.03 (0.31)
(c)	1993 Jun 01–1993 Dec 29	Fall	1.64 (0.64)

6.1 Analytic treatment of the 22–90 GHz spectral index flux correlation

Consider the 22–90 GHz spectral index (henceforth α) defined as follows:

$$\alpha = k \log(S_{90}/S_{22}) \tag{1}$$

where $k = 1/\log(90/22)$, and S_i represents the total observed flux at frequency i, which will normally be the sum of flare (F_i) and base (B_i) components. The base or underlying component will in turn be the sum of the quasi-steady quiescent flux and any residual decaying flux from previous flaring events.

We adopt a simplified view of the flaring component by assuming it to be two power-laws intersecting at some turn-over frequency $\nu_{\rm m}$ with an optically thin slope a for $\nu > \nu_{\rm m}$ and an optically thick index b for $\nu < \nu_{\rm m}$ ($a, b \neq 0$). The ratio of the two flare fluxes (henceforth F_{90}, F_{22} respectively) is a function of the parameters a, b and the position of the turn-over $\nu_{\rm m}$. If $\nu_{\rm m} > 90$ GHz, then

$$F_{90}/F_{22} = (90/22)^a. \tag{2}$$

During the early stages of the flare, the flare flux will dominate the base flux at 90 GHz, but not at 22 GHz (i.e. $F_{90} \gg B_{90}$, and $S_{22} \simeq B_{22}$). If this is the case then S_{22} will be roughly constant, and hence $\alpha' = k$ from equation (1).

The turn-over frequency of the flare will evolve to lower frequencies, until at some point $22 < \nu_{\rm m} < 90$ GHz. If we denote the flare flux at $\nu_{\rm m}$ by $F_{\rm m}$, then we have $F_{\rm m}/F_{22} = (\nu_{\rm m}/22)^b$ and $F_{90}/F_{\rm m} = (90/\nu_{\rm m})^a$. Thus

$$F_{22} = F_{\rm m}^{1-b/a} F_{90}^{b/a} (22/90)^b. \tag{3}$$

The flare turn-over flux ($F_{\rm m}$) has predicted evolutionary paths in flux/frequency space according to MG85. Specifically, $\nu_{\rm m} = \zeta F_{\rm m}^{1/c}$ where ζ is a constant of proportionality and c is a constant which depends on the phase of the flare evolution, and also on a and b. Thus for non-zero c

$$F_{\rm m} = F_{90}^{c/(c-a)} (\zeta/90)^{ca/(c-a)}. \tag{4}$$

During the later stages of the flare's lifetime, we make the assumption that the flare flux dominates any underlying component at both 22 and 90 GHz (i.e. $F_i \gg B_i$). Thus, substituting into equation (1) from equations (3) and (4), we can write

$$\alpha = k \left(\frac{b-a}{c-a}\right) \{\log(S_{90}) + c \log(\zeta/90)\} + kb \log(90/22) \tag{5}$$

which is linear in $\log(S_{90})$. For the synchrotron phase appropriate to the canonical value of $a = -0.75$ we have $c = 0$, and F_m is constant. In this case the equivalent formula to equation (5) is

Figure 9. Schematic summary of one possible example of the flaring behaviour treated analytically in the text. Both flux and frequency are printed on a logarithmic scale; the arrow indicates the direction of evolution of the flare; the numbers are the values of α' expected.

$$\alpha = k(1 - b/a) \log(S_{90}) - k \log(F_{\rm m}^{1-b/a} (22/90)^b) \tag{6}$$

which is again linear in $\log(S_{90})$.

Eventually $\nu_{\rm m} < 22$ GHz, and $F_{90}/F_{22} = (90/22)^b$, and hence α will be roughly constant before returning to the quiescent value.

The early stage of the flare (when the 22 GHz flux is assumed constant and probably $\nu_{\rm m} > 90$ GHz) has a slope (α') of k, equal to 1.63. Subsequent stages (as the self-absorption turn-over evolves to shorter frequencies) have values of α' critically dependent on the nature of the flare, specifically the values of the optically thin and thick spectral indices a and b. The value of a in turn determines the value of c for the later (synchrotron and adiabatic) phases of the flare (see MG85 for derivation of the appropriate formulae). The usual value of b for an homogeneous synchrotron self-absorption turn-over is $b = 2.5$. If the optically thin spectral index has the canonical value of $a = -0.75$, then the synchrotron phase has $c = 0$ whilst the decay phase has $c = 0.59$. Using equations (6) and (5) this gives values of α' of 7.1 and 4.0 respectively. Both are considerably steeper than observed. Whilst the values of the thin spectral index seen in Section 5.2 are typically around -0.5, slightly flatter than canonical, Fig. 5 suggests that the flare spectrum has a steeper optically thin slope, perhaps as steep as -0.9. It can be seen from equation (5) that, for a given b, α' flattens as a decreases. This would agree with the slopes in Fig. 8.

The behaviour of the flare according to this analytic treatment is summarized in Fig. 9. The evolution of the self-absorption turn-over is shown by the solid lines. Different phases of the evolution have different values of α', and are delimited by vertical lines. The numbers are the values of α' appropriate to $a = -0.75$ and $b = 2.5$ (with corresponding values of c).

6.2 Qualitative discussion

It is argued below that the values of α' will in general be flatter than calculated above. We suggest a number of possible explanations. For instance: the flare spectrum is not well described by two power-laws; such an approximation is bound to be rather poor, particularly near the absorption turn-over, where there is considerable curvature. Inclusion of this factor will tend to reduce the value of b and increase that of a; i.e. to flatten both indices (see section 6.3). Furthermore, the neglect of the underlying base component is almost certainly an oversimplification, particularly when considering the increased decay time at lower frequencies. The effects of residual emission are likely to increase the underlying 22 GHz flux. If the flare flux does not dominate the base flux at this frequency, then the effect will be to reduce the effective value of b. Inhomogeneities in the emitting region will have the same effect (MG85). If b is lower than 2.5 then the decay parts of the flares will have lower α' than expected, as will the rising portions. This would be expected to occur during epochs of densely packed flaring, i.e. late 1990 onwards, which is exactly as seen (see also Fig. 5).

One of the key features of the observations (Fig. 8)) is that the rise to flare maximum has a lower value of α' than the decay. This feature was seen to be common to all the flares observed, and is successfully accounted for by the treatment of section 6.1. If the plateau phase of evolution is either generally short lived, or narrow in terms of frequency range, then the chance of it being observed is probably rather low. The resulting behaviour would be exactly as seen in Fig. 8: two straight lines appearing to intersect, with the upper line corresponding to the rise of the flare and the steeper, lower one to the decay. Note that we see no strong evidence for an extended plateau phase in the previous section, nor was there any evidence seen in BLZ5. This supports the conclusion that the plateau phase is rather short, as might be expected from the dominance of gamma ray luminosity to synchrotron emission, assuming the former to be produced by the inverse Compton process. Quantitative estimates for the extent of the plateau phase are given below.

6.3 Modelling of the behaviour

There is scope for modelling of the passage of the flare in terms of the change in α as a simple synchrotron curve moves through the 22, 90 GHz window. To do this we can adopt a simple parametric description of the shock model of MG85 as described above. In this version of the generalized shock model the behaviour of the flares is parameterized by fixing the evolutionary tracks of the self-absorption turn-over in flux/frequency space, and assuming that the spectrum at any given time can be described by a homogeneous slab synchrotron curve. It is then necessary to adopt a suitable function for the dependence of turn-over frequency with time (typically $\nu_{\rm m} \propto t^{\delta}$, where δ depends on the evolutionary phase). Flare light curves can thus be generated at any desired frequency. Evolutionary tracks for the turn-over appropriate to this value are given by $S_{\rm m} \propto \nu_{\rm m}^{c}$, where c has the values appropriate to an optically thin spectral index of -0.75 (i.e. $c = -2.5, 0, 0.59$ for the three phases). The transitions between growth/plateau phases, and plateau/decay phases are chosen as 90 and 60 GHz, respectively. The 90 and 22 GHz light curves thus generated are shown in Fig. 10.

Figure 10. Simulated 90 and 22 GHz light curves (solid and dotted lines respectively).

The observed duration is a function not only of the frequency width of the phase (here set at 30 GHz), but also of the relationship between turn-over frequency and time (i.e how long the flare spends on that phase), and also of the sampling frequency. The delimiting values for the synchrotron phase (90 and 60 GHz) were chosen such that the observed duration of that phase was short. The values chosen for the extent of this phase are probably not an unreasonable estimate, and are consistent with the amplitude analysis of BLZ5. The time spent in the synchrotron phase is probably of order weeks rather than months. This is comparable to the length of the Compton phase, which is similarly expected to be rapid (MG85).

Fig. 11 shows a plot of simulated 22–90 GHz spectral index varying with log 90 GHz flux. Note the resemblance between this figure and Fig. 8. The simulation is produced in the manner described above with the addition of irregular sampling (using a uniform deviate) and superposition of the quiescent spectrum of Table 1. We also impose a random scatter on each data point, the amount of scatter chosen using a Gaussian deviate with standard deviation of 5 per cent of the flux. Points for which $\nu_{\rm m} > 90$ GHz are shown by a cross, whilst those for which $\nu_{\rm m} < 22$ GHz are shown by a square. Those points for which $\nu_{\rm m} \in [22, 90]$ GHz are marked by a triangle if the turn-over lay on the synchrotron phase, and by a circle if it lay on the adiabatic phase. The synchrotron phase is rapid, and hence few triangles are seen. Note also that the Compton phase is also fairly short lived in comparison with the later decay phases, and so there are fewer crosses than circles. This agrees with the real data depicted in Fig. 8.

The crosses, corresponding to the early Compton phase, are well described by a straight line with a slope of ~ 1.4. The points marked by circles also lie on a straight line (as

Figure 11. Simulated 22–90 GHz spectral index against log 90 GHz flux. See text for an explanation of the symbols.

expected from the analytic discussion above) and their slope is found by least squares fitting to be ~ 2.5. This is slightly flatter than that expected from equation (5) which probably reflects the effect of the curvature inherent in the synchrotron spectrum and the contribution from the underlying flux. A value of ~ 2.5 is, however, steeper than that seen in Fig. 8.

According to the treatment of section 6.1, when the flare peaks at 22 GHz, (corresponding to $\nu_{\rm m} < 22$ GHz), then the value of α is roughly constant before returning to the quiescent value. This phase is shown by the squares in Fig. 11. However, in Fig. 8 we see no similar behaviour. This may well be due to the fact that Fig. 8 has points from a number of successive flares, rather than an isolated example as modelled above. In other words, this may yet be another example of the difficulty of disentangling the flux from many flares: the 90 GHz emission probably contains a significant contribution from newer flares.

7 CONCLUSIONS

The main conclusions of this paper can be summarized as follows:

1) We find a general trend for the maximum flux to propagate to lower frequencies, which is consistent with a shock expanding down a jet (MG85, Hughes, Aller & Aller 1989). Because of the complexities of the flaring, we cannot critically test the details of the MG85 model (but c.f. Stevens et al. 1995). We suspect that the behaviour is not entirely consistent in detail, perhaps because of difficulties is disentangling the flaring emission. Alternatively, the model itself may need some modification (see e.g. Marscher, Gear & Travis 1992).

2) We have found examples for which the quiescent or preflare subtracted spectra resembled the homogeneous slab synchrotron form. Deviations from this form at low frequencies may be accounted for by inhomogeneities in the emitting region (MG85).

3) The infrared spectral index is shown to be strongly correlated with log J-band flux. The confirms earlier results for OJ 287 (Gear, Robson & Brown 1986, Brown et al. 1989b), and is interpreted as radiation losses (e.g. Kardashev 1962).

4) No such effect is seen for weighted 375–150 GHz spectral indices which are uncorrelated with log 270 GHz flux, in contrast with other sources (e.g. 3C 273, BLZ5). This may be due to undersampling of the peaks of the flares.

5) We see strong linear correlations between two-point 22–90 GHz spectral indices and log 90 GHz flux. This trend exists separately for the rise and fall of each flare isolated. The slopes of the linear trends can be found by least squares fitting, and are seen to be steeper on the decay of a flare than on the rise.

6) A simple analytic treatment is presented which can explain these linear relations in terms of the evolution of the flare according to the MG85 model. In particular, analytic expressions are given which explain the steepening of the decay of the flare in comparison to the rise. Numerical simulations of the same MG85 model similarly reproduce the

observed trends, and show better agreement with the observed values of α'.

3C 279 is revealed as a complex source, showing many flaring events over a short period of time. The extreme variability of the source may be a consequence of the fact that it is so well sampled (as is the case for 3C 273, see Robson et al. 1993). However, in BLZ5 it was shown, particularly from the 37 and 22 GHz data in that paper, that some sources are more dramatic and variable than others, and 3C 279 certainly falls into the former category. We therefore believe that better temporal sampling of flaring events is needed for a successful deconstruction of the spectral behaviour of this source.

In particular, in order to perform a proper analysis, we require an isolated and major flare with a lack of sub-flaring (Robson 1992). Weekly or monthly monitoring at a single high frequency may show when 3C 279 has reached a stable state and enable identification of a flare in the early stages of formation. From that stage regular daily monitoring can be employed to follow the flare evolution in its entirety. In particular, to directly observe the Compton phase of the flare's growth (which is liable to be rapid, as pointed out in MG85), near- and mid-infrared observations simultaneous with the millimetre are needed, on daily (or even hourly) monitoring time-scales (Robson 1992).

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