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The spectral evolution of high-frequency radio outbursts in the blazar PKS 0420–014

J. A. Stevens,[1] S. J. Litchfield,[1★] E. I. Robson,[1,2] W. K. Gear,[3] H. Teräsranta,[4] M. Tornikoski[4] and E. Valtaoja[4]

[1] *Centre for Astrophysics, University of Central Lancashire, Preston PR1 2HE*
[2] *Joint Astronomy Centre, 660 N. A'ohōkū Place, University Park, Hilo, Hawaii 96720, USA*
[3] *Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ*
[4] *Metsähovi Radio Research Station, Helsinki University of Technology, Otakaari 5A, SF–02150 Espoo, Finland*

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ABSTRACT

Multifrequency monitoring data between 375 and 22 GHz are used to investigate the spectral evolution of radio outbursts in the blazar 0420–014. It is shown that, after subtraction of the underlying 'quiescent' emission, the flare spectrum can be described by a simple homogeneous self-absorbed synchrotron component. The evolution of this spectrum is found to be qualitatively consistent with the shock model of Marscher & Gear, although not totally so in detail. Some of the discrepancies can possibly be resolved if the proposed relativistic jet, which is initially oriented close to the line-of-sight, bends away. The optically thin spectrum of the flare emission, however, is found to be flatter than allowed by the model. Strong correlations are found between the 90–22 GHz two-point spectral index and the logarithm of the 90-GHz flux. These trends are reconciled with the evolution of the synchrotron spectrum during the flares.

Key words: radiation mechanisms: nonthermal – galaxies: jets – quasars: general – quasars: individual: PKS 0420–014 – radio continuum: galaxies.

1 INTRODUCTION

The infrared to radio variability and polarization nature of blazars is well represented by synchrotron radiation from shock waves that propagate along a relativistic jet aligned towards the line-of-sight of the observer (see e.g. review by Bregman 1990). A model incorporating an adiabatically expanding shocked region (Hughes, Aller & Aller 1989) was successfully applied to the centimetre-wavelength monitoring data of Aller et al. (1985). At infrared to millimetre wavelengths the 1983 outburst of the quasar 3C 273, observed by Robson et al. (1983), was successfully explained by the shock model of Marscher & Gear (1985) (hereafter MG85), and Gear et al. (1986a) showed that this model was also broadly applicable to a sample of blazars.

One of the main aims of the long-term monitoring programmes has been to provide sufficient observations over a suitable frequency range to allow such models to be tested and improved further. In the case of the MG85 model it is imperative to make observations at frequencies close to and spanning the synchrotron self-absorption turn-over (i.e. millimetre and submillimetre observations), as the model makes specific predictions concerning the evolution of the turn-over frequency with turn-over flux.

In a previous paper (Stevens et al. 1994, hereafter SEA94), monitoring data between 375 and 22 GHz were used to show that the relationship between the flare amplitude and the time delay between light curves for a sample of blazars is in general accord with prediction. Additionally, it was shown that outbursts typically reach maximal development at around 90 GHz, and it is only now that large quantities of data are becoming available at frequencies higher than this that such radio outbursts can be followed during the early stages of their evolution. In this paper such data are used to study the spectral evolution of flares in the optically violently variable (OVV) quasar PKS 0420–014 for the period 1989.0–1994.5. The results are compared with the predictions of the MG85 shocked jet model.

2 OBSERVATIONS

The bulk of the observations at 375, 270, 230 and 150 GHz (800 μm, 1.1 mm, 1.3 mm and 2.0 mm respectively) were taken at the 15-m James Clerk Maxwell Telescope (JCMT) with the common-user ^{3}He-cooled bolometer UKT14 (Duncan et al.

★ Present address: University of Crete, Physics Department, 714 09 Heraklion, Crete, Greece.

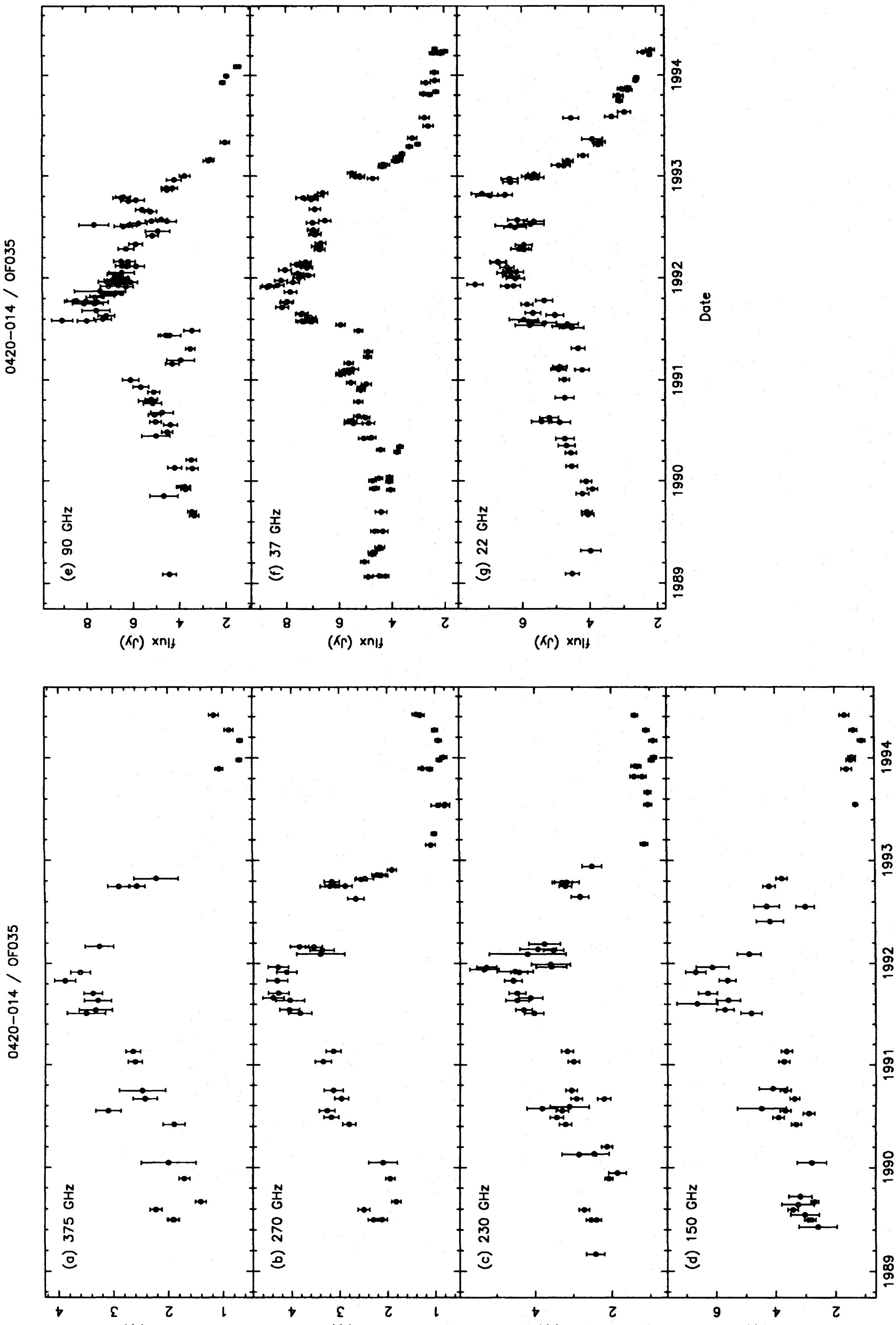

Figure 1. Light curves for 0420−014.

1990). The observing techniques and data reduction methods are described in Stevens & Robson (1994) and Sandell (1994).

90- and 230-GHz data were taken at SEST and the techniques used are described by Booth et al. (1989).

Further 90-GHz data together with additional 150- and 230-GHz observations from IRAM were taken from the literature (Steppe et al. 1993).

37- and 22-GHz data were taken from the extensive monitoring programme of the Metsähovi Radio Research Station (MRRS). See Teräsranta et al. (1992) for the techniques employed.

3 PREDICTIONS OF THE SHOCKED JET MODEL

The MG85 model considers the passage of a shock wave through a conical adiabatically expanding jet. The evolution of the shock spectrum is shown to be dependent on the dominant energy loss mechanism, namely Compton, synchrotron or expansion losses. Electron energies are assumed to be distributed as a power law, i.e. $N(E)\mathrm{d}E = KE^{-s}\mathrm{d}E$, leading to an optically thin spectral index $\alpha = (1-s)/2$. The magnetic field, B, and the parameter, K, are assumed to fall off radially with distance, R, down the jet, also as power laws, i.e. $B \propto R^{-a}$ and $K \propto R^{-b}$ with $b = 2(s+2)/3$ (Marscher 1980). For $a = 1$ (B perpendicular to the jet flow) and $s = 2$ it can be shown that Compton losses fall off as $R^{-4.7}$ whereas synchrotron losses fall off as $R^{-3.3}$ and expansion losses as R^{-2}. We thus expect to see a progression of the dominant energy loss mechanism as the shock evolves, with Compton losses playing a significant role during the early stages. The model predicts that, during the Compton (or rise) phase, the synchrotron self-absorption turn-over evolves to lower frequencies as the turn-over flux increases. During the synchrotron (or plateau) phase the turn-over frequency decreases whilst the turn-over flux remains approximately constant, and both turn-over frequency and flux decrease during the final adiabatic expansion (or decay) phase.

The evolution of the spectrum during outburst is related to the maximum amplitude (the difference between minimum and maximum flux levels) that a flare can attain and to the time delay between emission at different frequencies (Valtaoja et al. 1992; SEA94). Flares at monitoring frequencies commensurate with the Compton phase will reach maximum amplitude at the same time, i.e. when the spectrum evolves into the synchrotron phase. Consequently, such light curves will peak synchronously and the flare amplitudes will increase with decreasing frequency in a manner dependent on the optically thin slope of the synchrotron radiation. Monitoring frequencies commensurate with the synchrotron and adiabatic phases will be delayed with respect to those in the Compton phase by the time that it takes the turn-over to pass the observing frequency (i.e. become optically thin). The flare amplitudes will be constant during the synchrotron phase and will decrease with decreasing frequency in the adiabatic phase.

4 RESULTS

4.1 Overview

The light curves at 375, 270, 230, 150, 90, 37 and 22 GHz are presented in Fig. 1. Data prior to 1994.0 have been published elsewhere (SEA94).

It can be seen that the flaring behaviour is complex and that there were several events during the monitoring period. After a decline at all frequencies during the late 1980s (not shown; see SEA94) a small flare peaking in 1990 is followed by a larger event that peaked in late 1991 (hereafter the 1991 flare). The rise of the 1991 flare is rapid and was largely missed at frequencies higher than 37 GHz, and its decline was interrupted by another event that peaked in late 1992 (hereafter the 1992 flare) and subsequently decayed through 1993. At 90 GHz there is evidence for two flares during 1992, but the sampling during this period at the other frequencies does not enable us to confirm this. By 1994 the flux has decayed to a 'quiescent' level at 37 GHz and above although it may still be declining at 22 GHz.

Flare amplitudes and time delays between data trains were quantified in SEA94. For the 1991 flare it was found that the amplitudes increased between 375 and 90 GHz and decayed between 90 and 22 GHz. For the same period, lags of order 20 d, 50 d and 70 d were determined in the ranges 270–90 GHz, 90–37 GHz and 37–22 GHz respectively. This is consistent with the flare(s) reaching the transition from Compton to synchrotron phase between 150 and 90 GHz and then evolving to the adiabatic phase at a frequency between 90 and 37 GHz. The flare amplitudes presented in SEA94 for the 1992 flare are recalculated here due to the continued decay of the 1992 flare at 37 and 22 GHz. Amplitudes of 2.4, 5.1, 5.4 and 5.0 Jy are found at 270, 90, 37 and 22 GHz respectively, but again due to the fact that the 22-GHz flux may not yet have reached quiescence we can only draw limited conclusions. The flare is, however, still growing up to 37 GHz. In SEA94, zero lag was found between 270 and 90 GHz and possible lags of <20 d and <40 d were found in the ranges 90–37 GHz and 37–22 GHz respectively, and these results are unchanged. The two events thus display different lag behaviour, with the 1992 flare reaching maximum amplitude at lower frequency than the 1991 flare.

4.2 The shape and evolution of the outburst spectrum

In order to study the spectrum of the flaring component(s) it is first necessary to subtract the more slowly varying quiescent emission which is identified with the underlying jet (e.g. Dent & Balonek 1980; MG85; Valtaoja et al. 1988). Fig. 2 shows the derived quiescent spectrum which, between 375 and 90 GHz, was constructed by binning data points over the low-level period of 1993 and early 1994. Data points corresponding to epochs of slightly higher emission during this period were ignored. Since the flare decay times increase with decreasing frequency, the quiescent level was difficult to identify at the lower frequencies and hence at 37 and 22 GHz the 1994 data only were binned.

Composite flare and quiescent spectra for all other available epochs were then assembled by selecting dates on which we had at least three simultaneous observations between 375 and 150 GHz. The lower frequency data points corresponding to these epochs were obtained by linearly interpolating the better sampled 90-, 37- and 22-GHz light curves. Quiescent subtracted spectra are shown in Fig. 3 for 1991 July to 1992 November, a period encompassing two flares. The quoted dates correspond to the epoch of the JCMT observations.

In the following discussion, spectral indices are written $F_\nu \propto \nu^\alpha$ where F_ν is the flux density at frequency ν. With

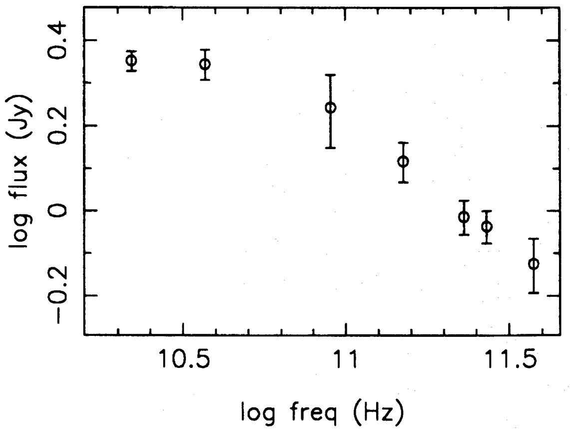

Figure 2. The binned quiescent spectrum with 1σ error bars.

the exception of 1991 July 05 and 1991 July 17 (see below), the quiescent subtracted data were fitted with homogeneous synchrotron spectra (equation 1) with F_1, ν_1 and s as free parameters (Pacholczyk 1970):

$$F_\nu = F_1 \left(\frac{\nu}{\nu_1}\right)^{5/2} \left[1 - \exp\left(-\left(\frac{\nu}{\nu_1}\right)^{-(s+4)/2}\right)\right] \quad (1)$$

where ν_1 is the frequency at which the optical depth reaches unity and F_1 is a constant. The peak flux and turn-over frequency can then be calculated by differentiating equation (1) with respect to frequency, yielding

$$e^{\tau_m} = 1 + \left(\frac{s+4}{5}\right)\tau_m \quad (2)$$

and by noting that

$$\tau_m = \left(\frac{\nu_m}{\nu_1}\right)^{-(s+4)/2} \quad (3)$$

where ν_m and τ_m are the turn-over frequency and optical depth respectively. In Table 1 we give the fitted values of ν_m, F_m, s and α for each of the spectra presented in Fig. 3. We find that the spectrum of the flaring component, which we attribute to the shock, is well represented by equation (1) and so, during the early stages of flare evolution, before the shock has expanded appreciably, the emitting region is essentially homogeneous. This result is supported by Valtaoja et al. (1988) who found that the composite of all flare spectra in a sample of compact radio sources could be fitted in this way, and by O'Dea, Dent & Balonek (1984) who found a similar result for the case of 3C 84. For the 1991 outburst of 3C 345 (Stevens et al., in preparation) the flare spectra can be fitted with a homogeneous model for over a year after the initial rise in flux. During most of this period the spectrum is evolving in a manner consistent with adiabatic expansion. In a recent paper (van der Walt 1993) it has been suggested that the procedure of subtracting the quiescent level is flawed, since the flare emission replaces some of the emission from the unshocked flow and we are essentially subtracting the wrong base level. Our findings, particularly the 3C 345 results, suggest that this effect is relatively unimportant, at least for emission over the frequency range considered here. This may be due to the shocks being thin and remaining relatively so even during the expansion phase. Lainela (1994), however, finds some deviation from the homogeneous form when considering

Table 1. Parameters from homogeneous synchrotron spectral fits. Epochs 1 and 2 correspond to straight line fits. The error in the quoted values of α is estimated at $\sim \pm 0.1$ (see text), leading to an error of about 10 per cent in s.

epoch	date	$\log(\nu_m)$ [Hz]	$\log(F_m)$ [Jy]	s	α
1	050791	...	...	1.58	−0.29
2	170791	...	...	2.16	−0.58
3	200891	10.70	0.743	1.81	−0.41
4	150991	10.67	0.800	1.89	−0.44
5	301091	10.67	0.771	1.76	−0.38
6	291191	10.63	0.823	1.91	−0.46
7	020292	10.59	0.736	1.82	−0.41
8	011092	10.51	0.705	1.99	−0.49
9	281092	10.41	0.693	1.99	−0.49

a sample of active galactic nuclei (AGN) between 90 GHz and 8.0 GHz. This may be due to difficulties in identifying the quiescent level at the lower frequencies, where the emission from successive bursts tends to merge due to opacity effects and the increased electron lifetimes (e.g. Robson et al. 1993).

It is obvious that the 1991 July data are not well fitted with a simple self-absorbed synchrotron spectrum. This could be due to a failure of the interpolation process, but may also be due to the existence of two or more components: one or more decaying and a new component turning over at around 150 GHz. At 37 and 22 GHz the fluxes only rose by about 10 per cent over the interpolation period for the July 05 JCMT data and were within 1 d of the July 17 JCMT data. Given the available time coverage and lack of substantial variability over this period, the interpolated data must be close to the true values at these frequencies. At 90 GHz the rapid rise in flux took place between 1991 June 28 and 1991 August 2, with the flux rising from ~3.5 to 8.0 Jy over this period. The rise is poorly sampled, but since we see a single rise in flux at 37 GHz it is reasonable to expect a similar rapid rise at 90 GHz and so linear interpolation would seem valid. Thus, on July 05 we probably see the new component emerging at JCMT frequencies with the lower frequencies yet to rise substantially. On July 17 the lower frequencies are rising, after which the new component dominates over any decaying components. The JCMT 375–150 GHz data for the two July spectra were fitted with weighted linear least-squares straight lines in order to derive the optically thin spectral index. We find -0.29 ± 0.17 for July 05 and -0.58 ± 0.13 for July 17.

We now use the fits (Fig. 3 and Table 1) to study the evolution of the outburst spectrum. As discussed in Section 3, the MG85 model predicts the form of the evolution on the (ν_m,F_m) plane and the quoted values of β below correspond to the relationship $F_m \propto \nu_m^\beta$. Predicted values are for $a = 1$ and $s = 1.88$ (the mean value from Table 1). In Fig. 4 all of the fitted spectra are plotted on the same diagram. Between epochs 3 and 4 the turn-over flux rises and the turn-over frequency falls, as expected during the Compton phase. A value of β=−1.9 is found, compared with the predicted value of −2.5. At epoch 5 the flux has fallen but the turn-over frequency has remained constant, and then Compton phase behaviour is once again seen between epochs 5 and 6 with β=−1.3. The fall in flux without change in turn-over frequency between epochs 4 and 5 cannot be easily explained in terms of evolutionary effects and may be due to jet turbulence (Marscher, Gear & Travis

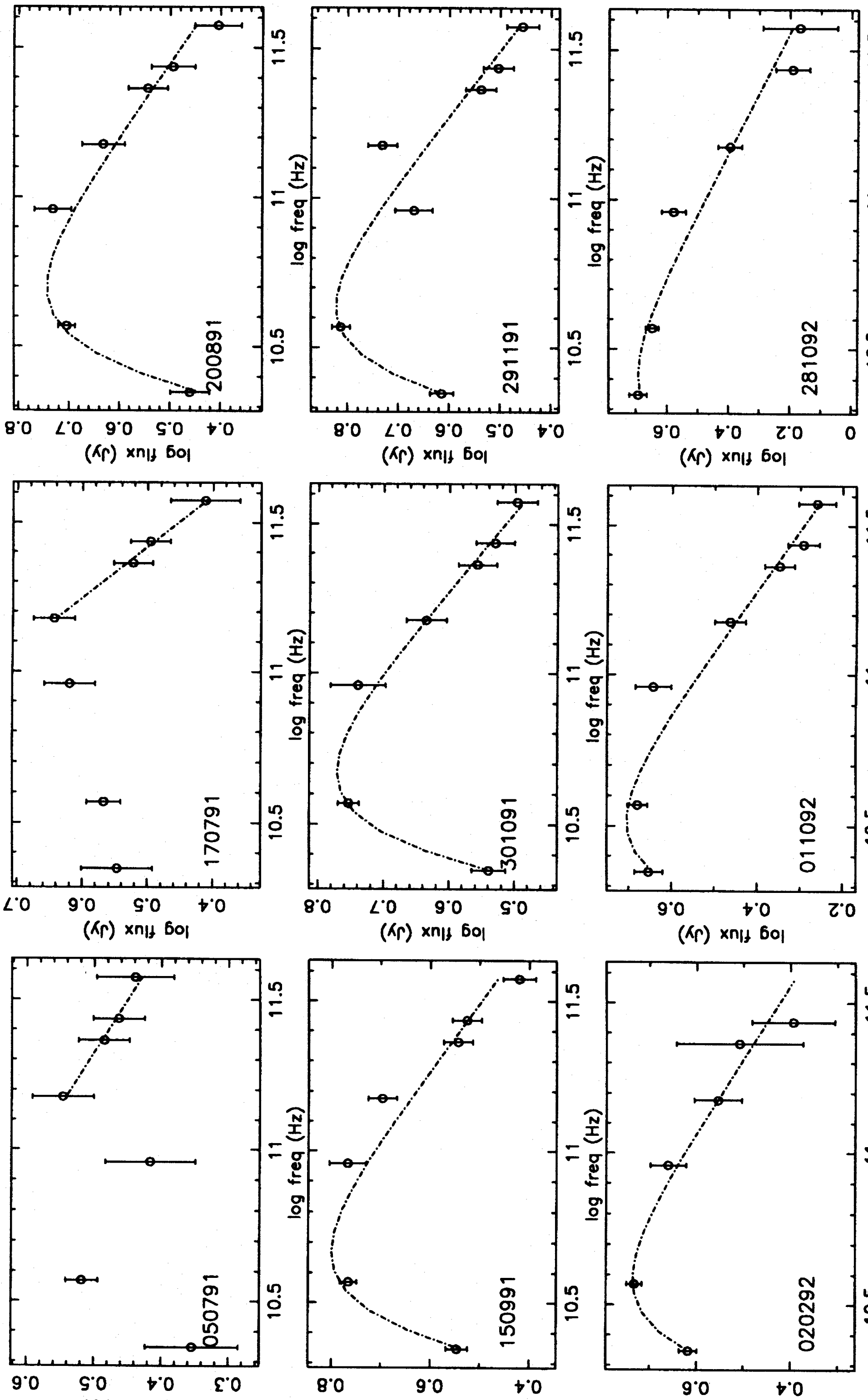

Figure 3. Quiescent subtracted spectra. The date on each plot indicates the epoch of the JCMT data.

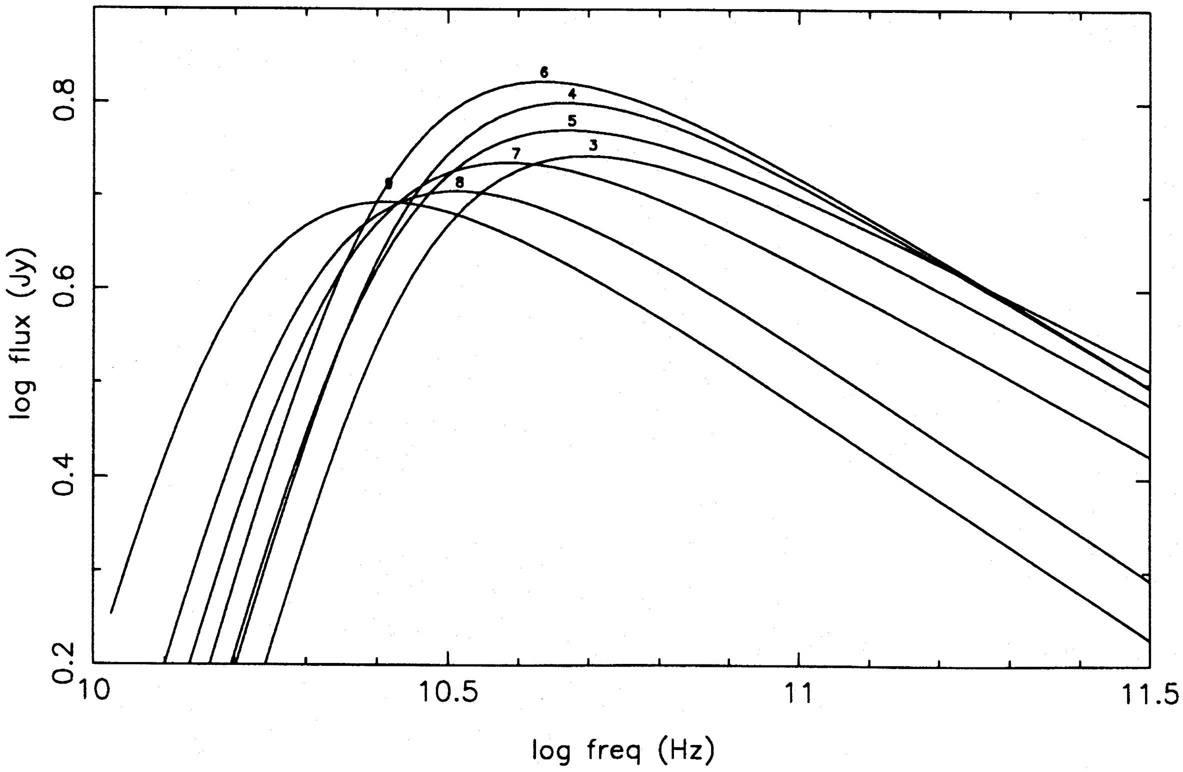

Figure 4. The fits of Fig. 3 plotted on the same diagram. The fits are labelled with an integer between 3 and 9 at the peak of the function. These numbers correspond to the epochs indicated in Table 1.

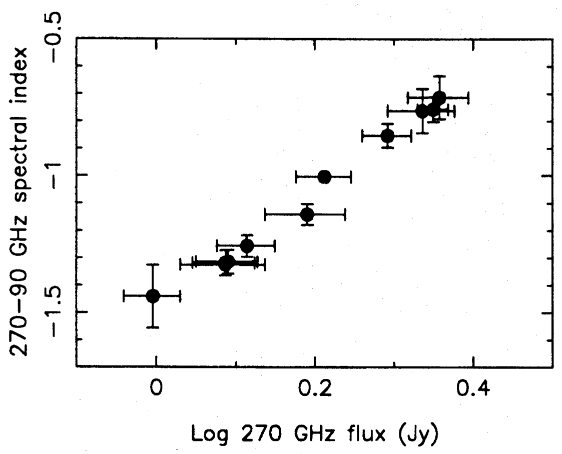

Figure 5. Correlation of 270–90 GHz two-point spectral index with 270-GHz flux. Quiescent level fluxes have been subtracted.

1992) or bends near the base of the jet (e.g. Krichbaum et al. 1993). At epoch 7 both turn-over flux and frequency have fallen, commensurate with the adiabatic phase, although with β=2.2 which is much greater than the predicted value of 0.42. We thus find no evidence of synchrotron phase evolution for the 1991 flare of 0420−014 and so, if such a phase exists, it must be short-lived in this case. Epochs 8 and 9 relate to the 1992 flare and here the spectral evolution provides the movement towards lower frequencies at approximately constant flux required by the synchrotron loss phase, although here β=0.12 compared with the predicted value of −0.34. The observations suggest that the 1992 flare peaks at lower frequencies than the 1991 flare, and possibly results from a rejuvenation of the former event. The continuity of the movement of ν_m to lower frequencies in Fig. 4 supports this hypothesis. Millimetre VLBI observations could in principle detect such an event which would produce a brightening of one of the knots, presumably the one closest to the core. The spectral evolution of the flare spectrum is thus found to be qualitatively in agreement with the MG85 model but not consistent with it in detail. The spectrum evolves towards lower frequencies with time as expected from an expanding emitting region, but the observed trends of peak flux with peak frequency do not correspond to prediction.

One interesting possibility is that the observed behaviour of the peak flux with peak frequency, particularly between epochs 6 and 7, could be related to a varying orientation of the relativistic jet with respect to our line-of-sight. For a similar rapid decay of a flare in the blazar 1156+295 (McHardy et al. 1990) it was proposed that the jet, which is initially oriented close to the line-of-sight, bends away. In this case the peak frequency is moved to lower values by an amount proportional to the Doppler factor, δ, but the peak flux $F_m \propto \delta^{2-\alpha}$ (continuous jet) or $F_m \propto \delta^{3-\alpha}$ (moving sphere) (e.g Marscher et al. 1991; Ghisellini et al. 1993). If this is the case then the index β will be between 2 and 3 (α=0 at the peak) plus the contribution from the adiabatic expansion which is in rough agreement with the observed value of β=2.2.

The optically thin slope, α, of the flare spectrum should steepen with time due to the radiative losses suffered by the emitting electrons (e.g. Kardashev 1962). From the values presented in Table 1 it is not clear whether or not any steepening is

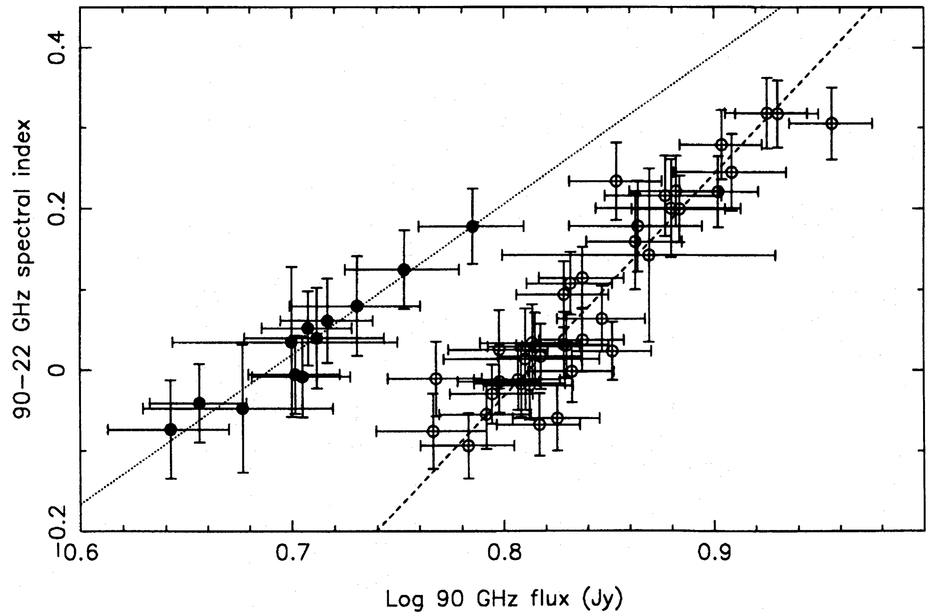

Figure 6. 90–22 GHz two-point spectral index against log 90-GHz flux. Filled circles represent the rise in flux during 1990 and open circles the decay in flux during 1991 and early 1992 (see Fig. 1). The lines are weighted fits to the data (see text).

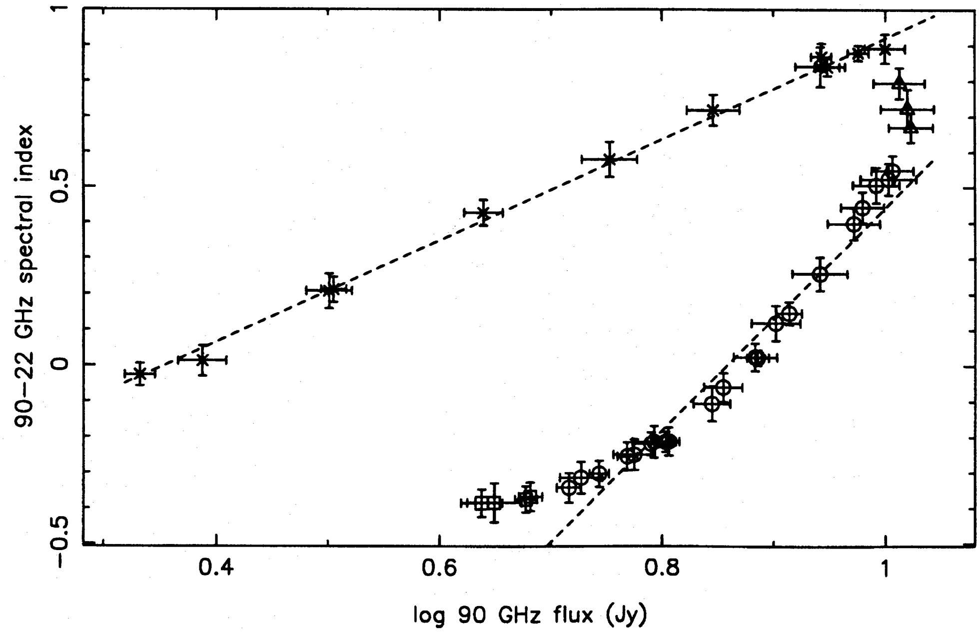

Figure 7. Simulated plot of 90–22 GHz two-point spectral index versus log 90-GHz flux. See text for symbol designations.

occurring. In order to investigate this point further we plot the 270–90 GHz two-point spectral index, which is always optically thin, against log 270-GHz flux (Fig. 5). The spectral indices were constructed by taking all available 270-GHz data between 1992 September 30 and 1992 November 27 (the 1992 flare) and linearly interpolating the better sampled 90-GHz light curve to obtain the corresponding 90-GHz fluxes. The quiescent level fluxes were then subtracted. As expected, the two quantities are correlated, with the spectral index steepening as the flux falls. We can also say that the spectral index steepens with time since it is the decay of the flare that is being investigated.

An important feature of the MG85 model is that it requires the exponent of the electron energy distribution, s, to be greater than 2 for the shock to remain non-radiative. If this is not the case then the shock must be initially very strong in order to propagate appreciably down the jet. For the quiescent spectrum (Fig. 2) a weighted least-squares fit to the 375–150 GHz data gives a slope of -0.59 ± 0.05 which is commensurate with the model requirements (assuming $\alpha = (1-s)/2$). The flare spectra (Table 1), however, appear to be flatter than this limit, with a mean value of −0.44. The curve fitting procedure gives no formal error on the fitted parameters, but we can infer an error in the slope of order ± 0.1 from the straight line fits to the 1991 July spectra of Fig. 3. Similar analysis of 3C 345 leads to an initial flare optically thin spectral index $\alpha = -0.5$. Although not as flat as previously claimed (Valtaoja et al. 1988), these values are considerably flatter than the -1.2 found for 3C 273 (MG85). The model runs into difficulties with such flat flare spectral indices since, during the Compton and synchrotron phases, the value of s is modified by the dependence of the shock thickness on frequency, i.e. $F_\nu \propto \nu^{(1-s)/2}\nu^{-1/2} \propto \nu^{-s/2}$. In this case $\alpha = -s/2 \lesssim -0.5$ leads to $s \lesssim 1$, in conflict with the above discussion.

4.3 Spectral indices

A second way to investigate the evolution of the flaring component is to monitor changes in spectral index with flux (e.g. Gear, Robson & Brown 1986b; Brown et al. 1989). The 90–22 GHz spectral index is particularly useful in this case since it typically spans the turn-over region. This quantity was constructed on each date that a 90-GHz flux was available; the 22-GHz points were assembled by linearly interpolating the better sampled 22-GHz light curve.

On plotting the 90–22 GHz spectral index against log 90-GHz flux a strong correlation was found. Fig. 6 shows the rise in flux (filled circles) during the second half of 1990 and the decay (open circles) from mid-1991 to mid-1992. The dotted and dashed lines are straight line fits weighted to errors in both axes (Press et al. 1992). In general, the spectral index becomes more positive as the flux increases and more negative as it decreases. Similar trends are seen for other blazars during outburst, e.g. 3C 279 (Litchfield et al. 1995, hereafter LEA95). In addition, the slope of the dotted line (1.86 ± 0.55) of Fig. 6 is flatter than that of the dashed line (2.76 ± 0.27). This was also found to be the case for a number of flares in 3C 279 (LEA95), i.e. the change in spectral index is more pronounced during the decay of flares than it is during the rise. It should be noted, however, that Fig. 6 refers to the rise of one flare and the decay of another.

We can model this behaviour by translating a homogeneous synchrotron spectrum, with the addition of the quiescent fluxes, through the three stages of flare evolution predicted by MG85. These three stages have a power-law form, and the exponents of the synchrotron and adiabatic phases are dependent on the value of the optically thin spectral index of the shocked emission. This quantity, α, was discussed in Section 4.2 and was deduced for a number of flare spectra (Table 1). We adopt the mean value from Table 1 of -0.44. The changes in turn-over frequency with turn-over flux for the three phases are then given by $F_{\rm m} \propto \nu_{\rm m}^{-2.5}$ (Compton), $F_{\rm m} \propto \nu_{\rm m}^{-0.34}$ (synchrotron), $F_{\rm m} \propto \nu_{\rm m}^{0.42}$ (adiabatic) (see MG85). For the 1991 flare the transition between the Compton and synchrotron phases was found to be between 150 and 90 GHz (SEA94 and Section 4.1), and so 120 GHz is adopted. The transition to the adiabatic phase was found to be between 90 and 37 GHz and 70 GHz is adopted.

The model results are presented in Fig. 7 where we include an appropriate random scatter to account for the observational uncertainty in the fluxes. Crosses correspond to $\nu_{\rm m} < 90$ GHz, triangles to $22 \leqslant \nu_{\rm m} \leqslant 90$ GHz with $\nu_{\rm m}$ in the synchrotron phase, circles to $22 \leqslant \nu_{\rm m} \leqslant 90$ GHz with $\nu_{\rm m}$ in the adiabatic phase and squares to $\nu_{\rm m} > 22$ GHz. The crosses depict the rise in 90-GHz flux and pertain mostly to the Compton phase since the synchrotron phase, at least for this flare, is probably short-lived, as concluded in Section 4.2. For this reason we also see few triangles. The circles correspond to the adiabatic phase, as do the squares, although the squares all have similar 90–22 GHz slopes since the turn-over is now longward of 22 GHz.

The model reproduces the observational dependences well (cf. Fig. 6). The slope of the rise (crosses; 1.42 ± 0.05) is flatter than that of the decay (circles; 3.12 ± 0.15). The fact that the observed and simulated decay slopes agree within the errors is at first sight surprising since, in the previous section, it was found that the decay phase was much more rapid than the simple model predicts (about 2.2 cf. 0.42). Furthermore, if we repeat the simulation and fix the decay phase to follow $F_{\rm m} \propto \nu_{\rm m}^{2.2}$, then the simulated decay slope is found to be about 1.3 which is much flatter than observed. Inspection of the light curves shows that the initial decay of the 1991 flare was indeed rapid. This is the period for which we found the exponent of 2.2. This rapid decline, however, is interrupted by low-amplitude flickering which may be the result of electron re-acceleration. The observed decay slope of Fig. 6 may thus not be totally determined by the expansion of the emitting region as given by MG85. Unfortunately, lack of 150–375 GHz data prevents monitoring of the 1991 flare spectrum after epoch 7.

5 DISCUSSION AND CONCLUSIONS

The 375- to 22-GHz spectral variability of the OVV quasar 0420–014 has been investigated for the period 1989.0–1994.5. Several flares were observed during this period. We have shown that data in this frequency range are important for testing existing shock jet models, as it is here where the synchrotron spectrum becomes self-absorbed. One problem is that the rise of flares is often abrupt and so, due to the nature of the sampling at the higher frequencies, the light curve is usually sparse in this region. This is unfortunate since it is this aspect of the flaring behaviour of blazars, the growth phase, about which least is known. To follow the evolution of the synchrotron spectrum through these early phases and to allow better estimates of the optically thin flare spectral index, simultaneous millimetre, submillimetre, mid- and near-infrared data are required; as was the case for the 1983 flare of 3C 273 (Robson et al. 1983). In practice, it proves difficult to isolate individual flares in many blazars and the extreme variability leads to difficulties in identifying a quiescent level. In these respects 0420–014 has proved a good source to monitor and, now that a prolonged period of quiescence has been observed, future monitoring should prove fruitful. Progress can be made with the existing data and the conclusions can be summarized as follows.

(1) After subtraction of the underlying quiescent emission it is found that the flare spectrum is commensurate with that of a simple homogeneous self-absorbed source.

(2) The evolution of this spectrum for the 1991 flare is found to be in rough agreement with the predicted Compton phase of the MG85 model, i.e. the peak flux increases as the turn-over evolves to lower frequencies, although the power-law exponent of this change is possibly smaller than predicted.

(3) No synchrotron phase is observed for the 1991 flare. The Compton phase behaviour is followed by a decay of peak flux with peak frequency. Although in the same sense as the

proposed adiabatic phase, the decay is too rapid. One possible explanation for this rapid decline is that the jet is initially aligned close to the line-of-sight and then bends away.

(4) For the 1992 flare we observe the outburst spectrum to evolve in a manner expected from the synchrotron loss phase of the model, i.e. the turn-over evolving to lower frequencies at approximately constant peak flux. Again the exponent is not in accord with prediction. Furthermore, the evolution of this flare in peak frequency connects smoothly with that of the former event. It is thus possible that the 1992 flare resulted from a brightening of the 1991 flare at some distance down the jet from the injection point.

(5) The 90–270 GHz spectral index, which is generally optically thin, steepens throughout the decay of the outbursts, consistent with the emitting electrons undergoing the expected radiative losses.

(6) The optically thin spectral index of the shocked emission is flatter than allowed by the MG85 model. During the synchrotron and Compton phases, the dependence of the shock thickness on frequency implies a value of $s \sim 1$ which is not allowed by the model since in this case the shocks are predicted to become radiative.

(7) Strong correlations are found between the 90–22 GHz spectral index and log 90-GHz flux for both the rise and decay of a flare, with the latter trend being steeper. For the 1991 flare, model simulations reproduce this observed behaviour well, but the decay of this flare was interrupted by complex flickering behaviour. This suggests that the actual slope of this decay is not solely determined by the expansion of the flaring region as given by MG85. Therefore, detailed comparison with model predictions is probably misleading.

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