Extremely rapid bursts of TeV photons from the active galaxy Markarian 421

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DISCRETE astronomical sources of photons in the TeV energy range are believed to be associated with regions in the relativistic outflow of particles and radiation from compact objects, such as neutron stars and black holes. The flux from such sources, together with the timescales on which they vary, can provide strong constraints on the emission mechanisms. Here we report the observation of two dramatic outbursts of TeV photons from the active galaxy Markarian 421 (Mrk421). In the first outburst, which had a doubling time of about one hour, the flux increased above the relatively quiescent value by more than a factor of 50, briefly making Mrk421 the brightest TeV source in the sky. In the second outburst, which lasted approximately 30 minutes, the flux increased by a factor of 20–25. These data suggest that the emission region is extremely small—perhaps even smaller than our Solar System. This could prove challenging for current theoretical models of such emissions.

A camera consisting of 109 fast photomultipliers with a pixel size of 0.25° at the 10-metre reflector at the Fred Lawrence Whipple Observatory[1,2] images Cherenkov radiation from air showers. Image processing techniques refined using detailed Monte Carlo simulations[2–4] and frequent observations of the Crab Nebula over several years (ref. 5) enable discrimination of γ-ray-induced showers from the dominant background of showers created by high-energy cosmic rays. Four parameters that form the basis for selection criteria known as 'Supercuts' (ref. 3) are used to describe the approximately elliptical images: the angular width and length of the reduced image, the distance of the image centroid from the centre of the camera, and the orientation angle α defined as the angle between a line from the centroid of the image to the centre of the camera and the major axis of the image ellipse. There is an excess number of events in the distribution of the angle α near 0°, providing evidence for γ-rays. Background subtraction is determined from off-source runs at the same telescope elevation and from events with large α angles in on-source data. A more thorough description of the methods used in the detection of γ-rays can be found in the literature[3–5].

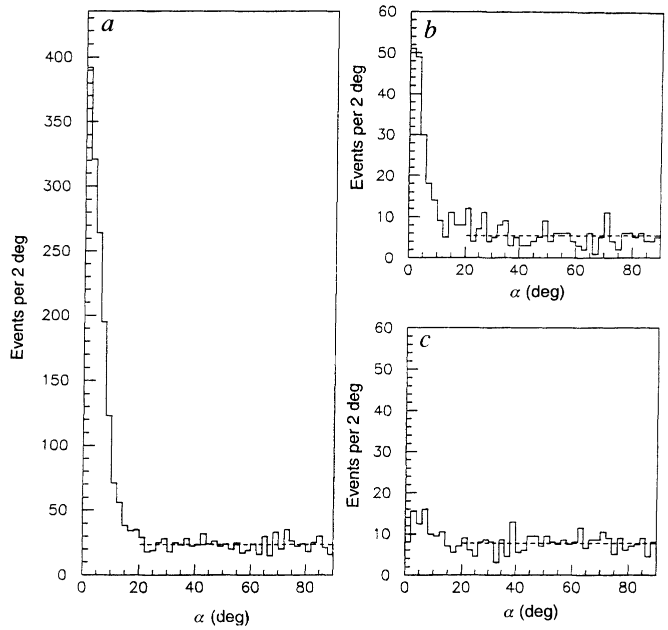

FIG. 1 Distributions in orientation angle α for events that satisfy the Supercuts selections on image width, length and distance for events with more than 400 ADC counts. The signal region is $\alpha < 15°$, and the broken line is the average level for $\alpha > 20°$. *a*, Events in the large flare on 7 May 1996. *b*, Events in the 28-min run on 15 May 1996, during which the flare peaked. *c*, An average of events in the runs before and after the flare shown in *b*. In addition to the standard set of Supercuts, a new set of selection criteria for small events, which is currently under development, was used to analyse the flare below the size cut of 400 ADC counts where the background is significantly larger. The results indicated that the flare behaviour of the small events in the energy range below 350 GeV is also dramatic, reaching a rate of ~12.5 γ-rays per min. The possibility of spectral variations accompanying the giant flare was investigated by computing hardness ratios during the flare and comparing them to hardness ratios from data acquired during pre- and post-flare periods. The hardness ratio is based on the distribution of shower size (the ADC count in an event), a quantity that is approximately proportional to the energy of the incident γ-ray primary. Three intervals of shower size were used to search for spectral variability. No detectable spectral variations are attendant with the flare, and no spectral variations are observed within the flare event itself in this preliminary investigation.

The active galaxy Mrk421 is a very high energy (VHE) γ-ray source that is known to be variable on timescales of ⩾1 day (refs 6, 7), and multi-wavelength observations have demonstrated a correlation between the VHE emission and emission at lower energies[7–9]. During routine monitoring of Mrk421 in the May 1996 observing period, the Whipple telescope recorded a dramatic flare, which produced the largest flux ever recorded from any source in the current VHE catalogue. The α plot for the data from the night of 7 May 1996, selected by cuts on the first three image parameters, is displayed in Fig. 1*a*; a threshold cut of 400 analogue to digital converter (ADC) counts has been applied corresponding to an energy threshold of approximately 350 GeV. Events beyond an α angle of 20° provide an estimate of the background contribution, which is very small for these data. We believe this to be the purest sample of VHE γ-rays ever recorded. A preliminary investigation of the spectrum reveals no large variations during the flare. The flux was observed to increase monotonically during the course of observation over a period of 2 h, beginning at a rate equal to the peak value of the highest previously observed flare[8], and twice as high as any flare recorded during the 1995 observing season[9]. A counting rate of ~15 γ-rays per minute was reached, ten times as high as the steady rate observed from the Crab Nebula, which is a steady source for which ϕ_{CN} is 1.5 γ-rays per min above 350 GeV. The doubling time of this giant flare was of the order of one hour during the observing session, which was terminated before moonrise. This change in rate is more than an order of magnitude faster than in previous data[8,9]. The temporal history of the observations is displayed in 9-minute intervals in Fig. 2*a*, where the γ-rate is determined from the excess events after background subtraction in the angular interval $\alpha < 15°$. Follow-up observations on 8 May 1996 showed that Mrk421 had relaxed to a quiescent flux level of $\sim 0.3\,\phi_{CN}$, suggesting that the decay timescale of the flare is probably shorter than one day. In its relatively quiescent state, the Mrk421 flux above 350 GeV is $\sim 0.1-0.3\,\phi_{CN}$.

A second flare from Mrk421, remarkable for its very short duration, was observed eight days later. The temporal history of the observations in 4.5-minute intervals on the night of 15 May 1996 is displayed in Fig. 2*b*, where a rise and fall within a duration of much less than one hour is clearly evident, and a peak flux of 4–5 times the steady ϕ_{CN} was reached. By relativistic causality, this astonishingly brief duration implies that the emission region is very compact. The doubling time of the flare event was <15 minutes, both for the rise and subsequent decline to the quiescent level. As in the case of the previous outburst, no large spectral variations are detectable during the flare, based on an analysis using hardness ratios. The α plot for this flare is shown in Fig. 1*b*; the histogram corresponds to the 28-minute observation in which the flare peak occurred. In Fig. 1*c* the average of the on-source runs before and after is shown, including the tail of the flare. An off-source run had been taken just before the flare.

Production of TeV γ-rays in active galactic nuclei (AGNs), of which Mrk421 is an example, is poorly understood. It is generally assumed that most of the non-thermal emission derives from relativistic jets of material beamed towards the observer[10]. One class of popular models assumes that low-energy photons are boosted to high energies by inverse Compton scattering[11–13]. However, the large density of target photons required for this process creates a large optical depth through pair-production for the escape of TeV γ-rays. This problem can be circumvented, for example, if the site of inverse Compton scattering is located within the relativistic jet so that both target photons and boosted γ-rays are moving in the same direction with their luminosities modified by the Doppler factor δ of the jet; $\delta^{-1} = \gamma(1 - \beta\cos\theta)$, where β and γ are the Lorentz factors of the jet, and θ is the angle with respect to the observer[14,15]. If it is further assumed that flaring is correlated from optical to γ-ray wavelengths during this outburst, as has been observed for Mrk421 (refs 7, 9), and that the emission region in the jet is approximately spherical, a constraint on the Doppler factor is given[9,15] by flare duration time T; $\delta \geqslant 4.6\,(T/10^5)^{-0.19}$. For a duration of 30 minutes, $\delta \geqslant 9$, larger than values reported for variable AGNs detected by EGRET[15] in the GeV energy range. However, this value of δ is consistent with a shift of the maximum luminosity of Mrk421 towards the TeV region, thereby making it a weaker source at EGRET energies, as is observed to be the case. Recent models[16] of the light curve for Mrk421 suggest that $\delta \sim 10$ for a multi-wavelength description. This may be regarded as a lower limit in that considerations of detailed constraints on highly relativistic jets suggest[17] Lorentz factors of $\gamma \sim 30-100$ are possible. For emission from a spherical blob with an observed time variability T, relativistic causality[9,15] requires the size of the emission region R in the jet to satisfy the inequality $R < cT\delta/(1+z)$, where z is the cosmological redshift; $z = 0.03$ for Mrk421. With $T \sim 1$ hour and $\delta \sim 10$, the spatial extent R is $1 < R < 10$ light hours, a remarkably small region.

These observations place severe constraints on models of the production mechanism and site of high-energy γ-rays from AGNs. For example, the tightly constrained one-zone models mentioned above[12,16] are very sensitive to the dimension of the emission region R for an adequate description of the total energy spectrum of strong, variable γ-ray sources. These models used data from the EGRET observation[18] of variability in γ-ray emission of 3C279, in which the flux rose and fell within a period of approximately 12 days with a peak increase in flux of a factor of 4. There was some

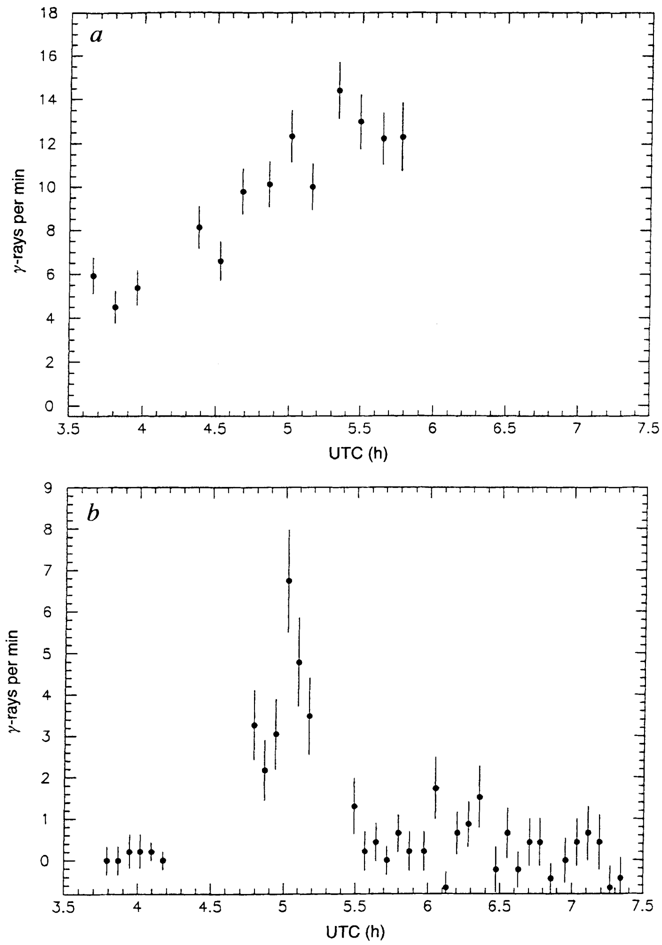

FIG. 2 Temporal histories of the two flare events. Rates are determined from the excess events after background subtractions in the interval $\alpha < 15°$. The time axes are coordinated universal time (UTC) in hours. For the 7 May flare (*a*), each point is a 9-min integration; for the 15 May flare (*b*), the integration time is 4.5 min. The error bars are statistical standard deviations.

evidence for small fluctuations on timescales down to one day. In dramatic contrast, the VHE γ-ray flares from Mrk421 reported here exhibited a flux increase an order of magnitude greater than that of 3C279 in the first event, and a timescale more than two orders of magnitude shorter in the second. □

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