A SEARCH FOR MICROFLARING ACTIVITY ON dMe FLARE STARS. I.
OBSERVATIONS OF THE dMeC STAR CN LEONIS

R. D. ROBINSON
Astronomy Programs, Computer Sciences Corporation, Goddard Space Flight Center, Code 681/CSC, Greenbelt, MD 20771

K. G. CARPENTER
Laboratory for Astronomy and Solar Physics, NASA/Goddard Space Flight Center, Code 681, Greenbelt, MD 20771

J. W. PERCIVAL
Space Astronomy Laboratory, University of Wisconsin, 1150 University Avenue, Madison, WI 53706

AND

J. A. BOOKBINDER
Smithsonian Astrophysical Observatory, Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

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ABSTRACT

Microflares are frequent, short-duration, energetically weak disturbances occurring in the nonradiatively heated regions of the Sun and other magnetically active stars. They are thought to be the low-energy extension of flares commonly seen on active dMe stars and may be a major source of heating the chromosphere and corona of cool stars in general. In this paper we describe rapid time sequence UV photometry of the dMe star CN Leo taken with the High Speed Photometer (HSP) aboard the Hubble Space Telescope (HST). The filter was centered at 240 nm, near wavelengths at which flares are expected to have maximum intensity and the stellar background is small. During 2 hr of on-source observing, a total of 32 flarlike events were detected, with integrated counts ranging from 12 to more than 14,000. In most cases the events had integrated energy ranging between $10^{27}$ and $10^{28}$ ergs and can be classified as microflares. A considerable fine structure was seen in these events, with substantial variations sometimes occurring on timescales of less than 1 s. The occurrence rates for the smaller events showed a power-law distribution, with a slope comparable to that seen for larger events observed from the ground. Extrapolating the occurrence rate relation to nanoflare energies indicates a predicted count rate that is significantly smaller than that observed, suggesting that the nanoflares have a different energy distribution than the larger events.

Subject headings: stars: activity — stars: flare — stars: individual (CN Leonis) — ultraviolet: stars

1. INTRODUCTION

The question of nonradiative heating in the atmospheres of cool dwarf stars has been a major topic of investigation for decades. A large variety of proposed mechanisms have been put forward during this time, including Alfven waves (Holweg & Sterling 1984; Steinolfson & Davila 1993), current dissipation (Rosner, Tucker, & Vaiana 1978), inverse bremsstrahlung (Oien & Alendal 1993) and electromagnetic coupling (Ionson 1984).

One very promising mechanism was proposed by Parker (1981, 1983) and involves the dissipation of magnetic energy at numerous "magnetic discontinuities" within individual flux tubes. These are thought to be formed by the random motions of the magnetic fields resulting from their interaction with the stellar convection. The energy released in each event was estimated as $10^{24}$ to $10^{25}$ ergs, about $10^{-9}$ of the energy released in a large solar flare. Because of this, Parker (1988) referred to them as nanoflare events. To support this idea Sturrock et al. (1990) has shown that coronal emission measures could be accurately modeled using this type of episodic heating, while Lu & Hamilton (1991) and Lu et al. (1993) have shown that the distribution of flare energies can be reproduced by avalanches of many small reconnection events occurring in a magnetic field subjected to a continuous driving force.

In the higher energy domain the nanoflares are normally referred to as microflares. The phenomenon was first observed on the Sun by Lin et al. (1984) in a balloon-based hard X-ray experiment in which they detected numerous small hard X-ray bursts, each lasting from a few seconds to about 30 s. These bursts were created by nonthermal electrons with integrated energies ranging from $10^{26}$ to $10^{28}$ ergs. They had an occurrence rate that increased with decreasing energy, with a slope in agreement with that found for brighter hard X-ray events by Dattow, Elcan, & Hudson (1975). Lin et al. (1984) speculate that the energy released to nonthermal electrons by these small events might be sufficient to account for the heating of the active solar corona. Recently Bastian (1991) has reported on the radio analog to these X-ray microflares, while numerous small brightenings in UV transition region lines such as C IV and Si IV have been found in solar active regions (Porter, Toomre, & Gebbie 1984) and the network (Porter et al. 1987).

Unfortunately, not much is known about microflaring activity on other stars, although there is some evidence that stellar flaring is related to coronal heating. For example, Doyle & Butler (1985) and Skumanich (1985) independently examined the activity in dMe flare stars and discovered a linear relation between the time-averaged U-band flux from flares and the quiescent X-ray emission over more than 3 orders of magnitude in X-ray flux. Butler et al. (1986) also showed a correlation

1 Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.
between soft X-ray fluctuations and small, flarelike events seen in the integrated flux of HX on several active stars. This study has been questioned by Pallavicini, Tagliaferri, & Stella (1990), who found no evidence for statistically significant variability on timescales less than a few minutes in a large sample of EXOSAT data.

Most flare observations on stars involve photometric monitoring using the Johnson U or B band. From these we know that the color temperature of the optical flare continuum generally lies between 10,000 and 20,000 K (see, e.g., Katsva & Livshits 1991) and that the frequency of occurrence of large flares is much smaller than for small flares (see, e.g., Gershberg & Shakhovskaya 1983). In fact, the rate of occurrence, \( v \) (hr\(^{-1}\)), of flares with time-integrated energy greater than or equal to a specified value, \( E \) (ergs), is a power law with a spectral index that is almost independent of the spectral type of the star (Shakhovskaya 1989). Because of counting statistics, sky background, variations in atmospheric transmission, and seeing effects, the smallest believable increase detectable over short time periods (around 10 s) from the ground is 5%–10% above the quiescent stellar background (see, e.g., Moffett 1974). Thus, the amount of energy released during the minimum detectable flaring event depends strongly on the spectral type and distance of the star. The smallest energy that can be detected given the energy 2 × 10\(^{27}\) ergs, on the very late type star CN Leo (Gershberg & Shakhovskaya 1983). In general, though, the threshold energies correspond to 10\(^{25}\) ergs or more. To find the microflaring contribution to the total flare output the standard procedure is to extrapolate the observed relations to energies as small as 10\(^{-3}\) of the observation threshold (see Ambruster, Sciortino, & Golub 1987; Haisch, Strong, & Rodono 1991). This is dangerous, both because of uncertainties in the established slope of the curve and also because of the questionable assumption that the occurrence rate for microflares follows the same relation as that seen in the larger flare events. To obtain a better understanding of the importance of microflaring activity both in the heating problem and as a component of the overall flare phenomena, it is important to study flare events with the minimum possible energy directly.

In this paper we describe observations that are part of a program of observing flaring activity in the UV. The target was the dMe star CN Leo (Gliese 406). The proximity (2.4 pc) and late spectral type of this star make it an ideal candidate for the study of weak flares. Further, the relatively large flare occurrence rate (Gershberg & Shakhovskaya 1983) ensured that a sufficient number of flares would be observed during our limited observing time to allow a statistically significant inter-

### TABLE 1

**OBSERVATIONAL DETAILS**

<table>
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<th>Orbit Number</th>
<th>Root Name</th>
<th>Date</th>
<th>Start Time (UT)</th>
<th>Duration (minutes)</th>
<th>Average Count Rate</th>
<th>Total Counts</th>
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<td>30.0</td>
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<td>...</td>
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* Value from time 0 to 600 s before major flare event.
Fig. 1.—(a) Filter response functions for the F240W filter used in these observations, as well as the Johnson U band, commonly used in observing stellar flares. (b) Spectrum of a 1.2 mag U-band flare on the dMe star AU Mic, obtained during a 10 minute period covering the impulsive phase and part of the early thermal decay. Spectrum taken during quiescence is shown for reference. The UV spectra were obtained with the IUE, while the optical spectrum represents the sum of several spectra taken with the 3.9 m Anglo-Australian telescope during the same time period as the IUE integration.

Fig. 2.—Summary of the HSP photometric time series. Data have been binned into 1 s time intervals.
for just over 2 s. During the impulsive phase the flare shows
significant fine structure on timescales as small as 0.1 s and a
peak flux nearly 18 times background. The second event, in
orbit 4, is much larger but shows a similar structure. Of particu-
lar interest is the rapid onset, in which the flux increases by a
factor of 8 over a time of less than 2 s. The impulsive phase
lasts for just over 1 minute and has at least three major bursts.
Note that after the impulsive activity disappears, the flux level
is close to that attained just after the initial onset but before the
commencement of major impulsive activity. This flux level then
decays slowly over the remainder of the orbit. The overall
appearance of the flare is of two components, one having a
slow decay after an initial rapid onset, and the other consisting
of strong, short-duration bursts.

The aberration of the primary mirror of the HST results in
an instrumental point spread function (PSF) that overfilled the
1" aperture of the HSP. Small errors in guiding, as well as the
"jitter" caused by flexure of the solar panels, can therefore
result in small variations in the measured flux that may mimic
microflare events. The importance of such effects can be
deduced through an examination of the time history of the
guide star positions, which are available in the engineering
data accompanying the observations and were sampled once
each 30 s. Figure 4 shows the guide star positions for two of the
four orbits. A close comparison with observations shows no
obvious correlation with variations in the flux. Further, experi-
ments using estimates of the PSF suggest that the measured
displacements would only produce variations in the flux that
were smaller than the expected Poisson noise. The one possible
exception is the strong recentering event in orbit 1 that started
approximately 22 minutes into the time sequence. The major
deviation for this event corresponds to the time of the strong,
short-duration flare shown in Figure 3. However, it is unlikely
that the event would have seriously influenced the measured
fluxes. Note in Figure 4 that the strong decentering preced- ing
the flare event was not reflected in the observed flux, which
remained constant. Further, it is difficult to understand how a
decentering could be responsible for a large increase in mea-
sured flux. Overall, we conclude that the variations of the
stellar position within the HSP aperture resulted in minimal
effects on the data.

3. SEARCHING FOR MICROFLARES

Microflare events are small, often having fluxes at or less
than the background against which they are measured. To
detect the events it was necessary to bin the individual time
sequences and then search the binned series for elements that
have counts significantly higher than would be expected by
chance. Strong events show up at small binning intervals, while
the weaker events sometimes require binning over their entire
duration before a significant number of counts are detected.

To determine which events are statistically significant it is
necessary to determine a probability distribution for any given
binning factor. This was obtained directly from the data by
first randomizing the order of the individual 0.01 s samples
within a given time sequence (after first removing the larger
flares events), then binning the resultant time sequence by the
required amount, and finally determining a histogram for the
number of counts in each binned sample, thereby determining
the probability for a given number of counts. Because each
integration time is small compared to the duration of a micro-
flare event, the act of randomizing the time sequence acts to
spread the power in each event over the entire time sequence.
The results are therefore conservative in that the actual
occurrence rate for a given count is somewhat larger than
would be the case if the microflares were not present. By
repeating this analysis thousands of times, each time using a
different randomization and averaging the resultant distribu-
tions, we were able to reduce the noise considerably, as well as
to determine the probabilities for extremely rare events. Figure
5a gives an example of the distributions obtained. As might be
expected, the probability was found to be accurately described
by a Poisson distribution for all three "quiescent" orbits, as
well as the quietest portion of orbit 4.

In searching for flare events we started by binning the
observed time sequences into intervals ranging from 0.1 s to 10
s. The binned time sequences were then searched for any points
having an integrated count that had a probability of occurring
by chance of 10⁻² (essentially 3 σ) or less, based upon the
probability analysis discussed above. A significance was then
assigned to each identified point based upon that probability.
A low probability indicated the presence of a possible micro-
flare event. Obviously, the number of counts within a bin can
depend critically upon the starting point, or phase, of the inte-
gration. This is especially true if the time sequence contains
short-duration, rapidly changing microflare events. In our
analysis we therefore examined all possible phases and
adopted the maximum value found in a given bin into the time
sequence. This procedure will increase the probability of
obtaining a higher level of counts by chance and modifies the
measured Poisson distribution of the background. Tests using
the randomized data show that when the maximum count from
every possible phase is selected for a given bin, the shape of
the distribution remains the same as for the case in which no
phase selection is used, but the number of counts at any given

![Probability distribution](image)

**Fig. 5.** (a) When integrating the time series over a specified interval, the
probability of obtaining a given number of counts through chance is accur-
ately modeled by a Poisson probability distribution. As an example, we show
the measured probability distribution for bins of 5 s duration, derived as
explained in the text (solid line), compared with a Poisson distribution (dashed
line). (b) When all possible binning phases are examined and the maximum
count obtained in each bin is selected, the probability distribution remains
roughly the same shape as in (a), but the average number of counts is increased
by N^{1/2}. Solid line shows the results of a numerical experiment employing this
 technique for a binning factor of 5 s; dotted line shows the same Poisson
distribution as used in (a), which has been shifted to the right by 4.7 (= N_{av})
counts.

probability level increases by N^{1/2}, where N_{av} is the average
number of counts per bin (see Fig. 5b). This is simply caused by
the fact that for any given phase the probability of having a
specific number of counts in a bin has a Poisson probability
distribution with a peak at N_{av} and a width of N^{1/2}_{av}. Thus, the
maximum value in a bin, selected from a suitably large sample
representing the different phases, will be N^{1/2}_{av} larger than that
expected from a standard binning of the data.

After determining the times at which the integrated counts
were significantly enhanced, the points were transferred to a
two-dimensional array specifying binning factor and time of
occurrence (equal to the time at the midpoint of the bin, taking
the phase into account). Figure 6 illustrates the procedure for a
short time interval of orbit 1. The result is a map of the micro-
flaring activity that gives some indication of the time history of
each event. For example, the first event seen in Figure 6 is a
highly significant burst starting 505 s into the time sequence
and having most of its power emitted over approximately 3 s.
This has enough power to remain significant even when the
counts are averaged over 10 s. This burst is followed by a much
less intense event of approximately 2.5 s duration.

Figure 7 shows the results of applying this analysis to all
four time sequences. This shows that flares often occur in
compact groups lasting 20–50 s, with the individual bursts
within the group having a significant count for binning inter-
vals as short as 1 s. There is also an apparent variation in the
average event rate. Note, for example, that orbit 1 and the first
half of orbit 2 have a much higher rate of highly significant
events than do the second half of orbit 2, orbit 3, and the first
part of orbit 4. The amount of data available, however, is not
sufficient to tell whether this is statistically significant. Note
also the increase in the occurrence rate during the decay phase
of the large flare event in orbit 4. These events have a lower
significance only because of the larger background against
Fig. 6.—Flare events detected and analyzed by binning the time sequence by specified amounts and then searching the binned series for elements that have counts significantly higher than would be expected by chance. Strong events show up at small binning intervals, while weaker events sometimes require binning over their entire duration before a significant number of counts are detected. In analyzing the data we examined binning intervals ranging from 0.1 s to 10 s. Top plot shows the level of significance as a function of binning interval. Black has a probability of $10^{-3}$ of occurring by chance (essentially a 3 $\sigma$ detection). Dark gray has a probability of $10^{-4}$, while light gray has a probability of $10^{-5}$. Two lower graphs indicate the relevant time series binned into 2 s and 6 s intervals. Dotted line indicates the average count rate, while dashed line shows the 3 $\sigma$ detection threshold.

which they are measured. The increase in count rate within these bursts is actually comparable to the events seen in orbit 1.

4. SMALL-AMPLITUDE ACTIVITY

The microflare events discussed in the last section were detected at a high confidence level. Examining the time sequences outside of these events shows additional variations that appear to be larger than expected from Poisson statistics or instrumental effects (see Fig. 2). To investigate the reality of these variations we have used the analysis technique of Collura et al. (1987), which was designed to study nonperiodic variability in data with low count rates and data gaps. The technique has been applied to X-ray time sequences for a variety of dMe stars (Ambruster et al. 1987; Collura, Pasquini, & Schmitt 1988) and is basically a $\chi^2$ test that is capable of determining not only the significance of the variability but also the effective amplitude and, in some cases, the characteristic timescale.

In simple terms, the technique involves binning the time sequence by a certain factor $(B)$ and then constructing a standard $\chi^2$ statistic, which compares the values in the individual bins with the mean number of counts per bin $(f)$, i.e.,

$$\chi^2(B) = \frac{1}{(n-1)} \sum_{i=1}^{n} \frac{(C_i - f)}{f},$$

where $n$ is the number of bins in the time sequence and $C_i$ is the number of counts in bin $i$, averaged over all possible phases. The effective variability of the time series, $V_{\text{eff}}$, for a given binning factor can then be calculated from the expression (see, e.g., Ambruster et al. 1987);

$$\frac{V_{\text{eff}}}{f} = \frac{(n - 1)}{n} \chi^2 - 1.$$

A measured value of $\chi^2$ is judged to be significant if it exceeds the tabulated $\chi^2$ for a given significance level. In Figure 8 we present the results of this analysis as applied to the time sequence taken in orbit 2, after removing the detected microflare events. A significant variability is detected at a binning factor of 4 s and continues to increase in significance as the binning factor increases. As the size of the binning factor increases above the characteristic timescale of the variability, the fluctuations average out and the effective amplitude of variability should decrease. The constant value of $V_{\text{eff}}$ in Figure 8 therefore suggests (a) that most of the power resides in variations with characteristic timescales greater than 5 minutes and (b) that there is relatively little power in the short-duration variations that would be identified as small microflares. This is also the impression given by the binned time series, e.g., Figure 8b. Orbit 1 shows identical behavior to orbit 2. In orbit 3, however, the variability is smaller and shows a shorter timescale.

5. DISCUSSION

To quantify the flaring activity we have used the maps shown in Figure 7 to determine the approximate duration and integrated counts for each of the events. In this analysis we have assumed that compact groups were actually one event and give the properties for the entire group. Events that occur close to another burst or group of bursts but were clearly separated at low binning factors were treated as separate events. The results of this analysis are presented in Table 2.

To calibrate the energy of the microflares we obtained observations of the white dwarf standard AGK +81D266 (see Table 1). These indicated a calibration factor of $2.0 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ A$^{-1}$ (counts s$^{-1}$)$^{-1}$. The equivalent width of the F240W filter is 645 Å, so the integrated energy through the filter is $1.3 \times 10^{-13}$ ergs cm$^{-2}$ counts$^{-1}$. Taking the distance to CN Leo as 2.4 pc results in an integrated energy at the stellar surface equal to $9 \times 10^{25}$ ergs counts$^{-1}$. The smallest detected flare event had 12 counts (above background), which therefore corresponds to an integrated energy of approximately $10^{27}$ ergs, about the same as a small subflare on the Sun (see, e.g., Svestka 1976).

To compare the characteristics of the microflares detected by the HSP with flares monitored from the ground it is necessary to estimate the amount of energy released by the HSP flares into the Johnson U band. To do this we note that Lacy, Moffett, & Evans (1976) showed that the fluxes in the Johnson B and V bands are directly proportional to the U-band flux over a wide range of flare energies. The same proportionality constant appears to apply to all of the stars in their sample. Assuming that the F240W and U-band fluxes are similarly related, it is only necessary to determine the proportionality constant. Unfortunately, we have no simultaneous U-band coverage for any of the HST flare events. However, during a 1992 observing campaign of the dMe star AU Mic we did obtain simultaneous UV and optical observations of a 1.2 mag U-band flare (see Robinson et al. 1993). The optical data consisted of a sequence of medium-resolution spectra covering the wavelength range from 3600 Å to 4400 Å obtained with the 3.8 m
Fig. 7.—(a) Significance plots as a function of time for orbit 1. Plots should be compared with the light curve presented in Fig. 2. The shading represents the same probabilities as specified in Fig. 6. Note the fine structure seen in many of the events. Significance plots as a function of time for (b) orbit 2, (c) orbit 3, and (d) orbit 4. Plot parameters are the same as in (a). The block starting at 640 s in orbit 4 represents the impulsive phase of the large flare event. The decay phase of this event has been suppressed in the analysis.
Fig. 7c

Fig. 7d
Anglo-Australian Telescope, while the UV was a 10 minute IUE low-resolution LWP exposure starting at the peak of the impulsive phase and continuing to the start of the thermal decay phase. The observations are shown in Figure 1b. By convolving the F240W and Johnson U-band filter responses with these spectra we see that the Johnson U-band filter detects approximately 1.5 times more flux than the F240W filter. Further, if we assume that this spectral range contains most of the optical/UV energy emitted by the flare, then the F240W filter will detect approximately 24% of that energy. Using these factors we see that the large flare observed during orbit 4, containing more than 14,000 counts, has a total optical/UV energy of nearly $5 \times 10^{30}$ ergs, near the maximum observed in this star (see, e.g., Gershberg & Shakhovskaya 1983). Of course, these approximations are extremely crude since they assume that the shape of the flare spectrum remains constant. In fact, the flare is known to be much bluer during the impulsive phase than during the decay (Panov, Piirola, & Korhonen 1988).

A common method of displaying flare occurrence rate is to plot the number of events with energy greater than or equal to a specified threshold value as a function of that threshold. For optical flares this normally has a power-law distribution of the form: $v = aE^b$, where $v$ is the occurrence rate (flares per hour), $E$ is the integrated flare energy, and $a$ and $b$ are constants. In Figure 9a we have used the results from Table 2 to construct a flare energy distribution plot for the uncalibrated HSP data. The curve is a rough power law with a slope of $-0.76$. Note, however, that since the observations only covered 2 hr, the occurrence rate for events with more than 100 counts (three events) is not reliable. By restricting attention to events with integrated counts of less than 100 and neglecting the smallest events, some of which may have been missed, we obtain a much better fit and a considerably larger slope of $-1.17$. This
Since the UV continuum, like hard X-rays, is strongest during the impulsive phase of a flare, we assume that the amount of flare-related UV radiation directly monitors the degree of coronal heating. If this is true, then we can estimate the relative contributions to heating from flares of different strengths. From Table 1 it is evident that the UV radiation from the large event seen in orbit 4 far exceeds the total of all other detected events. In fact, if we assume that all UV radiation detected by the HSP resulted from overlapping nanoflares with energies as low as $10^{25}$ ergs, then the integrated counts over the entire 2 hr time series are still only a factor of 50% greater than that seen in the single, large flare. Furthermore, if the distribution of microflare events shown in Figure 9a (dotted line) is extrapolated to events with only a single count (nanoflares), then we expect only about 400 events hr$^{-1}$, more than a factor of 20 less than actually observed. This suggests that the microflares may play a much smaller role than either the large flare events or the nanoflares in coronal heating and that the nanoflares and normal flares follow different energy distributions, as suggested by Collura et al. (1988) and Hudson 1991. One possibility for the difference in distributions was proposed by Zirker & Cleveland (1993), who suggested that the nanoflares resulted from reconnections within twisted magnetic fields, as suggested by Sturrock & Uchida (1981), while the normal flares originated in regions of flux braiding and avalanching, as proposed by Parker (1988).

6. CONCLUSIONS

During 2 hr of observations with the HSP we have reliably detected a total of 32 flare events on the dMe star CN Leo. The events show a great deal of fine structure and are variable on timescales as small as 0.1 s, in agreement with optical observations. The smallest events detected had energies near $10^{17}$ ergs and rarely last for more than a few seconds. Larger events appear to consist of closely packed groups of smaller flares, perhaps representing a cascade in which each component represents the excitation of one loop or loop arcade within an active region (see, e.g., Machado et al. 1988a, b; Rust, Simnett, & Smith 1985). These individual components may be more apparent in the UV than the optical because of the much shorter decay time at these wavelengths; i.e., flares are known to be very blue initially and to redden rapidly with time (Katsova & Livshits 1991).

The distribution of flare energies agrees reasonably well with that deduced from ground-based observations. The data suggest, however, that the energy distribution of nanoflares is significantly different from normal flare and microflare events, in agreement with previous authors.

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OBSERVATIONS OF CN LEO

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