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SIMULTANEOUS OPTICAL AND TeV GAMMA-RAY OBSERVATIONS OF THE CATACLYSMIC VARIABLE AE AQUARII

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ABSTRACT

In this paper we report on findings of simultaneous optical and TeV γ-ray observations (eight nights, 32 hr in total) of the magnetic cataclysmic variable AE Aquarii which contains the most rapidly spinning white dwarf ($P = 33^s.08$) known to date. The combined results of all the TeV observations (1992 July–1993 June) independently confirm previously identified (Meintjes et al. 1992b; Bowden et al. 1992) optical and TeV γ-ray periodicities at the 10^{-3} level without any period search, and confirm the finding that the observed duty cycle of these periodicities is $\sim 10\%$. The strongest TeV signal appeared to be confined to the time just before the onset of a strong optical flare. The observed pulsar-like spindown of the white dwarf (de Jager et al. 1994) would push the accretion disk outside the corotation radius, which gives a natural explanation of why the observed optical/TeV γ-ray periodicities are slightly redshifted relative to the spin period. Following an optical flare, we also observed two rapid bursts ($\sim$1–3 minutes duration) with three independent telescopes, within 25 minutes of each other. The significance of the largest burst was 4.6 σ per minute. The probability of finding two such bursts given all the trials is 5.3×10^{-4}. The observed spin-down power ($I\Omega\dot{\Omega} \sim 6 \times 10^{33}$ ergs s^{-1}) may account for the energy released by a TeV accelerator in AE Aquarii.

Subject headings: gamma rays: observations — novae, cataclysmic variables — radiation mechanisms: nonthermal — stars: individual (AE Aquarii)

1. INTRODUCTION

AE Aquarii is a disk accreting DQ Her type magnetic cataclysmic variable with distance $d \sim 100$ pc (Welsh, Horne, & Oke 1993). The secondary is a K4–K5 type red dwarf which is slightly evolved (De Jager et al. 1994). The magnetic moment of the white dwarf primary is $\sim 2 \times 10^{32}$ G cm^3 (Warner & Wickramasinghe 1991), with a spin period $P_0 = 33.08$ s (Patterson 1979). The 33.08 s optical pulse profile shape is a double sinusoid with some bridging emission between the two pulses, whereas the 0.1 to 4 keV X-ray pulse profile is a single broad sinusoid (Patterson et al. 1980).

The system is highly variable in optical, with the visual magnitude varying from $\sim$12.5 during quiescence to $\sim$10 during flares, making AE Aquarii accessible even for amateur telescopes. The flares are accompanied by flickering and QPO signals with coherency timescales of $\sim$1 hr. When these QPO signals appear, their frequencies are always redshifted relative to the spin frequency $F_0 = 30.23 = 1/P_0$ mHz and its first overtone at $F_1 = 2F_0 = 60.47$ mHz (or 16.54 s) (Patterson 1979; Meintjes et al. 1992b).

UV observations of AE Aquarii allows us to probe the primary component alone, since the contribution from the secondary is negligible in this case. The quiescent UV luminosity inferred from ultraviolet observations made by the *HST* at $\sim$2000 Å is (K. Horne 1993, personal communication)

$$L_{\rm UV}^{\rm quies} \sim 1.7 \times 10^{31}\left(\frac{\Omega}{4\pi}\right)\left(\frac{d}{100\ {\rm pc}}\right)^2 \times \left(\frac{f}{1\ {\rm mJy}}\right)\left(\frac{20000\ {\rm Å}}{\lambda}\right)\ {\rm ergs\ s^{-1}}\ . \quad (1)$$

This value would be raised by a factor ~ 3 when averaging $L_{\rm UV}$ over flares. Recent World Astronomy Day observations indicated that the colors of AE Aqr at longer wavelengths shows at times only evidence of the late-type secondary, so that the accretion rate can be approximated by $L_{\rm acc} \sim 3L_{\rm UV}^{\rm quies} = 5 \times 10^{31}$ ergs s^{-1}.

A recent optical pulse timing study (from observations taken between 1978 and 1992) revealed that the white dwarf is spinning down at a rate of $\dot{P} \sim 5.6 \times 10^{-14}$ s s^{-1}, supplying a reservoir of rotational kinetic energy loss of $I\Omega\dot{\Omega} \sim 6 \times 10^{33} I_{50}$ ergs s^{-1} (De Jager et al. 1994). This is $\sim$100 times more than $L_{\rm acc}$.

Apart from the variable optical emission from this source, optically thick radio and millimeter synchrotron emission with similar variability has been reported (Bookbinder & Lamb 1987; Bastian, Dulk, & Chanmugam 1988; Abada-Simon et al. 1993). The maximum luminosity is $L_{\rm radio} \sim 10^{29} d_{100}^2$ ergs s^{-1} at 240 GHz (from Abada-Simon et al. 1993). VLBI observations allowed the source to be resolved during individual flare events (A. E. Neil 1991, personal communication).

Transient TeV γ-ray signals from AE Aquarii were reported by two independent groups (Meintjes et al. 1992b; Bowden et

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al. 1992). The radio and TeV observations imply episodes of transient particle acceleration in the magnetosphere of AE Aquarii. A more detailed summary of the nonthermal properties of AE Aquarii can be found in de Jager (1994).

This paper reports the results of the most intensive attempt to date to observe AE Aquarii simultaneously in optical and TeV. We will be looking for correlated optical and TeV features, and an attempt will be made to confirm previous TeV reports.

2. PREVIOUS SEARCHES FOR TeV GAMMA-RAYS

Several reports of pulsed TeV γ-rays from AE Aquarii have been published since 1988. The first evidence of pulsed TeV γ-rays was given by Brink et al. (1990) at a frequency of (30.04 ± 0.05) mHz with a coherency timescale of ~ 2 hr. This frequency is close to, but slightly redshifted from the $F_0 = 30.23$ mHz spin frequency of the white dwarf. Further observations also showed pulsed emission around 30.04 mHz (De Jager et al. 1991; Meintjes et al. 1991a, b), as well as weak evidence for pulsed emission at the spin period of the white dwarf (Raubenheimer et al. 1991; Meintjes et al. 1992a, b). Meintjes et al. (1992b) have shown that the most significant QPO in optical (based on available flare observations) occurs in the redshifted frequency interval ~ 29.9 to 30.23 mHz, with ~ 30 mHz as a prominent feature. The search for pulsed TeV γ-rays (Meintjes et al. 1992b) was then conducted by selecting the independent frequencies $f_1 = 29.90$ mHz, $f_2 = 30.04$ mHz, and $F_0 = 30.23$ mHz, based on ~ 2 hr per observing run and the distribution of optical QPO. It should be noted that the f_1 and f_2 are by no means unique frequencies, but represent samples from the above-mentioned redshifted range. The cumulative chance probability (after $a - \log_{10}$ transformation) between 1988 and 1993 (128 observations) at f_1, f_2, and F_0 are shown in Figure 1, and it can be seen that the significances of these features increased steadily with time. The f_2 pulse appeared most often in optical and is also the most significant γ-ray feature. The arrows in Figure 1 mark the positions where previous reports of f_2 have been made. From Figure 1 it can be seen that approximately one out of 10 TeV observations reveals a pulse at any one of these frequencies.

Given the observed spindown of the white dwarf, a search for coherent pulsed TeV γ-ray emission was carried out on all the data, revealing no evidence for coherent pulsed emission in the combined data set (Meintjes et al. 1993).

AE Aquarii was also observed by the Durham group at Narrabri (Australia) beginning in 1990 September (Bowden et al. 1992). The first overtone ($F_1 = 2F_0 = 60.47$ mHz) was seen on a few occasions by this group. Bowden et al. also observed short (1 minute duration) bursts in their data of 1990 October and 1991 August. The 1990 October burst was the most significant event and was detected by two independent telescopes with an overall DC significance $\sim 6\,\sigma$. This burst was shown to be pulsed with the 16.54 s period and was shown to be in phase with the strongest sustained periodic signal in their data. Indepentent evidence in favor of a true γ-ray origin was presented, and the spectral information revealed a source spectrum which

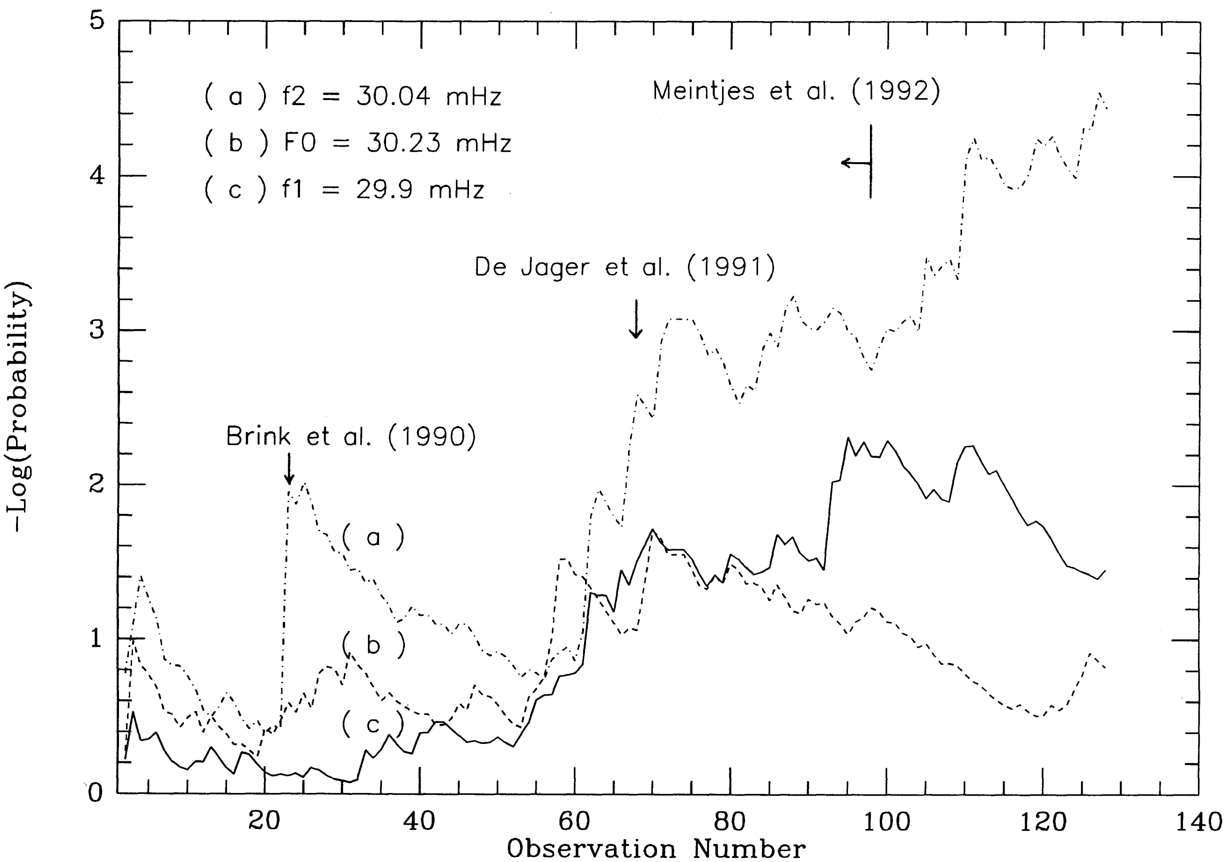

FIG. 1.—The cumulative chance probability (expressed as $-\log_{10}$ of the probability) of the three previously identified frequencies (Meintjes et al. 1992b) indicated by (*a*), (*b*), and (*c*), as covered by 5 years of observations. The two vertical arrows indicate the times when positive detections of f_2 were reported. The horizontal arrow bounded by a vertical line indicates the Meintjes et al. (1992b) summary of all observations up to the observation number indicated.

is significantly flatter than the background spectrum consisting mostly of cosmic-ray protons.

Most of the observed TeV emission features in our data closely resembles optical flaring emission, and to investigate this phenomenon further, a simultaneous optical and TeV γ-ray observation campaign was carried out in collaboration with the South African Astronomical Observatory (SAAO). Our first attempt to observe AE Aquarii simultaneous in optical and TeV energies was on 1990 September 14 (see observation 67 in Fig. 1 of de Jager et al. 1991), and resulted in a TeV γ-ray observation bracketed by two optical observations: the first during quiescence and the second in a flaring state (see also Meintjes et al. 1992a, b). The optical/TeV observation overlapped for $\sim$15 minutes, with the optical flare starting when the TeV observation ended. However, the TeV observation showed pulsed emission at $f_2 = 30.04$ mHz, and by analyzing the flaring part of the adjacent optical observation, the same pulse frequency was seen. Since the optical/TeV observations of f_2 were not simultaneous, we could not claim a correlation in time. The second simultaneous observation was made on 1991 June 14 with the optical and TeV γ-ray observations overlapping for $\sim$4.5 hr. However, no TeV signal with a compelling significance was found from that observing run.

3. OBSERVATIONS

During the period 1992 July to August and 1993 June we made eight simultaneous optical and TeV γ-ray observations of AE Aquarii. The average length of these observations was between 4 and 5 hr, resulting in more than 31 hr of simultaneous optical/TeV γ-ray observations compared to the 4.5 hr during earlier campaigns before 1992. The TeV γ-ray observations were made with the Nooitgedacht Mk I TeV γ-ray telescope, while the optical observations were made by P. J. Meintjes, D. A. H. Buckley, and C. Koen at the SAAO site at Sutherland, 915 km from the Nooitgedacht site. The log of the observations are summarized in Table 1.

The telescope used for the optical photometry is a 30 inch (76 cm) cassegrain, with the blue sensitive University of Cape Town (UCT) photometer, which fits the description given by Nather (1973). AE Aquarii was observed continuously, with occasional sky background measurements, using short integrations of 1–2 s. Since the relative flare intensity in the *B* and *U* bands is larger than observed at longer wavelengths (van Paradijs, Kraakman, & Van Amerongen 1989; Bruch 1991), we assumed that the QPO activity would also be more pronounced in the *B* and *U* bands. Based on this, all the optical measurements were made with the Johnson *B* and *U* filters, respectively (see Table 1). After subtracting the sky counts, and correcting for atmospheric extinction, the data were transformed to the magnitude scale. The light curves are shown in Figures 2*a*–2*h*.

The Nooitgedacht Mk I TeV γ-ray telescope was designed to study periodic TeV γ-ray emission from short period pulsars (De Jager et al. 1986). The telescope consists of four independent units, 55 m apart, and a Cherenkov event is defined as a threefold coincidence between the three photomultiplier tubes (PMTs) from any unit. These coincidences are taken within a gate time of 12 ns to eliminate the night sky background. The field of view is $\sim 2°$. All the Cherenkov arrival times were measured with an accuracy of 0.1 μs and transformed to UTC. The count rate per minute for each observation is also shown in Figures 2*a*–2*h*, and consists mostly of cosmic-ray background (proton-induced showers). Atmospheric extinction causes the count rate λ to scale with zenith angle z as $\lambda \propto \cos^a z$ where $a \sim 2.5$ to 3.5. Upper culmination corresponds to that time when the Cherenkov count rate is a maximum due to minimum airmass and hence minimum absorption.

The individual photomultiplier count rates were also recorded which enables a continuous monitor of the night sky brightness (NSB), as well as a display of the stability of each individual PMT. The Mk I telescope was designed to observe periodic γ-ray sources in the tracking mode, which makes the detection of DC enhancements on timescales of hours difficult, except if the duration of the DC enhancement is much shorter in comparison to the observation time (e.g., short bursts as reported by Bowden et al. 1992).

Both the optical and TeV times were corrected to the solar system barycenter using the MIT PEP 740 barycenter program (kindly supplied by J. F. Chandler), as well as to the center of mass of the binary system using the latest orbital parameters (Welsh, Horne, & Gomer 1993; De Jager et al. 1994).

The total time of overlap between the optical and TeV observations was 32 hr. The optical observations on the nights of 1992 June 26 and 27, 1992 August 20, and 1993 June 20, and 21 consist of several runs, as indicated in Figure 2*a*–2*e*. The optical observations during the other three nights consist of a continuous uninterrupted observation. However, during the last two nights the Sutherland site was hampered by poor photometric conditions during certain parts of the night. This is why the optical coverage only overlaps with a part of the TeV γ-ray observations (see Figs. 2*a*–*h*).

All the optical observations clearly show the nearly continuous multiple flaring activity from AE Aquarii. Brightenings of

TABLE 1

LOG OF SIMULTANEOUS OPTICAL AND TeV γ-RAY OBSERVATIONS

	OPTICAL					TeV γ-RAY		
DATE	Start (UT)	End (UT)	Filter	Integration Time (s)	Intensity (magnitude)	Start (UT)	End (UT)	Counts per minute
1992 Jul 26	19^h44	26^h00	*U*	1	13.15–11.40	20^h00	26^h00	7
1992 Jul 27	20 19	25 45	*U*	1	13.00–11.10	20 00	25 48	7
1992 Aug 20	19 20	22 20	*U*	1	12.40–10.44	19 30	22 15	8
1993 Jun 20	22 00	28 00	*U*	1	12.56–10.65	22 24	27 24	11
1993 Jun 21	23 00	25 00	*B*	1	12.40–12.18	23 20	27 24	10
1993 Jun 21	25 12	27 40	*U*	1	12.90–11.50	...	...	...
1993 Jun 22	23 12	27 36	*U*	1	12.85–11.50	22 12	27 24	7
1993 Jun 24	25 00	27 24	*B*	2	12.40–11.90	22 12	27 24	7
1993 Jun 25	22 12	25 24	B	2	12.55–11.48	22 00	27 00	8

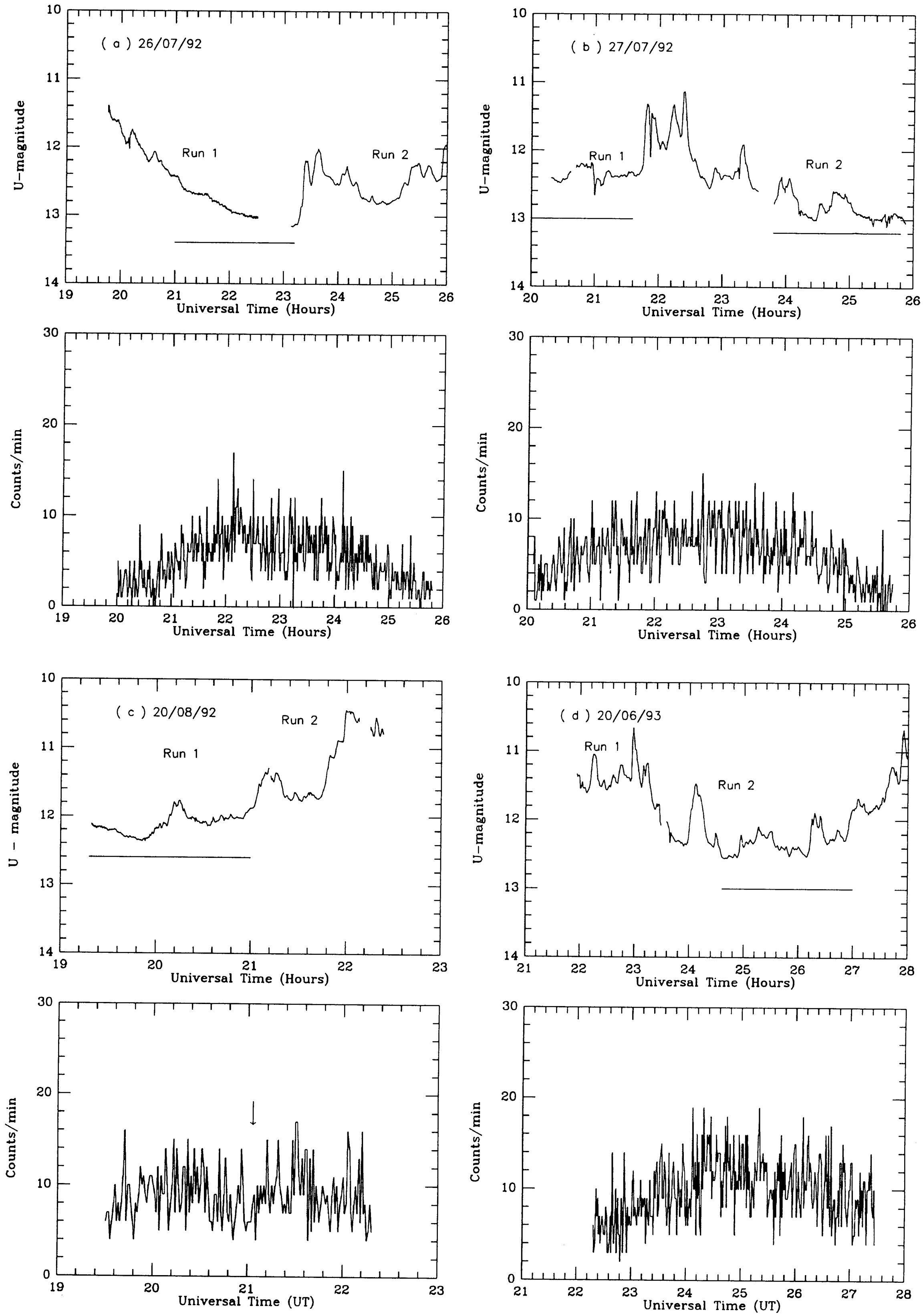

FIG. 2.—Simultaneously measured optical and TeV γ-ray light curves (*a*) to (*h*). The optical intensity is expressed in terms of the *B* or *U* magnitude, and the TeV light curves are in terms of the Cherenkov counts per minute. The horizontal bars on some of the optical intensity profiles represent the time of quiescence (subjectively chosen). The arrows on the two TeV light curves (*c*) and (*h*) (the two positive detections) indicate the time when AE Aquarii went through upper culmination on the nights of 1992 August 20 and 1993 June 25, respectively.

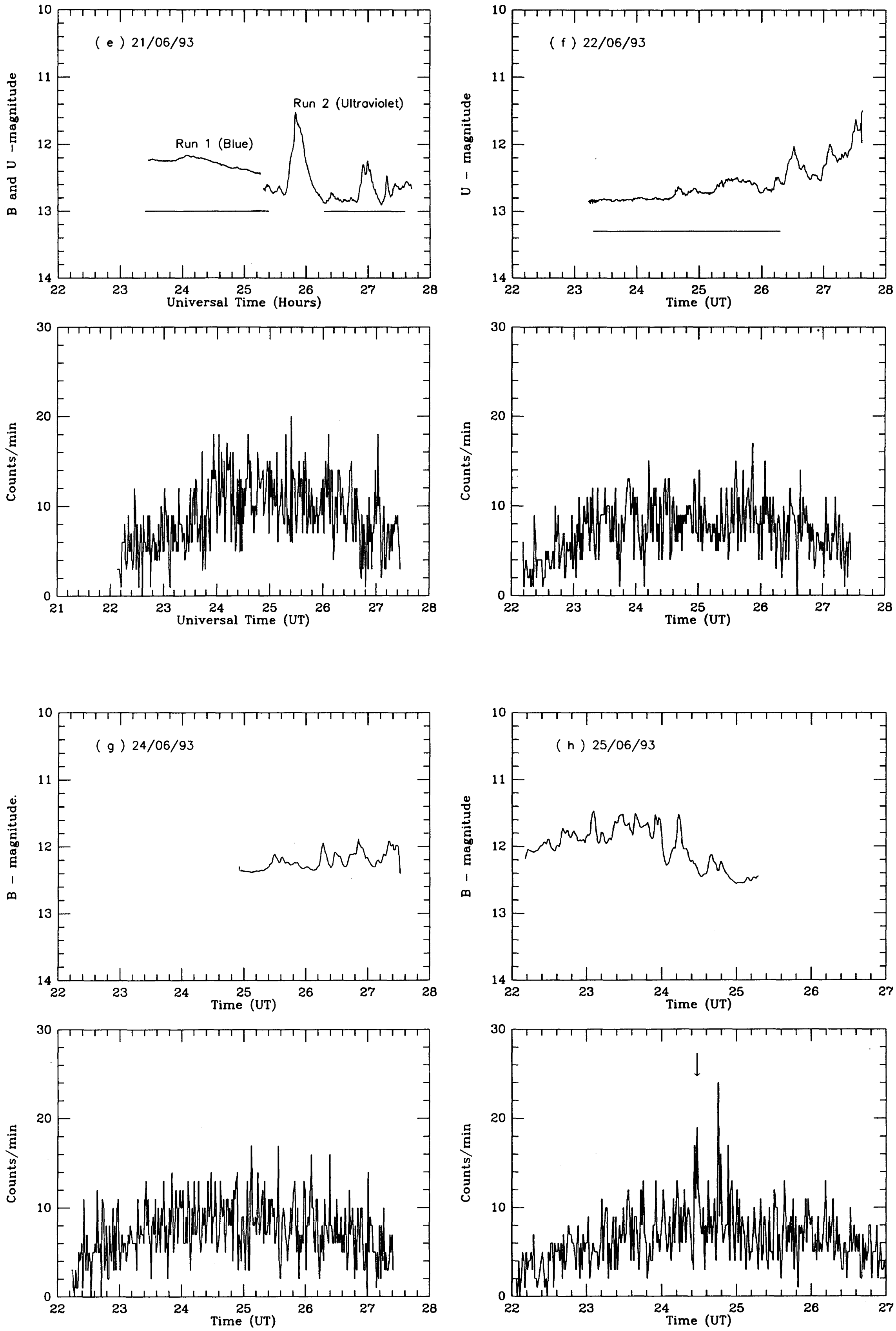

FIG. 2—*Continued*

the source of a magnitude or more in a few minutes are not uncommon. AE Aquarii was the brightest on the night of 1992 August 20 (see Fig. 2*c*), where the average quiescent magnitude in the *U* band, between 19^h12 and 21^h00, was ~ 12, and increased to a maximum ~ 10.44 during the flare at $\sim 22^h00$. This was also the night when we saw a pulsed TeV signal (see § 4.3).

4. DATA ANALYSIS

The optical count rates were first prewhitened, that is, a 100 s moving average was subtracted from the count rate to remove the low-frequency noise, after which the data were analyzed with a standard Fast Fourier Transform (FFT) over a wide-frequency range from 10 to 100 mHz. The Fourier power *P* (which equals unity on average for white noise) is then transformed to pulsed fraction by taking $2(P/N)^{1/2}$, where *N* is the total number of photons registered during the observing run. The pulsed fraction (in percentage) is displayed on the vertical axis of the optical frequency spectra (see Figs 3*a*–3*h*).

The TeV γ-ray data were folded over the same frequency range using the Rayleigh test for sparse data (Mardia 1972). The vertical axes were transformed to $-\log_{10}$ of the chance probability for uniformity. The respective frequency spectra of the TeV and optical observations are shown in Figures 3*a*–3*h*. During nights where the optical observations consist of more than one run, the optical frequency spectrum of each run is shown with the TeV γ-ray spectrum (see Figs 3*a*–3*e*).

4.1. *Search for Correlated Optical and* TeV *Periodicities*

The optical frequency spectra from flare observations taken in unfiltered light sometimes showed little or no power at the white dwarf oscillation frequency F_0, whereas QPO frequencies around $f_2 = 0.994F_0$ would dominate the frequency spectrum (Meintjes et al. 1992b). We do not see this optical feature repeated here, whereas F_0 and $2F_0 = F_1$ appears to be the dominant features in most observations. The reason for this is simple: the observations presented here were taken with either *U* or *B* filters in an attempt to exclude the red light from the secondary and to isolate the hot white dwarf surface. Such a hot surface results in the intensity of the signal at F_0 to increase with photon frequency ν as $\propto \nu^{0.9}$ in the visible to UV bands (Welsh, Horne, & Oke 1993). Any optical QPO signal remaining at f_2 would be difficult to identify due to power leakage from F_0 given the finite run lengths, and the possibility that the colors of the QPO signals may be redder if they originate in the disk which is far removed from the stellar surface.

We see no significant TeV features at F_0 or F_1, and the TeV pulse profiles at these frequencies are flat within statistics. It would therefore be pointless to compare optical and TeV pulse profiles at these stable frequencies. Only in Figures 3*d*, 3*e*, and 3*h* do we see optical QPO features, redshifted relative to F_0 as expected, but with frequencies less than 29.9 mHz. However, these features are unsupported by any statistically significant (better than 3 σ) TeV periodicities at the same frequencies, leaving pulse profile comparisons once again meaningless.

The only significant TeV features are the short bursts seen in the Cherenkov count rate profile of 1993 June 25 (JD 2,449,164) (see Fig. 2*h*), resembling the bursts reported by Bowden et al. (1992). This will be reported in § 4.5.

4.2. *Confirmation of the Meintjes et al. 1992b* TeV *Result*

Our next attempt is to confirm the frequencies previously identified by Meintjes et al. (1992b): $f_1 = 29.90$ mHz, $f_2 = 30.04$ mHz, and $F_0 = 30.23$ mHz, even though f_1 and f_2 are unsupported by these optical observations as discussed in § 4.1.

Without searching in period, the transformed chance probabilities of the pulsed TeV γ-ray emission at f_1, f_2, and F_0 are summarized in Table 2. Since Bowden et al. (1992) also reported pulsed VHE γ-ray at the first overtone of the F_0 pulse ($F_1 = 60.46$ mHz), the chance probability of this pulse is also included in Table 2. All these probabilities were combined incoherently (Eadie et al. 1971) to give a final chance probability of 1×10^{-3} for confirmation. These probabilities were added to the cumulative plot shown in Figure 1. From this Figure and Table 2, one can see that f_2, which was previously identified as the most significant QPO feature in TeV, is again the most significant TeV periodicity. This holds especially for observation 110 on 1992 August 20 (JD 2,448,855), which will be discussed in § 4.3.

It should be noted that the TeV periodicities are not persistent features and the corresponding duty cycle for occurrence is $\sim 10\%$.

4.3. *The Observation on 1992 August 20*

The starting time of both the optical and TeV γ-ray observations was 19^h30 UTC, and their corresponding light curves are shown in Figure 2*c*. AE Aquarii was brighter on average on this night than on the other nights, with the *U*-magnitude varying between 12.4 and 10.44, as discussed previously. The arrow shown in Figure 2*c* (bottom panel) represents the time when the source went through upper culmination (21^h00 UTC).

The TeV γ-ray power spectrum (see Fig. 3*c*) shows pulsed emission at $f_2 = 30.04$ mHz with a change probability of $P \sim 5 \times 10^{-4}$. Apart from a peak at ~ 77 mHz which has a chance probability of 2×10^{-4}, the pulse at f_2 is the most significant feature in the power spectrum.

To investigate whether the pulsed TeV γ-ray emission correlates with the optical flaring activity, the TeV observation was divided into two runs, as indicated in Figure 2*c*: run 1 corresponding to the optical low state before upper culmination, and run 2, after upper culmination, corresponds to the optical high state. The respective TeV frequency spectra are shown on Figures 4*a* and 4*b*. The TeV signal at f_2 was most significant during the optical low state (run 1), since the corresponding change probability decreased from 5×10^{-4} (for the entire observation) to 10^{-4} (Fig. 4*a*) for run 1 only, despite the halving of statistics. However, the TeV pulse appears to be completely absent during the large optical flare.

The TeV data were also subdivided into six 30 minute intervals. The pulsed fraction (see de Jager, Raubenheimer, & Swanepoel [1989] on the calculation technique) of the f_2 pulse

TABLE 2

$\log_{10}$ (probability) AT EXPECTED TeV γ-RAY PERIODICITIES

Data	$-\log(P_{f_1})$	$-\log(P_{f_2})$	$-\log(P_{F_0})$	$-\log(P_{F_1})$
1992 Jul 26	0.02	0.04	0.2	1.70
1992 Jul 27	0.6	2.2	0.08	0.49
1993 Aug 20	0.04	3.33	0.9	0.06
1993 Jun 20	1.07	0.33	0.26	0.09
1993 Jun 21	1.3	1.56	0.37	0.02
1993 Jun 22	1.52	0.4	0.35	0.67
1993 Jun 24	0.06	1.27	0.31	1.12
1993 Jun 25	0.12	0.16	0.57	1.39
Total	0.83	3.53	0.22	1.21

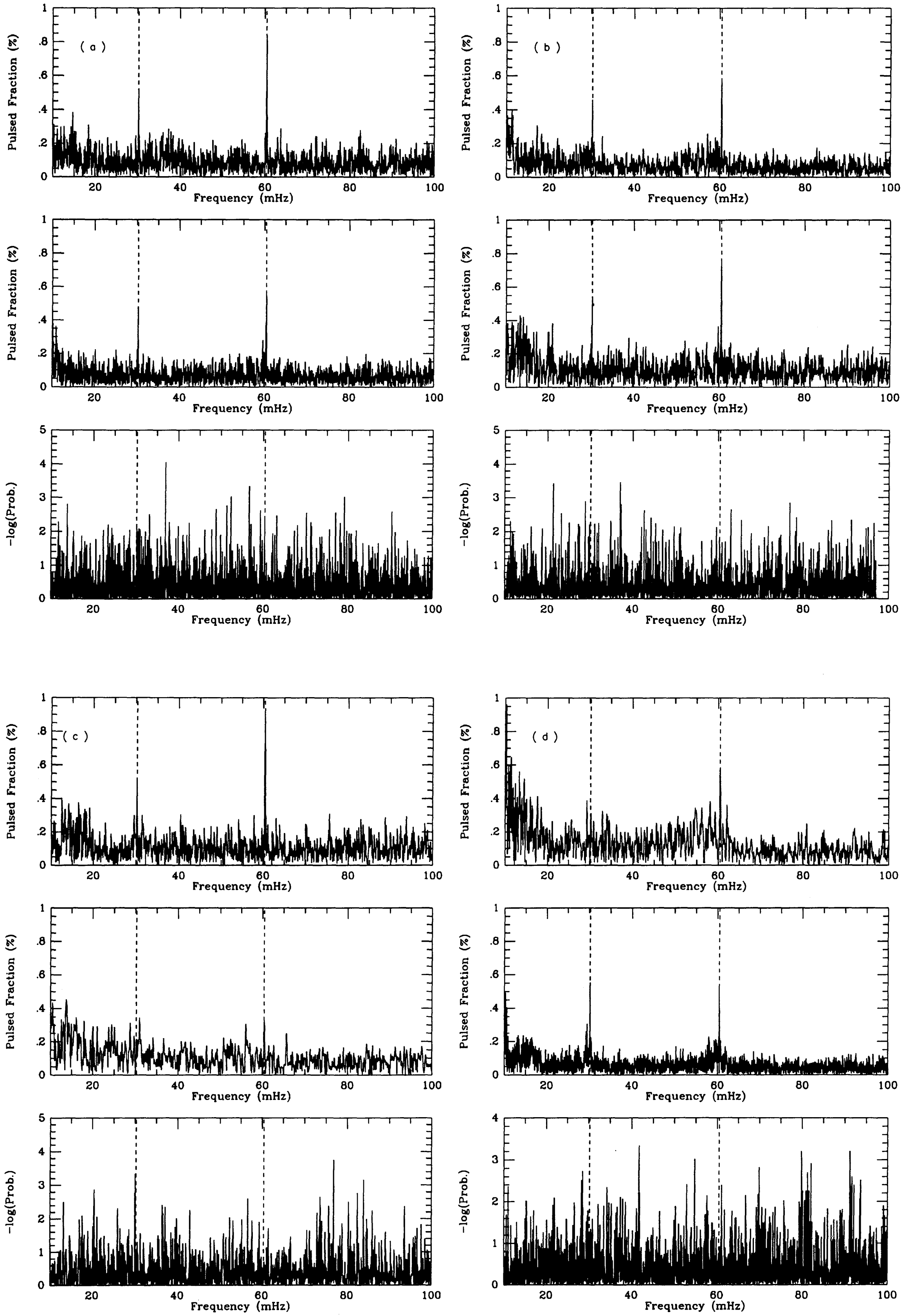

FIG. 3.—The optical (vertical axes indicated by "Pulsed Fraction") and TeV γ-ray [vertical axes indicated by "-log (Prob.)"] frequency spectra of the simultaneous optical/TeV observations (*a*) to (*h*). The vertical dashed lines represent the spin frequency $F_0 = 30.23$ mHz and its first harmonic $F_1 = 60.46$ mHz.

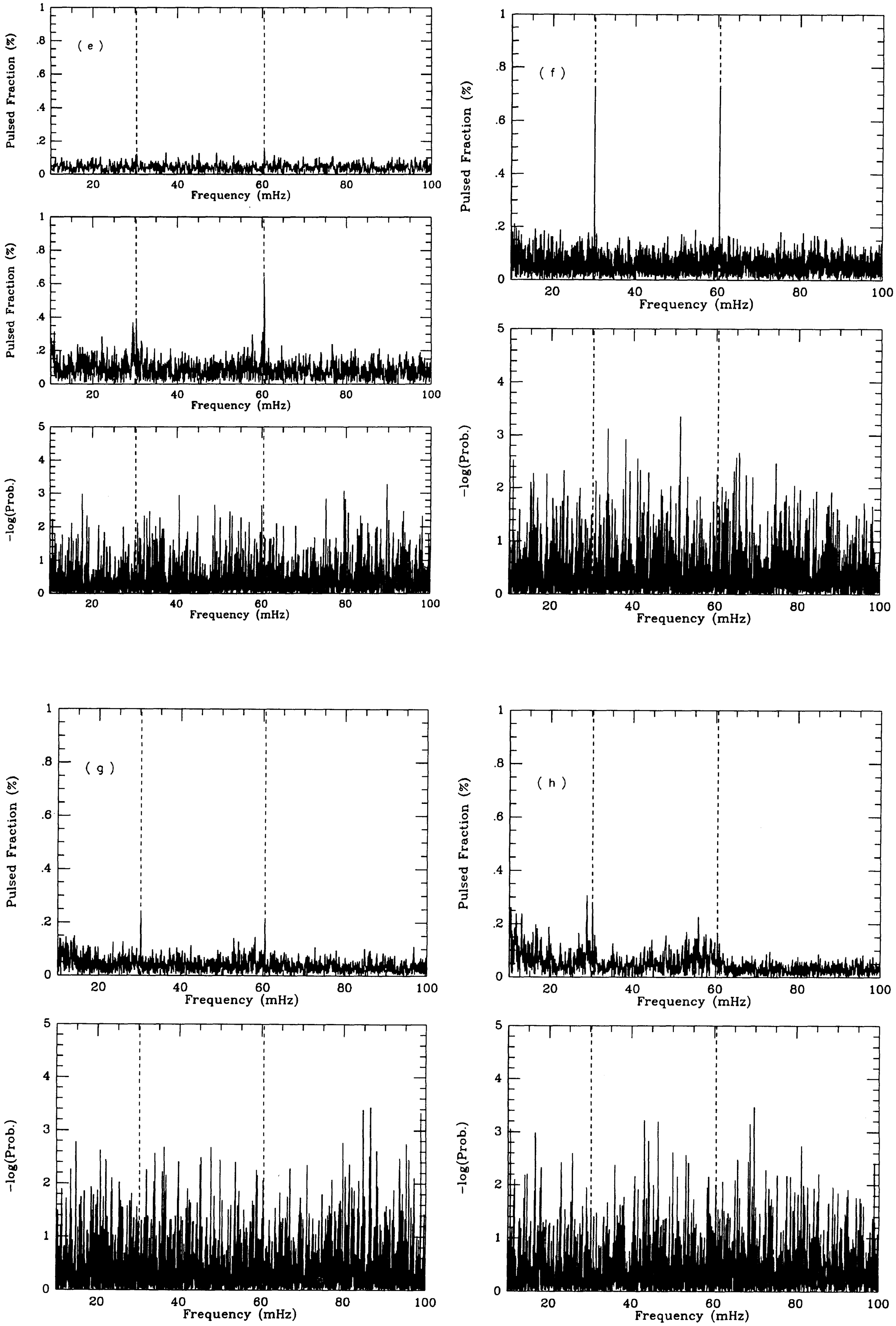

FIG. 3—*Continued*

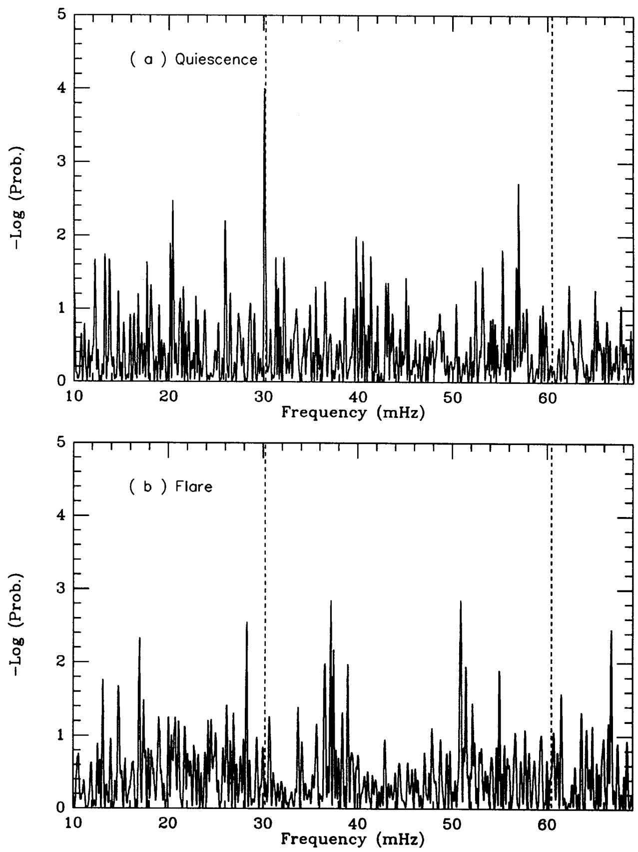

FIG. 4.—(*a*) The TeV frequency spectrum [significance again expressed as "−log (Prob.)"] of the 1992 August 20 observation, corresponding to the quiescent part before upper culmination (indicated as "run 1" in Fig. 2*c*), and (*b*) the flare part after upper culmination ("run 2" in Fig. 2*c*).

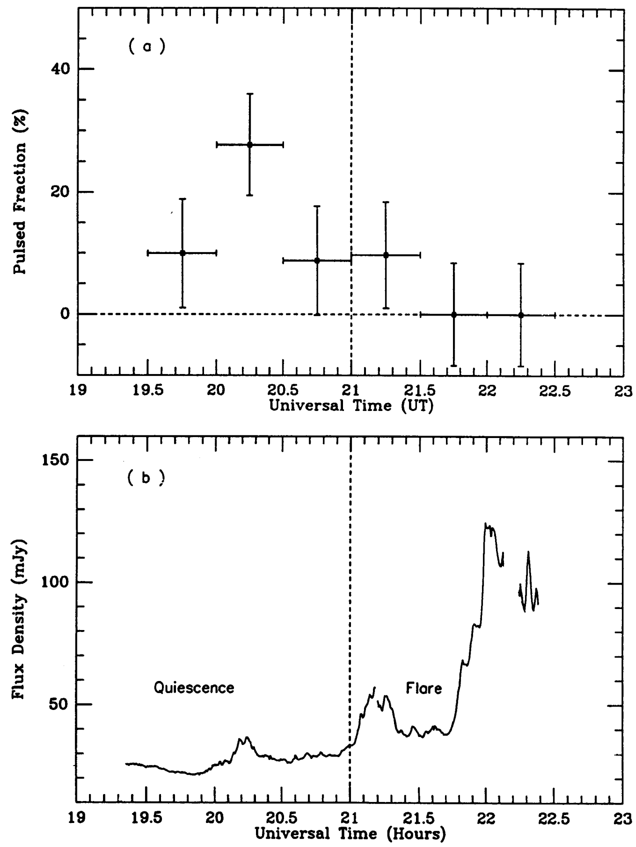

FIG. 5.—(*a*) The TeV pulsed fraction (at $f_2 = 30.04$ mHz) from independent 30 minute intervals on 1992 August 20. (*b*) The corresponding optical light curve.

was calculated for each interval and plotted with the intensity profile (see Figs. 5*a* and 5*b*). There is no evidence of a TeV signal during the strong flare at the end of the observation. A possible theoretical explanation of this behavior will be discussed in § 5. The time of γ-ray activity corresponds to the orbital phase interval 0.88 to 0.08, where phase 0 corresponds to superior conjunction of the white dwarf, i.e., when the red star is between the white dwarf and Earth (see de Jager et al. 1994 for a full summary of the orbital and spin elements of the white dwarf).

Since we see a TeV signal above the noise level, we compared the optical (run 1) and TeV pulse profiles (corresponding to run 1) at exactly $f_2 = 30.04$ mHz. To remove the power leakage from F_0 (as discussed in § 4.1), we subtracted the periodic signal at F_0 from the optical run ("prewhitening"). This was done by calculating the Fourier sine- and cosine components at F_0, and subtracting a Fourier series representing the count rate at this fundamental harmonic from the entire run. The pulse fraction subtracted is of the order of 1%. The pulse profile of the optical data folded at f_2, (see Fig. 6) is then uncontaminated by the optical pulsations from the white dwarf spin, but is weak, as seen from the error bars. The TeV pulse profile (folded with the same reference phase as done for the optical) is also shown in Figure 6. Both pulse profiles are significant at the 4 σ level. It is clear that the optical pulse is in phase with the TeV pulse, except for one low optical bin (phase 0.8–0.9).

4.4. *Search for Other Episodes of Pulsed* TeV *Emission during the Optical Low State*

To see if the TeV activity is correlated with quiescent optical emission in general, we identified the times when the optical intensity was relatively low as shown by horizontal bars in Figure 2 (note that this definition is somewhat arbitrary), and searched for pulsed TeV signals during these intervals. No

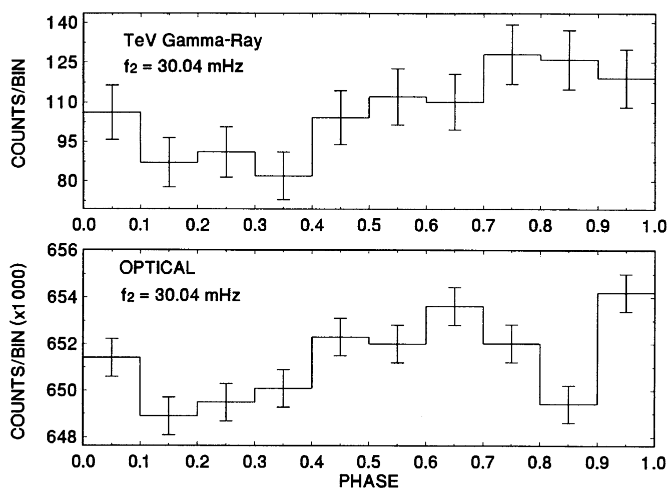

FIG. 6.—The TeV γ-ray (*top panel*) and optical (*bottom panel*) pulse profiles during the optical low state of "run 1" in Fig. 2*c*. Both pulse profiles have been folded at f_2 with the same reference time.

further episodes of pulsed TeV emission were found. The fact that only one out of eight TeV observations showed a significant periodic signal (with all emission confined to the first half of the observation) is again consistent with a $\sim 10\%$ or less duty cycle for pulsed emission.

4.5. *Short Bursts on 1993 June 25*

AE Aquarii was observed in the Johnson *B* filter on 1993 June 25, with an integration time of 1 s. The optical observation started at 22^h12 UTC and lasted till 25^h12 UTC and was stopped because of bad weather. The optical data showed nearly continuous flaring activity, with the *B*-magnitude varying from 12.6 to 11.5 (see Fig. 2*h*). The TeV γ-ray observation started at 22^h00 UTC and lasted till 27^h00 UTC with good weather conditions. AE Aquarii went through upper culmination around 24^h30 UTC (see the arrow in the bottom panel of Fig. 2*h*). Our central unit was not operational on that night, so the TeV observation was made with only three units.

The TeV count rate profile shows short burstlike features near upper culmination which resembles the bursts reported by Bowden et al. (1992) (see Fig. 2*h*). To exclude the possibility that these bursts may be attributed to a malfunction of the γ-ray telescope, e.g., spurious events caused by terrestrial optical flashes, the average NSB measured by each unit (see Fig. 7*c*) is also plotted with the optical (Fig. 7*a*) and TeV count rate profiles (see Fig. 7*b*). From Figure 7*c* it can be seen that the maximum NSB rate per unit is $\sim 30000\ s^{-1}$ for 3 PMT, or, $N \sim 10000\ s^{-1}$ per mirror (PMT). This photon flux will then trigger $N_f \sim (3\tau^2 N^3) \sim 0.018$ minute^{-1} spurious events given a gate time of $\tau \sim 12$ ns per trigger. Since N_f is much less than the observed Cherenkov rate, it is clear that these events are not artificially induced due to optical flashes in the 2° field of view of the detector.

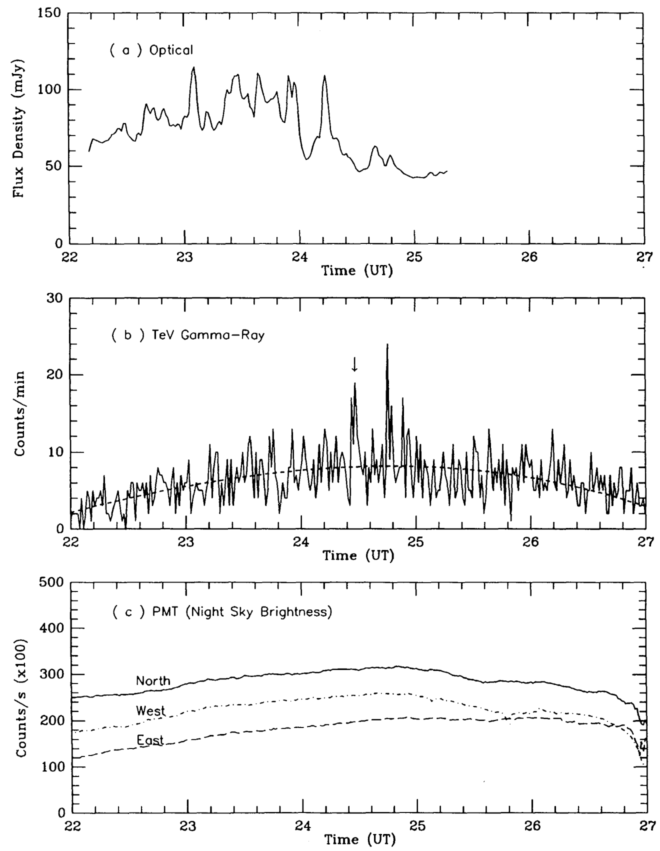

FIG. 7.—(*a*) The optical light curve of the observation made on 1993 June 25, is shown with (*b*) the corresponding TeV count rate profile for that same night. The two arrows indicate the two strongest bursts. The dashed line in (*b*) represents the cosmic background level as determined by a polynomial fit through the count rate. The bottom panel (*c*) shows the summed night sky brightness as measured by the three mirrors of each Cherenkov unit as indicated.

A polynomial fit (see Fig. 7*b*) was fitted through the TeV counts, representing the cosmic-ray background level. The counts per minute were transformed to chance probability by using the Poisson distribution (due to the low count rate per minute), after which the probabilities were transformed to Gaussian standard deviations (see Fig. 8*a*). Also shown (Fig. 8*b*) is the distribution of these standard deviations, showing a $N(0.07, 1.06)$ distribution which corresponds within 1.1 σ to a pure $N(0, 1)$ standard normal distribution. The slight deviation for a pure standard normal distribution is caused by the bad fit of the data at large zenith angles near the end of the observation, but this would not affect the data near the middle where the bursts are located. The first burst lasted ~ 3 minutes, while the second burst showed a significant 1 minute enhancement in the Cherenkov count rate followed by further enhancements. There are also indications of a third burst which lasted 1 minute. From Figure 8*a* the combined significance of the first 3 minute structure is 4.44 σ, with one 3.33 σ peak the most significant point in this group. The strong single burst in the second structure has a significance of 4.63 σ.

To avoid the problem of assigning significances to arbitrary groupings of 1 minute events and to structures of unequal length in this count rate profile, we calculate the significance of these bursts as the probability of getting the largest peak $A \geq 4.63\ \sigma$ and the second largest $B \geq 3.33\ \sigma$ from 300 data points, since there are $n = 300$ minutes in this observation. This problem was solved analytically as well as with a Monte Carlo simulation. The analytical expression for the probability is (J. W. H. Swanepoel 1993, personal communication)

$$P(X_{n-1} \geq B, X_n \geq A) = 1 - [F(A)]^n - n[F(B)]^{n-1}[1 - F(A)]\,, \quad (2)$$

where

$$F(A) = \int_{-\infty}^{A} \left(\frac{1}{\sqrt{2\pi}}\right) e^{-(1/2)x^2}\, dx = 1\text{–}1.8 \times 10^{-6}$$

and

$$F(B) = \int_{-\infty}^{B} \left(\frac{1}{\sqrt{2\pi}}\right) e^{-(1/2)x^2}\, dx = 1\text{–}4.3 \times 10^{-4}\,.$$

The chance probability of this particular outcome is $P \sim 6.7 \times 10^{-5}$, which reduces to $P \sim 5.3 \times 10^{-4}$ (significance $= 1\text{–}P = 99.947\%$) after multiplying with eight trials induced by eight observations. The Monte Carlo simulation was done by simulating 300 Gaussian standard deviations 100,000 times repeatedly. The amount of successes where the maximum and second largest exceeds 4.63 σ and 3.33 σ, respectively, were 7 from 100,000, giving a chance probability of $P \sim 7 \times 10^{-5}$, thereby confirming the analytical result. It must be mentioned that in all the other data from AE Aquarii obtained from 1988, no detailed search for such bursts was made.

The Cherenkov count rate profiles of each of the three independent units that were on line on this night were also plotted

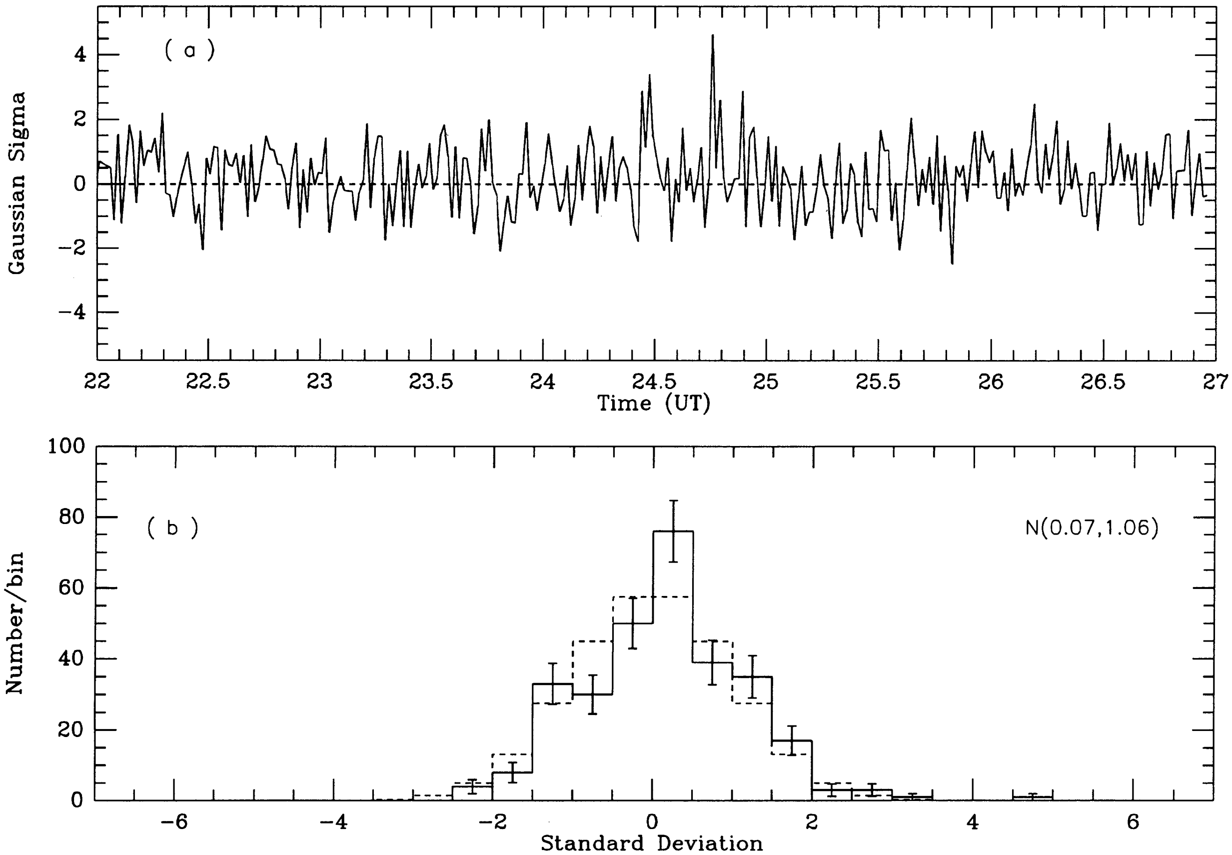

FIG. 8.—(*a*) The Cherenkov count rate of the observation made on 1993 June 25 transformed to Gaussian standard deviations. The distribution (*b*) of these Gaussian standard deviations is shown by the solid histogram, while the expected theoretical distribution is indicated by the dashed histogram.

(Figs 9*a*, 9*b*, 9*c*). From Figure 9 one can see that the bursts appear in all three units that were on line on this particular night, therefore excluding the possibility that it may be spurious events caused by electronic malfunction of one particular unit.

The data containing the bursts, i.e., $24^{h}24$ UTC to $25^{h}00$ UTC, were analyzed for a periodic signal. The TeV γ-ray power spectrum is plotted over the frequency range from 10 to 100 mHz (see Fig. 10*a*). It is clear that no pulsed emission is seen at the suspected frequencies. The data of the first and second bursts were also analyzed for periodic signals at the 33.08 s spin period of the white dwarf. The pulsed light curve of each burst dataset is shown in Figures 10*b*–10*c*. No evidence for pulsed emission is again seen.

Although we did not have any simultaneous OFF source coverage, the DC bursts identified here pass the fundamental tests of being Cherenkov induced since (1) they are not the result of optical flashes due to either astronomical or atmospheric sources (see Fig. 7*c*) and (2) they are not the result of a malfunction of the coincidence counter from a single unit (i.e., the bursts were seen in all three units). The burst duration is much less than the duration of the observation, making the identification of such bursts from a polynomial fit reliable. We could also argue that these events are most likely from AE Aquarii and not another burst source inside the 2° field of view of the telescope, since no keV–MeV γ-ray bursts (as usually seen by BATSE) were ever observed during a TeV observation from any ground-based observatory (Connaughton et al. 1993). However, similar bursts from AE Aqr have been detected in TeV (Bowden et al. 1992) and optical (De Jager & Meintjes 1993).

The DC signal strength of the strongest burst (4.63 σ) is $\sim$200% above the cosmic-ray background, and for a γ-ray threshold energy of $\sim$2.4 TeV, the energy flux is $\sim 8 \times 10^{-9}$ ergs cm^{-2} s^{-1}, which corresponds to a burst luminosity of $L_\gamma \sim 10^{34} d_{100}^2$ ergs s^{-1} if we assume isotropic emission. The total amount of energy radiated in 1 minute is $E \sim 6 \times 10^{35}$ ergs.

The orbital phase interval covered by these bursts is $\phi \sim 0.04$–0.05, which is again close to the time of superior conjunction as found for the pulsed detection on 1992 August 20, (Section 4.3). However, when calculating the orbital phase of the burst reported by Bowden et al. (1992), we find $\phi = 0.40$ for the 6 σ burst on 1990 October 13, and based on this observation, we find that the time of superior conjunction does not present a unique phase for TeV production.

5. WHITE DWARF SPIN-DOWN IN AE AQUARII

The cataclysmic variable AE Aquarii is probably the most unique disk accreting source yet detected, since the observed spindown implies a spin-down power which exceeds the mean accretion luminosity by two orders of magnitude. This may imply that a significant fraction of the spin-down power may go into the acceleration of charged particles (De Jager 1994). At least two types of mechanisms can operate to accelerate charged particles to very high energies during periods when little or no accretion takes place: (1) pulsar-type acceleration

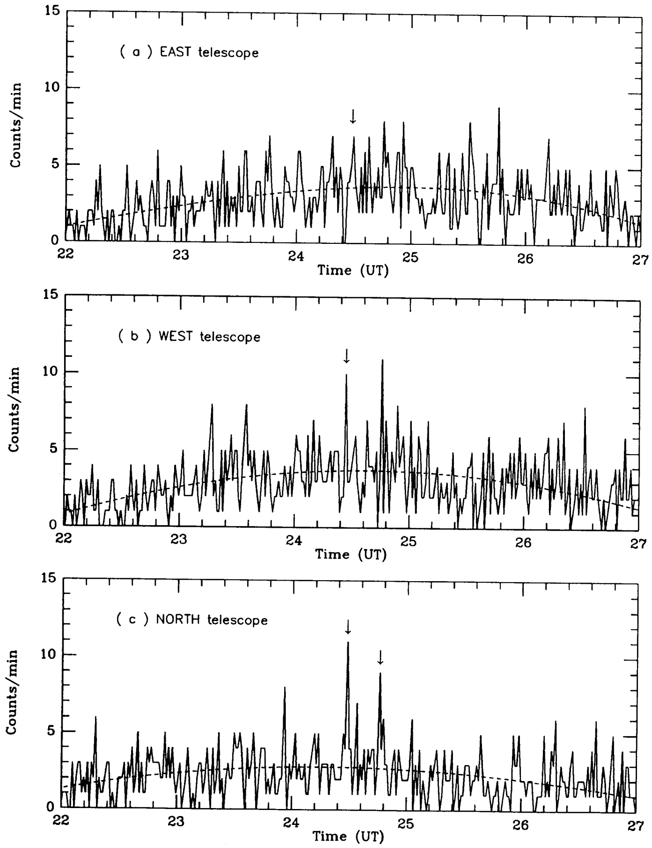

FIG. 9.—The count rate profiles (*a*), (*b*), and (*c*) of each operating unit of the telescope on the night of 1993 June 25. The dashed line on each graph represents the background level as determined from a polynomial fit through the data. The two burstlike features (from Fig. 7*c*) are indicated by arrows.

and (2) double-layer formation (Lamb, Hamilton, & Miller 1993). Both mechanisms require a low particle density in the magnetosphere, which may be met because of the low accretion rate in AE Aqr, and especially when the system is in a relatively low state as we have seen above. Wang & Robertson (1985) have also discussed how particle acceleration to TeV energies can take place during rapid spin-down in such a system.

De Jager (1994) has shown that the disk inner edge radius r_i must lie outside the corotation radius $r_c \sim 1.5 \times 10^9$ cm:

$$r_i \sim 13 r_c \left(\frac{\mu}{2 \times 10^{32}\ \mathrm{G\ cm^3}}\right)^{4/7} \left(\frac{L_{\rm acc}}{5 \times 10^{31}\ \mathrm{ergs\ s^{-1}}}\right)^{-2/7} \quad (3)$$

The redshifted optical QPO features can be interpreted either as blobs released from the disk inner edge (the *magnetospheric gating effect* proposed by van Paradijs et al. 1989) and forced into near corotation by the white dwarf's magnetic field, or as a beat period $f_{\rm QPO} = F_0 - [(GM/r^3)]^{1/2}/2\pi$ with $r_i \leq r \leq r_D$, where r_D is the outer disk radius. However, it remains to be shown if accretion can take place if $r_i \gg r_c$; one possibility is that matter will be expelled by the "propeller" effect (Wang & Robertson 1985) during nonsteady episodes.

Cheng & Ruderman (1989, 1991) and Ghosh & Lamb (1991) have shown that the differential rotation between the star and disk would induce an EMF between the star and the disk. This EMF is ~ 0 if $r_i \sim r_c$; i.e., for stars spinning close to equilibrium, which is usually the case for most X-ray pulsars and intermediate polars (Warner 1990), but since r_i is significantly larger than r_c, the stellar term would dominate, giving an EMF if (De Jager 1994)

$$\epsilon \sim \frac{\mu\Omega}{2cr_i}$$

$$\sim 10^{13}\left(\frac{\mu}{2 \times 10^{32}\ \mathrm{G\ cm^3}}\right)^{3/7} \left(\frac{L_{\rm acc}}{5 \times 10^{31}\ \mathrm{ergs\ s^{-1}}}\right)^{2/7} \mathrm{V}\,. \quad (4)$$

This EMF is well above the 2 TeV threshold energy of the MkI telescope. Thus, the EMF is ~ 0 for $r_i \sim r_c$, increases as r_i increases relative to r_c until a certain maximum is reached (so that eq. [4] holds), and decreases again as r_i ($\gg r_c$) approaches the light cylinder radius c/Ω, resulting in the classic Goldreich & Julian (1969) polar cap potential drop for isolated pulsars. Thus, AE Aquarii appears to be in the most favorable state to experience a maximal EMF since $c/\Omega \gg r_i \gg r_c$.

The large EMF in the star-magnetosphere-disk circuit drive a large electrical current I_c between the disk and star (Lamb, Hamilton, & Miller 1993) with a time development given by

$$\epsilon = L\frac{dI_c}{dt} + IR\,. \quad (5)$$

The circuit inductance $L \sim r_i/c^2$ (Cheng & Ruderman 1991), and the total circuit resistance is R. The current would grow with time, but Hamilton, Lamb, & Miller (1993) have shown that microscopic and/or MHD instabilities will intervene before the EMF has been shorted out. This leads to events of particle acceleration due to magnetic reconnection and/or MHD instabilities, which would explain the continuous source of mildly relativistic electrons that are needed to explain the radio synchtrotron emission, and, under more special conditions, acceleration to TeV energies.

Ghosh & Lamb (1991) gave a natural explanation for the detection of periodic TeV signals that are slightly shifted in frequency: "*Because the potential drop across the acceleration region necessarily leads to differential rotation within the magnetosphere, we do not expect these mechanisms to produce γ-radiation that oscillates in intensity at exactly the stellar spin frequency.*" If the abovementioned blobs that are forced into near corotation are threaded by the azimuthally twisted magnetic field lines from the acceleration region, TeV γ-radiation can result from the decay products of very high energy protons after encountering a column density of ~ 50 g cm^{-2}. This would result in the detection of a TeV signal with a period that is slightly redshifted relative to the spin period, as observed. If the column density of the blob (along the line of sight) is much less than this critical value, but if it is magnetized, the protons can be magnetically trapped and isotropized until the effective column density seen by the proton exceeds ~ 50 g cm^{-2} (De Jager et al. 1991). In this case the TeV pulse profile would be phase-shifted relative to the optical pulse profile if the particle trapping time is more than ~ 10 s before converting to γ-rays, It is interesting to note the detection of a spin-up (-4×10^{-5} s s^{-1}) on a timescale of 2 hr of the signal at f_2 by Brink et al. (1990) (smallest chance probability: 2×10^{-6}). Such a spin-up would be consistent with a blob that is forced into corotation with the white dwarf. However, we did not see such a spin-up from the observation on 1992 August 20.

The luminosity of the burstlike features (on 1993 June 25) exceeded the spindown power for a brief time. Such transient events are also expected in the framework of Hamilton et al

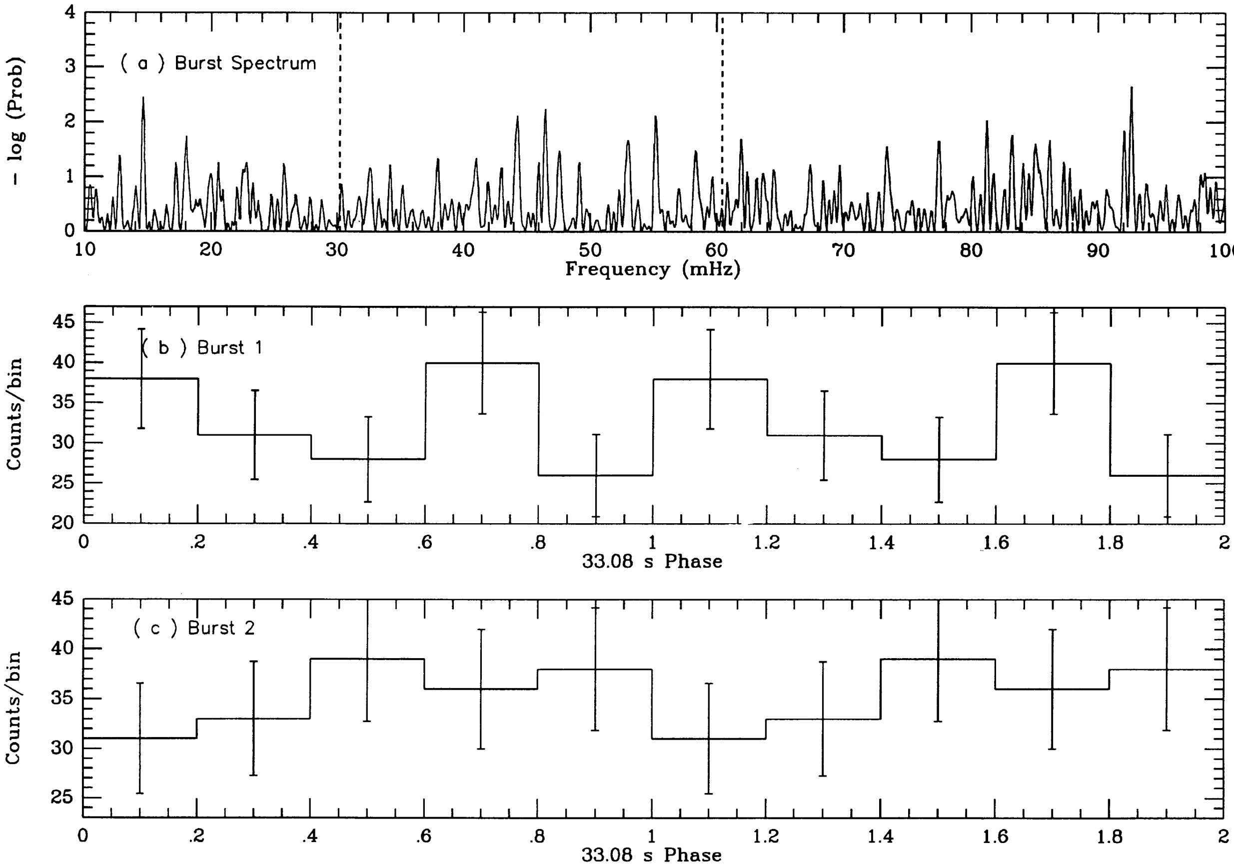

FIG. 10.—(*a*) The TeV power spectrum of the data containing the bursts, i.e., 24^h24–25^h00 UTC. Indicated by dashed lines on (*a*) are the frequencies of the white dwarf spin ($F_0 = 30.23$ mHz), and its first overtone ($F_1 = 60.47$ mHz). Data of the first (24^h24–24^h36 UTC) and second (24^h42–24^h54 UTC) bursts were selected and analyzed at the spin period of the white dwarf (33.08 s), as indicated by the light curves (*b*) and (*c*).

(1993): if the electron density is low enough (e.g., during an optical low state as seen during the TeV bursts in Figs. 7*a* and 7*b*), microinstabilities would occur, possibly followed by the formation of a relativistic double layer[8] with a potential drop exceeding a TeV. Lamb, Hamilton, & Miller (1993) have shown that if the current I_c flowing through such a double layer is too large, it will be disrupted, relasing the stored energy in the inductor $E \sim LI_c^2/2$ ergs over a short timescale T. The resistance R is small (Lamb et al. 1993), so that the potential drop over the double layer can be approximated by $\Delta V \sim LI/T$. The quantity LI_c is known to be equal to the magnetic flux. If the latter is calculated in the disk plane, $LI_c = \Phi \sim B(2\pi r)\delta r$, and the potential drop can then be approximated as

$$\Delta V \sim 2 \times 10^{13}\left(\frac{\mu}{2 \times 10^{32}\ \mathrm{G\ cm^3}}\right)\left(\frac{60\ \mathrm{s}}{T}\right)\left(\frac{\delta r}{r}\right)\ \mathrm{V}\,. \quad (6)$$

The total energy release from such an exploding double layer is (with $L = r_i/c^2$),

$$E = \frac{1}{2}\,LI_c^2 \sim 8 \times 10^{35}\left(\frac{\mu}{2 \times 10^{32}\ \mathrm{G\ cm^3}}\right)^2\left(\frac{\delta r}{r}\right)^2 \times \left(\frac{10^{10}\ \mathrm{cm}}{r_i}\right)^3\ \mathrm{ergs}\,, \quad (7)$$

which is of the correct order of magnitude as observed. It would take the white dwarf a minimum time of $E/I\Omega\dot{\Omega} \sim 120$ s to restore this amount of energy in another double layer, which can result in more than one burst duration one observation, as observed.

6. CONCLUSION

Meintjes et al. (1992b) identified a narrow range of periodicities where optical QPO are usually seen, and searching for these frequencies in TeV did result in a positive detection in ~10% of all the AE Aqr observations considered by Meintjes et al. (1992b). When restricting ourselves to these same few frequencies *without any seach in period*, we confirm the Meintjes et al. result at the 1×10^{-3} level. Furthermore, as in our first report (Meintjes et al. 1992b), the $f_2 = 30.04$ mHz signal was again the most significant pulse during this campaign, occurring with a duty cycle of ~10%. The strongest TeV detection at f_2 resulted from the 1992 August 20 simultaneous optical/TeV observation. The signal-to-noise ratio was a maximum during the optical low state (smallest chance probability: 10^{-4}), but was consistent with zero during the optical high state. The optical and TeV pulse profiles were found to be in phase (after removing the optical pulse at the spin frequency). However, more correlated detections would be needed to see if such a phase matching of optical and TeV QPO features is a persistent feature.

Another observation showed peculiar burstlike TeV γ-ray emission, similar to the TeV burst reported by Bowden et al.

[8] The reader is referred to the textbook of Peratt (1992, chap. 5), for an in-depth discussion of the plasma physics of double layers, and their role in astrophysics.

(1992). De Jager & Meintjes (1993) reported the detection of similar short bursts in optical. However, this detection (significance $>4.6\ \sigma$) did not correlate with a similar optical burst, but occurred following some intensive flaring activity in the optical. These bursts were detected in all three units that were on-line on that particular night and are independent, meaning that these bursts can be interpreted as a simultaneous detection from three independent telescopes. It was also shown that they are not the result of artificial events induced by optical flashes of local origin. The significance of these bursts were calculated analytically as well as with a Monte Carlo simulation, and is 99.947% after all the statistical trials were considered.

The pulsed and burstlike TeV detections have one property in common: the optical was in a relatively low state. This is, however, consistent with the prediction of de Jager (1994) and the details given in the previous section: (1) the accretion luminosity must be relatively low to allow the disk inner edge radius to be well outside the corotation radius, so that the stellar EMF significantly dominates the counter effect of the disk EMF. In this case the expression for the stellar EMF is equal to the Goldreich & Julian polar cap potential, but enlarged since the stellar field lines have been forced open by the disk to a distance well inside the light cylinder radius. The slower rotating (relative to the star) disk and blobs released by the disk act as target material for the conversion of accelerated particles to γ-rays, which allows the detection of redshifted TeV periodicities. (2) The star-magnetosphere-disk environment can be seen as a circuit with inductance L and a relatively low resistance R. The energy stored $E = LI_c^2/2 \sim 10^{35}$–$10^{36}$ ergs in this L, R circuit can be released on short timescales (minutes) in an exploding double layer if the electron density is low enough (i.e., during the optical low state as observed) with an associated potential drop exceeding 10^{13} eV. Particles (possibly protons) accelerated to these energies (nearly monoenergetic), and converted to γ-rays from π^0 decay in any available target, would explain why the γ-ray spectrum is hard relative to the cosmic ray background spectrum (Bowden et al. 1992), making the signal only detectable above ~ 1 TeV. The observed duty cycle of such bursts is small: ~ 3 minutes/31 hr $\sim 0.2\%$, which is understandable given the special conditions needed for double-layer formation, acceleration to TeV energies, and the presence of a suitable target.

However, the constraint on the electron density is less restrictive for magnetic reconnection events resulting from the azimuthal magnetic field created by the large conduction currents, driven by the large net EMF and small resistance (Hamilton, Lamb, & Miller 1993). This would result in particle acceleration events (but not always to TeV energies), and would provide the source of mildly relativistic electrons (with a much larger duty cycle as seen in TeV), resulting in the continuous and flarelike radio synchrotron emission (Bastian, Dulk & Chanmugan 1988). Furthermore, the optically thin part of the radio synchrotron spectrum would be in the far infrared range where the synchrotron lifetime of relativisitic electrons becomes less than the spin period, so that QPO features resulting from synchrotron emission can be seen (De Jager 1994), and correlated far infrared/TeV searches for QPO would also be worthwhile.

The first results of a search for a MeV to GeV γ-ray signal from AE Aqr (averaged of a few years) was unsuccessful (Barrett et al. 1994), but this can be understood if the emission is transient and the spectrum is hard as discussed above.

The more sensitive Mk II TeV γ-ray telescope (Brink et al. 1991) scheduled for 1994 will be ideally suited to allow the detection of QPO features, and the DC enhancements which should accompany these periodic signals, since it will be able to do simultaneous off-source measurements.

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REFERENCES

Abada-Simon, M., et al. 1993, ApJ, 406, 692
Barrett, P., et al. 1994, in Proc. 2d Compton Gamma-Ray Symp., ed. N. Gehrels & C. E. Fichtel (New York: AIP), in press
Bastian, T. S., Dulk, G. A., & Chanmugam, G. 1988, ApJ, 324, 431
Bookbinder, J. A., & Lamb, D. Q. 1987, ApJ, 323, L131
Bowden, C. C. G., et al. 1992, Astroparticle Phys., 1, 47
Brink, C., et al. 1990, Proc. 21st Internat. Cosmic Ray Conf. (Adelaide), 2, 283
———. 1991, Proc. 22nd Internat. Cosmic Ray Conf. (Dublin), 2, 283
Bruch, A. 1991, A&A, 251, 59
Cheng, K. S., & Ruderman, M. 1989, ApJ, 337, L77
———. 1991, ApJ, 373, 187
Connaughton, V., et al. 1993, in Proc. 23rd Internat. Cosmic Ray Conf. (Calgary), 1, 112
de Jager, H. I., et al. 1986, South African J. Phys., 9, 107
de Jager, O. C. 1994, ApJS, 90, 775
de Jager, O. C., & Meintjes, P. J. 1993, A&A, 268, L1
de Jager, O. C., Raubenheimer, B. C., & Swanepoel, J. W. H. 1989, in Data Analysis in Astronomy III, ed. V. Di Gesu, L. Scarsi, P. Crane, J. H. Friedman, S. Levialdi, & M. C. Maccarone (London: Plenum), 21
de Jager, O. C., et al. 1991, in Lecture Notes in Physics, Vol. 391, Relativistic Hadrons in Cosmic Compact Objects, ed. A. A. Zdziarski & M. Sikova (Heideleberg: Springer), 173
———. 1994, MNRAS, 267, 577
Eadie, W. T., Drijard, D., James, F. E., Roos, M., & Sadoulet, B. 1971, Statistical Methods in Experimental Physics (Amsterdam: North-Holland)
Ghosh, P., & Lamb, F. K. 1991, in Neutron Stars: Theory and Observation, ed. J. Ventura & D. Pines (NATO ASI Ser. C), 344, 363
Goldreich, P., & Julian, W. H. 1969, ApJ, 157, 869
Hamilton, R. J., Lamb, F. K., & Miller, M. C. 1993, in AIP Conf. Proc. 280, Compton Gamma-Ray Obs. Symp., ed. M. Friedlander, N. Gehrels, & D. J. Macomb (New York: AIP), 438
Lamb, F. K., Hamilton, R. J., & Miller, M. C. 1993, in Compton Gamma-Ray Observatory Symposium, ed. M. Friedlander, N. Gehrels, & D. J. Macomb (New York: AIP)
Mardia, K. V. 1972, Statistics of Directional Data (London: Academic)
Meintjes, P. J., et al. 1991a, in Structure and Emission Properties of Accretion Disks, ed. C. Bertout, S. Collin-Souffrin, J. P. Lasota, & J. Tran Thanh Van (Paris: Editions Frontiéres), 483
———. 1991b, Proc. 22nd Internat. Cosmic Ray Conf. (Dublin), 1, 360
———. 1992a, in ASP Conf. Ser., Vol. 30 Variable Stars and Galaxies, ed. B. Warner (San Francisco: ASP), 351
———. 1992b, ApJ, 401, 325
———. 1993, Proc. 23d Internat. Cosmic Ray Conf. (Calgary), 1, 338
Nather, R. E. 1973, Vistas Astron., 15, 91
Patterson, J. 1979, ApJ, 234, 978
Patterson, J., et al. 1980, ApJ, 240, L133
Peratt, A. L. 1992, Physics of the Plasma Universe (New York: Springer)
Raubenheimer, B. C., et al. 1991, AIP Conf. Proc. 220, High Energy Gamma-Ray Astronomy, ed. J. Matthews (New York: AIP), 72
van Paradijs, J., Kraakman, H., & van Amerongen, S. 1989, A&AS, 79, 205
Wang, Y.-M., & Robertson, J. A. 1985, A&A, 151, 361
Warner, B. 1990, Ap&SS, 164, 79
Warner, B., & Wickramasinghe, D. T. 1991, MNRAS, 248, 370
Welsh, W. F., Horne, K., & Gomer, R. 1993, ApJ, 410, L39
Welsh, W. F., Horne, K., & Oke, J. B. 1993, ApJ, 406, 229