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# TIME VARIABILITY DETECTED IN THE GAMMA-RAY EMISSION OF 3C 273 BY OSSE

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## ABSTRACT

We report results of a 3 week observation of the quasar 3C 273 with the Oriented Scintillation Spectrometer Experiment (OSSE) instrument on the *Compton Gamma Ray Observatory* (*CGRO*). During the observation between 1994 August 31 and September 20, 3C 273 exhibited variability on timescales as short as 3–4 days in the 0.05–0.15 MeV energy range. This is the shortest measured variability of 3C 273 in this energy range. The measured flux at 100 keV is 2.40 ± 0.06 ($\times 10^{-2}$ ph cm$^{-2}$ s$^{-1}$ MeV$^{-1}$), which is the highest recorded flux for 3C 273 by OSSE in 5 years of monitoring and nearly twice as great as the previously recorded peak flux measured in 1991 June. While the flux varied by a factor of ≅1.7, no significant gamma-ray spectral evolution in the OSSE band was observed throughout the viewing period. The data for the full viewing period are described better with a broken power law than a single power law, with photon spectral index $\Gamma = 1.62 \pm 0.08$ below a break at 300 ± 100 keV, and with a spectral index change of $\Delta\Gamma = 0.9^{+1.6}_{-0.6}$. This break energy is significantly lower than the 1 MeV break reported by Johnson et al. in 1991 June.

*Subject headings:* galaxies: active — gamma rays: observations — quasars: individual (3C 273)

## 1. INTRODUCTION

The unusual high-energy properties of the quasar 3C 273 were suggested by the *COS B* detection of this source at energies above 50 MeV (Swanenburg et al. 1978). Interpolation between the available hard X-ray data up to ∼120 keV (Primini et al. 1979; Ricker et al. 1980; Pietsch et al. 1981; Bezler et al. 1984) and the *COS B* data indicated that the peak in the power output of 3C 273 occurs in the soft gamma-ray regime. This inference has been established through observations made by *CGRO*. One of the first projects for *CGRO* was the simultaneous observations of 3C 273 with OSSE, COMPTEL, and EGRET as part of an international observation campaign at several different wavelength bands ranging from $\sim 10^9$ to $\sim 10^{25}$ Hz (Lichti et al. 1995). This campaign reveals a spectrum of 3C 273 with two distinct maxima at UV and MeV energies in a $\nu F_\nu$ plot of the multiwavelength spectrum. Assuming isotropic emission, the power radiated in these broad maxima are $\approx 4.5 \times 10^{46}\, h^{-2}$ erg s$^{-1}$ and $\approx 3.9 \times 10^{46}\, h^{-2}$ erg s$^{-1}$ at $\nu = 2.32 \times 10^{15}$ Hz and 1 MeV, respectively. Here we use a Hubble constant of 50 $h$ km s$^{-1}$ Mpc$^{-1}$.

3C 273 is known to be variable at all wavelengths. Variability at radio (Robson et al. 1993), IR (Lichti et al. 1995), UV (Ulrich, Courvoisier, & Wanstecker 1988), and optical (Smith et al. 1993; Courvoisier et al. 1988) frequencies has been reported on timescales of ∼0.5 years, 10 months, ∼3–6 months, and hours, respectively. Temporal variability of 3C 273 at X-ray and gamma-ray energies is not well known, but Courvoisier et al. (1990) compiled a light curve of 3C 273 at X-rays using the data of *Einstein*, *EXOSAT*, and *Ginga*. During 10 years of observation with poor sampling, intensity variations up to a factor of ∼3 were observed. The fastest variation observed during this time span was a decrease by ∼40% in 20 days (Courvoisier et al. 1987; see also Turner et al. 1990). The only claim of high amplitude X-ray variations on timescales shorter than ∼1 month comes from an *Ariel V* observation reported by Marshall, Warwick, & Pounds (1981). Variability at higher energies is reported at a timescale of more than 100 days by EGRET (Von Montigny et al. 1995), where they have defined $T_{var}$ as the minimum timescale on which the source flux in the EGRET energy band has been observed to change by a factor of 2.

Prior to 1996 January, OSSE observed 3C 273 a total of 13 times. Data taken prior to and including observations made during the period 1992 December 22–1993 January 12 were reported earlier (Johnson et al. 1995). They presented evidence for long-term time variability in the 50–150 keV energy range by a factor of ∼4 on a timescale of 3–4 months. Over a period of 2 weeks, the hypothesis that the data were consistent with a uniform flux could be excluded at a significance of more than 2.5 $\sigma$. Variability on day-to-day timescales was suggested by 25% deviations in the daily fluxes.

In this paper we present results from a 1994 September observation during which the 50–150 keV flux from 3C 273 nearly doubled in ≈7 days. Flux variations are also evident on timescales of 3–4 days. This is the shortest variability timescale recorded for this source in this energy range. In § 2, we describe the observations and spectral fitting, and in § 3, we discuss the implications of this short-term flare and the observed break in its spectrum.

## 2. OBSERVATIONS AND RESULTS

OSSE observed 3C 273 in the energy range 0.05–10 MeV during the period from 1994 August 31 to September 20 (Viewing Period [VP] 338.5). A total on-source observation time of $6.05 \times 10^5$ detector-seconds of screened data for the sum of four detectors was used in the analysis. A similar amount of time in background observations was used, with background offsets −4°.5 and 7°.0 (the latter offset designed to avoid the potentially confusing target NGC 4593).

During VP 338.5, 3C 273 was detected at a significance level of greater than 7 $\sigma$ per day in the energy range 50–150 keV. Significant positive flux (>5 $\sigma$) is observed in the average total spectrum out to 800 keV. During this viewing period, 3C 273 was an X-axis target so no contemporaneous observations of

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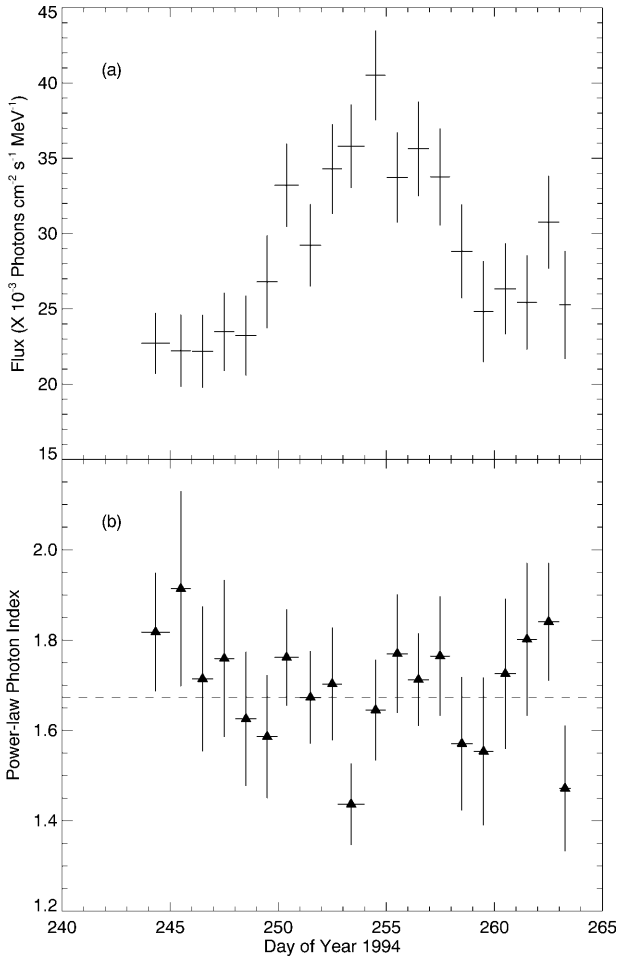



FIG. 1.—(*a*) OSSE light curve for 3C 273. The horizontal bars show the extent of the daily time bins. The vertical bars are 1 $\sigma$ uncertainties in flux in the 50–150 keV range. (*b*) Value of the best-fit power-law index for each daily time bin. Vertical bars are 1 $\sigma$ uncertainties in spectral index.

3C 273 with COMPTEL or EGRET were made. Furthermore, due to Sun constraints over this part of the sky in September, no strictly contemporaneous observations have been reported of 3C 273 except for the University of Michigan Radio Astronomy Observatory, which detected a total flux density from 3C 273 of 41.46 $\pm$ 0.51 Jy at 8.0 GHz on 1994 August 31 and 32.65 $\pm$ 0.74 Jy at 14.5 GHz on 1994 September 9 (Aller 1996). The total flux densities at these frequencies are roughly constant from early 1994 through mid-1995.

The OSSE data for VP 338.5 were analyzed using the standard methods described in Johnson et al. (1993). Background estimation was performed by fitting the nearest three or four background spectra, channel-by-channel, using a quadratic function in time. The background estimate was then subtracted from the source spectrum and the resulting difference spectra for each day were summed separately for each detector. Because no significant differences in the spectra from each detector were seen, the spectra for the four detectors were summed together in order to improve the daily count statistics. The resultant spectra were fitted by folding a model photon spectrum through the instrument response matrix and comparing the resultant count spectrum with the observed spectrum. The parameters of the photon model were adjusted to minimize $\chi^2$.

Fits to the daily spectra are well described by simple power-law models ($\Phi(E) \propto (E/E_o)^{-\Gamma}$). Figure 1*a* shows the average integrated daily flux intensities for the sum of all four detectors in the 50–150 keV energy range. The flux in this band gradually increases by a factor of 1.7 times between days 94/248 and 94/254 (7 days) and then gradually decreases to a steady flux by day 94/259 (total number of days of enhancement is 11 days). The values of photon indices, $\Gamma$, are provided in Figure 1*b*. The average power-law index for this set is 1.67 with a variance of 0.12. No significant change in spectral shape was observed during the flux enhancement. Similar enhancements that peak at the same time are seen in the 150–300 keV and 300–800 keV energy ranges. The spectral indices obtained for single power-law fits for the nonflaring (days 244–249 and 259–263) and flaring (days 250–258) periods are 1.73 $\pm$ 0.07 and 1.71 $\pm$ 0.06, respectively. The lack of spectral variability in the OSSE energy range is in contrast to *ROSAT* results in the soft X-ray regime (0.1–2.4 keV) of observations taken in 1990 June and December. Under the assumption of a single power-law model, there were significant variations in the power-law index from one *ROSAT* observation to the next, demonstrating spectral variability on timescales of 5–12 months (Staubert et al. 1994).

When the total spectrum for 3C 273 during this observation is fit by a simple power-law model, we obtain the best-fit photon flux given by

$$\Phi(E) = 2.40 \pm 0.06 \times 10^{-2} \left(\frac{E}{0.1\ \mathrm{MeV}}\right)^{-1.71\ \pm\ 0.05}, \qquad (1)$$

in units of photons cm$^{-2}$ s$^{-1}$ MeV$^{-1}$, where $E$ is photon energy in MeV. The reduced $\chi^2$ for this fit is $\chi^2_\nu = 1.28$. The errors given are the 90% confidence limits for joint variation of the respective parameters of interest. This spectrum is consistent with results of previous OSSE observations of 3C 273 (Johnson et al. 1995), where the data are all well described by a single power law with an average photon index of $\Gamma = 1.7 \pm 0.1$. Figure 2 shows the 50–150 keV flux of 3C 273 as monitored by OSSE over 5 years of observation; the duration of each viewing period varied from approximately 1–3 weeks. The highest flux observed from this source with OSSE occurred during VP 338.5, and is nearly twice as great as any

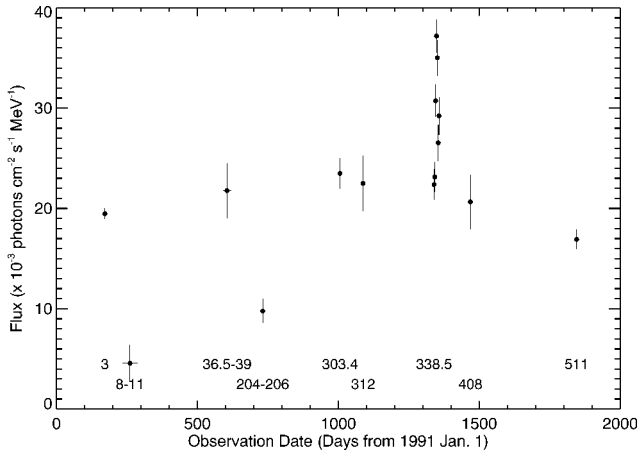



FIG. 2.—Time-averaged flux in the 50–150 keV band over a 5 year time span. Each data point represents the average flux observed during individual viewing periods, or for a group of *CGRO* viewing periods. The exception is for VP 338.5, where each data point represents a contiguous 3 day period. *CGRO* viewing period numbers are displayed at the bottom.

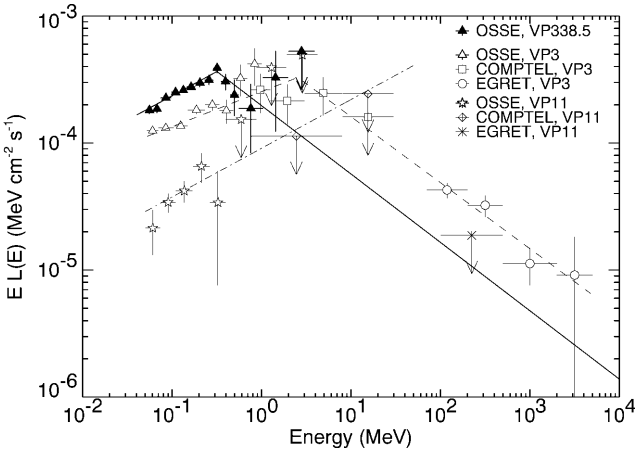



FIG. 3.—Spectrum of 3C 273 for period 1994 August 31–September 20 displayed as $E^2\Phi(E)$, where $\Phi(E)$ is the differential photon flux. Included in the plot for comparison are the spectra from 1991 June 15–28 (VP 3) and 1991 October 3–17 (VP 11). The best-fit broken power-law model for VP 3 (*dashed line*) is a simultaneous fit with the OSSE through EGRET data. The broken power-law model for 338.5 (*solid line*) is a fit with OSSE data only with an extrapolation to the EGRET energy range. The simple power-law model for VP 11 (*dash-dotted line*) is also a fit to OSSE data only with an extrapolation to higher energies. The EGRET data is from Von Montigny et al. (1993) and Thompson et al. (1995); the COMPTEL data is from Lichti et al. (1995) and Williams et al. (1995).

previously recorded peak flux. The highest ever recorded flux from 3C 273 in the 20–200 keV range, however, is from the balloon-borne AIT/MPE hard X-ray telescope HEXE on 1981 September 28 (Bezler et al. 1984), where the observed flux is still 43% higher than that found with OSSE during VP 338.5.

The single power-law fit to the full data set for VP 338.5 is adequate with a reduced $\chi^2_\nu = 1.28$ and $P(\chi^2) = 0.17$. A fit to the contemporaneous *CGRO* data from OSSE, COMPTEL, and EGRET for 3C 273 during VP 3 shows that the spectrum measured at that time breaks gradually to a steeper spectrum with increasing energy (Johnson et al. 1995). Similar softening is apparent in several other blazars observed by OSSE and EGRET (McNaron-Brown et al. 1995). When the 3C 273 OSSE data for VP 338.5 are fitted with a broken power-law model, we obtain $\chi^2_\nu = 0.66$ and $P(\chi^2) = 0.86$. The best-fit photon flux below the break has the form

$$\Phi(E) = 3.6 \pm 0.1 \times 10^{-3} \begin{cases} \left(\dfrac{E}{E_B}\right)^{-\Gamma} & E \le E_B\,, \\ \left(\dfrac{E}{E_B}\right)^{-(\Gamma+\Delta\Gamma)} & E > E_B\,, \end{cases} \quad (2)$$

in units of photons cm$^{-2}$ s$^{-1}$ MeV$^{-1}$, where $E_B = 0.3 \pm 0.1$ MeV and the photon spectral index $\Gamma = 1.62 \pm 0.08$. The change in spectral index between the two power laws is found to be $\Delta\Gamma = 0.9$ $(+1.6, -0.6)$. An $F$ test indicates that the improvement in fit obtained using a broken power-law fit is highly significant ($F_x = \Delta\chi^2/\chi^2_\nu = 21.7$). The likelihood that this improvement is by chance is $2 \times 10^{-5}$. The best-fit broken power-law spectrum is shown in Figure 3. Upper limits are displayed at the 2 $\sigma$ level.

## 3. DISCUSSION

Observations of superluminal motion in 3C 273 (e.g., Davis, Unwin, & Muxlow 1991) are explained if radiating plasma is ejected at relativistic speeds from a compact nucleus. Gamma-ray observations can provide additional evidence for beaming of the emission and ejection of radiating plasma (see Dermer & Gehrels 1995 and McNaron-Brown et al. 1995 for a discussion of these relations). We first consider the Elliot-Shapiro (1974) relation, which tests for beaming by considering whether it is consistent to assume that a source isotropically radiates Eddington-limited emission given the observed variability timescale.

The luminosity emitted by an isotropically radiating source at redshift $z$ in the *observed* photon energy range $E_1 \le E \le E_2$ is given by

$$L[E_1(1+z), E_2(1+z)] = 4\pi\, d_L^2 \int_{E_1}^{E_2} dE E\Phi(E)\,. \quad (3)$$

Substituting the broken power-law fit of equation (2) into equation (3), we find that if 3C 273 is assumed to radiate isotropically, it radiates $4.5 \times 10^{46}$ ergs s$^{-1}$ between 58 keV [=50 keV $\times$ (1 + 0.158)] and 350 keV. The total luminosity radiated by 3C 273 between 58 keV and 4.6 MeV is found to be $9.3 \times 10^{46}$ ergs s$^{-1}$. We note that 81% of the power radiated by 3C 273 in the OSSE energy band is observed at energies between 50 keV and 1 MeV.

Neglecting Klein-Nishina corrections to the Compton cross section, the Elliot-Shapiro relation can be written as

$$\frac{L(\text{ergs s}^{-1})}{\delta t(\text{days})} \lesssim \frac{10^{47}}{(1+z)(R/10R_S)}\,, \quad (4)$$

where $\delta t$(days) is the observed minimum variability timescale in units of days. The variable $R$ denotes the characteristic size scale in which the luminosity is generated, and we have scaled this size to 10 $R_S$, where the Schwarzschild radius $R_S = 2GM/c^2$ and $M$ is the mass of the central black hole. If equation (4) is not satisfied, then the assumption that the source is Eddington limited and radiating isotropically must be called into question. For 3C 273, $L/\delta t \approx 0.1$–$0.3 \times 10^{47}$ ergs s$^{-1}$ day$^{-1}$. Even for a 1 day variability timescale, we cannot convincingly argue that the Elliot-Shapiro relation is violated, particularly since the inclusion of Klein-Nishina effects increases the Eddington limit.

The detection of gamma-ray photons above the pair production threshold also provides arguments for beaming through $\gamma\gamma$ transparency arguments (Maraschi, Ghisellini, & Celotti 1992; Mattox et al. 1993). Using the relations quoted in McNaron-Brown et al. (1995), given the luminosity and variability timescale found in VP 338.5 for 3C 273, we find that the optical depth $\tau_{\gamma\gamma}$ to pair-production attenuation of photons with observed energies of 1 MeV is 3.4 for a 3 day variability, and 10.1 for a 1 day variability. This provides weak evidence in favor of ejection of bulk radiating plasma or the production of anisotropic radiation from beamed particle distributions.

We now consider the implications of the measured spectral break energies and luminosities. In VP 3 (Johnson et al. 1995) and VP 338.5, we measure spectral break energies at $E = 0.98^{+0.94}_{-0.37}$ MeV and at $E = 0.3 \pm 0.1$ MeV, respectively. The luminosity emitted by 3C 273 in VP 3 and VP 338.5 in the range of photon energies detected between 50 keV and 1 MeV is $2.3 \times 10^{46}$ ergs s$^{-1}$ and $7.5 \times 10^{46}$ ergs s$^{-1}$, respectively. Although the statistics are not compelling, there is a suggestion that as the source luminosity increases, the break energy goes to lower values. In Figure 3, we plot the $E^2\Phi(E)$ spectrum of 3C 273 for VPs 3, 11, and 338.5, which indicates that the

break energy decreases with increasing source luminosity in the OSSE energy band. If this behavior is confirmed in more detailed observations, then it provides a strong constraint upon source models.

In summary, we have reported observations of 3C 273 made with the OSSE telescope on *CGRO* during 1994 August–September. The source flux was unusually intense and varied on the shortest measured timescale to date in the 0.05–0.15 MeV range. Nevertheless, there was no evidence of spectral evolution throughout the 3 week observing period. The variability timescale provides evidence for beaming through $\gamma\gamma$ transparency arguments. A correlation of the peak of $\nu F_\nu$ spectrum at soft gamma-ray energies with flux in the OSSE energy band is suggested by these observations and, if confirmed by future observations, will provide an important constraint on models of 3C 273.

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