THE ASTROPHYSICAL JOURNAL, **252**:239–249, 1982 January 1


# COORDINATED X-RAY, OPTICAL, AND RADIO OBSERVATIONS OF FLARING ACTIVITY ON YZ CANIS MINORIS

S. KAHLER
American Science and Engineering, Inc.
L. GOLUB, F. R. HARNDEN, JR., W. LILLER, F. SEWARD, AND G. VAIANA[1]
Harvard-Smithsonian Center for Astrophysics
B. LOVELL, R. J. DAVIS, R. E. SPENCER, AND D. R. WHITEHOUSE
Nuffield Radio Astronomy Laboratories, University of Manchester
P. A. FELDMAN
Herzberg Institute of Astrophysics
M. R. VINER
Department of Physics, Queen's University
B. LESLIE
Haystack Observatory
S. M. KAHN AND K. O. MASON
Space Sciences Laboratory, University of California at Berkeley
M. M. DAVIS
Arecibo Observatory
C. J. CRANNELL AND R. W. HOBBS
Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center
T. J. SCHNEEBERGER AND S. P. WORDEN
Sacramento Peak Observatory
R. A. SCHOMMER
Yerkes Observatory
S. S. VOGT
Lick Observatory
B. R. PETTERSEN
McDonald Observatory and Department of Astronomy, University of Texas at Austin
G. D. COLEMAN
Department of Astronomy, University of Michigan
J. T. KARPEN
Astronomy Program, University of Maryland; and
Laboratory for Solar Physics and Astrophysics, NASA Goddard Space Flight Center
M. S. GIAMPAPA
Steward Observatory and Department of Astronomy, University of Arizona
E. K. HEGE
Steward Observatory
V. PAZZANI, M. RODONO, AND G. ROMEO
Catania Astrophysical Observatory
AND
P. F. CHUGAINOV
Crimean Astrophysical Observatory
*Received 1981 April 15; accepted 1981 July 21*

## ABSTRACT

A coordinated search for flares from the dMe star YZ Canis Minoris was performed in 1979 October using the *Einstein* Observatory and ground-based optical and radio telescopes. An event was detected in the optical, radio, and X-ray wavebands on October 25, and a second optical event on October 27 was seen as a marginal ($2\,\sigma$) X-ray enhancement. The properties of the first event are discussed in detail, and it is shown that the similarities to solar flares are considerable. These include the presence of a gradual and an impulsive phase, an X-ray temperature of $\sim 10^7$ K, and the appearance of a 408 MHz burst delayed by 17 minutes from the flare onset. We argue that the 408 MHz burst is similar to solar type IV bursts. The ratio of X-ray to optical emission, $L_X/L_C$, is found to increase considerably in time throughout the event. The interpretation of the optical spectrum as a Planck function of $T = 8500$ K yields an area of $10^{19}$ cm$^2$, which, in combination with the X-ray emission measure of

[1] Also Osservatorio Astronomico di Palermo, Italy.

$\sim 2 \times 10^{51}$ cm$^{-3}$, yields an electron density of $1.4 \times 10^{11} \leq n_e \leq 5 \times 10^{11}$ cm$^{-3}$. The close agreement between the estimated radiative decay time and the observed cooling time for the X-ray plasma and the large values of $L_X/L_C \sim 1$ during the decay phase suggest that radiation is an important mechanism for cooling the coronal X-ray plasma.

*Subject headings:* stars: flares — stars: individual — stars: radio radiation — X-rays: sources

## I. INTRODUCTION

YZ Canis Minoris (Gliese 285), a late-type dwarf star with Balmer emission (dM4.5e), is a member of the UV Ceti class of flare stars. The properties of these stars were reviewed by Kunkel (1975). They have masses and radii several tenths that of the Sun and are characterized by flaring activity in the optical and radio ranges. Because of their cool temperatures and low luminosities the flaring activity in the optical range is best observed in the $U$ and $B$ bands and on nearby ($d < 10$ pc) stars.

Past attempts to observe flare X-ray emission from UV Ceti stars have been hampered by several factors. Heise *et al.* (1975) reported detection by *ANS* of a soft X-ray flare on YZ CMi which was unaccompanied by optical or radio coverage and detection of another X-ray flare on UV Ceti for which the rise phase was not observed. The MIT X-ray satellite *SAS 3* has been used in two programs coordinated with optical and radio observations to search for X-ray emission from flare stars. In the first Karpen *et al.* (1977) observed YZ CMi for a 3 day period in 1975 and reported 31 optical flares (none greater than 3 mag) and 11 radio events, but no detectable X-ray events. In the other program Haisch *et al.* (1978) observed Proxima Centauri for a 3 day period and reported similar results—30 optical flares and 12 possible radio events but no X-ray events. While no substantial X-ray emission may have occurred during the *SAS 3* observations, the lack of any detected events may also have been the result of low detector sensitivity. Kahn *et al.* (1979) detected two X-ray flares from each of two nearby dMe stars, AT Mic and AD Leo, with the A-2 experiment on *HEAO 1*. While a thermal spectrum with a temperature of $30 \times 10^6$ K and an emission measure of $10^{54}$ cm$^{-3}$ was obtained for one event, no time profiles of the X-ray events were observed and no simultaneous ground-based coverage was available.

Obtaining good X-ray observations of a dMe star flare is important not only for understanding the physics of flares but also for testing current ideas regarding the similarity between stellar and solar flares. The known properties of solar flares (cf. Svestka 1976) have been used as the basis for several predictions of the ratio of X-ray to optical fluxes (Kahler and Shulman 1972; Crannell, McClintock, and Moffett 1975; Mullan 1976). Further evidence for the solar analogy comes from observations suggesting that all dMe stars undergo slow, quasi-sinusoidal variations of optical brightness of the order of 0.1 mag, known as the BY Draconis syndrome (Bopp and Espenak 1977). Following the original suggestion of Chugainov (1966), this phenomenon is currently attributed to the presence of cool starspots which are carried into and out of view by stellar rotation. In the solar analogy the starspots are due to areas of intense magnetic fields which cover $\sim 10^{-1}$ of the surface area rather than only $10^{-4}$ as in the case of the Sun (Grinin 1979; Giampapa 1980).

The *Einstein* X-ray Observatory has given us the opportunity to make X-ray observations of dMe stars with unprecedented sensitivity. We now know that dM stars, including YZ CMi, form a class of quiescent soft X-ray emitters (Vaiana *et al.* 1980). The presence of X-ray emitting coronae on these stars further strengthens the case for a stellar analog of solar flares. In this paper we report the results of a program of ground-based optical and radio observations of YZ CMi coordinated with those of the *Einstein* Observatory. Variations in the quiescent optical and X-ray fluxes observed in this program were reported previously by Pettersen *et al.* (1980). The results of a similar program using the *Einstein* Observatory to monitor the X-ray fluxes from Proxima Centauri have been reported by Haisch *et al.* (1980, 1981).

## II. THE OBSERVATIONS

The observations were carried out as part of a coordinated program on 1979 October 25, 26, and 27, when YZ CMi was on the dawn side of the Earth. The observing period was optimized for radio and optical observers in the Western Hemisphere, which limited the times of the coordinated observations to the interval 0700–1200 UT on each day. The X-ray observations were obtained with the Imaging Proportional Counter (detector A) on the *Einstein* Observatory. The energy range of that detector is 0.2–4.0 keV (Giacconi *et al.* 1979), and its sensitivity is one to two orders of magnitude greater than those of the *SAS 3* and *ANS* soft X-ray detectors. The *Einstein* observations were made during each of two consecutive orbits on each day. The detailed observing times are shown in Figure 1, which also shows the times of the radio and optical observations.

In Table 1 we list the telescopes, passbands, sensitivities, and resolution times of the optical facilities involved in this program. The third column of Table 1 gives the minimum detectable flux per resolution time in units of $I_f$, where $I_f = L_{\rm flare}/q$, the ratio of the flare luminosity to the quiescent luminosity, both measured in ergs s$^{-1}$. The resolution time of the fourth column is the same as the flux integration time in each case except for the McDonald Observatory measurements, in which the integration times were 1.0 s for each band. At two facilities spectroscopic measurements were made with Reticon arrays.

In Table 2 we list the telescopes, frequencies, sensitivities, and integration times of the radio facilities. All are

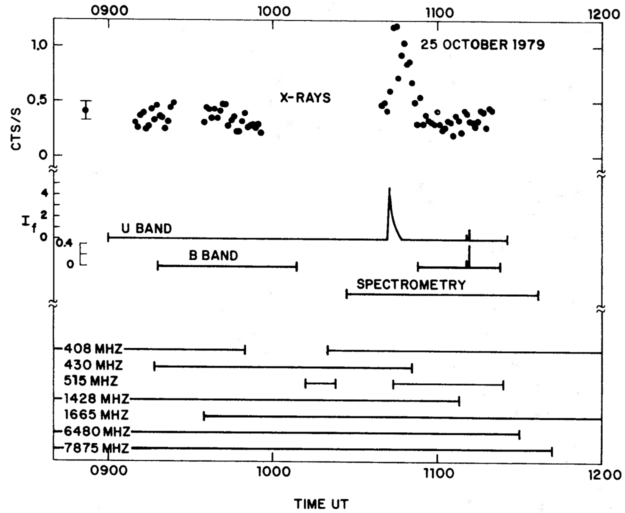


FIG. 1*a*

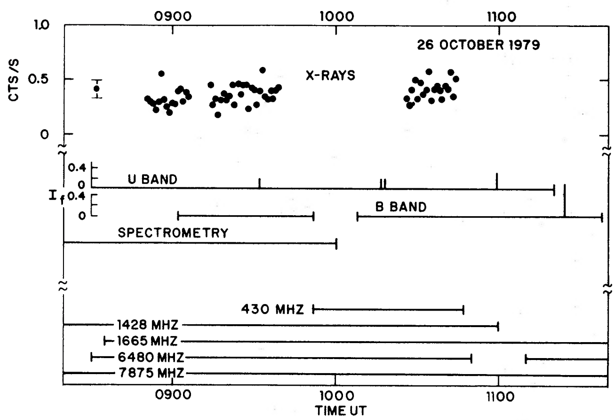


FIG. 1*b*

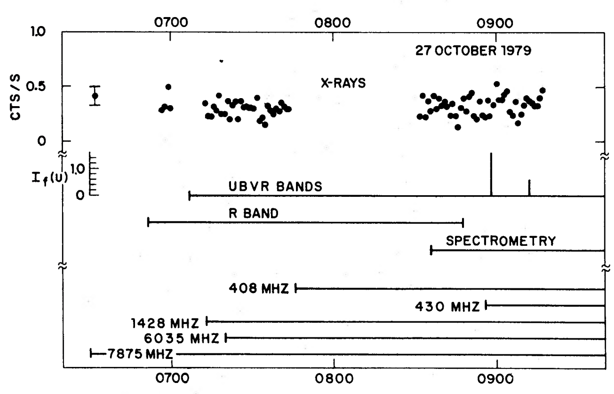


FIG. 1*c*

FIG. 1.—(*a*) Coordinated coverage of YZ CMi during the times of the Einstein observations on 1979 October 25. The X-ray counting rates from the Einstein Observatory are shown as 1 min averages. Spectrometric observations were made at McGraw-Hill Observatory. Much of the radio coverage extended beyond the times shown here. (*b*) Same as Fig. 1*a* for 1979 October 26, except that spectrometric observations were made at Steward Observatory. (*c*) Same as Fig. 1*b* for 1979 October 27.

TABLE 1

OPTICAL FACILITIES

| Observatory | Bandpass | Minimum Detectable $I_f$ $3\sigma$ per $\Delta t$ | Resolution Time (s) |
|---|---|---|---|
| Cerro Tololo (61 cm)... | *R* | 0.02 | 10 |
| Cloudcroft (1.2 m)...... | *U* | 0.3 | 0.1 |
| Kitt Peak (1.3 m)....... | *B* | 0.1 | 0.5 |
| Lick (91 cm)............ | *B* | 0.02 | 10 |
| McDonald (91 cm)..... | *U* | 0.33 | 9 |
| | *B, V* | 0.06 | 9 |
| | *R* | 0.03 | 9 |
| McGraw-Hill (1.3 m)... | 4200–5900 Å spectrometry; $\Delta\lambda = 4$ Å | 0.2 | 33 |
| Steward (2.3 m)......... | 3850–4850 Å spectrometry; $\Delta\lambda = 3.8$ Å | 0.03 | 180–240 |

single-receiver instruments except for the Jodrell Bank interferometer, which consists of two telescopes separated by 68 km (Davis *et al.* 1978).

As part of the observing program, optical monitoring of YZ CMi was carried out in the *B* band during the 11 day period preceding the coordinated observations to determine how the level of flaring activity during that period compared with the long-term average value. The ratio of the time-averaged *B*-band flaring luminosity, $[L_B]$, to the quiescent *B*-band luminosity, $q_B$, was determined by Gershberg (1972) as 0.012, by Cristaldi and Rodono (1975) as 0.010 and by Lacy, Moffett, and Evans (1976) as 0.007. Using the most recent and complete photoelectric data set collected by Shakhovskaya (1979) from different sources, the average observed ratio $[L_B]/q_B$ in 951 hours of flare patrolling in the *B* band was $0.012 \pm 0.002$. Actually, according to Catania data, the activity level of YZ CMi undergoes sizable seasonal variations spanning about three orders of magnitude in $[L_B]/q_B$.

In the 10.0 hours of observations with the 91 cm Cassegrain reflector at Catania on October 14, 15, 21, and 23, four flare events were detected with $[L_B]/q_B = 0.009$. In 4.1 hours of observations with the 64 cm reflector at the Crimean Astrophysical Observatory on October

TABLE 2

RADIO FACILITIES

| Observatory | Frequency (MHz) | Minimum Detectable Signal (Jy) | Integration Time (s) |
|---|---|---|---|
| Algonquin (46 m)......... | 6035, 6480 | 0.02 | 720 |
| Arecibo (300 m)........... | 430 | 0.1 | 0.1 |
| Hat Creek (26 m)......... | 1665 | 0.3 | 1.28 |
| Haystack (37 m).......... | 7875 | 0.07 | 5 |
| Jodrell Bank (76 m/25 m interferometer).......... | 408 | 0.06 | 30 |
| NRAO (42 m)............. | 1428 | 0.1 | 2 |
| NRAO (91 m)............. | 275, 315 | 15.0 | 2 |
| | 370 | 20.0 | 2 |
| | 440 | 12.0 | 2 |
| | 515 | 0.8 | 2 |

14–15 two flares were seen which resulted in a value of $[L_B]/q_B = 0.038$, well above the average value. Both sets of data were dominated by the same large flare on October 15 for which the equivalent duration (ED, measured in units of the quiescent star energy emission in 1 minute) was measured as 8.8 at Crimea and 4.8 at Catania. Using the two sets of photometric data together, comprising 758 minutes of total coverage, $[L_B]/q_B$ ranges from 0.008 to 0.013, assuming the Catanian or the Crimean estimate of the ED for the October 15 flare, respectively. Although the value is primarily the result of a single large flare, it indicates that flare activity on YZ CMi during the 11 days preceding the coordinated observations was fairly close to the range normally observed.

### III. THE FLARE EVENTS

Flare events on YZ CMi are most easily and accurately detected in the $U$ and $B$ bands as noted in § I. The peak and integral radiated energies of the flares detected in those bands during the coordinated program are listed in Table 3. In cases where measurements were made in only one band the flare luminosity of an unmeasured band can be estimated to within a factor of 3 by using the empirical relationship of Lacy, Moffett, and Evans (1976):

$$L_U = 1.20 L_B = 0.48 L_C, \qquad (1)$$

where $L_C$ is the white-light luminosity. This result, used here and by Karpen *et al.* (1977), was originally derived by Lacy *et al.* using total energies for entire flare events and is not strictly valid for relating the different luminosities at a particular time in a flare. It is, nevertheless, the best approximation to use in making the necessary conversions for comparisons of various results.

The three largest optical flares shown in Table 3 were those of 1042 UT October 25; 1124 UT October 26; and 0858 UT October 27. Although each optical flare was monitored at three or more radio frequencies, the October 25 event was the only radio flare event detected during the 3-day program. Similarly, it was the only significant X-ray event detected during the *Einstein* observations, although no X-ray observations were made during the 1124 UT event on October 26. Therefore we confine our attention to the two events of 1042 UT October 25 and 0858 UT October 27.

#### *a) The Event of 1042 UT October 25*

The detection of this event (hereafter event A) is the most important result of the coordinated observing program, because it was well observed and detected in the radio, optical and X-ray ranges. The flux profiles for the event are shown in Figure 2. $U$-band observations at Cloudcroft Observatory show that the optical event consisted of three maxima at 1042:53, 1043:15, and 1043:38 UT with $I_f = 4.77$, 3.52, and 3.12, respectively. Flare spectrometric flux profiles of the H$\beta$ and H$\gamma$ lines and the continuum at 4680 Å, shown in Figure 2, were derived by subtracting the quiescent fluxes averaged over the 25 scans prior to the flare. Although the time resolution of these measurements was much coarser than that of the $U$-band photometry, the 4680 Å flux appears to track the $U$-band fluxes well. On the other hand, the H$\beta$ and H$\gamma$ fluxes peaked somewhat later and declined more uniformly than the continuum fluxes. The time-integrated ratio of H$\beta$/H$\gamma$ is 2.3, but the high counting rates, especially for the H$\beta$ line, resulted in large dead-time corrections which could be in error by 20–30%. No systematic change in this ratio appeared during the course of the event.

The 30 s averages of the YZ CMi soft X-ray counting rates are also shown in Figure 2. These counts are due to both the quiescent coronal emission (Pettersen *et al.* 1980) and the flare, which lasted from 1043 to 1052 UT. The total X-ray emission due to the flare alone was $3.6 \times 10^{31}$ ergs, with the peak emission of $8 \times 10^{28}$ ergs s$^{-1}$ at 1045 UT. The X-ray emission at the peak of the optical event was $\leq 3 \times 10^{28}$ ergs s$^{-1}$.

Enhanced radio fluxes were observed during this event with the Jodrell Bank interferometer at 408 MHz. This was the only event seen during 40 hours of observation of YZ CMi at that time with the Jodrell Bank interferometer

TABLE 3

OPTICAL FLARE ENERGIES

| Date (1979) | Maximum Time (UT) | *U*-Band Peak (ergs s$^{-1}$) | *U*-Band Total (ergs) | *B*-Band Peak (ergs s$^{-1}$) | *B*-Band Total (ergs) |
|---|---|---|---|---|---|
| Oct. 25 ........ | 1042:53 | $1.9 \times 10^{29}$ (C) | $1.2 \times 10^{31}$ | ... | ... |
| | 1110:59 | $1.8 \times 10^{28}$ (C) | $4 \times 10^{28}$ | $1.7 \times 10^{28}$ (K) | $5 \times 10^{28}$ |
| | 1111:25 | $3.6 \times 10^{28}$ (C) | $1 \times 10^{29}$ | $4 \times 10^{28}$ (K) | $1.5 \times 10^{29}$ |
| Oct. 26 ........ | 0932:05 | $8 \times 10^{27}$ (C) | ... | ... | ... |
| | 1016:50[a] | $8 \times 10^{27}$ (C) | ... | ... | ... |
| | 1018:30[a] | $8 \times 10^{27}$ (C) | ... | ... | ... |
| | 1058:50[a] | $1.1 \times 10^{28}$ (C) | ... | ... | ... |
| | 1124:18[a] | ... | ... | $1.3 \times 10^{29}$ (K, L) | $1 \times 10^{31}$ |
| Oct. 27 ........ | 0858:33 | $6.4 \times 10^{28}$ (M) | $3 \times 10^{30}$ | $3.1 \times 10^{28}$ (M) | $2 \times 10^{30}$ |
| | 0912:30 | $2.4 \times 10^{28}$ (M) | $8 \times 10^{29}$ | $1.2 \times 10^{28}$ (M) | $6 \times 10^{29}$ |

NOTE.—C = Cloudcroft, K = Kitt Peak, L = Lick, M = McDonald.

[a] No simultaneous X-ray observations.

and is regarded as a definite flare. The graph of the amplitude of the signal, shown in Figure 2, consists of a three point running mean of 2 minute integrations. The amplitude record indicates that an event took place over the period 1112–1122 UT. In addition to the amplitude, the interferometer records the phase of the signal, which was fairly coherent over the longer time interval 1100–1120 UT, indicating that a weak signal was present. The event was not detected at the higher monitored frequencies of 1428, 1665, 6480, and 7875 MHz. It was also not detected at 430 MHz at Arecibo, but those observations ended at 1051 UT when the star moved out of tracking range, approximately 10 minutes before the 408 MHz event onset at ~ 1100 UT.

NRAO Green Bank measurements at 515 MHz were made with lower sensitivity but higher time resolution than those at Jodrell Bank. At 1054 UT a rapid burst was observed with a total duration of less than 30 s consisting of two resolvable spikes 2 s apart. If the burst, with an integral flux density of 18 Jy s, was of stellar origin, it was a rather narrow-band event because it was seen at neither 430 nor 1428 MHz. A second observed feature was a rapid rise in the flux level at 1113 UT by approximately 3 Jy. This event was not likely to have been of stellar origin since the enhanced flux was still observed 20 minutes after the telescope traveling feed reached its limit, at which point the star left the telescope field of view. Terrestrial interference cannot be ruled out as the source of either the spike or the long-lived 3 Jy feature in the 515 MHz data. It should be noted that the interferometer based at Jodrell Bank provides unambiguous detection of signals from the flare star, since the phase of the signal indicates the position of the radio emission to approximately 10″.

### *b*) *The Event of 0858 UT October 27*

The *U*-band fluxes and X-ray counting rates for this event (hereafter event B) and the later event at 0912 UT are shown in Figure 3. The X-ray data points are 3 minute averages of the total counting rate. The two points

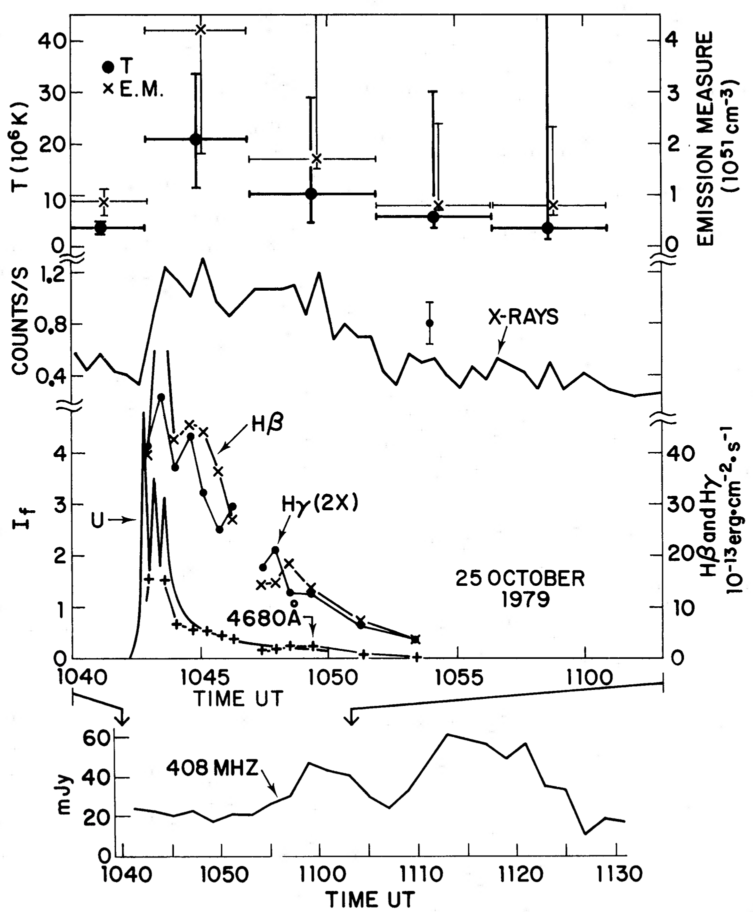


FIG. 2.—X-ray, optical, and radio fluxes during event A on October 25. X-ray temperatures and emission measures (with 90% confidence error bars) are shown along with 30 s averages of the *Einstein* X-ray counting rates. *U*-band photometric data are from Cloudcroft Observatory, and the Hβ, Hγ, and 4680 Å continuum data are spectrometric observations ($\Delta\lambda = 4$ Å) from McGraw-Hill Observatory. The *U*-band and 4680 Å data are presented in units of $I_f$. The Jodrell Bank 408 MHz flux data, shown on an expanded time scale, have been vector integrated into 2 min intervals and then smoothed with a three-point running mean. These data show that an event was present from 1112 to 1122 UT. In addition, the phase (not shown) was coherent over the radio flare interval.

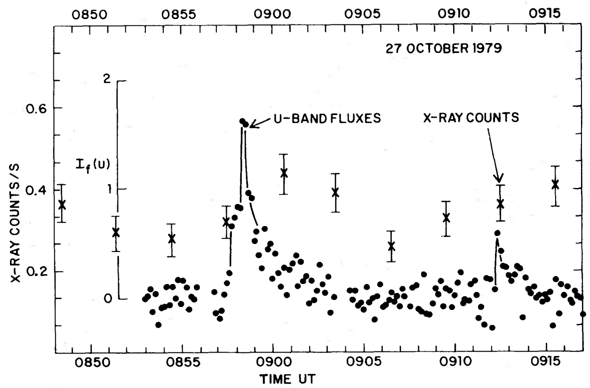


FIG. 3.—The *U*-band fluxes from McDonald Observatory and the *Einstein* X-ray counts in 3 min bins during event B, the marginal 2 $\sigma$ enhancement at 0858 UT. A second smaller *U*-band event at 0912 UT was not detected as an X-ray event.

following the 0858 UT optical event are enhanced above the pre-event level by only a 2 $\sigma$ increase, so the presence of an associated X-ray flare in this case is questionable. If we assume that the average of the X-ray counting rate over the 12 minutes preceding the flare represents the quiescent stellar emission, then the integral X-ray flare emission for this event is $4 \times 10^{30}$ ergs. No associated radio bursts were detected, and no significant increase was observed in the H$\gamma$ line fluxes monitored at Steward Observatory.

## IV. ANALYSIS AND DISCUSSION

As indicated in Table 3, the total *U*-band energy of event A was $1.2 \times 10^{31}$ ergs. From Figure 11 of Lacy, Moffett, and Evans (1976) and Figure 3 of Shakhovskaya (1979) we see that this event is comparatively large, occurring statistically only once in 6–10 hours. The detection of this event in different energy ranges makes it particularly appropriate to compare the event characteristics with those of solar flares, for which extensive observational data exist (Svestka 1976).

Mochnacki and Zirin (1980, hereafter MZ) observed two flares on YZ CMi and UV Ceti with multichannel spectrophotometry and found that the continuum region 4200–6900 Å could be well fitted with a Planck function. The McGraw-Hill spectroscopic data for event A cover a narrower wavelength range (4200–5900 Å), but the data are generally not well fitted by a Planck function, because the continuum distribution (in wavelength units) is peaked too narrowly around 4600 Å, especially during the decay phase after 1044 UT. However, the continuum spectrum obtained at 1043 UT, during the peak of the optical event, is fairly well fitted by a Planck function for $T = 8500$ K, which is approximately the peak temperature found by MZ for their YZ CMi optical flare data. We follow an analysis similar to that of MZ and let

$$f_\lambda = A\mu F_\lambda(T)/4\pi d^2 , \qquad (2)$$

where $f_\lambda$ is the apparent stellar flux at the Earth, $d$ the distance (6.06 pc) to the star, $A$ the effective area of blackbody radiation, $\mu$ the cosine of the angle between the line of sight and the normal to the flare area, and $F_\lambda(T)$ the Planck function. Then $A\mu = 1.0(\pm 0.3) \times 10^{19}$ cm$^2$, where the uncertainty corresponds to $\pm 500$ K in $T$. This area corresponds to a solar flare of importance 2. Assuming a value for the stellar radius, $R_*$, of $2.6 \times 10^{10}$ cm (Pettersen 1980), $A\mu$ is 0.5% of the projected stellar disk and is similar to the values derived by MZ.

The X-ray fluxes of event A have been fitted to model thermal spectra (Raymond 1979) with cosmic abundances to derive coronal temperatures and emission measures. (It appears reasonable to eliminate the interstellar hydrogen column density as a free parameter, in view of the proximity of the star, and we have fixed $N_H \leq 1 \times 10^{18}$ cm$^{-2}$.) Our procedure consists of convolving the model spectra with the instrument response, varying the free parameters of the model, and determining their best-fit values by minimizing the $\chi^2$ values of the predicted versus the observed pulse height data. Uncertainties in the free parameters are similarly obtained by examining the variation in $\chi^2$ around the minimum value. The method includes an allowance for gain uncertainty, which is known to be in the range of $\pm 5$%, at the 90% confidence level (i.e., in-flight calibration data have shown the gain in the region of the detector center to be approximately normally distributed about the measured mean value). Single-parameter, 90% confidence error bars have been plotted with the derived temperatures and emission measures shown at the top of Figure 2.

Because of the low counting rates, the fits were done over five time intervals and on the total X-ray counts from both the quiescent-coronal and flare plasmas. As a result, the temperatures and emission measures of the flare plasma alone are somewhat higher and lower, respectively, than the derived values shown in Figure 2. The best fits to the data prior to the flare onset at 1043 UT and after the flare end at 1056 UT yield temperatures of $\sim 3.5 \times 10^6$ K and emission measures of $\sim 7 \times 10^{50}$ cm$^{-3}$. During the three time intervals of the flare the temperatures showed a decreasing trend in time, similar to the solar case, as did the emission measures. The latter usually peak sometime during the decay phase in solar events. Because of the short rise time in this event we cannot exclude the possibility that the development of the emission measure also matched the typical solar case. The peak flare temperature of $\sim 20 \times 10^6$ K is similar to the solar case. The derived emission measures of 1–6 $\times 10^{51}$ cm$^{-3}$ are about an order of magnitude larger than those of the largest solar flares (Moore *et al.* 1980).

We can use the X-ray emission measure and temperature and the flare area deduced from the optical measurements to calculate the coronal energy and cooling rate. Let us assume that $\mu = 1$ and that the optical flare area, $A$, is the same as that of the coronal X-ray flare (the geometry of solar flares is generally more complex, however, with X-ray–emitting arches linking regions of chromospheric emission). If the height $H$ of the coronal emission ranges from $10^9$ to $10^{10}$ cm ($\sim 0.4R_*$), then the electron density

$$n_e \sim \left(\frac{2 \times 10^{51}}{HA}\right)^{1/2} = 1.4 \times 10^{11} \text{ to } 4.5 \times 10^{11} \text{ cm}^{-3} . \quad (3)$$

We can calculate the radiative energy loss time, $\tau$, from the equation

$$\tau = \frac{(\frac{3}{2})n_e kT}{n_e{}^2 P} , \quad (4)$$

where $k$ is the Boltzmann constant, and $P$ the total radiative cooling coefficient given by Raymond, Cox, and Smith (1976). For $H = 10^{10}$ cm and $n_e = 1.4 \times 10^{11}$ cm$^{-3}$, $\tau \sim 4.5 \times 10^2$ s, close to the 600 s duration of the X-ray event. The total radiated energy of the coronal plasma is then $\sim 4.5 \times 10^{31}$ ergs, within a factor of 2 of the total bolometric optical emission. If $H = 10^9$ cm and $n_e = 4.5 \times 10^{11}$ cm$^{-3}$, then $\tau \sim 1.4 \times 10^2$ s, shorter by a factor of 4 than the observed duration of the X-ray event. In this case continued energy release must have taken place. These calculations suggest that in either case radiation must be an important coronal energy loss mechanism.

The long tail on the $U$-band profile, which also appears in the 4680 Å continuum profile, lasts approximately as long as the soft X-ray event and is probably due to a physical mechanism different from that which produced the earlier spikes. If we interpret the soft X-ray event as emission from a thermal plasma contained in magnetic flux tubes, the $U$-band fluxes may be due to chromospheric emission at the footpoints of those tubes. The simultaneous, monotonic decline of the X-ray and optical emission is in qualitative agreement with a model of Mullan (1977) in which the optical emission in that phase is due to heating of the lower atmosphere by conduction and radiation from a hot ($T \sim 10^7$ K) overlying plasma. The $U$-band luminosity at that time is $L_U \sim 8 \times 10^{27}$ ergs s$^{-1}$, which, from equation (1), yields $L_C \sim 1.5 \times 10^{28}$ ergs s$^{-1}$. For a coronal flare emission measure of $2 \times 10^{51}$ cm$^{-3}$ the radiative loss rate is $P_r \sim 10^{29}$ ergs s$^{-1}$. In Mullan's model the white light luminosity is $L_C = \phi_c P_c + \phi_r P_r$, where $\phi_c$ and $\phi_r$ are the fractions of the coronal conductive loss $P_c$ and radiative loss $P_r$, respectively, which heat the cooler optical flare region. Since $L_C$ is a factor of only 7 less than $P_r$, and the calculated radiative decay time is close to the observed X-ray and $U$-band event durations, $\phi_c P_c$ is probably less than $\phi_r P_r$, with the optical and X-ray emitting regions closely coupled.

Predicting ratios of X-ray to optical fluxes has generally been considered the crucial test for models of stellar flares. Past predictions have usually considered a steady-state situation and, consequently, produced a single number as the predicted ratio. It is obvious from Figure 2 that the ratio $L_X/L_C$, where $L_X$ is the soft X-ray emission, varies throughout the event. At the peak of the impulsive $U$-band event at 1043 UT, when the soft X-ray flux is still rising, $L_X/L_C \sim 0.08$, but just after 1050 UT, when the optical emission has returned to the quiescent level, $L_X/L_C$ becomes infinitely large. The impulsive phase value is consistent with the prediction of Kahler and Shulman (1972) that $L_X/L_C \sim 0.14$ during that phase. The X-ray wavelength range of their prediction was 1–20 Å, but, as discussed below, this prediction also applies to the 3–60 Å nominal waveband of the *Einstein* IPC detector. During most of the decay of the optical event the calculated ratio of $L_X/L_C$ is 1–10, well above the upper limits of 0.02–0.07 calculated by Mullan (1976) for a model of the period during and after the peak thermal energy content of a YZ CMi flare. The value of $L_X/L_C$ averaged over the entire event $A$ is $\sim 1.5$.

Because $L_X/L_C$ is an important parameter for understanding the physics of flare stars, we must determine whether event A can be considered as typical in terms of this ratio. The only other X-ray event we can examine is event B. As mentioned earlier, the X-ray flux enhancement observed in that event is significant only at the 2 $\sigma$ level. Nevertheless, we can calculate the X-ray flux and the ratio $R = \int L_X dt / \int L_U dt$ for that event and find $R = 1.3 \pm 1.0$, where the error is due primarily to the uncertainty in determining the quiescent X-ray counting rate. For event A, $R = 3.0 \pm 0.2$, comparable to the value of 1.3 for the much weaker event B. This suggests that the variation in $R$ from event to event may be small. Assuming that most events can be characterized by the value $R = 2$, the estimated mean $U$-band flaring rate of YZ CMi, $[L_U] = 8.7 \times 10^{26}$ ergs s$^{-1}$ (Lacy, Moffett, and Evans 1976), yields the mean X-ray flaring rate, $[L_X] \sim 1.7 \times 10^{27}$ ergs s$^{-1}$. With the quiescent X-ray emission value of $q_X = 3 \times 10^{28}$ ergs s$^{-1}$ (Pettersen *et al.* 1980) we find that $[L_X]/q_X = 0.06$, compared to $[L_U]/q_U = 0.022$. The same calculation using the more recent optical data of Shakhovskaya (1979) yields $[L_X]/q_X = 0.13$, compared to $[L_U]/q_U = 0.06$. Thus, an assumption that $R$ varies little from event to event leads us to conclude that the fraction of the X-ray emission produced by flaring on YZ CMi is at least as large as that in the $U$ band. It should be noted, however, that the low quiescent X-ray counting rates of YZ CMi observed in the *Einstein* IPC detector ($\sim 0.4$ counts s$^{-1}$) preclude positive detection of the implied low X-ray fluxes accompanying small or moderate $U$-band flares.

The lack of $UBV$ photometry on solar flares makes it difficult to predict the ratio of optical to soft X-ray flux for a solar-type flare on YZ CMi. A relevant ratio that has been measured for solar flares is $L(\mathrm{H}\alpha)/L(8\text{–}12\ \text{Å})$. Thomas and Teske (1971) concluded that this ratio is $\sim 1.6$ when each flux is measured at the time of its maximum. Assuming $T = 12 \times 10^6$ K and using the results of Raymond, Cox, and Smith (1976) for the X-ray wavebands, we calculate that $L(\mathrm{H}\alpha)/L_X \sim 0.5$ for the *Einstein* X-ray fluxes. There are no H$\alpha$ measurements for event A, but according to MZ the McGraw-Hill measurements of the H$\beta$ and H$\gamma$ line fluxes approximately equal the flux of the H$\alpha$ line. For this event $L(\mathrm{H}\beta)/L(0.2\text{–}4 \text{ keV}) \approx 0.25$ and $L(\mathrm{H}\gamma)/L(0.2\text{–}4 \text{ keV}) \approx 0.12$. The present results are somewhat difficult to compare with their solar counterparts due to the uncertainties in matching the H$\alpha$ and 8–12 Å fluxes with the H$\beta$ and H$\gamma$ and *Einstein* fluxes, respectively, but the stellar and solar results do not appear to be in serious disagreement.

The three $U$-band spikes which occurred during the rise phase of event A had full widths on the order of 15–20 s, were separated from each other by about 23 s, and showed no evidence of the short time scale fluctuations described by Moffett (1972). Their time scales and appearance during the soft X-ray rise phase are similar to the impulsive phases of solar flares, which are characterized by hard ($E > 10$ keV) X-ray and microwave emission during the rise phase of the soft X-ray event. The solar hard X-rays are interpreted as bremsstrahlung from electrons with energies of tens of keV. The time correlation of solar flare EUV and white-light emission with the hard X-ray flux profiles has been interpreted as "evaporation" of chromospheric material heated by the electrons precipitating from the corona (Kane *et al.* 1980).

We now ask whether the presence of an optical impulsive phase and the lack of an observed impulsive phase in both microwaves (408 to 7875 MHz) and the 1.5–20 keV energy range of the Monitor Proportional Counter (MPC) of the *Einstein* Observatory (Giacconi *et al.* 1979) are compatible with the solar analogy. Following the arguments based on the solar analogy advanced by Kahler and Shulman (1972), we calculate the ratio of the hard X-ray ($E > 10$ keV) luminosity, $L_{\rm HX}$, to that of the white-light luminosity, $L_C$, to be $\sim 10^{-5}$. Kane (1973) has reviewed solar measurements showing that in the impulsive phase $L(\geq 20\,{\rm keV})/L_{\rm (microwaves)} \sim 10^2$, where $\Delta f \sim 10^4$ MHz is taken as the effective bandwidth of the microwave emission. Many impulsive hard X-ray bursts are well fitted by a power-law spectrum of the form

$$\frac{dF}{dE} = KE^{-\gamma} \text{ photons cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1}, \qquad (5)$$

where $\gamma \sim 4$, $E$ is the photon energy, and $K$ is a constant (Kane 1973); thus, using equation (5) to extrapolate down to 10 keV, $L_{\rm HX}/L_{\rm (microwave)} \sim 10^3$. The above value for $L_{\rm HX}/L_C$ yields $L_{\rm (microwave)} = 10^{-8} L_C$, for $L_C$ in units of ergs s$^{-1}$ and $L_{\rm (microwave)}$ in Jy cm$^2$. Again taking $L_C = 2.1 L_U$ (eq. [1]), we calculate for the peak of event A that $F_{\rm (microwave)} \approx 10^{-2}$ mJy, a value orders of magnitude below the sensitivities of the radio telescopes which failed to detect the event.

A flux can also be calculated for the MPC low-energy end of the impulsive hard X-ray spectrum by extending the $\gamma = 4$ power-law spectrum down to 2 keV and using the relation, given above, that $L_{\rm HX}/L_C \sim 10^{-5}$. The resulting flux of $10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ yields only about $10^{-2}$ counts s$^{-1}$ in the MPC, again a value too small to be detected. We see that the appearance of the impulsive event in the $U$ band but in neither the microwave nor the hard X-ray ranges is quite consistent with the results of scaling from the solar case.

The 408 MHz emission reported for event A was observed to commence about 17 minutes after the 1043 UT impulsive phase. The event was weak from 1100 to 1113 UT but then rose rapidly at about 1113 UT (see Fig. 2) to reach a peak flux of 60 mJy. A similar 408 MHz event with a shorter delay from the impulsive phase was reported for a flare on UV Ceti (Lovell, Mauridis, and Contadakis 1974). The radio brightness temperature is found to be $\sim 2 \times 10^{12}$ K for the peak flux of 60 mJy and an effective area of emission equal to that of the stellar disk. Temperatures this high must be due to nonthermal processes. The high brightness temperature and the delay in the onset of the 408-MHz emission are suggestive of either the solar type II drift bursts, due to characteristic emission from plasma oscillations, or the solar type IV continuum bursts attributed to gyrosynchrotron emission from quasi-relativistic electrons (Svestka 1976).

While the 10 minute duration of the most intense part of the 408 MHz burst is similar to those of solar type II bursts, other features of the observed burst render the type II analogy doubtful. The main problem is the very long time delay between the impulsive phase at 1043 UT and the onset of 408 MHz emission 17 minutes later. For solar flares this delay averages only 2 minutes (see Fig. 78 of Svestka 1976). This shorter duration is comparable to the time required for a shock disturbance generated during the impulsive phase to travel with a speed of $\sim 10^8$ cm s$^{-1}$ to a height of $\sim 10^{10}$ cm, where the electron density of $\sim 10^8$ cm$^{-3}$ corresponds to a plasma frequency of 100 MHz. A longer delay time would be appropriate for YZ CMi if its pressure scale height were substantially greater than in the solar case. However, the YZ CMi surface gravitational force is about 2.5 times greater than its solar counterpart, so that the deduced quiescent coronal temperature of $T \sim 4 \times 10^6$ K yields a scale height for YZ CMi which is less than the solar value (Pettersen *et al.* 1980). Thus, the atmospheric pressure profile on YZ CMi is not likely to differ substantially from that of the Sun and therefore cannot provide the explanation for the long onset delay of the 408 MHz event within the context of the type II burst analogy. The fact that very few type II bursts are seen with fundamental frequencies starting above 200 MHz and correspondingly few second harmonics above 400 MHz (Svestka 1976) only compounds the problem. It is possible that the 408 MHz event was not a part of the 1043 UT flare, but the fact that this was the only 408 MHz event seen in two nights (8 hours) of observing and that it was so close in time to the largest optical event seen during the three nights of observation makes a chance coincidence unlikely.

A more likely solar-based explanation for the 408 MHz burst is that it was gyrosynchrotron emission from energetic electrons, as postulated for solar type IV bursts. The observed duration, brightness temperature, time delay from the impulsive phase, and frequency of the burst are all consistent with solar type IV bursts. An examination of typical type IV burst spectra (Fig. 74 of Svestka 1976) shows, however, that they are usually complex, with energy spectra which characteristically increase with increasing frequency between 1000 MHz and 10,000 MHz. The lack of any radio event detected in this frequency range for the 1043 UT flare, particularly at 6480 MHz for which the Algonquin observations place an upper limit of $\sim 20$ mJy, rules out any comparably increasing spectrum. However, the shape of the typical solar burst is determined by the characteristic magnetic field strength, electron energy spectrum, and ambient particle density (Svestka 1976). Because we have no information about any of these flare quantities for YZ CMi, we cannot *a priori* expect the detailed shape of the YZ CMi microwave spectrum to match those characterizing solar bursts. Although the data rule out a microwave spectrum matching those of solar type IV bursts, the other 408 MHz burst characteristics are in good agreement with the solar case.

The X-ray and optical results presented above can be compared with previous efforts to detect flare X-ray emission from YZ CMi and other stars. Karpen *et al.* (1977) observed YZ CMi with the *SAS 3* Observatory and detected no significant X-ray emission from an optical flare with a peak $I_f(U) = 7.15$, 1.5 times brighter than event A. While the X-ray flux at the peak of the latter event was 0.012 photons $s^{-1}$ $cm^{-2}$, Karpen *et al.* derived an upper limit of 0.04 photons $s^{-1}$ $cm^{-2}$ for their event, a factor of 3 greater than the peak flux we observed. The passbands of the *Einstein* IPC and the *SAS 3* detector differ, but the effects of this difference are minor if the emission is attributed to thermal bremsstrahlung with $T = 12 \times 10^6$ K; in this case the bulk of the emission is in the 8–14 Å band with about one-third that much in each of the 1–8 Å and 14–23 Å bands (Raymond, Cox, and Smith 1976). The value of $L_X/L_C = 0.08$ derived for the optical peak of event A is consistent with the Karpen *et al.* upper limit of 0.1, but our integral value of $L_X/L_C = 1.5$ exceeds the Karpen *et al.* upper limit by an order of magnitude. Heise *et al.* (1975) observed an X-ray event on YZ CMi which was about a factor of 5 larger in integral flux than event A. However, it was also 45 times larger at peak flux due to its shorter duration of only 1.5 minutes in the 2–12 A band. The ratio of fluxes observed in their 44–60 Å and 2–12 Å passbands is in reasonable agreement with emission from a plasma at $T = 10^7$ K. No optical observations were obtained of the event observed by Heise *et al.*

Heise *et al.* (1975) also observed an X-ray flare on UV Ceti of duration 48 s. They reported $L_X/L_V \leq 3 \times 10^{-2}$ for the 44–60 Å passband. Assuming $T = 12 \times 10^6$ K and converting to the *Einstein* passband and the bolometric waveband, we get $L_X/L_C \leq 0.08$, similar to our value for the optical peak but about an order of magnitude lower than the integral value for event A on YZ CMi. This number is also close to the upper limit of $L_X/L_C <$ 0.08 derived by Haisch *et al.* (1978) from the *SAS 3* observations of a bright optical flare on Proxima Centauri.

The most recent result of interest is the X-ray flare event observed on Proxima Centauri by Haisch *et al.* (1981) during a coordinated observing program using the *Einstein* Observatory. That event had a peak $L_X \sim 7 \times 10^{27}$ ergs $s^{-1}$, approximately an order of magnitude smaller than event A, and was not accompanied by any detected corresponding radio, optical, or UV flare emission. Assuming that the chromospheric footpoints of the flare lay on the visible disk, Haisch *et al.* (1978) derived $L_X/L_C \geq 1$ at the soft X-ray peak, comparable to our values of 1–10 after the impulsive optical peak of event A. They used $n_e = 10^{11}$ $cm^{-3}$ and an arch length $l = \pi \times 10^{10}$ cm, values characteristic of a large solar flare, to deduce that coronal radiative cooling dominated conductive cooling. Their deduced radiative cooling time agreed well with the observed decay time of $\sim 1200$ s. For event A we also found that radiative cooling times were less than or comparable to the event duration. In summary, the *Einstein* observations of X-ray flares on YZ CMi and Proxima Centauri suggest that, except during the impulsive phase, $L_X \geq L_C$, and radiative cooling dominates in the corona.

## V. CONCLUSIONS

The coordinated program to monitor YZ CMi for three consecutive nights in X-ray, optical, and radio wavelengths resulted in comprehensive observations of an event (A) detected in all three wavelength regions on 1979 October 25. A second, smaller optical event (B), observed on 1979 October 27, was associated with 2 $\sigma$ soft X-ray enhancement seen from the *Einstein* Observatory. The ratios of the total soft X-ray emission to the total $U$-band emission for events A and B are approximately $R = 2$. Comparison of the flare fluxes with the quiescent fluxes suggests that a somewhat larger fraction ($\sim 10\%$) of the total stellar X-ray emission is in the form of flares than is the case for the $U$-band ($\sim 5\%$).

A basic similarity between the physical characteristics of flares on dMe stars and those of solar flares has long been suspected. The observations of event A lend strong support to this hypothesis. Strong evidence for the solar analogy comes from the appearance of two phases: an impulsive phase seen in the $U$-band emission, and a gradual phase observed in both the $U$-band and soft X-ray flux profiles. Furthermore, the impulsive event was not detected by the microwave and hard X-ray instruments, in agreement with the negligible fluxes predicted by scaling from the solar case. The more gradual and, presumably, thermal phase is interpreted in terms of a large solar optical (class 2) and X-ray ($n_e^2 V = 2 \times 10^{51}$ $cm^{-3}$) event. Assuming an area equal to that inferred for the optical event and a height less than half the stellar radius yields a coronal electron density in the range $1.4 \times 10^{11} \leq n_e \leq 5 \times 10^{11}$ $cm^{-3}$. At these densities radiation is an important loss mechanism for the coronal plasma. The inferred ratio of the H$\alpha$ emission to the soft X-ray emission for event A is in general agreement with the solar case.

The onset of a 408 MHz event 17 minutes after the impulsive phase and the high brightness temperature ($10^{12}$ K) of the burst are very similar to the characteristics of solar type IV radio bursts. These bursts are evidence of the acceleration of energetic electrons in solar flares, thus implying the presence of energetic electrons in stellar flares as well.

S. Kahler was supported by NASA contract NAS8-33339 as an *Einstein* Guest Investigator. B. R.

Pettersen was supported by the Norwegian Research Council for Science and the Humanities. D. Rautenkranz assisted in the reduction of the Steward Observatory Reticon data. Arecibo Observatory is operated by Cornell University under contract with the National Science Foundation. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract to the National Science Foundation. The Catania group acknowledges financial support from Consiglio Nazionale delle Ricerche of Italy (contract N. 79.00722.02) through "Gruppo Nazionale di Astronomia."

REFERENCES

Bopp, B. W., and Espenak, F. 1977, *A.J.*, **82**, 916.
Chugainov, P. F. 1966, *Inf. Bull. Var. Stars*, No. 122.
Crannell, C. J., McClintock, J. E., and Moffett, T. J. 1974, *Nature*, **252**, 659.
Cristaldi, S., and Rodono, M. 1975, in *IAU Symposium 67*, *Variable Stars and Stellar Evolution*, ed. V. Sherwood and L. Plaut (Dordrecht: Reidel), 75.
Davis, R. J., Lovell, B., Palmer, H. P., and Spencer, R. E. 1978, *Nature*, **273**, 644.
Gershberg, R. E. 1972, *Ap. Space Sci.*, **19**, 75.
Giacconi, R., *et al.* 1979, *Ap. J.*, **230**, 540.
Giampapa, M. S. 1980, SAO Spec. Rept. 389, p. 119.
Grinin, V. P. 1979, *Izv. Krymsk. Ap. Obs.*, **59**, 154.
Haisch, B. M., Linsky, J. L., Harnden, F. R., Jr., Rosner, R., Seward, F. D., and Vaiana, G. S. 1980, *Ap. J.* (*Letters*), **242**, L99.
Haisch, B. M., Linsky, J. L., Slee, O. B., Hearn, D. R., Walker, A. R., Rydgren, A. E., and Nicolson, G. D. 1978, *Ap. J.* (*Letters*), **225**, L35.
Haisch, B. M., *et al.* 1981, *Ap. J.*, **245**, 1009.
Heise, J., Brinkman, A. C., Schrijver, J., Mewe, R., Gronenschild, E., den Boggende, A., and Grindlay, J. 1975, *Ap. J.* (*Letters*), **202**, L73.
Kahler, S., and Shulman, S. 1972, *Nature Phys. Sci.*, **237**, 101.
Kahn, S. M., Linsky, J. L., Mason, K. O., Haisch, B. M., Bowyer, C. S., White, N. E., and Pravdo, S. H. 1979, *Ap. J.* (*Letters*), **234**, L107.
Kane, S. R. 1973, in *High Energy Phenomena on the Sun*, ed. R. Ramaty and R. G. Stone (NASA SP-342), p. 55.
Kane, S. R., *et al.* 1980, in *Solar Flares*, ed. P. Sturrock (Boulder: Colorado Associated University Press), p. 341.
Karpen, J. T., *et al.* 1977, *Ap. J.*, **216**, 479.
Kunkel, W. E. 1975, in *IAU Symposium 67*, *Variable Stars and Stellar Evolution*, ed. V. Sherwood and L. Plaut (Dordrecht: Reidel), p. 15.
Lacy, C. H., Moffett, T. J., and Evans, D. S. 1976, *Ap. J. Suppl.*, **30**, 85.
Lovell, B., Mauridis, L. N., and Contadakis, M. E. 1974, *Nature*, **250**, 124.
Mochnacki, S. W., and Zirin, H. 1980, *Ap. J.* (*Letters*), **239**, L27 (MZ).
Moffett, T. J. 1972, *Nature Phys. Sci.*, **240**, 41.
Moore, R., *et al.* 1980, in *Solar Flares*, ed. P. Sturrock (Boulder: Colorado Associated University Press), p. 341.
Mullan, D. J. 1976, *Ap. J.*, **207**, 289.
———. 1977, *Ap. J.*, **212**, 171.
Pettersen, B. R. 1980, *Astr. Ap.*, **82**, 53.
Pettersen, B. R., Kahler, S., Golub, L., and Vaiana, G. S. 1980, SAO Spec. Rept. 389, p. 113.
Raymond, J. C. 1979, private communication.
Raymond, J. C., Cox, D. P., and Smith, B. W. 1976, *Ap. J.*, **204**, 290.
Shakhovskaya, N. I. 1979, *Izv. Krymsk. Ap. Obs.*, **60**, 14.
Svestka, Z. 1976, *Solar Flares* (Dordrecht: Reidel).
Thomas, R. J., and Teske, R. G. 1971, *Solar Phys.*, **16**, 431.
Vaiana, G. S., *et al.* 1980, *Ap. J.*, **245**, 163.

P. F. CHUGAINOV: Crimean Astrophysical Observatory, Nauchny, Crimea, 334413 USSR

G. D. COLEMAN: Department of Astronomy, University of Michigan, Ann Arbor, MI 48109

C. J. CRANNELL and R. W. HOBBS: Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771

M. M. DAVIS: Arecibo Observatory, P.O. Box 995, Arecibo, PR 00612

R. J. DAVIS, B. LOVELL, R. E. SPENCER, and D. R. WHITEHOUSE: Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire, SK11 9DL England

P. A. FELDMAN: Herzberg Institute of Astrophysics, 100 Sussex Drive, Ottawa, Ontario K1A 0R6, Canada

M. S. GIAMPAPA, L. GOLUB, F. R. HARNDEN, JR., S. M. KAHN, W. LILLER, F. SEWARD, and G. VAIANA: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

E. K. HEGE: Steward Observatory, University of Arizona, Tucson, AZ 85721

S. KAHLER: American Science and Engineering, Inc., 37 Broadway, Arlington, MA 02174

J. T. KARPEN: Code 4169K, Naval Research Laboratory, Washington, DC 20375

B. LESLIE: Haystack Observatory, Westford, MA 01886

K. O. MASON: Space Sciences Laboratory, University of California, Berkeley, CA 94720

V. PAZZANI, M. RODONO, and G. ROMEO: Osservatorio Astrofisico, 1-95125 Catania, Italy

B. R. PETTERSEN: Institute of Physical Sciences, University of Tromso, P.O. Box 953, N-9001 Tromso, Norway

T. J. SCHNEEBERGER: 10508 Towner NE, Albuquerque, NM 87112

R. A. SCHOMMER: Yerkes Observatory, Williams Bay, WI 53191

M. R. VINER: Department of Physics, Queen's University, Sterling Hall, Kingston, Ontario K7L 3N6, Canada

S. S. VOGT: Lick Observatory, University of California, Santa Cruz, CA 95064

S. P. WORDEN: Department of Astronomy, University of California, Los Angeles, CA 90024