RXTE observations of 3C 279 during a high-energy flare

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Abstract

We present details of a large X-ray flare in the blazar 3C 279 detected during a 3-week period of daily observations by the satellite RXTE in early 1996. The flare lasted for a total of 7 d. The shape of the flare is well described by a symmetrical, exponential rise and fall with e-folding time-scales in each case of 1.1 d. The peak measured flux is three times the quiescent level. The flare is superimposed on a well-defined quiescent level and appears to represent a separate emission component. There is no statistically significant variability of the X-ray spectral index during the observations, but the errors are large and the data hint at a hardening of about 0.1 at the peak of the flare. Such a hardening is required to allow the X-ray flare spectrum to join on, in a single power law, to the γ-ray flare that occurred at the same time. The exponential rise and decay most likely correspond to a variation in the acceleration of relativistic electrons or in the flux of seed photons, if the latter do not originate in the jet, as the energy loss time-scales are shorter than the rise and decay time-scales and the flare profile does not match that expected if light-travel delays determine the light curve.

Key words: galaxies: active – quasars: individual: 3C 279 – X-rays: galaxies.

1 INTRODUCTION

3C 279 is the classic broad-line blazar and, despite a redshift of z = 0.538, one of the brightest γ-ray sources in the sky as seen by EGRET (Kniffen et al. 1993). It is thought that the emission from blazars is dominated by a relativistic jet pointed directly towards us. The source of the high-energy photons is most likely Compton upscattering of lower energy photons by the energetic particles in the jet. However, the source of the scattered photons is uncertain. Some, if not all, of the low-energy photons may be synchrotron photons produced naturally in the jet (Ghisellini, Maraschi & Treves 1985; Jones, O’Dell & Stein 1974). However, other sources, such as the broad-line region or reprocessed jet emission, have been suggested (Melia & Königl 1989; Dermer & Schlickeiser 1993; Sikora, Begelman & Rees 1994; Blandford & Levinson 1995; Ghisellini & Madau 1996). The differing mechanisms should show differing behaviour in different wavebands; therefore simultaneous observations, preferably over a long time base, are needed to place limits on the models. A number of multiwaveband campaigns have been attempted (Maraschi et al. 1994; Hartman et al. 1996) with the latest in 1996 February, the results of which are presented in Wehrle et al. (1998). During this latest observing period a large flare was observed in the high-energy range by the Rossi X-ray Timing Explorer (RXTE) and the Compton GRO. Here we describe the data analysis of, and the results from, the RXTE observations.

2 OBSERVATIONS AND RESULTS

The main instrument on RXTE (Bradt, Rothschild & Swank 1993) is the proportional counter array (PCA). With five xenon-filled counters (PCUs), it has an energy range of 2–60 keV, an energy resolution of 18 per cent at 6 keV, a large (~0.7 m²) effective area, and a circular field of view [full width at half-maximum (FWHM) of 1°]. Each PCU has three separate anode layers. Only data from layer 1 have been used, as the majority of the counts in layers 2 and 3 during observations of faint sources are caused by the background.

The RXTE observations (see Table 1) were made on a roughly daily basis between 1996 January 22 and February 11 and have an average exposure of about 650 s. Data reduction was carried out using RXTE-specific ftool programs. The Standard2 data were filtered using internally applied good times (e.g. times of SAA passage), as well as the criteria that the elevation of the source above the horizon should be greater than 10° and that the angle between the source and the PCA pointing direction should be less then 0.01°. Light curves and spectra were produced using saextract.

The PCA is non-imaging and does not routinely nod off-source, so the background during an observation cannot be directly measured and must be modelled. The RXTE team has produced a program that provides a model of the background resulting from particles and radiation induced by the satellite passing through the South Atlantic Anomaly (SAA). A component representing the cosmic X-ray background is also included. Here pcabackest v1.5.

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Table 1. *RXTE* observation parameters and spectral fitting results.

<table>
<thead>
<tr>
<th>Obs</th>
<th>Date</th>
<th>Day</th>
<th>Exp</th>
<th>Count rate</th>
<th>$\alpha$</th>
<th>$\chi^2/\nu$</th>
<th>2–10 keV flux</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(count s$^{-1}$)</td>
<td></td>
<td></td>
<td>($10^{-14}$ W m$^{-2}$)</td>
</tr>
<tr>
<td>1</td>
<td>Jan 22</td>
<td>21.636215</td>
<td>656</td>
<td>3.027±0.379</td>
<td>0.99$^{+0.27}_{-0.25}$</td>
<td>30/43</td>
<td>1.31±0.18</td>
</tr>
<tr>
<td>2</td>
<td>Jan 23</td>
<td>22.781307</td>
<td>704</td>
<td>3.088±0.375</td>
<td>0.95$^{+0.16}_{-0.17}$</td>
<td>36/43</td>
<td>1.32±0.17</td>
</tr>
<tr>
<td>3</td>
<td>Jan 24</td>
<td>23.771122</td>
<td>672</td>
<td>2.520±0.375</td>
<td>0.92$^{+0.19}_{-0.20}$</td>
<td>25/43</td>
<td>1.07±0.17</td>
</tr>
<tr>
<td>4</td>
<td>Jan 25</td>
<td>24.713623</td>
<td>656</td>
<td>3.197±0.377</td>
<td>0.68$^{+0.15}_{-0.16}$</td>
<td>33/43</td>
<td>1.37±0.17</td>
</tr>
<tr>
<td>5</td>
<td>Jan 26</td>
<td>25.772141</td>
<td>624</td>
<td>2.470±0.377</td>
<td>0.97$^{+0.20}_{-0.21}$</td>
<td>29/43</td>
<td>1.06±0.17</td>
</tr>
<tr>
<td>6</td>
<td>Jan 27</td>
<td>26.906216</td>
<td>624</td>
<td>2.304±0.377</td>
<td>1.00$^{+0.21}_{-0.22}$</td>
<td>31/43</td>
<td>0.96±0.17</td>
</tr>
<tr>
<td>7</td>
<td>Jan 28</td>
<td>27.974735</td>
<td>688</td>
<td>2.815±0.375</td>
<td>0.94$^{+0.17}_{-0.18}$</td>
<td>22/43</td>
<td>1.19±0.17</td>
</tr>
<tr>
<td>8</td>
<td>Jan 30</td>
<td>29.710567</td>
<td>1056</td>
<td>3.132±0.367</td>
<td>1.08$^{+0.13}_{-0.14}$</td>
<td>30/43</td>
<td>1.32±0.17</td>
</tr>
<tr>
<td>9</td>
<td>Jan 31</td>
<td>30.711308</td>
<td>1056</td>
<td>3.032±0.367</td>
<td>0.91$^{+0.15}_{-0.16}$</td>
<td>29/43</td>
<td>1.29±0.17</td>
</tr>
<tr>
<td>10</td>
<td>Feb 01</td>
<td>31.445660</td>
<td>1136</td>
<td>3.196±0.367</td>
<td>0.84$^{+0.12}_{-0.13}$</td>
<td>28/43</td>
<td>1.36±0.19</td>
</tr>
<tr>
<td>11</td>
<td>Feb 02</td>
<td>32.575752</td>
<td>448</td>
<td>4.069±0.392</td>
<td>1.26$^{+0.16}_{-0.17}$</td>
<td>27/43</td>
<td>1.72±0.22</td>
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<tr>
<td>12</td>
<td>Feb 03</td>
<td>33.923344</td>
<td>192</td>
<td>5.275±0.452</td>
<td>0.84$^{+0.18}_{-0.19}$</td>
<td>27/43</td>
<td>2.24±0.22</td>
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<tr>
<td>13</td>
<td>Feb 04</td>
<td>34.244087</td>
<td>544</td>
<td>5.831±0.391</td>
<td>0.79$^{+0.10}_{-0.10}$</td>
<td>19/43</td>
<td>2.52±0.22</td>
</tr>
<tr>
<td>14</td>
<td>Feb 05</td>
<td>35.521309</td>
<td>512</td>
<td>8.774±0.398</td>
<td>0.77$^{+0.07}_{-0.07}$</td>
<td>22/43</td>
<td>3.80±0.23</td>
</tr>
<tr>
<td>15</td>
<td>Feb 06</td>
<td>36.674919</td>
<td>624</td>
<td>4.580±0.382</td>
<td>0.83$^{+0.11}_{-0.11}$</td>
<td>26/43</td>
<td>1.92±0.21</td>
</tr>
<tr>
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<td>Feb 07</td>
<td>37.316494</td>
<td>736</td>
<td>4.147±0.378</td>
<td>1.16$^{+0.12}_{-0.13}$</td>
<td>21/43</td>
<td>1.74±0.20</td>
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<tr>
<td>17</td>
<td>Feb 08</td>
<td>37.545567</td>
<td>384</td>
<td>3.856±0.399</td>
<td>1.26$^{+0.13}_{-0.13}$</td>
<td>26/43</td>
<td>1.66±0.23</td>
</tr>
<tr>
<td>18</td>
<td>Feb 10</td>
<td>40.389641</td>
<td>928</td>
<td>3.213±0.369</td>
<td>0.73$^{+0.12}_{-0.13}$</td>
<td>22/43</td>
<td>1.37±0.19</td>
</tr>
<tr>
<td>19</td>
<td>Feb 09</td>
<td>39.606030</td>
<td>528</td>
<td>2.912±0.383</td>
<td>0.94$^{+0.18}_{-0.18}$</td>
<td>28/43</td>
<td>1.27±0.21</td>
</tr>
<tr>
<td>20</td>
<td>Feb 11</td>
<td>41.787514</td>
<td>240</td>
<td>2.991±0.423</td>
<td>0.97$^{+0.29}_{-0.29}$</td>
<td>22/43</td>
<td>1.23±0.26</td>
</tr>
</tbody>
</table>

Notes:

- Obs: Observation number.
- Date: Date and time in the middle of the observation (year is 1996).
- Day: Decimal day of 1996, where 1996 Jan 01 at 00:00:00 is day 0.0.
- Exp: Exposure in s (after data selection).
- Count rate: From PCA observations.
- $\alpha$: Power-law index.
- $\chi^2/\nu$: Reduced chi-squared.
- 2–10 keV flux: From *RXTE* observations.

with the q6 model was used to produce background model files. Using the same techniques as for on-source observations, spectra and light curves were then extracted from the background model files.

To estimate the accuracy of the background model, we have subtracted model spectra from a large number of slew spectra. From the resulting spectra we calculate the residual 3–10 keV count rate. The intrinsic scatter is 0.35 count s$^{-1}$ and provides an upper limit on the systematic error associated with each measurement of the on-source count rate in that band (see Appendix A for more details). The count rate in the 3–10 keV band for each observation is listed in Table 1, and the error includes the systematic error added in quadrature.

The *RXTE* spectra were analysed using the XSPEC fitting package. The data were fitted (over the 3–15 keV band) with a simple power-law model with a fixed Galactic $N_H$ absorbing column of $2.22 \times 10^{20}$ cm$^{-2}$ (Elvis, Lockman & Wilkes 1989). Table 1 shows the results from this fitting for each observation. The reduced $\chi^2$ values show that in each case the power-law model is an acceptable fit to the data, and that a more complex model is not required.

As a result of the relatively short observations and the faintness of the source, the errors on the spectral indices are quite large and the indices are all consistent with a single energy index of $\alpha = 0.89 \pm 0.03$ (Fig. 2). This is above the steep end of the range of indices, 0.6–0.8, that was measured by earlier experiments (Lawson & Turner 1997), and is rather higher than the index of $\alpha = 0.7$ (no error given) measured by ASCA on January 27, a few days before the flare. However, we note that spectral indices derived from *RXTE* PCA observations seem to be about 0.1 steeper than those derived from observations by other instruments over roughly the same band (e.g. our own observations of the bright blazar 3C 273, Lawson, M'Hardy & Marscher, in preparation). This 'problem' is known about by the *RXTE* Guest Observer Facility (GOF), and much effort is currently being put into understanding the reasons for this (see their Web pages for more information). As yet, therefore, we cannot comment on any possible difference between our indices and other indices. We do note, however, that the *RXTE* flux is identical to the ASCA flux measured on the same day.

The 2–10 keV integral fluxes given in Table 1 are derived assuming that $\alpha = 0.89$. The error on the fluxes comprises the uncertainty in the spectral normalization and the systematic background error added in quadrature. The typical overall error is 12 per cent.

The 2–10 keV light curve is shown in Fig. 1. A large flare is seen lasting about 7 d, which appears to rise from, and fall back to, the same constant level. Fitting to the points not obviously involved in the flare (observation numbers 1–11, 19–21) gives a mean value for the 'quiescent' emission of $1.23 \times 10^{-14}$ W m$^{-2}$ in the 2–10 keV band. Assuming $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$, the quiescent flux corresponds to an (isotropic) 2–10 keV luminosity of $1.88 \times 10^{39}$ W. As the pre- and post-flare levels are the same, the flare does not seem to have permanently perturbed the physical conditions in the emitting region.

The highest measured flux during the flare is a factor of $\sim 3 \times$ the quiescent level. This factor is only a lower limit, as the peak flux may not have been sampled. There is also the problem of not knowing the
The X-ray emission.

...are. The peak measured flux for the are. The most obvious explanation for this temporal agreement hint that the X-rays may lag the are. Similar with no significant delay between them, although there is a hint that the X-rays may lag the gamma-rays slightly on the rising part of the are. The most obvious explanation for this temporal agreement is that both the X-rays and gamma-rays are produced in the same region during the are. The peak measured flux for the gamma-rays is a factor of ~9 above the base level, compared with only 3 for the X-rays. Thus the gamma-ray emission from 3C 279 is much more flare-dominated than the X-ray emission.

3 DISCUSSION

We have presented observations of the best resolved X-ray flare yet observed in an OVV quasar. Our observations occurred every day, yet inspection of Fig. 1 shows that even more frequent observations, at least at half-day intervals, would have been required to sample the variability fully. We therefore probably do not sample the peak flux of the are, but we can measure the are rise, fall and total duration times (Section 2) reasonably robustly, as well as obtaining a good value for the quiescent flux level.

3.1 Amplitudes and spectra

The present quiescent and flare X-ray flux levels are similar to previous low and high levels detected by the Ginga and ASCA satellites (Makino & Kii 1996; Lawson & Turner 1997). Also, in 1996 June, we observed the source (Lawson & McHardy 1998) with RXTE and ROSAT at close to the present quiescent level. Over a 17-day period of daily monitoring we detected no flares, but the 2–10 keV flux did decrease steadily by 25 per cent over the course of the observations. Thus there is evidence that the quiescent level can change on time-scales of months. Therefore, although the present (and past) observations of gamma-ray emission from 3C 279 are consistent with purely flaring behaviour, the X-ray observations are best explained by the combination of relatively steady emission with superimposed flares.

The determination of an X-ray flare amplitude is therefore difficult and may not be meaningful. If the flare X-rays arise in a completely different region from the quiescent X-rays then the ‘quiescent’ X-ray level of the flaring region may be close to zero, and hence the flare amplitude is close to infinite. However we note that the X-ray spectral indices during the are are similar to those of the quiescent emission, which suggests some relationship between either the location of the emitting regions or the particle acceleration mechanisms of the are and quiescent emission.

Regarding the X-ray spectra, although the data are consistent with a constant spectral index, there is an indication of a small flattening of the spectrum of $\alpha = 0.08$ during the peak of the are. Such a flattening, relative to pre-flare observations, is required if we are to join the X-ray and gamma-ray flux measurements (without the subtraction of any quiescent levels) with a single power law during the are. Any such power law must have an index of 0.7 or flatter (Wehrle et al. 1998). The present average $RXTE$ X-ray index of $\alpha = 0.89$ is therefore too steep to allow a single power law to explain both the X-ray and gamma-ray emission. However as $RXTE$ indices seem to be systematically steeper than that of other instruments by about 0.1 then, together with a slight flattening during the are, we can reconcile the X-ray and gamma-ray emission with one power law.

3.2 Profile and time-scales

The exponential rise and decay of the light curve of the X-ray flare is similar to the profiles of millimeter-wave flares in blazars (Ter astranta & Valtaoja 1996). A general model for such flares must therefore reproduce this characteristic. The first question to address is whether some geometric effect is responsible. The leading possibility is light-travel delay, i.e. the fact that different parts of the emitting region inevitably lie at different distances from the observer and may also light up at different times.

An emission region of size $a \times \tau_{\text{var}} \delta (1 + z)$, where $\tau_{\text{var}}$ is the variability time-scale, would require a Doppler factor $a \approx 1$ times the...
minimum time-scale for a flare to be quenched by radiative losses as for the X-ray emission. Acceleration and subsequent energy loss of the electrons responsible for the X-ray light curve might be related to time variability in the context of a model in which the seed photons originate from infrared photons, in the SSC scenario, that the flare traces the electron acceleration, modulated by light-travel delays. The variation in the number of high-energy (radiating) electrons could correspond either to the variation in the strength of the acceleration mechanism or to the density of electrons encountered by the excitation front. As an example of a reasonable physical situation we show, in Fig. 4, a simulated light curve of self-scattered emission caused by a square-wave excitation passing through a spherical emitting region with electron density falling off exponentially with distance from the centre. The fit to the X-ray light curve of 3C 279 is quite reasonable. However it should be noted that the exact details of the model are not important and the geometry that we describe is probably not the only one that will explain the light curve, although the mm–submm photons have too low a frequency to be scattered into the γ-ray regime by such a population of electrons. Hence, the X-ray variations should be correlated with the mm–IR fluctuations, while the γ-ray and IR–optical variations should be closely correlated.

The implication of the short synchrotron loss times for mm–infrared photons, in the SSC scenario, is that the flare traces the electron acceleration, modulated by light-travel delays. The variation in the number of high-energy (radiating) electrons could correspond either to the variation in the strength of the acceleration mechanism or to the density of electrons encountered by the excitation front. As an example of a reasonable physical situation we show, in Fig. 4, a simulated light curve of self-scattered emission caused by a square-wave excitation passing through a spherical emitting region with electron density falling off exponentially with distance from the centre. The fit to the X-ray light curve of 3C 279 is quite reasonable. However it should be noted that the exact details of the model are not important and the geometry that we describe is probably not the only one that will explain the light curve, although we could show a number of other possibilities that do not reproduce the light curve. What is important is that the light curve can be reproduced with a relatively simple geometry and that the radiation loss time-scales do not dominate the shape of the light curve. Within the context of a model in which the seed photons originate from outside the jet, the exponential rise and fall of the X-ray/γ-ray flare could be caused by a variation in the seed photon flux as viewed by the relativistic electrons in the jet.
In order for the high-energy photons to escape before pair-producing on the electrons in the jet, an external source of seed photons that are Compton scattered by the magnetic field strength with distance from the centre. The higher density sphere has a scale length of 15 light-days in the source frame and the lower density sphere, required to explain the wings of the light curve, has a normalization of 20 per cent of the main sphere with a scale length of 150 light-days. The emission is excited for a short time after passage of a square-wave excitation front propagating at 0.98c in the source frame, with a relativistic Doppler factor in the observer’s frame of 8.4. Light-travel delays of the seed photons (as seen by the scattered electrons) and of the scattered emission in the observer’s frame are taken into account in the calculations.

The simultaneity of the X-ray and γ-ray emission constrains inhomogeneous SSC jet models (Maraschi, Ghisellini & Celloti 1992) for the flare (but not necessarily for the ‘static’ underlying spectrum). As discussed above, if the high-energy photons are produced by the SSC mechanism, the X-rays are mainly scattered mm/submm/far-IR photons and the γ-rays are mainly scattered near-IR photons, which are produced in much smaller volumes than the mm/submm/far-IR photons in the inhomogeneous jet model. Hence, substantial time delays are implied between the X-ray and γ-ray emission in the inhomogeneous jet model, although detailed calculations have yet to be carried out to quantify the delays. The shock model (Marscher & Gear 1985) predicts shorter time delays between the X-ray and γ-ray emission than does the inhomogeneous jet model. The delays between wavebands are less than the radiative loss times at the longest wavelengths involved (mm/submm/X-ray). Thus the time delay between various wavebands is always shorter than the duration of the flare at the longest wavelengths.

4 CONCLUSIONS

Because the X-ray and γ-ray flares are essentially simultaneous, it is highly likely that both wavebands are emitted from the same region. In order for the γ-rays to escape before pair-producing on the X-rays, the jet Doppler factor, δ, must be greater than 6 (Wehrle et al. 1998), which lowers the X-ray photon density required to explain the X-ray flux. Unless δ is unrealistically larger than this minimum value, light travel delays must be important.

The relatively short derived synchrotron energy loss time-scales imply that the profile of the X-ray light curve reflects the time dependence of the acceleration mechanism. The importance of light travel effects suggests that the manner in which the electrons are accelerated (e.g. via a square-wave excitation front) and the density profile of the electrons are both important factors in determining the shape of the light curve. The exponential flare profile observed in 3C 279 therefore requires an exponential variation in the efficiency of acceleration of relativistic electrons or in the number of electrons that are energized. Alternatively, the flare could have been caused by an exponential rise and decay of an external source of seed photons that are Compton scattered by the electrons in the jet.

ACKNOWLEDGMENTS

We thank the staff at the RXTE GOF for their help and advice, and Ann Wehrle and Bob Hartman for the EGRET γ-ray data.

REFERENCES


APPENDIX A: DERIVATION OF THE SYSTEMATIC ERROR FOR THE BACKGROUND MODELLING

180 sets of slew data from observations of 3C 279 and 3C 273 during gain period 3 were used to estimate the systematic error in the background modelling. The data were extracted and background models were generated as with the on-source data. The background subtracted count rates in the 3–10keV band were then derived. The individual slew observations were then cleaned to remove obvious contamination above the scatter by deleting all data points with a background subtracted count rate of greater than 5 count s⁻¹. Observations with a good time exposure of less than 256 s after the above cleaning were then ignored, leaving a total of 122 observations with an average exposure of 450 s. The mean count rates from these observations were then cleaned...
again to remove any points at greater than $\pm 3\sigma$ (two more observations) and their dispersion was then calculated as $\sigma = 0.384 \text{ count s}^{-1}$. Removing the effect of the errors (average 0.166 count s$^{-1}$) gives a remaining intrinsic scatter of $\sigma_i = 0.35 \text{ count s}^{-1}$, which we have adopted as a measure of the systematic error. This value is likely to be an overestimate because we have not been able to remove the effects of any remaining serendipitous sources.

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