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A STUDY OF FLARE STARS

Leonard H. Solomon

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A STUDY OF FLARE STARS

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Leonard H. Solomon[2]

1. INTRODUCTION

1.1 General

Flare stars comprise a relatively new class of variable stars, whose properties are such that it is now of great interest to obtain all possible observational data pertaining to them. By definition of the IAU Tenth General Assembly (1958), a flare star is

> ... characterized by rare and very short flares with amplitudes from one to six magnitudes. Maximum brightness (usually sharp) is attained in a few, or several tens of seconds after the commencement of the flare, total duration of the flare being equal to about ten or several tens of minutes. A typical representative is UV Ceti. . . .

Although this definition roughly covers the situation, more recent observations, especially including the joint radio-optical observations to be described in this paper, add much to our knowledge of the properties of flare stars.

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[1] This work was supported in part by grant number NsG 87-60 of the National Aeronautics and Space Administration.

[2] Astronomer, Smithsonian Astrophysical Observatory.

1.2 Historical

Short-lived stellar brightenings were reported several times prior to 1948, by van Maanen (1940), Wachmann (1939), and possibly one by Hertzsprung (1924). Luyten (1949a, b) reported a flare of more than 2.5 mag on the star L726-8 (UV Ceti) on 7 December 1948, and calculated the approximate excess energy production during the outburst. Furthermore, he noted the similarity of this outburst to the events on other dMe stars BD +44°2051B and Ross 882, as reported by van Maanen. Confirmation of the flare observation was provided by another flare of UV Ceti observed by Luyten (1949c). These observations prompted a search for previous flares of L726-8 on patrol plates in the Harvard collection; Shapley (1949) reported brightenings dating back to 1900. Other lists have appeared periodically; a complete tabulation would probably contain over 100 known flares of UV Ceti to the present day.

Flares of other dMe stars were rather quickly reported (Shapley, 1951; Gordon and Kron, 1949), as a result of both new observations and reexamination of old plates. By 1952, eight flare stars were listed by Lippincott (1953). Newer observations have increased the number of known flare stars, and from various lists (Petit, 1961a, b; Joy, 1961) a more or less complete working register of 24 known or probable flare stars has been compiled and is shown in Table 1. Petit (1961b) also gives a list of candidates for the class, picked largely from stars included in Bidelman's (1954) catalog of emission-line stars. Inclusion of stars in Petit's list is generally based on similarity of the star's physical properties to those of known flare stars. We note in passing that there exists the possibility of an observational selection effect, because of investigation of emission-line stars for the flare characteristic. On the other hand, there may be a sound physical reason for expecting flares to be associated with emission-line stars; we shall discuss this later.

Table 1. Working list of flare stars

Name	1950_{α}	1950_{δ}	Spectral type	V	B-V	π	M_v	m	Ref.	Notes
+43° 44B	$00^h15^m34^s$	+43° 44!7	M4e	11.04	1.80	0!'278	13.26	spectrum	1, 2	
Wolf 47	01 00 08	+62 05.8	M3e	13.66	0.91	0.108	13.83	1	3, 1	
UV Ceti	01 36 25	-18 12.7	M6e	12.95	1.76	0.370	15.79	6	3, 1	L726-8B
V371 Ori	05 28.5 (1900)	+01 52	M3e	11.7		0.066	10.8	1.8	1	Wachmann's star
+1° 1522	06 43.2 (1900)	+01 13	K2e	9.5				0.7	4	Possibly "flash" star
YZ CMi	07 42 04	+03 40.8	M4.5e	11.35	2.05	0.182	12.66	1.4	3, 1	Ross 882
AD Leo	10 16 54	+20 07.3	M4e	9.43	1.54	0.227	11.05	1.3	1, 2	+20° 2465
Wolf 359	10 54 05	+07 19.0	M6e	13.66	1.75	0.427	16.82	1.5	3, 1	
DH Car	11 10.6 (1900)	-61 13		12.2				1.8	1	
WX UMa	11 03 02	+43 46.7	M5.5e	14.8	1.2	0.173	16.0	1.8	3, 1	+44° 2051B
α Cen C	14 26 19	-62 28.1	M5e	10.68	2.72	0.762	15.09	1.1	3, 1	V645 Cen
+55° 1823	16 14.2 (1900)	+55 32	M1.5e	10.1		0.05	8.4	0.5	1	
-8° 4352B	16 52 48	-08 14.7	M3e	9.71	1.57	0.152	10.62	1	3	GC 22805A
Ross 867	17 17 54	+26 32.8	M5e	13.4	1.3	0.096	13.3	1	3	close double with 11.2 star
HD 234677	18 32.8	+51 41	K6e	8.3			8.0	spectrum	4, 1	+51° 2402
V1216 Sgr	18 46 45	-23 53.5	M4.5e	10.62	1.8	0.351	13.34	0.4	3, 1	Ross 154
+4° 4048B	19 14 32	+05 04.7	Me	17.78	2.33	0.174	18.99	spectrum	4, 1	
Wolf 1130	20 02.7 (1900)	+54 10	M3e	12.2			11.0	spectrum	4, 1	
-32° 16135B	20 38 44	-32 36.6	M4.5e	10.9	1.3	0.118	11.3	spectrum	3, 1	
Furj. 54	20 58 09	+39 52.7	M2e	10.26	1.25	0.072	9.55	spectrum	1	
DO Cep	22 26 13	+57 26.8	M4.5e	11.41	1.44	0.249	13.40	1.5	3, 1	Kru 60B
-21° 6267B	22 36 01	-20 52.8	M4.5e	11.0	1.7	0.219	12.7	1.7	3	
EV Lac	22 44 40	+44 04.6	M4.5e	10.05	1.45	0.198	11.53	2	3, 1	+43° 4305
EQ Peg	23 29 20	+19 39.7	M5.5e	12.58	1.19	0.144	13.31	0.4	3, 1	+19° 5116B

[1] Joy, 1961 [3] Petit, 1961
[2] Johnson, 1965 [4] Petit, 1958

Suggestions were made by Whipple (1949) and Struve (1959), among others, to the effect that stellar flares might produce sufficient radio energy to be detectable. The first attempts at making such observations did not demonstrate the existence of radio flares correlated with optical events. However, results were encouraging enough to justify further attempts with better optical coverage such as that provided by the Baker-Nunn photographic telescopes. The results of one such program provide the basic material for this paper.

Before proceeding further, we should summarize the older information concerning flare stars, derived from optical observations and theoretical work available prior to 1961.

1.3 General Properties of Flare Stars at Normal Light

1.3.1 Spectrum

Of the known or probable flare stars, all are dwarfs of spectral class dK2e or later. All but two are later in spectrum than dM0e, and all but five are later than dM3e. Emission lines common to the group are H and Ca II lines: sometimes weak He I lines are seen.

1.3.2 Duplicity

Of the 24 stars listed in Table 1, 17 are known binaries. Four of these are as yet unresolved. Of the remaining 13, the fainter star is, in all cases, the flare star. Five of these pairs are sufficiently separated that no interaction between components is expected (Joy, 1961).

1.3.3 Mass

For those flare stars of known mass, none is above 0.37 $M_{\odot}$. All data are from Petit (1958, 1961).

1.3.4 Parallax

All known parallaxes are quite high, the smallest being 0".066 (V371 Orionis). The largest, of course, is Proxima Centauri.

1.3.5 Motion

Proper motions are generally high, as expected for such nearby stars, but radial velocities are low, generally on the order of 20 km/sec (Petit, 1961). Hence, the flare stars are probably all of Population I. Haro (1957) has noted that they all seem to be moving in the galactic plane.

1.3.6 Luminosity

Since most flare stars have known trigonometric parallaxes, good absolute magnitudes are available. The brightest is $M_v = 8.0$; others are some of the faintest stars known, e.g., +4° 4048B, $M_v = +19.0$.

1.3.7 Location on the Hertzsprung-Russell diagram

Plotted on a color-magnitude array (Figure 1) derived from Praesepe values (Johnson, 1952), and recently measured field stars (Johnson, 1965), the flare stars (crosses) appear to fall at various places with respect to the main sequence defined by the "normal" stars. Greenstein (1964) has stated that new color determinations put at least some of them definitely above the main sequence.

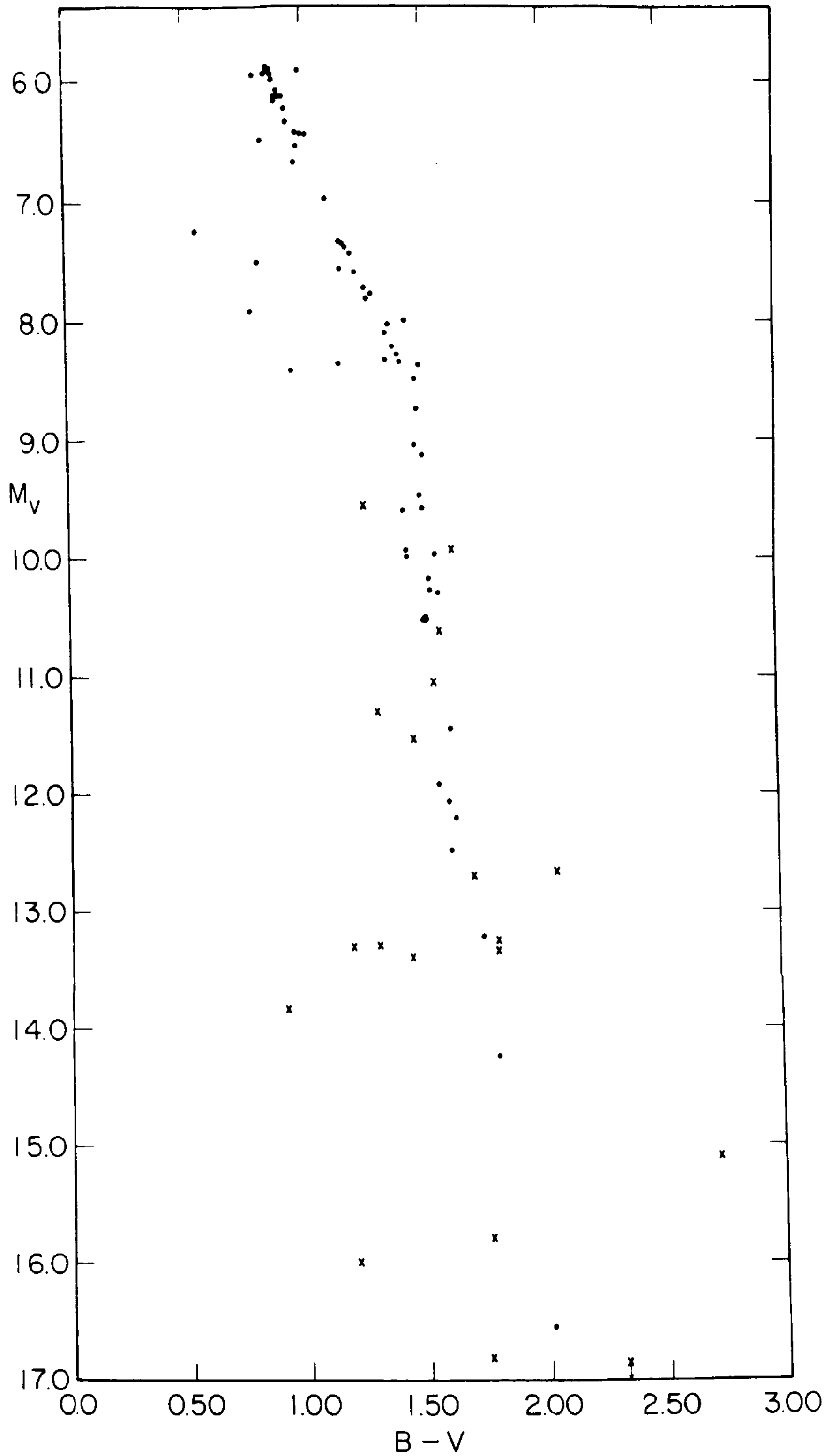

Figure 1. Lower main sequence. Crosses denote flare stars, dots are Praesepe and well-determined field stars.

On the usual M_v versus spectral-type diagram of the nearby stars, the flare stars generally fall at or below the main sequence, but when the data are examined closely, the main sequence is seen to be largely defined by the flare stars themselves.

1.4 Properties of the Light Variations

1.4.1 Optical flares

In perusing the more recent observations we find that the form of light variation used by the IAU (1958) to define the flare stars is only roughly correct. Most events known at the time the classification was catalogued were of visual or photographic origin, in which the small flares were unnoticed or regarded as questionable. However, many well-observed small flares have been recorded in the literature since about 1951, primarily from photoelectric observations (Petit, 1965; Engelkemeir, 1959; Roques, 1954; Lovell *et al.*, 1963; Liller, 1952). In any case, the lower limit of amplitude should be deleted from the definition.

1.4.2 Secondary variations

In addition to flares, the UV Ceti stars appear to exhibit aperiodic secondary variations. Amplitudes are several tenths of a magnitude, with time scales much longer than those of flares (Petit, 1961), as indicated in Table 2.

The secondary variations were first reported by Petit (1955) and confirmed by Oskanjan (1954). Possible indications of such variations have been seen in the present work, but cannot be confirmed because of the scatter inherent in the data.

Table 2. Flare-star time scales

Variation	Rate of rise
Flares	0.02 to 0.25 mag/sec
Secondary	0.002 to 0.005 mag/sec

1.4.3 Periodicity

There is no evidence for periodicity of the flares themselves. However, the rates of occurrence (number of flares/hour of observing time) have been given in 1961 as about one in 30 hours for UV Ceti, and roughly of the same order for other well-observed flare stars.

The rate of flare occurrence may fluctuate in an analogue of the solar cycle (Petit, 1961; Struve, 1959). Oskanjan (1957) reported few flares of UV Ceti in 1949-50, 1953-54, and 1954-55 observing seasons, but many during the 1950-53 period. The range given was from one in 11 hours to one in 25 hours (Petit, 1961).

The Smithsonian-Jodrell Bank program described here found an increase in bright flares of UV Ceti between the 1960-61 season and the (partial) 1963 period so far reduced. However, the overall rate for all flares increases only from one in about 5.5 hours to one in 4.5 hours, which is not statistically significant. The difference between these rates and those results quoted above may be due to the size of the flares included.

1.4.4 Spectra

In 1949 a spectrum of UV Ceti was fortuitously obtained by Joy and Humason (1949) during a 1-mag flare. The absorption lines were nearly blotted out by a strong continuous spectrum. Continuum brightness at shorter wavelengths than H_δ(4101 Å) was much greater than in the normal dM5.5e spectrum and the hydrogen emission lines were strengthened relative to the Ca II lines. The lines λλ 4026, 4471 He I, and 4685 He II appeared in emission. Most of the light increase was due to the continuum, the temperature of which appeared to be about 10,000°K, by comparison with the Planck function (Joy and Humason, 1949).

For a similar 1-mag flare observed in 1958, Joy reported lines of hydrogen widened and strengthened, and the calcium K line strengthened but not widened. The bright lines were displaced the equivalent of 30 km/sec to the red as compared to those on normal plates of the same series (Joy, 1958).

According to Joy (1961) the most common effect of a flare is to widen and strengthen the hydrogen lines. Four stars in his list have shown strong Balmer lines, possibly due to flares, although the lines are normally weak in these stars. In five of Joy's stars, the only evidence of flaring was the hydrogen-line enhancement. It should be noted, however, that pure flare spectrograms are not generally obtainable because of the time scale and faintness of the objects involved.

1.4.5 Colors

Multicolor photoelectric observations of flares have also yielded interesting results. In addition to the total light increase, the star becomes definitely bluer. Two events on AD Leonis have been so measured; numerical results are given in Table 3:

Table 3. Color measurements of stars

Observer	Phase	Color (B-V)
Johnson and Morgan (1953)	normal	+1.53
Engelkemeir (1959)	before flare	+1.40
	during flare	+0.65
	after flare	+1.52
Abell (1959)	maximum	0.00

Similar results have been noted on EV Lacertae by Chugainov (1961, 1962).

1.5 Flash Stars

Stars with similar, if not related, characteristics are the nebular variables, or flash stars. These were discovered and typed by Haro (1954; Haro and Morgan, 1953; Haro and Rivera, 1965; and Haro and Chavira, 1965) and his coworkers. A list is given by Joy (1961).

General properties of flash stars are as follows:

a. Membership in T associations generally.

b. Spectrum in the range dK6-dM6, usually with emission of the same type as the flare stars.

c. M_V about 8 to 9 mag brighter than flare stars.

d. Light variations somewhat resembling flare outbursts, but with the rise to maximum taking tens of minutes rather than a few seconds. Amplitudes of several magnitudes are common.

In 1955, Haro and Chavira (1955) found a relation between the total time of outburst and the spectral type of the varying star. Their plot, shown in Figure 2, included both flash and flare stars. Haro (1965) has more recently modified his view of this spectrum-time relation; on the basis of much new observational material the correlation is stated to be valid provided that the apparent rise in magnitude is the same in stars of different spectral type or absolute luminosity. Therefore, the total time duration of the outburst depends strictly on the absolute intensity of the flare.

A tendency toward similar correlation of the variation time and flare amplitude can be seen when the available data for a single flare star are examined. The UV Ceti material forms a good example.

1.6 Energy Considerations for Optical Flares

From the characteristics of the first UV Ceti flare he observed, Luyten (1949a) derived a minimum excess energy of 4×10^{31} ergs, or about 4000 sec of normal radiation. Liller (1952), using the same reasoning, found 5×10^{31} ergs produced by a 0.25-mag flare of AD Leonis; this is equivalent to approximately 30-sec normal radiation.

Gordon and Kron (1949) noted that the AD Leonis flare they observed (13% rise in light) could be accounted for by a general temperature increase of 40° K across the star, or, of course, by a smaller area rising to a much higher temperature. The latter idea is in much better agreement with color and spectral observations. In a paper considering one possible flare mechanism, Greenstein (1950) noted that the largest solar flares would be visible if transferred to a nearby dMe star, and might even produce the observed increases in brightness.

Further speculation along these lines led to the attempt to observe radio flares, and ultimately to the joint radio-optical program.

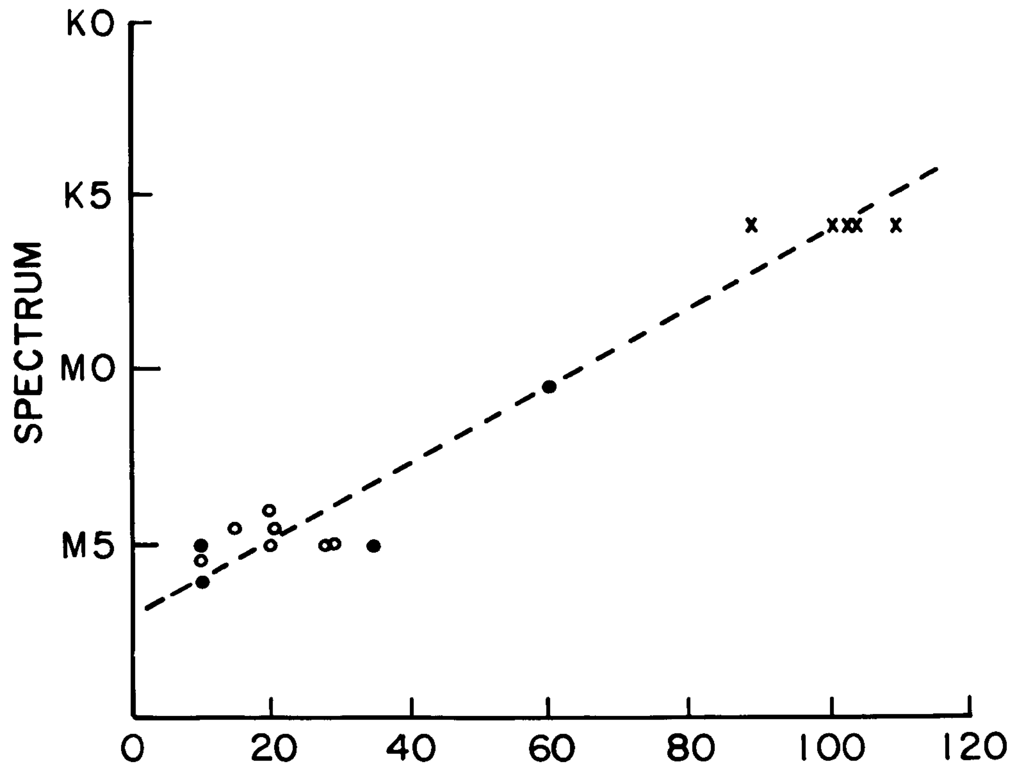

Figure 2. Spectrum-time relation (after Haro and Chavira, 1955) for flare and flash stars.

o denotes flare stars near the sun
● denotes flash stars in the Taurus dark clouds
x denotes flash stars of the Orion Nebula

2. GENERAL CONSIDERATIONS AND OBSERVING PROCEDURES

In 1960 a cooperative program of flare-star observation was started between the Jodrell Bank Experimental Station and the Smithsonian Astrophysical Observatory (SAO). Later collaborations were established by SAO with observers at the radio telescopes at Parkes, N.S.W., Australia, and Arecibo, Puerto Rico.

The original problem involved in the joint observational program was to ascertain the existence of any correlation between radio and optical brightenings of the selected star. The first approach to the problem was an attempt to maintain a joint patrol of a star as continuously as possible, and to correlate the positive events, if any occurred. The primary limitations on the Jodrell Bank radio telescope were horizon limits; only secondary limitations were imposed by weather conditions. Optical observations with the Baker-Nunn cameras (Henize, 1957), however, were rather more restricted. In dark-sky conditions the 20-inch f/1 camera, using Royal-X Pan Recording film of ASA speed 2400, yields 13^{th}-mag images in about 3 to 5 sec (Solomon, 1966). Unfortunately, bright-sky conditions fog the film very rapidly. Under full-moon conditions fog-density 1.0 is reached in less than 9 sec, whereas under dark skies, density 0.6 occurs after approximately 60-sec exposures. Therefore, the observing periods were restricted to ± 1 week from new moon.

The exposure times necessary to record the stars are certainly short enough to prevent large errors in measured brightness because of averaging brightness of even these rapidly varying stars. For a flare of 1 mag the rise might be of the order of 0.1 mag/sec, according to various data in the literature. In a 5-sec exposure, the maximum error is then about 0.5/2 = 0.25 mag, which is substantial, but still permits detection of the event.

Selection of the stars to be observed was based primarily on knowledge of previous flares, although other stars from Petit's (1961) list of candidates have been used. The stars had to be visible from the radio site for a sufficient length of time to permit gathering large amounts of data; this imposed a southern declination limit of -30° in the case of Jodrell Bank. Similar limits obtain for the Arecibo and Parkes instruments. Baker-Nunn station latitudes similarly restrict declinations available. However, for any camera-radiometer combination an abbreviated working list of observable stars can be formed.

To keep the stars within reach of the cameras on short exposures with minimal guiding, the list of stars was further restricted to those normally brighter than $m_{pv} = 13.0$. Although all brightness estimates are made using nearby stars on the same frame, it also seemed wise to minimize extinction problems by photographing as near the meridian as possible. Hence, one shifts from star to star in the list as the seasons change. Fortunately, for program continuity, the stars are well distributed in right ascension.

Another consideration was to provide continuous optical coverage corresponding approximately to the time of observation by the radio telescope. In the case of Jodrell Bank this is roughly 8 hours per night. Part of the restriction on this arrangement was to keep the observing load on the cameras distributed as evenly as possible, because of the prior commitment to observe satellites, and to minimize effects of adverse weather. The satellite-observing requirement actually imposes the most severe restriction on use of the camera network. Since satellites must be observed on demand, it is not possible to provide any schedule variation, and all other observations must be interrupted for them. As a rule, observable satellite passages become more frequent as the time difference from local midnight increases, becoming almost continuous near twilight; hence, the flare-star observing programs were scheduled, as far as possible, about local midnight.

The Baker-Nunn cameras were evenly distributed in longitude around the earth in order to provide satellite data evenly distributed in time and position along the orbit (Henize, 1957). This network feature was used to spread the workload and to keep observations near local midnight. A sample observing schedule is given in Appendix 1.

The radio observations at Jodrell Bank are made by continuously monitoring the star over the observing interval, usually at several frequencies. In addition to the aerials at the normal focus, other aerials were mounted so as to record the flux from a nearby area of sky. It was anticipated that terrestrial disturbances would appear on both channels, while stellar bursts would appear only on the channel recording the flare star (Lovell, 1964).

As previously noted, the time scale of the light variation is short, requiring closely spaced short exposures to allow flare identification. On the other hand, practical problems of film handling limit the amount of film (hence, number of plates) exposed to about 100 frames in any sequence. Furthermore, data reduction becomes rather tedious for great amounts of film. After some experimentation, one exposure every 2 min was selected as being the best compromise between detecting event occurrences and limiting the amount of film used. It is estimated that for "normal" flare light curves, with an exponential decay lasting 10 to 20 min for a 1-mag event, this procedure will allow detection of 100% of all flares 1.0 mag or more, and may not detect up to 50% of those flares of $\Delta m < 0.5$ mag if the developed film is of poor quality. For best quality film, the 50% detection level is at about 0.3- to 0.4-mag flares on this system.

The work reported here was done according to the following scheme. About 8 hours of radio observation was covered by as many as five Baker-Nunn photographic stations, observing as long as 2 hours each under dark-sky conditions. Exposures were made at intervals of 2 min. Each exposure was sufficiently long to bring the quiescent flare star to about 0.5 to 1 mag above the plate limit, and was never more than 5 sec. The time at some known point in each exposure is automatically recorded on the film. Film processing was normal for film exposed in the Baker-Nunn camera (Solomon, 1962).

The observing procedure has been modified in later work to provide greater time resolution through multiply exposing each frame, but the essential character of the method used for photography has not changed. Figure 3 is a multiply exposed frame showing a flare of UV Ceti.

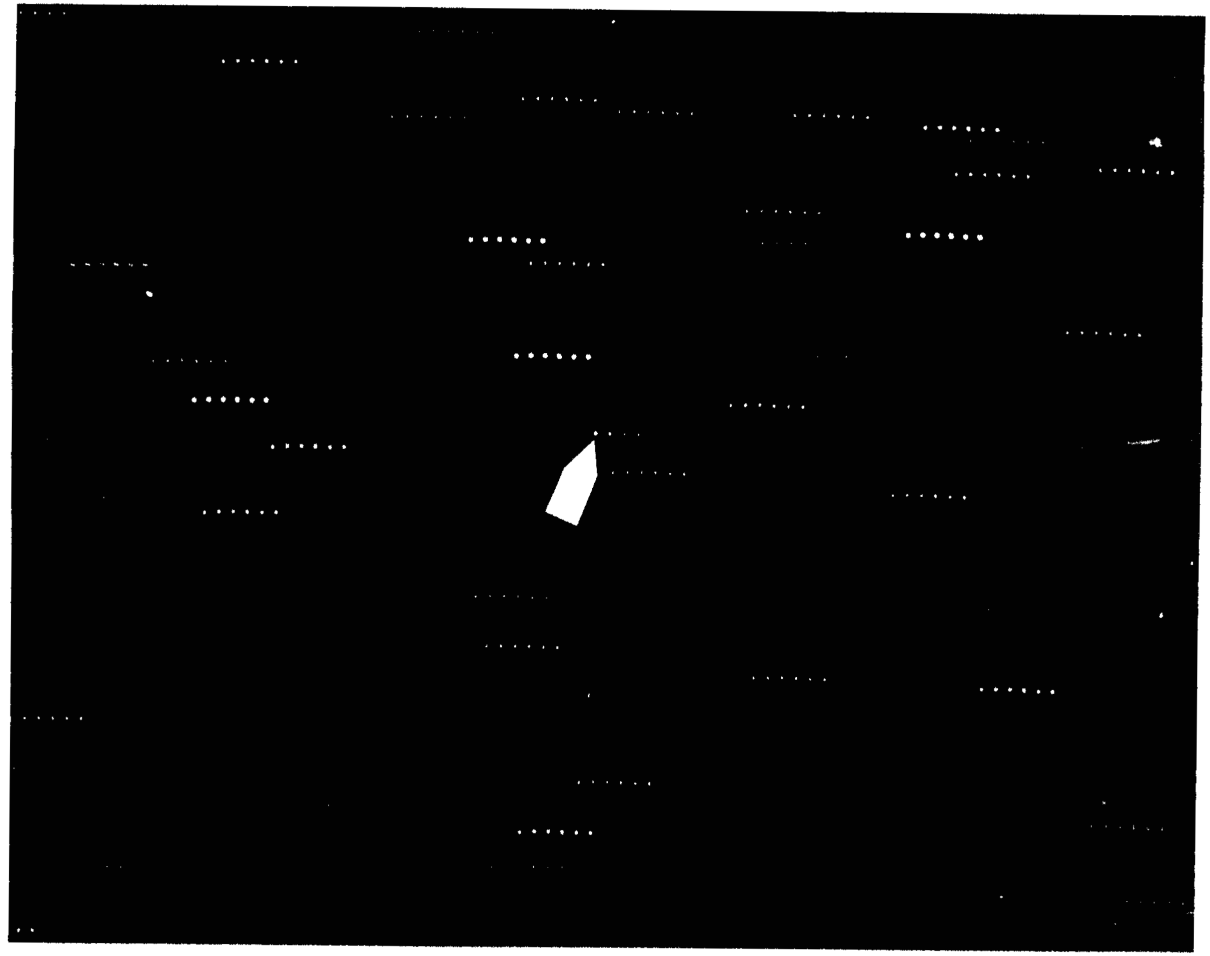

Figure 3. Multiply exposed photograph of UV Ceti, Baker-Nunn camera. Each exposure time 3.8 sec, time between exposures 19.2 sec. Star appears to brighten almost 4 mag at indicated point. Note time increases left to right.

3. REDUCTION METHODS FOR THE PHOTOGRAPHIC OBSERVATIONS

The essential part of the optical program is the identification of flares and preparation of the light curves. These two problems have been combined, for although this procedure reduces the speed with which one finds activity, each film need be scanned only once, and even the most minor activity can be included in the correlation with radio data.

The reduction method was chosen largely because of the need for speed of reduction; the rather variable sky and developing conditions at field stations make really precise photometry impossible without major changes in station operating procedures. On the basis of estimates on the north polar sequence and various other photovisual magnitude sequences, it was concluded that the Baker-Nunn (B. N.) working color system was not very far from the photovisual (pv). The assumption of a magnitude error of 0. 0 for the flare star comparison sequence (average spectral types G through K) yields a magnitude difference (pv-B. N.) for the star UV Ceti, spectral type dM6e, of less than 0. 5 mag. Therefore, it was assumed throughout that the color system is photovisual. This assumption introduces no error, except for energy calculations, as all light curves are purely internally calibrated at the point in the joint program where they are used for correlation with radio flux data.

The first reduction method tried was one of direct estimation of the variable star against a known magnitude sequence. By remeasurement of some films it was found that the values obtained were reasonably consistent and repeatable, but they did tend to depend on only one or two of the many comparison stars. The remeasurements yielded an error, for each frame, of $0.1 \text{ mag} < \sigma < 0.2 \text{ mag}$, in most cases. As a check, and later as a primary system, a modified Argelander estimation method was introduced, which used a minimum of four comparison stars directly for each estimate.

Briefly, the Argelander system is as follows: The unknown star is compared in brightness with each comparison star in turn. The comparison is visual, with no aids. An arbitrary system of step differences is used, in which one step is a barely perceptible brightness difference between the two stars. Since the method is subjective, both density and size of the star images enter into the measurement. All frames on one film are measured at once time, in an attempt to keep the measuring system uniform. A sample data set and the numerical reduction of these data are found in Appendix 2.

A calibration curve is formed by taking the mean differences between comparison stars, one (generally the brightest) is then used as a zero point. The mean differences are then combined to increase the precision of determination of the stars at the other end of the measurement scale. Variability of any comparison star is easily detectable by this method, by comparison of the calibration curves. Finally, when the calibration curve for a film is established, a scale value for the variable is found from each original direct estimate, using the mean scale value of each comparison star. The mean scale value of the variable is found for every frame and the entire set is used to form a "light curve," or plot of brightness against time. A set of calibration curves is shown in Figure 4, and light curves, showing probable flares, are given in Appendix 3.

The scale values are easily transformed into magnitudes, if at least two of the comparison stars have known magnitudes, or if one star and the value in magnitudes of the step are known. Generally, the

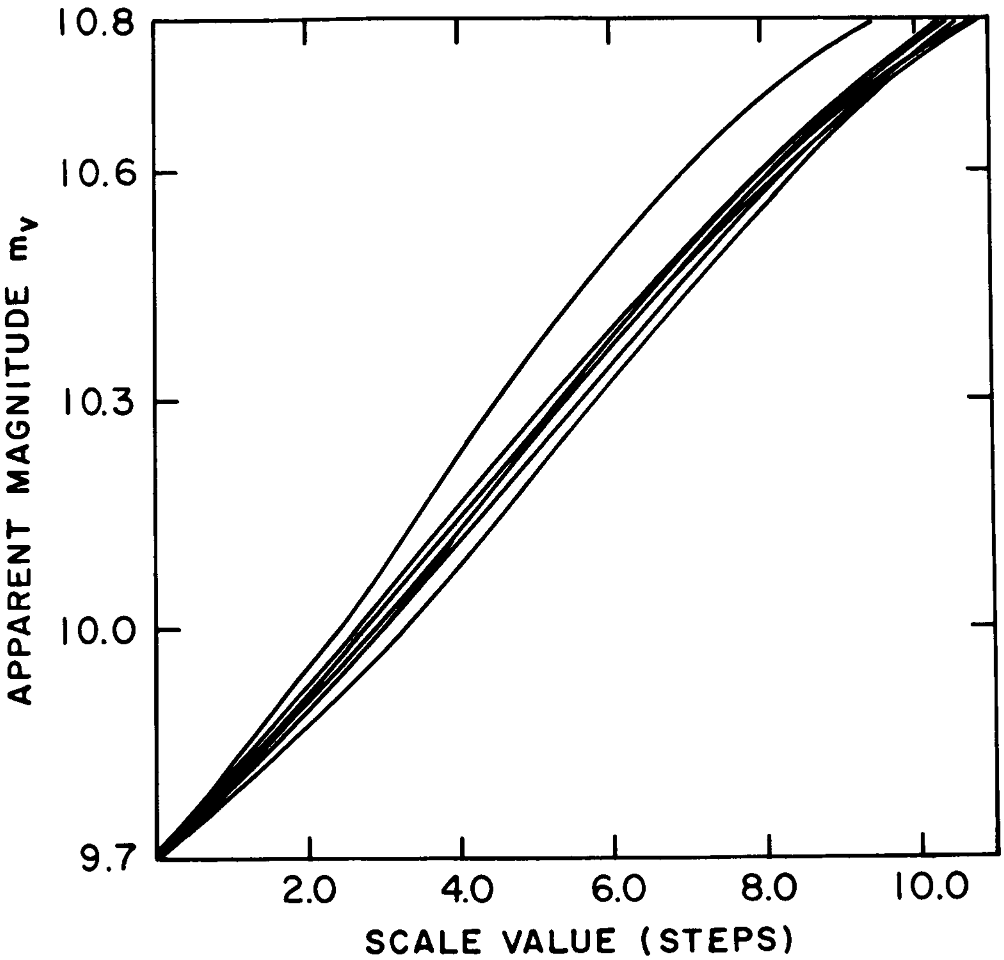

Figure 4. Sample calibration curves of EV Lacertae, August 1961. Each curve represents one film, containing 20 to 60 frames.

first case has been true; the resulting conversion has been on the order of one step $\lesssim 0.1$ mag. The Argelander method also allows a direct, quantitative estimate of the errors involved in the estimates of brightness. The standard deviation of the mean of scale values for the "quiescent" state is taken to be a measure of the error of any one observation. This is found by the relation (Beers, 1957)

$$\sigma = \sqrt{\frac{\sum (x - \bar{x})^2}{(n - 1)}} \quad ,$$

where each measurement is assumed independent. Generally, for good films the value of σ is on the order of 0.1 mag or less.

A flare is assumed to have occurred when $\Delta m \gtrsim 3\sigma$. Although photoelectric photometry yields a characteristic, nearly exponential decay, our data points are separated sufficiently that this shape does not always appear for small events.

Identification charts for the star fields have been taken from various sources. Several were supplied by the American Association of Variable Star Observers (AAVSO); some of these charts show comparison stars with known photovisual magnitudes. For some other stars fainter than the Bonner Durchmusterung (BD) limiting magnitude, or which do not appear on BD charts, Sproul Observatory charts were obtained, again through the good offices of the AAVSO. Finally, for the one case (V1216 Sgr) remaining, the star's given coordinates were precessed to 1950 epoch. The star field was photographed, and the star identified by its magnitude and position with respect to known BD stars.

Comparison magnitude sequences found in the literature have been used as much as possible. On stars with no such sequences the question has been avoided by producing light curves in terms of scale values, without conversion to magnitudes. This still allows detection of flares. However, it is planned to determine magnitude sequences, preferably by photoelectric photometry on the Johnson (1952) (B, V) system, as there generally exist no nearby sets of standard stars suitable for photographically transferring magnitudes.

Originally, some overlap in observation time was scheduled for the cameras, in the hope that flares could be verified by identification on more than one film. With the realization that the observed flare frequency was quite low, it was decided that more information would be gained by extension of the observation period, and the elimination of overlap as much as possible. The amount of good overlap actually obtained was small, but it showed that results from two stations are consistent with one another. A sample is given in Figure 5. During the period covered by now reduced data no flare was obtained on overlapping films. The camera stations in South America still attempt to observe concurrently; unfortunately, these sites have the poorest weather and the yield is low.

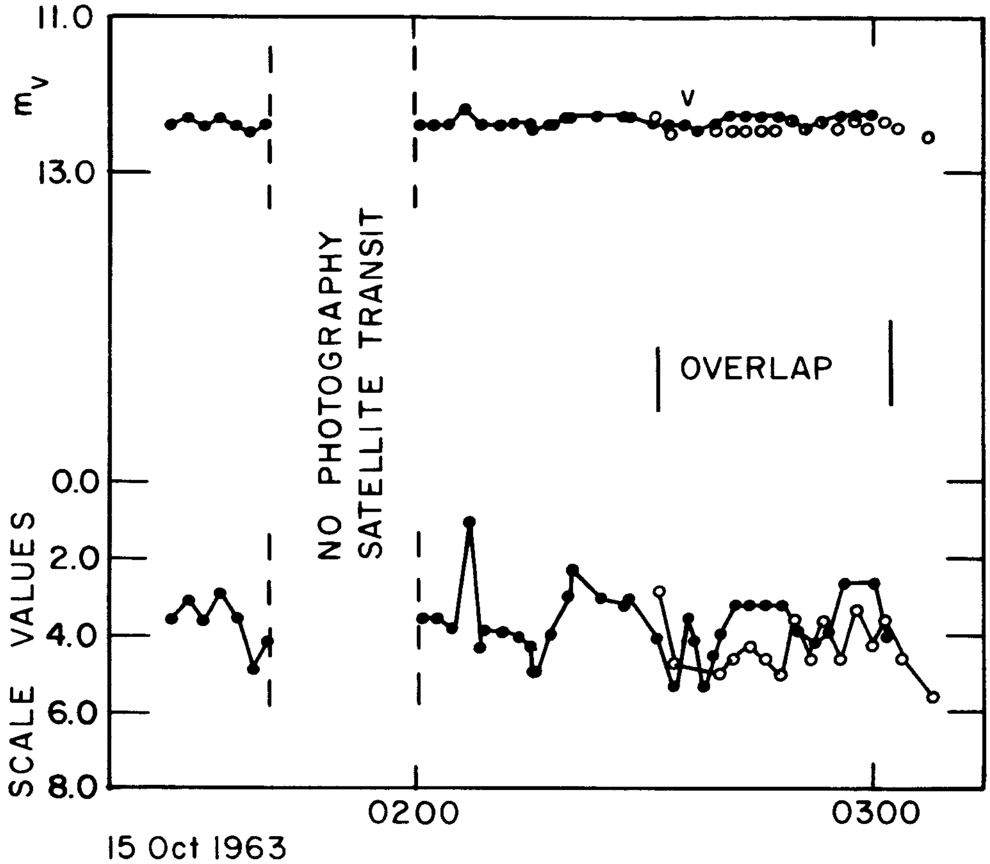

Figure 5. Sample of overlapping light curves. Open circles denote low-weight estimates.

4. SUMMARY OF OBSERVATIONS

The observations made in this program commenced in September 1960 and have been continued, with some breaks, up to September 1965. It is currently expected that the observations will continue, with increased sensitivity of the radio receivers.

Table 4 lists the interval of observation, star, and cooperating radio observatory for all periods, and notes those for which the photographic reductions and correlations have been completed as of January 1966.

Table 5 gives a chronological list of stellar events detected from the photographic patrol. We have included all statistically significant events, and some of low probability that had light curves resembling previously known events. Not all of the flares with $\Delta m \leq 0.4$ in this list were accompanied by radio events, but it is not possible to identify spurious events on this basis. Some spurious events may appear to be statistically significant because of the effects of momentary variations in seeing during the short exposures. The smallest events should be most affected.

Table 4. Summary of observations

Period	Star	Date	Approximate optical coverage (hrs)	Measurement status	Cooperating Observatory Jodrell Bank
P I	UV Cet	Oct. 1960	60.5	complete	
II	UV Cet	Nov. 1960	50.0	"	
III	UV Cet	Jan. 1961	26.7	"	
IV	YZ CMi	Feb. 1961	39.9	"	
V	EV Lac	Aug. 1961	13.4	"	
VI	UV Cet	Oct. 1961	25.9	"	
VII	YZ CMi	Dec. 1961 - Jan. 1962	23.3	"	
VIII	YZ CMi	Feb.-Mar. 1962	18.8	"	
IX	V1216 Sgr	May-June 1962	23.0	"	
X	EV Lac	July-Aug. 1962	33.5	not meas.	
XI	UV Cet	Sept.-Oct. 1962	30.3	"	
XII	UV Cet	Nov.-Dec. 1962	30.5	"	
XIII	UV Cet	Dec. 1962 - Jan. 1963	10.7	"	
XIV	YZ CMi	Feb.-Mar. 1963	21.5	"	
XV	AD Leo + V1216 Sgr	Mar.-Apr. 1963	28.0	"	
XVI	V1216 Sgr	Apr. 1963	26.1	"	
XVII	V1216 Sgr	June 1963	19.4	"	
XVIII	UV Cet	Oct. 1963	56.9	complete	
XIX	UV Cet + V371 Ori	Dec. 1963	66.6	not meas.	
XX	YZ CMi	Feb. 1964	7.7	"	
XXI	V1216 Sgr	June 1964	43.0	"	
XXII	EV Lac	Aug. 1964	74.1	"	
XXIII	UV Cet	Sept.-Oct. 1964	58.7	"	
XXIV	UV Cet	Nov.-Dec. 1964	17.8	"	
XXV	YZ CMi	Feb.-Mar. 1965	44	"	
XXVI	UV Cet	Sept.-Oct. 1965			

Table 4. (Cont.)

Period	Star	Date	Approximate optical coverage (hrs)	Measurement status	Cooperating Observatory Jodrell Bank
A I	V371 Ori	Nov. 1962	8.4	complete	CSIRO, Parker
II	AD Leo	Feb. 1963	6.1	not meas.	Australia
III	V645 Cen	Apr. 1963	11.4	"	
IV	$-21^\circ 6267B$	Sept. 1963	13.9	"	
V	V645 Cen	Apr. 1964	14.2	"	
VI	YZ CMi	Jan. 1965	8.3	"	
VII	EQ Peg	May 1965	11.0	"	
VIII	EQ Peg + GC 22805A	July 1965	14.0	"	
C I	Ross 867B	June 1964	22.5	not meas.	Arecibo Ionospheric
II	Ross 165A	July 1964	26.7	"	Observatory
III	EQ Peg	Sept. 1964	23.2	"	
IV	EQ Peg	Oct. 1964	6.5	"	
V	V371 Ori + YZ CMi	Nov.-Dec. 1964	21.5	"	

Table 5. Probable stellar flares found by Baker-Nunn photographic patrol.

Period number	Star	Date (UT)	Approximate UT	Approximate Δm
PI 1960	UV Ceti	12 Oct.	2116.3 2149.6	0.3 0.3
		16 Oct.	2100.2	0.6
		17 Oct.	2209.1	0.5
PII 1960		12 Nov.	1823.5	0.2*
		12 Nov.	2256.8 2259.3	0.2* 0.2*
		13 Nov.	1842.4	0.3
		13 Nov.	2152.8	0.3
		14 Nov.	2129.6	0.5
		15 Nov.	0017.7	0.4
		19 Nov.	0015.1	0.2*
		24 Nov.	2338.0	0.3
		25 Nov.	1805.1	0.2*
		25 Nov.	2144.8	0.4
PIII 1961		5 Jan.	1626.6	0.3
		7 Jan.	1454.5	0.3
		7 Jan.	1557.6	0.3
		8 Jan.	1545.1	0.3
		9 Jan.	1504.5	0.3
		11 Jan.	1931.0	0.75
PIV 1961	YZ CMi	14 Feb.	1826.6	0.2*
		18 Feb.	1921.1	0.75
PV 1961	EV Lacertae	3 Aug.	2153	0.35
		8 Aug.	2220.0	0.2*
		9 Aug.	2218.1	0.2*
		10 Aug.	2209.1	0.2*
		12 Aug.	2255.0	0.3
		14 Aug.	0003.3	0.2

Period number	Star	Date (UT)	Approximate UT	Approximate Δm
PVI 1961	UV Ceti	5 Oct.	2202.0 2204.0	0.3 0.3
PIX 1962	V1216 Sgr	31 May	0116.0	0.4
		31 May	0208.0 0218.0	0.3 0.25*
		1 June	0100.1	0.4
		1 June	0217.0	0.3
		3 June	0110.0	0.5
		3 June	0456.0	0.3
		5 June	0420.0	0.4
PXII 1962	UV Ceti	24 Nov.	0024.1	0.25*
PXVIII 1963		10 Oct.	0142.7	0.9
		12 Oct.	2124.1	0.25*
		14 Oct.	0014.7	0.25*
		14 Oct.	0123.5	1.0
		16 Oct.	0320.3	0.4
		17 Oct.	0028.7	0.5
		17 Oct.	0316.1	0.4
		17 Oct.	2336.0	0.4
		19 Oct.	0003.9	0.4
		19 Oct.	2304.0	1.1
		21 Oct.	2136.0	0.3
		22 Oct.	0126.3	0.3
		25 Oct.	2350.0	0.45
		26 Oct.	0030.1	0.25*
PXXVI 1965	UV Ceti	28 Sept.	0436	>3.5
AI 1962	V371 Ore	30 Nov.	1452.2 1459.2 1507.2	1.0 0.4 0.3
AII 1963	AD Leonis	20 Feb.	1552.2	0.25*

*Events of low statistical significance, included mainly because of light-curve appearance.

5. RESULTS

Correlation of the radio and optical data has generally been carried out by the cooperating radio astronomers. The method used has been superposition of epochs. Originally, this was done because only very small flares had been observed and it was necessary to separate the events from the noise level. Since larger flares have been observed, this method has provided the most convenient way to attach significance to various features of the light- and radio-energy curves. An example of superposed curves is in Figure 6. A description of the correlation is given by Lovell et al. (1963).

Results of the first six observing periods yielded a probability of 1 in 10^8 that the correlation of radio and optical flares was spurious.

Energy calculations for a flare observed by the Australia Baker-Nunn, a group of Australian amateur astronomers, and the Parkes 210-foot telescope (Slee et al., 1963) showed that both radio and optical energy of a stellar flare are several orders of magnitude larger than emission from the largest solar flares.

From the Jodrell Bank observations, we have also identified at least two types of stellar flares, with different temporal and energy characteristics (Lovell et al., 1964a). The type 2 flare is similar to frequency-drift solar bursts; they are compared in Table 6.

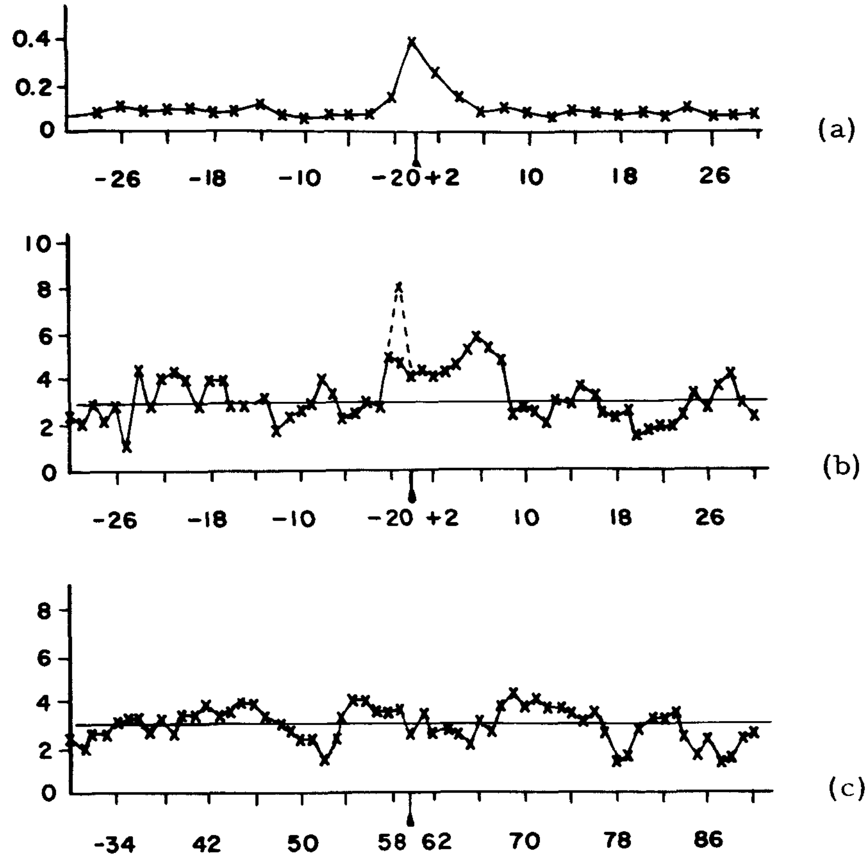

Figure 6. (a) Twenty-three cases of minor photographic flares superimposed taking zero time as the epoch of maximum of the flare. Ordinates, change in photographic magnitude Δm; abscissas, time in min. (b) The 23 radio records superimposed taking zero time as the epoch of maximum of the photographic flare. Ordinates, change in flux units (10^{-26} W/m^2/c.p.s.); abscissas, time in min. (c) The 23 radio records superimposed taking zero time as the epoch of maximum of the photographic flare + 60 min. Ordinates and abscissas as for (b).

Note: The dashed peak in b is from a single large burst recorded with flare of 0.9 mag.

Table 6. Comparsion of solar and stellar frequency-drift bursts

	Time after optical flare	Duration	Radio drift-rate from high to low frequencies	Spectrum. Approximate variation of radio flux with frequency (f)
Type II solar bursts	5-20 min	5-30 min	Up to 1 Mc/sec per sec	$f^{-0.6}$
UV Ceti flare	2 min on 408 Mc/sec 3 min on 240 Mc/sec	5-10 min on 408 Mc/sec 10-20 min on 240 Mc/sec	2.8Mc/sec	$f^{-0.6}$
Type III solar bursts	Near start of event	Bursts of approximately 10 sec. Group of bursts approximately 1 min	150 Mc/sec to 500 Mc/sec in this frequency range	$f^{-0.6}$

Using the data from this program we have found an upper limit to the difference between the velocities of light and radio wave (Lovell et al., 1964b). Over a wavelength range of 2×10^6 the velocities are the same within at least 1×10^6.

6. DISCUSSION

A general view of the problem of flare stars brings out several useful points:

a. The similarities between the two classes of stars indicate that it will probably be necessary to provide a mechanism explaining both flare and flash stars at once. A step in this direction is found in recent work by Kumar (1963a, b), extending previous development of Hayashi (1962). Both the T Tauri and UV Ceti stars appear to be in the contracting phases of evolution; moreover, the UV Ceti stars may be below the lower limit of mass for stable stars.

b. Stellar flares are almost certainly not of thermal origin. This conclusion is based on results of the joint radio-optical studies.

c. Most of the events observed in these studies are somwhat analogous to solar-noise storms (Type I solar bursts).

d. The event of 25 October 1963 is of a rarer type, possibly analogous to the frequency-drift-type solar bursts.

e. The rate at which energy must be produced by a flare mechanism is at least a large fraction of the stellar energy-production rate.

Although a great deal of information is now available on the properties of stellar flares on UV Ceti stars, many questions remain. For determination of a direct flare mechanism for the two types of event now known, more information is required on the structure of the red-dwarf atmosphere. Additional flare observations are needed at higher time resolution, at more radio frequencies, in narrow optical spectral regions, and with measured polarization.

Little is known of the generality of the flare mechanism as a process affecting a large class of stars, or possibly all stars. Flare-like events have been confirmed on UV Ceti stars, T Tauri stars, and at least one main sequence G-spectrum star (the sun). An unconfirmed report of flares on a B-type star has also been made (Andrews, 1965). Certainly, more investigation is necessary of the distribution of flares with stellar spectral type, and such observations appear to be much more difficult as the stars become brighter and hotter.

7. CONCLUSIONS

The joint observations by the SAO Baker-Nunn cameras and cooperating radio observatories have shown, on the basis of both statistical and direct evidence, that optical stellar flares are accompanied by bursts of radio energy in the meter wavelengths. From the forms displayed by the initially observed events, it seems possible that the stellar flares are analogues of certain solar events. It also seems reasonably certain that the flare phenomenon is nonthermal in at least one, and probably all, of the cases studied. The program is being continued to allow determination of the similarity between stellar and solar flares.

In addition to the direct results of the observations, operation of the optical portion of the flare-star program has shown that the network, cooperative approach to large-scale astronomical-observing programs is useful. Furthermore, for work in which highest precision is not required, operation of field stations by one observatory is a direct, inexpensive, and relatively sure way to obtain a great deal of data in a short time, and with relatively uniform results.

Although the present use of the Baker-Nunn cameras has introduced no new methods to astronomy, it has aided in the study of a significant problem. Certainly, the cost of such an observing program would have been much higher had it been attempted by more conventional means. Success in the flare-star program has led to utilization of the cameras for other nonsatellite-tracking purposes, such as a program of nearly continuous observations of comet-tail structure, which could be performed otherwise only with great difficulty and expense (SAO, 1965).

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APPENDIX 1

SAMPLE OBSERVING SCHEDULE

P XXIII

28 September - 13 October 1964 - dark sky

UT $00^h \approx 01^h 00^m$ ST at center of interval

Use UV Ceti - $\alpha = 01\ 38;\ \delta = -18°$

Star transits approx 0030 local time at center of interval

Observe → 2030 - 0400 UT

$04^h 00^m <$ transit Jodrell Bank $< 03^h 30^m$

Baker-Nunn Schedule

Station	UT	Local time	No. frames
8. Iran	2030-2230	0000-0200	60
2. South Africa	2230-0030	0030-0230	60
4. Spain	0030-0230	0000-0200	60
9. Curaçao	0230-0400	2200-2330	45
11. Argentina	0230-0400	2200-2330	45

APPENDIX 2

SAMPLE CALCULATION OF MAGNITUDES FROM ONE BAKER-NUNN FILM

Sample Data UV Ceti Magnitude Estimates
(Baker-Nunn Film #SC4-10853)

Time UT	Scale estimates	Magnitude estimate	
01 03 29	A4B5v2C4D	12.4	poor focus
05 28	A5B4v0C5D	12.5	or sky
07 25	A4B4v2C7D	12.4	throughout
09 ?	A5B5v2C7D	12.5	
11 23	A5B5v1C7?D	12.5	
13 20	A4B4v2C7D	12.4	
15 16	A4B3v3C5D	12.4?	
17 12	A3B3v4C8D	12.3?	
19 10	A5B4v1C7D	12.4	
21 05	A4B5v1C5D	12.5	
23 06	A5B5v1C4D	12.5	
25 01	A4B4v1C7D	12.4	
27 02	A4B6v0C6D	12.6	
28 58	A5B3v0C5D	12.5	
30 57	A4B5v1C6D	12.5	
32 55	A6B5v2C5D	12.5	
34 52	A6B3v1C6D	12.5	
36 53	A3B3v3C8D	12.3	
38 47	A4B3v2C7D	12.4	
40 47	A6B4v0C5D	12.6	
42 42	J10v4B6A12C-	11.5	
44 42	B2A1v5C8D	12.1	
46 37	A3B3v3C8D	12.3	
48 37	A3B3v3C7D	12.3	
50 35	A2B1v4C9D	12.2	
52 33	A4B3v3C7D	12.3	not in
54 31	A3B2v3C7D	12.3	σ
56 29	A4B3v2C7D	12.4	
58 28	A3B3v4C7D	12.3	
02 00 24	A3B2v4C9D	12.2	
02 25	A3B3v2C--	12.3	
04 21	A3B4v2C7D	12.4	
06 21	A4B2v2C7D	12.4	
08 16	A4B4v1C6D	12.5	
10 13	A4B3v3C8D	12.3	
12 11	A3B3v2C7D	12.3	
14 07	A2B2v4C7D	12.3	

Sample Data UV Ceti Magnitude Estimates (cont.)

Time UT	Scale estimates	Magnitude estimate
02 16 06	A4B4v2C7D	12.4
18 02	A6B4v0C4D	12.6
20 03	A2B4v3C--	12.3
22 01	A3B4v2C5D	12.4
24 00	A4B2v2C--	12.4
25 59	A3B3v2C8D	12.3
27 58	A3B4v2C--	12.4
29 53	A4B4v2C8D	12.4
31 49	A4B3v2C8D	12.4
33 46	A2B4v2C8D	12.3
35 42	A2B1v4C9D	12.2
37 41	A4B4v1C5D	12.5

Step Differences, Comparison Stars

(UV Ceti Baker-Nunn Film #SC4-10853)

A-B	A-C	A-D	B-C	B-D	C-D
-1	6	8	7	9	2
1	5	10	4	9	5
0	6	11	6	11	5
0	7	12	7	12	5
0	6	12	6	12	6
0	6	11	6	11	5
1	7	9	6	8	2
0	7	11	7	11	4
1	6	12	5	11	6
-1	5	9	6	10	4
0	6	9	6	9	3
0	5	11	5	11	6
-2	4	10	6	12	6
2	5	10	3	8	5
-1	5	10	6	11	5
1	8	11	7	10	3
3	7	12	4	9	5
0	6	11	6	11	5
1	6	11	5	10	5
2	6	11	4	9	5
-2	6		8		
-1	6	9	7	10	3
0	6	11	6	11	5
0	6	10	6	10	4
1	6	11	5	10	5
1	7	11	6	10	4
1	6	10	5	9	4
1	6	11	5	10	5
0	7	10	7	10	3
1	7	12	6	11	5
0	5		5		
-1	5	10	6	11	5
2	6	11	4	9	5
0	5	10	5	10	5
1	7	12	6	11	5
0	5	10	5	10	5
0	6	9	6	9	3
0	6	11	6	11	5
2	6	10	4	8	4

Step Differences, Comparison Stars (cont.)

A-B	A-C	A-D	B-C	B-D	C-D
-2	5		7		
-1	5	8	6	9	3
2	6		4		
0	5	11	5	11	6
-1	5		6		
0	6	12	6	12	6
1	6	12	5	11	6
-2	4	10	6	12	6
1	6	11	5	10	5
0	5	9	5	9	4
$\frac{11}{49} = 0.22$	$\frac{286}{49} = 5.84$	$\frac{462}{44} = 10.50$	$\frac{275}{49} = 5.61$	$\frac{449}{44} = 10.20$	$\frac{203}{44} = 4.61$

Mean Step Values of Comparison Stars
UV Ceti Baker-Nunn Film #SC4-10853

A-B = 0.22		
A-C = 5.84	(A-B) + (B-C) = 5.83	
A-D = 10.50	(A-B) + (B-C) + (C-D) = 10.44	(A-B) + (B-D) = 10.42
	(A-C) + (C-D) = 10.45	

A = 0.00
B = 0.22
C = 5.84
D = 10.45

Final UV Ceti Scale Values

(Baker-Nunn Film #SC4-10853)

A	B	C	D	Mean	
4.00	5.22	3.84	6.45	4.88	
5.00	4.22	5.84	5.45	5.13	
4.00	4.22	3.84	3.45	3.88	
5.00	5.22	3.84	3.45	4.38	
5.00	5.22	4.84	3.45	4.63	
4.00	4.22	3.84	3.45	3.88	
4.00	3.22	2.84	5.45	3.88	
3.00	3.22	1.84	2.45	2.63	
5.00	4.22	4.84	3.45	4.38	
4.00	5.22	4.84	5.45	4.88	
5.00	5.22	4.84	6.45	5.38	
4.00	4.22	4.84	3.45	4.13	
4.00	6.22	5.84	4.45	5.13	
5.00	3.22	5.84	5.45	4.88	
4.00	5.22	4.84	4.45	4.63	
6.00	5.22	3.84	5.45	5.13	
6.00	3.22	4.84	4.45	4.63	
3.00	3.22	2.84	2.45	2.88	
4.00	3.22	3.84	3.45	3.63	
6.00	4.22	5.84	5.45	5.38	
-6.00	-3.78	-6.16		-5.31	
1.00	2.22	0.84	2.45	1.63	
3.00	3.22	2.84	2.45	2.88	
3.00	3.22	2.84	3.45	3.13	
2.00	1.22	1.84	1.45	1.63	
4.00	3.22	2.84	3.45	3.38	not in σ
3.00	2.22	2.84	3.45	2.88	
4.00	3.22	3.84	3.45	3.63	
3.00	3.22	1.84	3.45	2.88	
3.00	2.22	1.84	1.45	2.13	
3.00	3.22	3.84		3.35	
3.00	4.22	3.84	3.45	3.63	
4.00	2.22	3.84	3.45	3.38	
4.00	4.22	4.84	4.45	4.38	
4.00	3.22	2.84	2.45	3.13	
3.00	3.22	3.84	3.45	3.38	
2.00	2.22	1.84	3.45	2.38	
4.00	4.22	3.84	3.45	3.88	

Final UV Ceti Scale Values (cont.)

A	B	C	D	Mean
6.00	4.22	5.84	5.45	5.38
2.00	4.22	2.84		3.02
3.00	4.22	3.84	4.45	3.88
4.00	2.22	3.84		3.35
3.00	3.22	3.84	2.45	3.13
3.00	4.22	3.84		3.69
4.00	4.22	3.84	2.45	3.63
4.00	3.22	3.84	2.45	3.38
2.00	4.22	3.84	2.45	3.13
2.00	1.22	1.84	1.45	1.63
4.00	4.22	4.84	5.45	4.63
				$\Sigma x = 147.75$
				$\overline{x} = 3.99$
				$\sigma = 0.993$

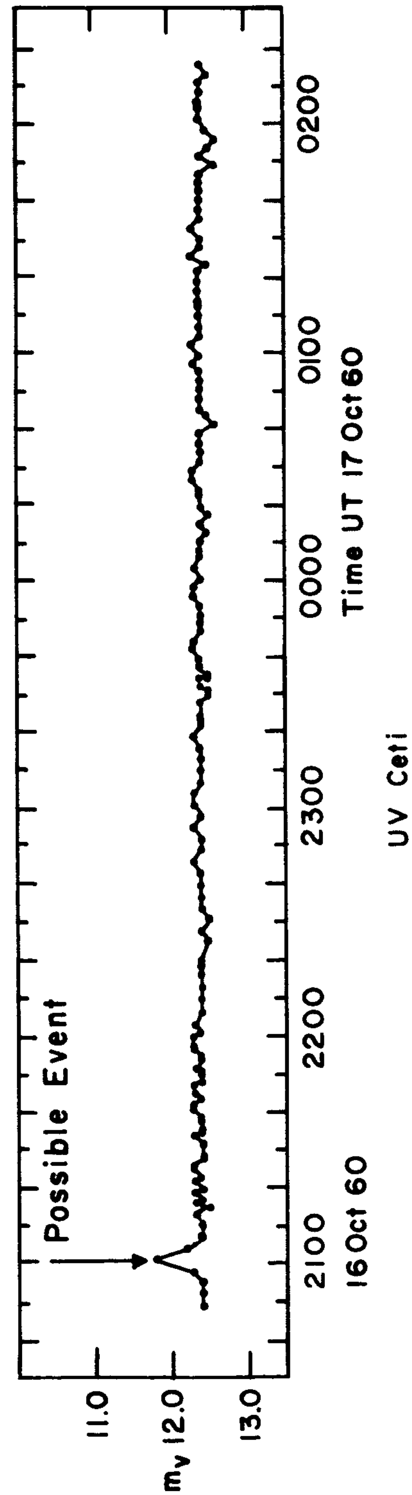
APPENDIX 3

REPRESENTATIVE LIGHT CURVES

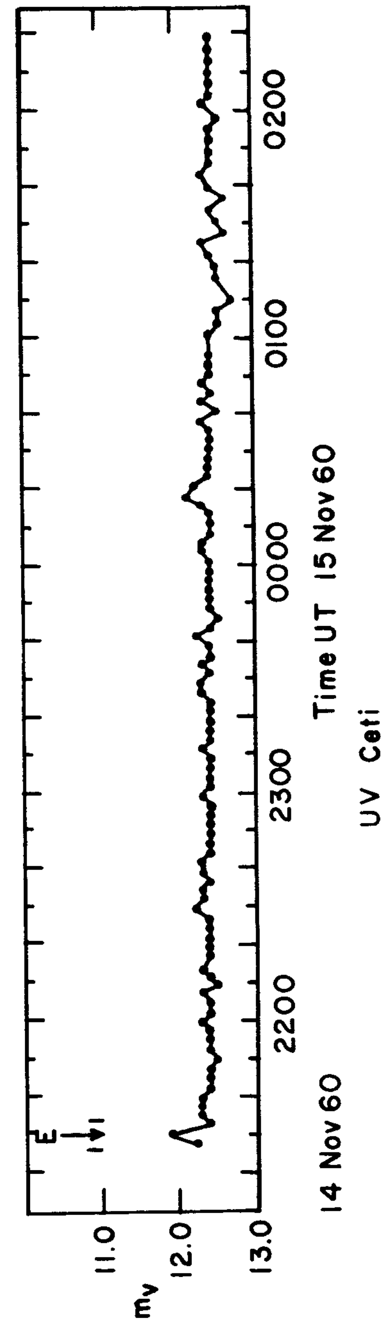
The representative flare-star light curves that follow are based on data taken for this observing program. A short segment only of each day's light curve is reproduced. Letters denoting peaks or intervals of the curves are arbitrary, and were used only for internal identification purposes.

Light curves for events of 1960 and 1961 are based only on the original quick estimation scheme, later curves are plotted from scale values or both estimation methods (see pp. 18-21).

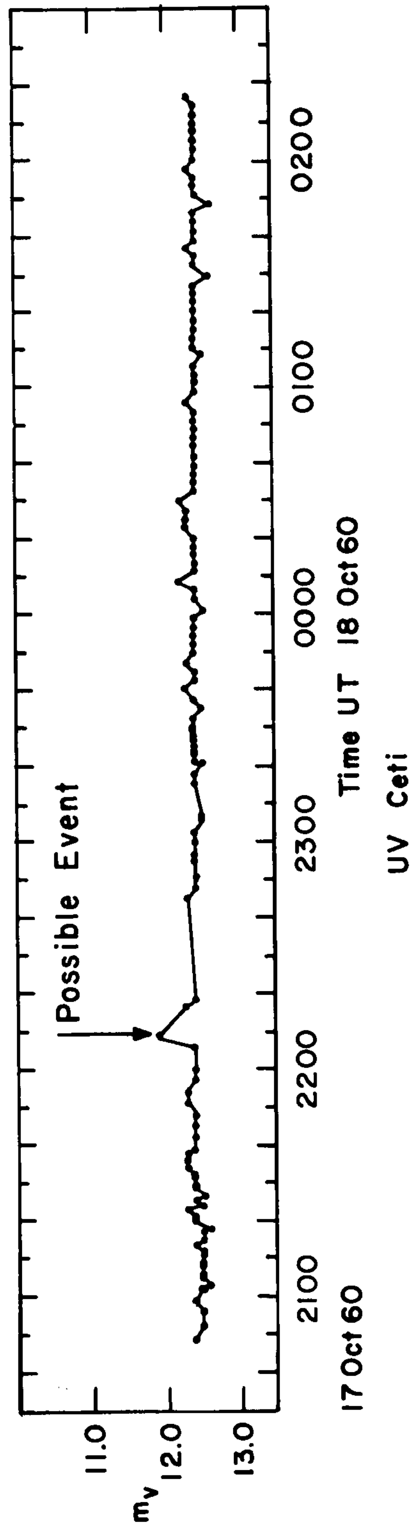
Each light curve is labeled with the star name.

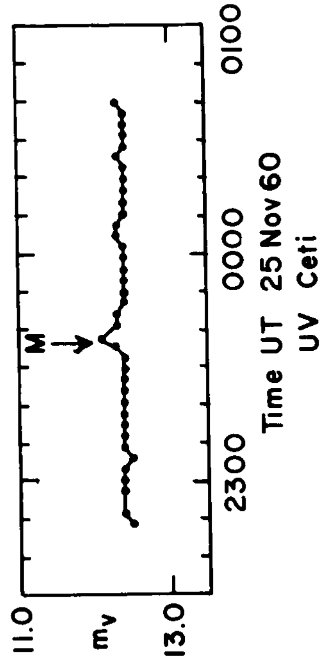


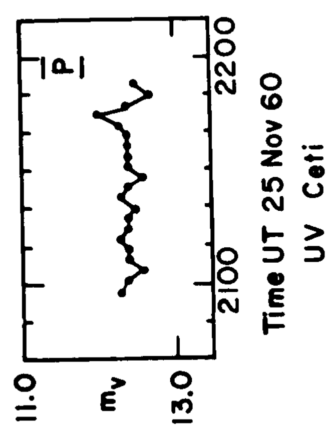
Possible Event
11.0
m_v 12.0
13.0
2100
2200
2300
0000
0100
0200
16 Oct 60
Time UT 17 Oct 60
UV Ceti

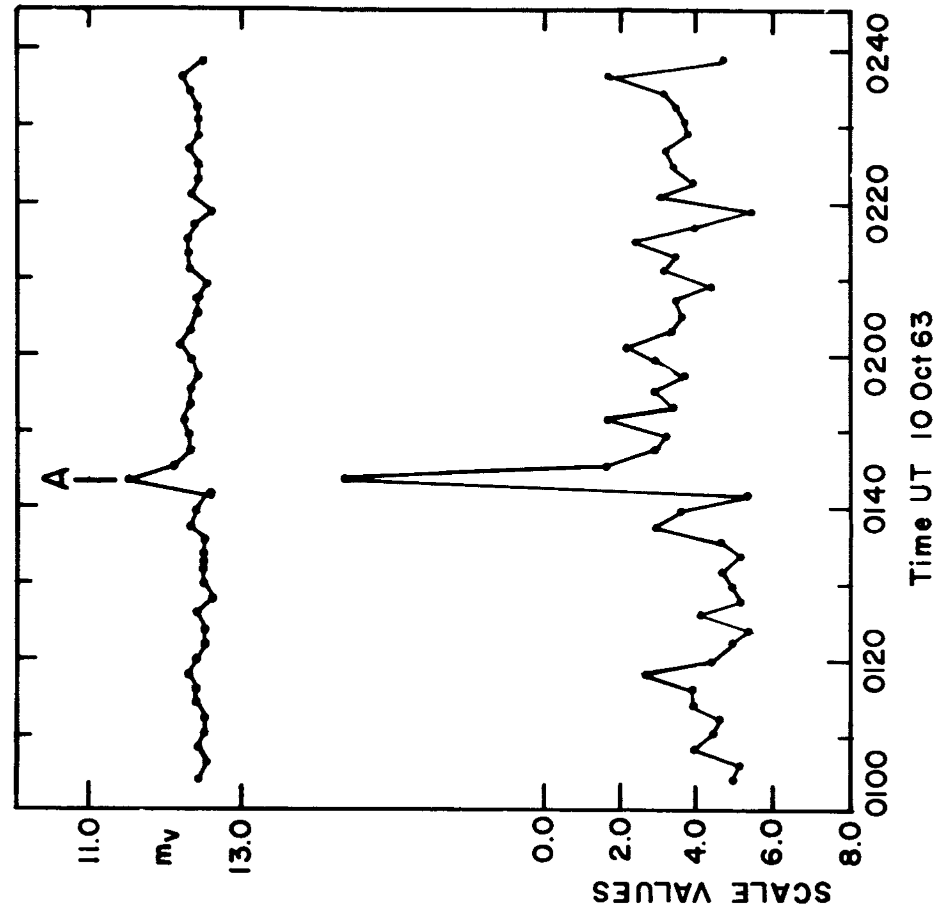


11.0
m_v 12.0
13.0
2200
2300
0000
0100
0200
14 Nov 60
Time UT 15 Nov 60
UV Ceti

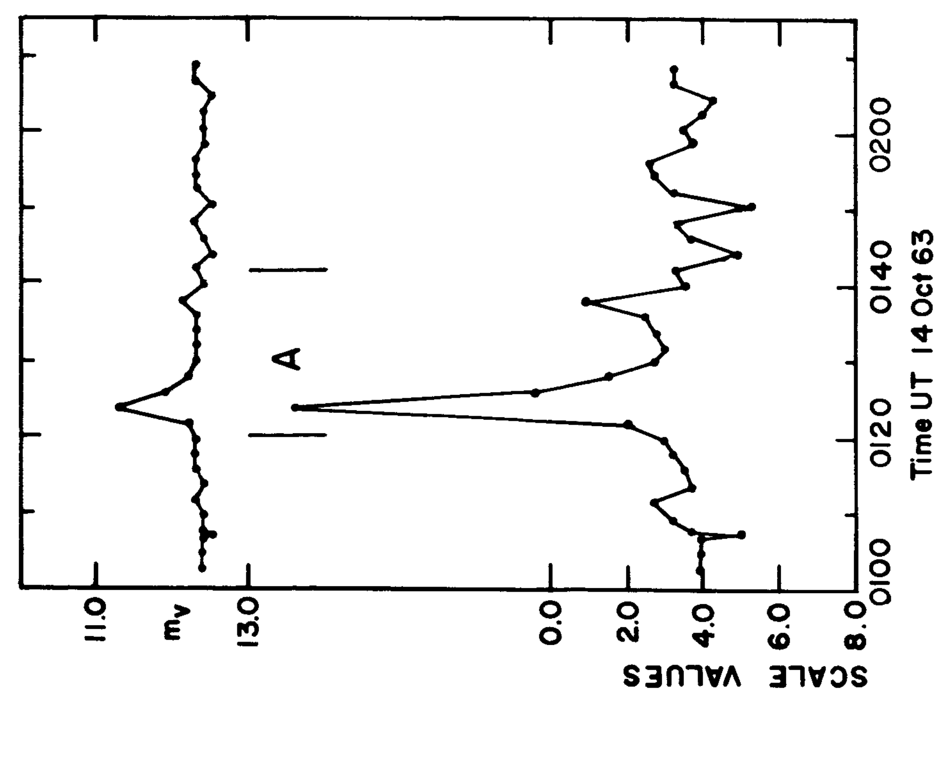

Possible Event
m_v
11.0
12.0
13.0
2100
2200
2300
0000
0100
0200
17 Oct 60
Time UT 18 Oct 60
UV Ceti


M
m_v
11.0
13.0
2300
0000
0100
Time UT 25 Nov 60
UV Ceti

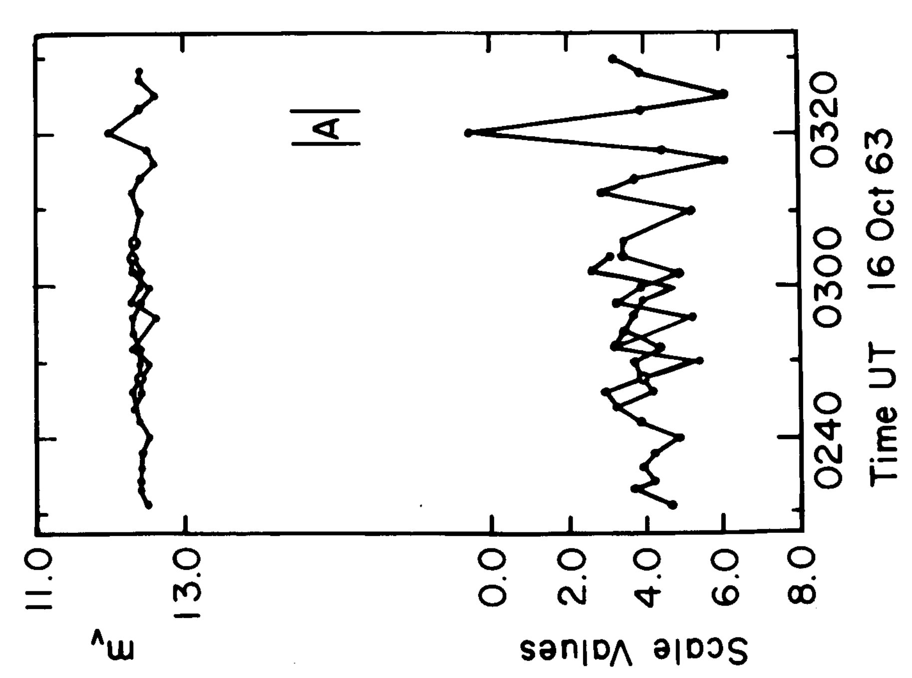

P
m_v
11.0
13.0
2100
2200
Time UT 25 Nov 60
UV Ceti



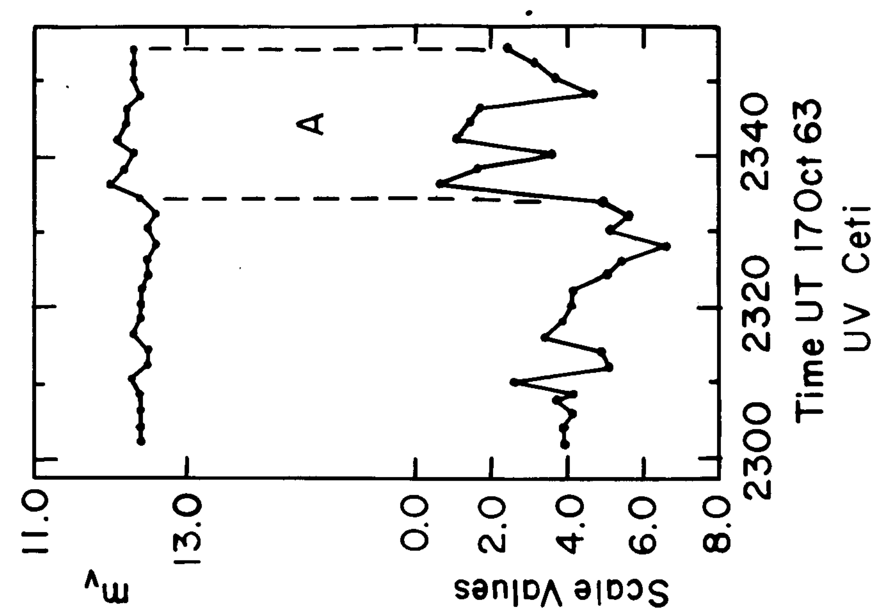
11.0
m_v
13.0
0.0
2.0
4.0
6.0
8.0
SCALE VALUES
A
0100
0120
0140
0200
0220
0240
Time UT 10 Oct 63
UV Ceti



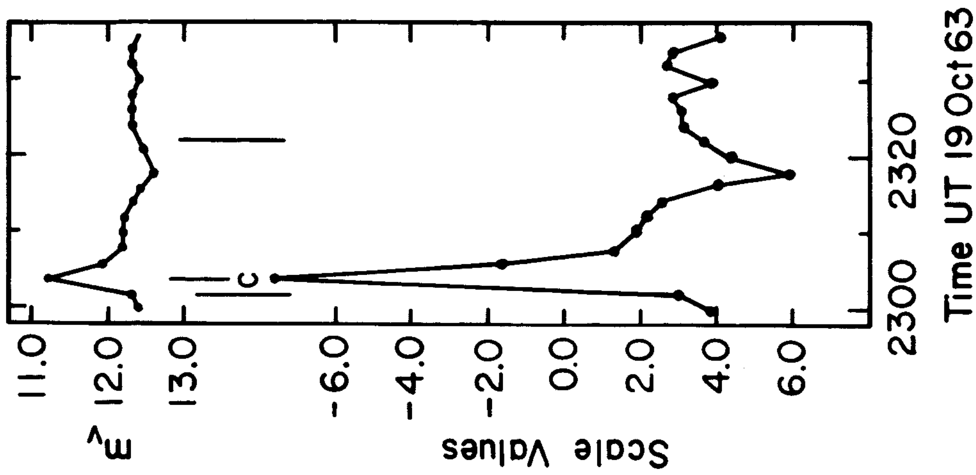
11.0
m_v
13.0
0.0
2.0
4.0
6.0
8.0
SCALE VALUES
A
0100
0120
0140
0200
Time UT 14 Oct 63
UV Ceti

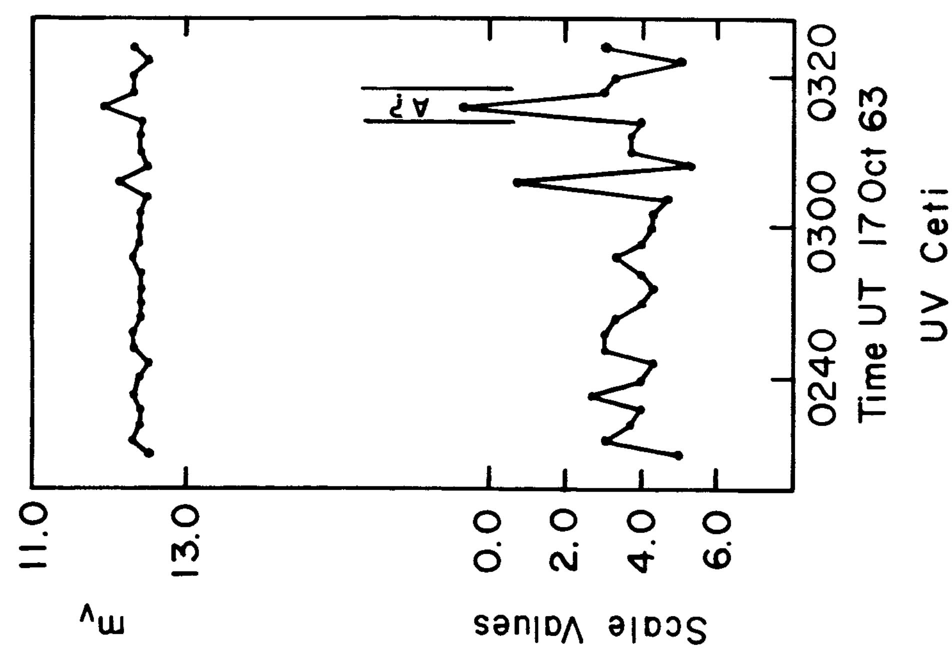


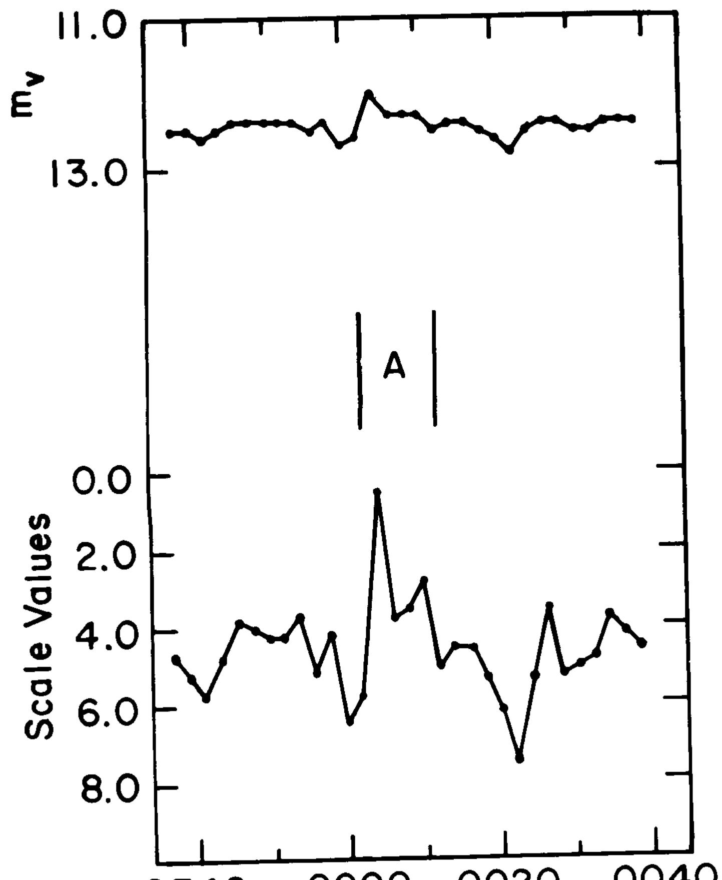
11.0
13.0
m_v
0.0
2.0
4.0
6.0
8.0
Scale Values
A
0240
0300
0320
Time UT 16 Oct 63
UV Ceti



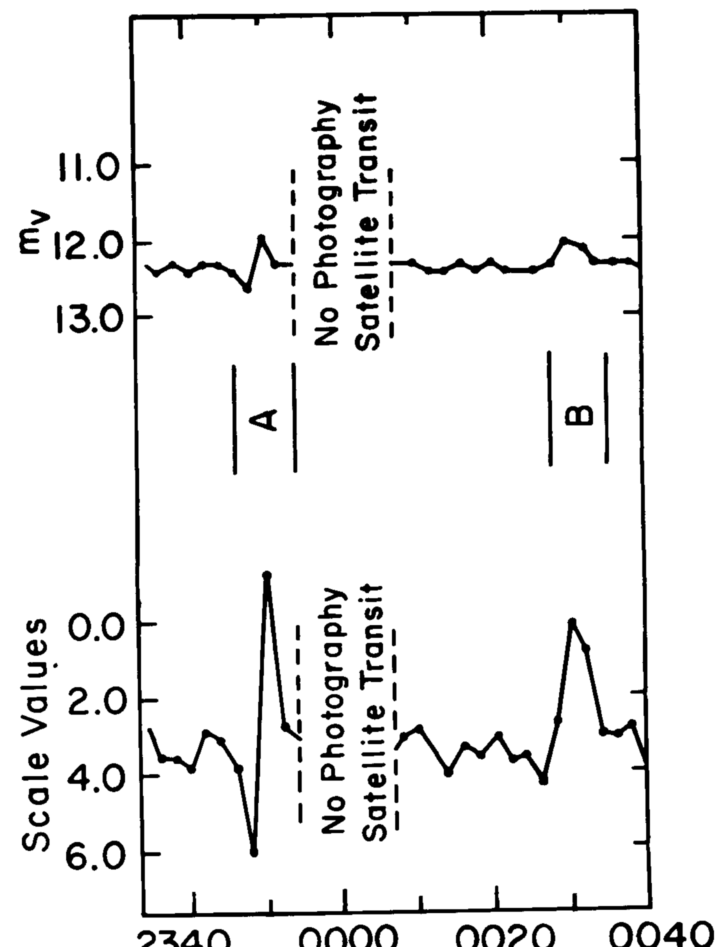
11.0
13.0
m_v
0.0
2.0
4.0
6.0
8.0
Scale Values
A
2300
2320
2340
Time UT 17Oct 63
UV Ceti


m_v
11.0
12.0
13.0
Scale Values
-6.0
-4.0
-2.0
0.0
2.0
4.0
6.0
C
2300
2320
Time UT 19 Oct 63
UV Ceti

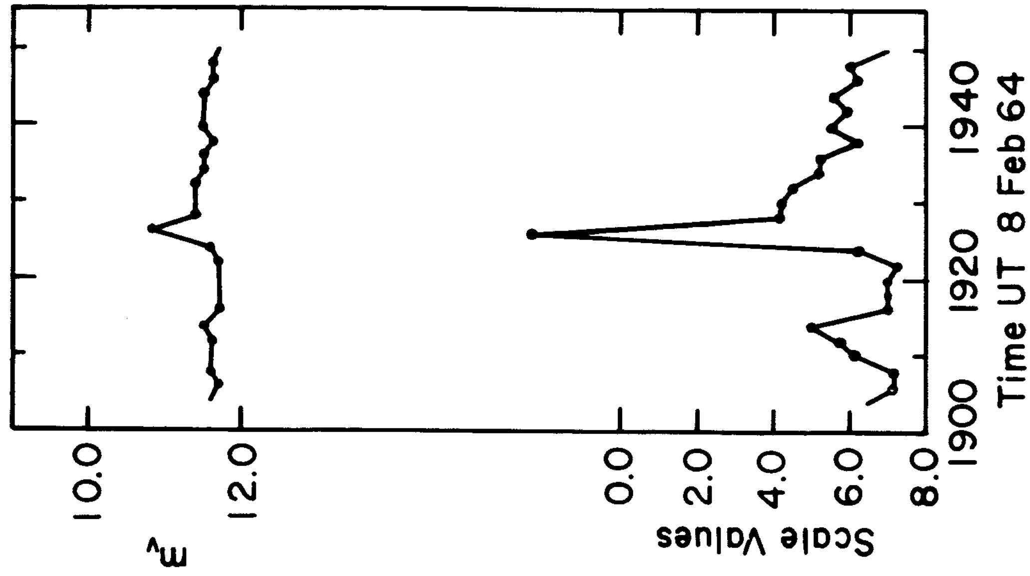

m_v
11.0
13.0
Scale Values
0.0
2.0
4.0
6.0
A?
0240
0300
0320
Time UT 17 Oct 63
UV Ceti



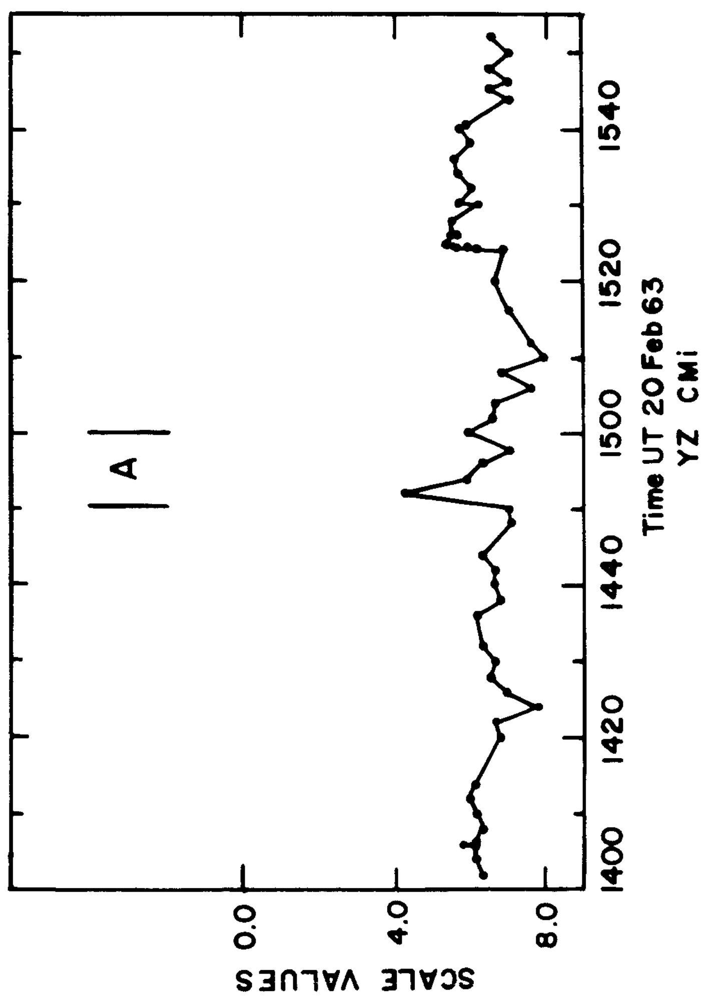
Time UT 19 Oct 63
UV Ceti



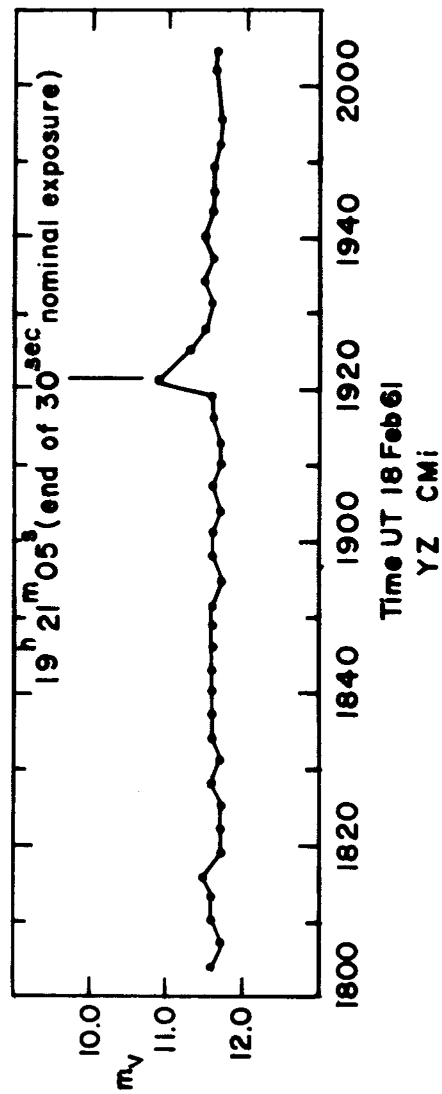
Time UT 26 Oct 63
UV Ceti



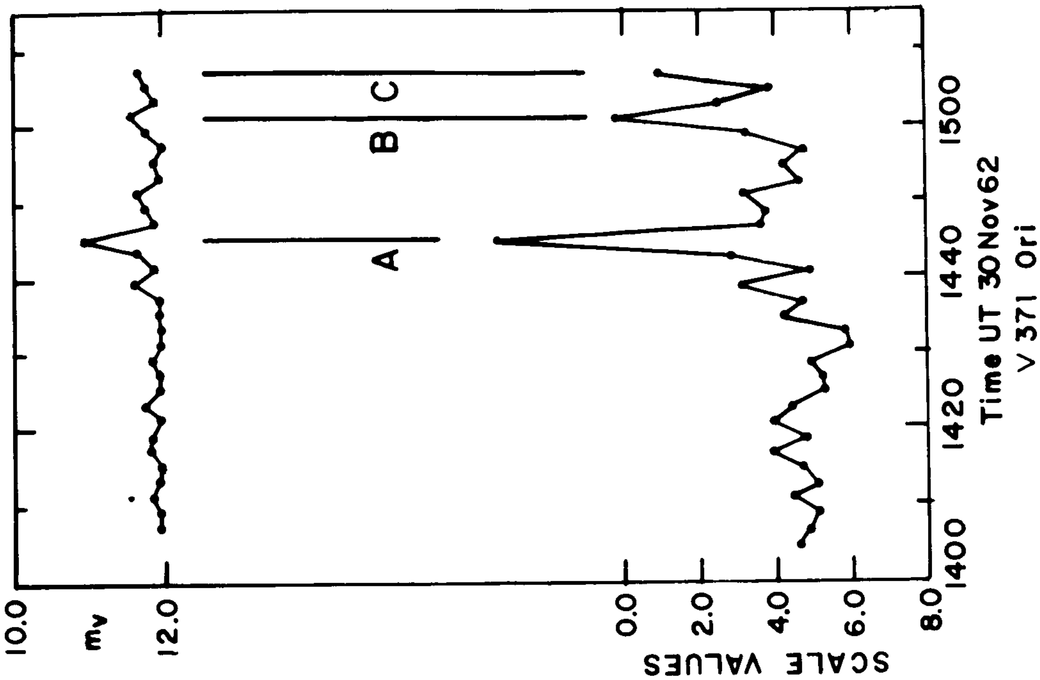
Time UT 8 Feb 64
YZ CMi
Scale Values
m_v

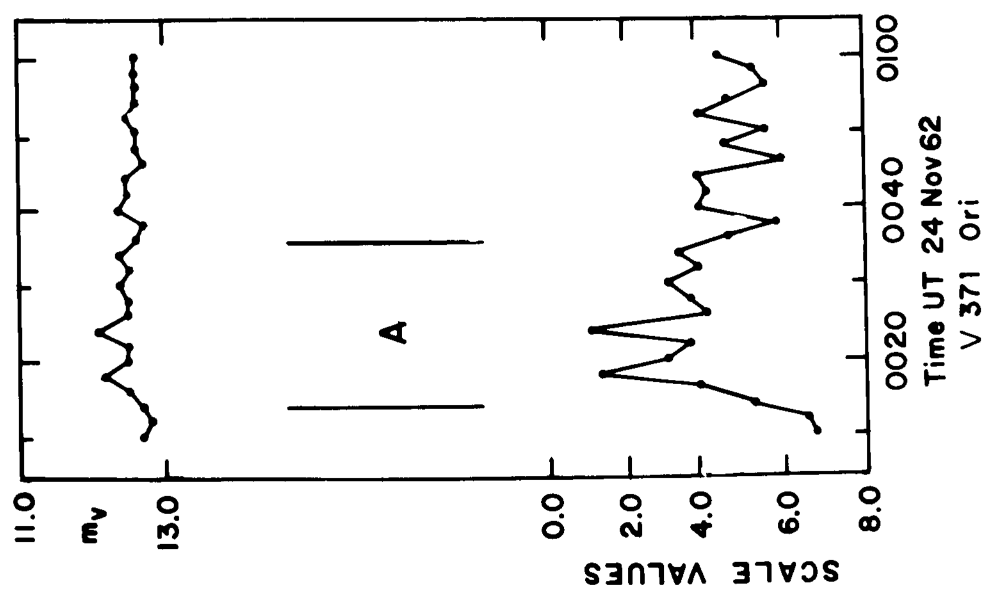


A
Time UT 20 Feb 63
YZ CMi
SCALE VALUES



$19^h 21^m 05^s$ (end of 30^{sec} nominal exposure)
Time UT 18 Feb 61
YZ CMi
m_v


10.0
m_v
12.0
0.0
2.0
4.0
6.0
8.0
SCALE VALUES
A
B
C
1400
1420
1440
1500
Time UT 30 Nov 62
V 371 Ori


11.0
m_v
13.0
0.0
2.0
4.0
6.0
8.0
SCALE VALUES
A
0020
0040
0100
Time UT 24 Nov 62
V 371 Ori

NOTICE

This series of Special Reports was instituted under the supervision of Dr. F. L. Whipple, Director of the Astrophysical Observatory of the Smithsonian Institution, shortly after the launching of the first artificial earth satellite on October 4, 1957. Contributions usually come from the Staff of the Observatory. First issued to ensure the immediate dissemination of data for satellite tracking, the Reports have continued to provide a rapid distribution of catalogs of satellite observations, orbital information, and preliminary results of data analyses prior to formal publication in the appropriate journals.

The Reports are also used extensively for the rapid publication of preliminary or special results in other fields of astrophysics.

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