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FLASHES FROM NORMAL STARS

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ABSTRACT

I would like to point out to the astronomical community the possibility that normal stars can undergo large-amplitude flashes on time scales from one to several thousand seconds. The evidence consists of flashes observed on 24 normal stars as well as the 141 flashes on field stars observed by Johnson. These stars are "normal" in the sense that they are not late-type dwarf stars and have no particularly exotic characteristic other than the flash. The flashes have amplitudes ranging up to greater than 7 mag involving energies greater than 10^{40} ergs. It is possible that these flashes are evidence for a rare class of previously unknown phenomena. If so, an "average" star undergoes a flash every century or so, although our Sun must have a much longer recurrence time scale. Further observations and calculations are required to confirm the reality and cause of these flashes.

Subject heading: stars: variable

I. INTRODUCTION

In his 1970 presidential address to the Royal Astronomical Society, H. Bondi gave an impassioned appeal for what he called short-time constant astronomy. As justification he said, "I think it is sometimes overlooked that perhaps we are missing a whole continent. I do not know exactly what I am looking for: it may be that one might discover that there are brick ends flying about space and obscuring stars every now and then for very brief moments; and it may be that there are bits in the interstellar medium that suddenly just flash up like a neon light. I just do not know." (Bondi 1970). This declaration of ignorance is still valid today. Harwit (1981) points out that poorly sampled regions of parameter space for celestial observations (like short-time constant astronomy) may contain new and unexpected classes of phenomena. Surely, we are justified at examining the relatively sparse data available for short-time constant astronomy to see what continents we might be missing.

The night sky is full of flashes. I take a flash to be any pointlike burst of optical light isolated in time which occurs on time scales typically from seconds to an hour. The flashes reported in the astronomical literature can be divided into two classes—those that are not associated with a particular star and those that are.

Flashes without a stellar association may be caused by near-Earth phenomena such as satellite glints (Schaefer *et al.* 1987*b* and references therein; Katz *et al.* 1986; Maley 1986; Bishop 1975; Sommer 1980; Schaefer *et al.* 1984*b*; Hale 1986; Warner 1986; Liemohn 1969; and McLeod 1980), satellites (Pedersen *et al.* 1984; Schaefer *et al.* 1987*a*; Pedersen *et al.* 1987), balloons (McLeod 1980), airplanes (Honda 1986*a*, *b*; Greiner *et al.* 1987, Schwartz 1986), fireflies (Schaefer *et al.* 1987*b*; Patterson 1979), lightning (Bhat *et al.* 1983), meteors (Byrne and Wayman 1975, 1977; O'Mongain and Weekes 1974; Baird, Delaney, and Lawless 1975; Ceplecha 1977; Pedersen *et al.* 1984, 1987; Schaefer *et al.* 1987*a*; Schwartz 1986; Denning 1879, 1923; Schaefer *et al.* 1987*b*), asteroids (NSV 1208, 2754, 4924, and 12015 in Kukarkin *et al.* 1982 and references therein), instrumental effects (Vanderspek 1985; Warner, van Citters, and Nather 1970; Robinson 1980), and plate defects (Schaefer 1983, 1987 and references therein; Hudec *et al.* [1987] and references therein; Greiner *et al.* [1987] and references therein; and NSV 206, 1329, 1336, 1375, 1879, 2734, 13433, 13994, and 14770 in Kukarkin *et al.* [1982] and references therein). Some flashes without stellar association are likely to have a true stellar cause (Lovas 1977*a*, *b*; Anderson, Luyten, and Sandage 1967; Zwicky 1974; Hertzog 1987; Bignami, Caraveo, and Paul 1984; Honda 1983*a*, *b*, 1986*a*, *b*; Hudec 1986; Hudec *et al.* 1987*a*; Pedersen *et al.* 1984; Schaefer *et al.* 1987*a*; NSV 2853 and 6101 in Kukarkin *et al.* [1982] and references therein). In many cases, the true cause cannot be identified (Sanderson 1986; McWhorter 1986; Christen 1982; Johnson 1981; Fisher 1987; Isles 1987; NSV 238, 312, 4550, 7542, 9445, 9663, 10112, 11055, 11164, and 13440 in Kukarkin *et al.* [1982] and references therein).

Of the flashes with stellar associations, many arise from known "exotic" classes of stars (see Table 2), of which the ordinary flare stars are best known. Flashes on "exotic" stars can have suprisingly large amplitude: 1.7 mag on W UMa (Kuhi 1964), 1.8 mag on LkHα 198 (Chavarria -K. 1985), 2.4 mag on TV Col (Szkody and Mateo 1984), 3.1 mag with a duration of 2.4 s on EV Lac (Gershberg and Petrov 1986), 6.6 mag on EV Lac (Roizman and Shevchenko 1982), and >19 mag for gamma-ray bursters (Schaefer 1981; Schaefer *et al.* 1984*a*). Flashes on most classes of "exotic" stars have never been explained, although the mechanism is presumably related to the peculiarities of the parent star.

However, there are a significant number of celestial flashes for which the associated star has no obvious peculiarities. For these stars, there is no obvious mechanism for causing the flash.

II. OBSERVATIONS

I have collected a total of 24 "normal" stars for which flashes have been observed (see Table 1 where the flashes are ordered roughly by spectral type). These events have been selected by the following criteria. (1) Main-sequence stars later than K0 are excluded as these could be ordinary flare stars. This excludes events on Butler's star (K0 V; Andrews 1966; Andrews, Butler, and Eksteen 1966; Andrews 1967; Malcolm 1984), DH Car (K2; Gurzadyan 1980), V774 Her (K2 V; Mahmoud and Soliman 1980; Chugainov 1984), PZ Mon (K2

TABLE 1

FLASHES FROM NORMAL STARS

No.	Star	Type	m_v	Δm	τ (s)	D (s)	N	log (E)	θ (″)	Detector	References
1	66 Oph	B2 Ve	4.4	1.0, 1.8	100, 50	400, 400	9	40	~ 10	12″ Schmidt	1–3
2	BW Vul	B2 III	6.3	>0.8	~ 10	~ 60	~ 10	>39	~ 10	photometer	4
3	BD +31°1048	B7 V	6.0	~ 2.2, ~ 1.2	300, 300	$\gtrsim 4000$	8	39	~ 10	12″ Schmidt	5, 6
4	HD 160202	B8	8.4	2, $\gg 7$	~ 1	~ 100	8	$\sim 39\frac{1}{2}$	~ 10	television	7–9
5	BD +26°870	B8 III	5.7	2.2, 2.2	?	$\lesssim 4000$	2	$\lesssim 40\frac{1}{2}$	~ 10	photography	10, 11
6	SS 199 II	A0 III	13.1	2.4	360	1100	82	39	~ 10	photometer	12
7	β Eri	A3 III	2.8	~ 3	?	>9000	~ 10	$>40\frac{1}{2}$	~ 300	visual	13
8	X Tri	A5 V + G0 V	8.9	0.35	1400	1700	9	$37\frac{1}{2}$	~ 10	photometer	14
9	ζ Lyr	Am + F0 IV	4.1	~ 2	$\lesssim 1$	~ 1	1	36	~ 300	visual	15–17
10	α Cir	F0 Vp	3.2	~ 2, ~ 2	<1, <1	2, 2	1, 1	$35\frac{1}{2}$	~ 300	visual	18
11	SS Leo	F0	11.4	0.7	$\lesssim 250$	$\lesssim 700$	6	$37\frac{1}{2}$	~ 10	photometer	19
12	UU CrB	F8	8.6	0.30	2600	2600	27	36	~ 10	photometer	20
13	S For	F8	8.5	2.9	<480	~ 3600	3[a]	$38\frac{1}{2}$	~ 10	visual	21
14	β Cam	G0 Ib + F0 IV	4.1	~ 1.2	0.1	0.25	7	$36\frac{1}{2}$	~ 300	vidicon	22
15	MT Tau	G5 V	14.7	0.7	?	?	?	~ 35	~ 10	photography	23
16	HD 282773	G5	9.9	0.25	2	60	60	34	~ 10	photometer	24
17	HD 97766	G5	8.5	0.28, 0.24	<1600, <2000	<900, <1400	5	$35\frac{1}{2}$	38	photometer	25
18	CF UMa	G8 VI	6.4	0.62	300	$\gtrsim 600$	4	35	0.03	photography	26–28
19	ν Oph	G9 III	3.3	~ 7	~ 10	>80	~ 10	>40	~ 300	visual	29
20	τ CrB	K0 III	4.7	~ 1.7	<0.25	0.5	1	$35\frac{1}{2}$	~ 300	visual	30
21	V654 Her	K2 III	10.0	0.15	140	300	50	36	~ 10	photometer	31–33
22	ϵ Peg	K2 Ib	2.4	1.7	250	>660	~ 10	>41	~ 1	visual	34, 35
23	μ Cep	M2 Ia	4.2	0.034	150	$\gtrsim 1000$	190	$39\frac{1}{2}$	~ 10	photometer	36
24	G99–47	DAP 9	14.1	1.1	110	380	350	32	10	photometer	37

[a] Three independent observers.

REFERENCES.—(1) Page and Page 1970*a*; (2) Page and Page 1970*b*; (3) Cousins 1952; (4) Eggen 1949; (5) Andrews 1964; (6) Solomon 1966; (7) Bakos 1968; (8) Bakos 1970; (9) Bakos 1985; (10) Volk 1967; (11) Shao 1967; (12) Philip 1968; (13) Brunner 1985; (14) Rovithis and Rovithis-Livaniou 1983; (15) Hagen 1903; (16) Warner 1986; (17) Johnson 1900; (18) Bell 1987; (19) Skillin, Fernley, and Kilkenny 1987; (20) Olson 1980; (21) Ashbrook 1959; (22) Wdowiak and Clifton 1985; (23) Weaver and Naftilan 1973; (24) Kovalchuk and Pugach 1984; (25) Zhang, Li, and Wang 1987; (26) Beardsley, Gatewood, and Camper 1974; (27) Heintz 1984; (28) Van de Kamp 1968; (29) Cook 1987; (30) Durda 1986; (31) Moffett and Vanden Bout 1973; (32) Tsvetkov and Pettersen 1985; (33) Christiansen and Kaitchuck 1975; (34) Wood 1972; (35) Schmidt 1985; (36) Arsenijevic 1985; (37) Middleditch 1988.

V; Cristaldi and Rodono 1968), and Roques's star (K3 V; Roques 1984) which may be extreme cases of flare stars. (2) Sufficient information must be available about the event. This excludes the three events when normal stars were on one occasion seen to exhibit a much hotter spectrum (Ludendorff and Everhard 1905; Vyssotsky and Balz 1958; Alden 1958; Irvine 1972; Pope 1983; Pickering 1896; Thackeray 1974). Also excluded is the large-amplitude flash of 65 s duration on KY Cep (Chkhikvadze 1970) for which the quiescent counterpart is uncertain. Other flashes excluded are those discussed in Hoffmeister (1968), Jackisch (1969), and Hoffmeister (1951). (3) The stars must be "normal" in the sense that no rare or exotic phenomena are associated with it other than the flash. Any star, if studied closely enough, will be found to be peculiar in some properties, so, the definition of "normal" is somewhat subjective. I will take a "normal" star to be one that can be MKK typed and which has no rare peculiarity which distinguishes it from other stars of similar type. The normal stars (i.e., those presented in Table 1) include four intrinsic variables, one eclipsing binary, and one Be star, for which I judge the flash to be unrelated to these properties.

Half of the stars in Table 1 are visible to the unaided eye, and they cover much of the H-R diagram (however, excluding late-type dwarfs which have been selected against). The flash amplitude (Δm) given in the table is for the color with the largest measured amplitude (usually V). The minimum e-folding rise or fall time (τ) and the total event duration (D) are derived from the available light curve information. The quantity N is an estimate of the number of independent measurements which confirm the existence of an anomaly. The flash energy (E) is

$$E = L_*(10^{\Delta m/2.5} - 1)(D/S) , \quad (1)$$

where L_* is the luminosity of the flash star, and S is a dimensionless parameter which depends on the shape of the light curve. For a square-wave–shaped flash, $S = 1$, while $S = 2$ for a triangular-shaped wave. This energy calculation implicitly assumes that the bolometric correction for the star and flash are identical. The angular resolution of the detector (θ) is a measure of the positional coincidence of the flash and the star.

Five of the flashes in Table 1 were detected photographically; in all cases the event was recorded on more than one image. The existence of multiple images and multiple events provided a powerful argument that plate defects, satellite glints, and other artifacts are not involved. This method has the advantage that excellent angular resolution is achieved, so the positional coincidence between the flash and the star can be accurately ascertained. These advantages combine to make these cases some of the strongest evidence for the existence of flashes on normal stars. For these cases, I can conceive of no reasonable alternative explanation.

Only one exception need be made to the previous strong statement. This arises for the case of CF UMa because of the different observing mode under which the plate was exposed at Allegheny Observatory. Since CF UMa was much brighter than nearby astrometric comparison stars, the central portion of the plate was exposed through a rotating disk with a segment missing. W. Heintz (1984, 1988, private communication) has questioned the existence of the flash on the grounds that the rotating disk may cause the apparent flash. However, he can provide no specific mechanism: (1) Any irregularities in the shape of the clear disk section would have to vary by roughly a factor of 2 in size to explain the observed amplitude. (2) Diffraction and reflection effects have not been found during experimentation and they should affect the image location and shape. In addition, these effects should be visible on a sizable fraction of program star images. Heintz knows of perhaps four other apparent flares in the $\sim 10^5$ Sproul Observatory archival plates and suggests that the same instrumental effect caused these also. However, if we are testing the existence of rare flashes, then Heintz's argument is inconclusive since these additional events could be interpreted as evidence for the existence of additional flashes.

Two of the flashes in Table 1 were detected with imaging electronic detectors. These devices have all the advantages of photographic detectors. Unfortunately the instrumental effects are less well known and no control studies exist. For example, one could postulate that some instrumental effect associated with the brightest star in the field caused the apparent flashes on β Cam. Although the possibility of such a "sparkle" cannot be ruled out, it must be stressed that there is no positive evidence to support such an ad hoc hypothesis and that no similar "sparkle" was seen in $\sim 10^{7.5}$ frames of data.

The pictures which show the flashes from HD 160202 also show three other images which do not correspond to real stars. G. Bakos (1988, private communication) identifies these as being caused by reflections in the orthicon. These reflection images are distinctly different from star images in that they are out-of-round and have a mottled edge. The reflection images are constant in all frames. The flashes on HD 160202 are apparently not related to this instrumental effect because the images are round, not mottled in appearance, and vary from frame to frame.

The flash on HD 160202 deserves special comment both because of its extreme nature and because of the difficulty in determining its Δm and τ. The original published light curve (Bakos 1968, 1970) shows that HD 160202 was as bright as first magnitude. Another calibration (Bakos 1985) places the maximum brightness as fifth magnitude, the difference arising from alternate ways of extrapolating the calibration curve. Each light curve point is based on *two* photographs of the television screen spaced 8 s apart. Bakos (1970) reports seeing "a bright flash, as if a meteor had entered the field of view," some time *before* the TV screen was photographed. A reasonable interpretation (G. Bakos 1987, private communication) is that HD 160202 had an extremely large ($\Delta m \gg 7$) flash of short duration ($\tau \sim 1$ s) which was photographed a minute or so later during its decay.

Ten of the flashes in Table 1 were detected photometrically and hence, high-resolution light curves with good photometric accuracy are available. (The flash on G99–47 was observed with the Lick 61 cm telescope on 1971 December 21 with 4 ms time resolution that has been binned to 1.024 s resolution.) In general, two alternative explanations are available to the flash hypothesis. One alternative is that some instrumental glitch is adding counts, while the other alternative is that some luminous object (a meteor, satellite, fire fly, or airplane) passed through the field of view. The rates and morphology for both classes of events have been extensively investigated with a coincidence experiment (Schaefer *et al.* 1987*a*). We were never able to generate any instrumental artifacts which had a rise time of longer than tens of milliseconds, nor are we aware of any other observers identifying slowly rising glitches (cf. Robinson 1980). Similarly, any object passing through the very small field of view must have a velocity relative to the background stars that is slower than the sidereal rate to produce a duration as long as one second. The light curves of all 10 photometrically detected flashes have relatively slow rise times and relatively long durations. It will be difficult to explain these events as artifacts.

Seven of the flashes in Table 1 were detected visually. This creates a difficulty in that the eye is not a permanent storage medium, so it is impossible to later examine the data at leisure. In addition, the eye is notoriously susceptible to psychological and physiological effects when the flash duration is short. Finally, in modern times, satellite glints can fool the eye quite easily because of the eye's poor angular resolution. As such, the flashes on α Cir (1986 October 11 9:15 UT and 1987 June 15 9:48 UT from Tabulam, N.S.W., Australia), τ CrB (1986 July 30 4:30 UT from Alger, Michigan), and ζ Lyr are only weak evidence for flashes on normal stars. However, the long durations of the flashes on S For, β Eri, ν Oph (1987 July 22 $\sim$4:30 UT from Prescott, Arizona), and ϵ Peg (three Harvard plates show no anomaly from 1972 September 26 19:47 to 21:47 UT) are good evidence against the satellite, physiological, and psychological explanations. Both S For and ϵ Peg were visually examined with a telescope during the flash. In the case of S For, the flash was independently discovered by observers in Germany, Italy, and Austria.

III. RATE ESTIMATES

If a flash had an amplitude of less than a magnitude or so, a visual observer is likely to either not notice the change if the event duration is long or mistake it for a particularly violent twinkle if the event duration is short. Schaefer (1985) has collected 12,800 hr of amateur meteor observations during which 158 "head-on" meteors were seen. Many of these events are undoubtedly real head-on meteors, so let us estimate that the number of short duration, large amplitude flashes is less than, say, 50. The number of stars monitored at any time by the amateurs will be of order 10^3. This implies a recurrence time scale for average stars of longer than 30 yr.

Photographic surveys are, in general, insensitive to detecting short flashes. If nonlinearities in the photographic process are ignored, the instantaneous maximum amplitude (Δm) will be related to the photographed apparent magnitude ($\Delta m_{\rm OBS}$) as

$$\Delta m_{\rm OBS} = 2.5 \log\,[1 + (10^{\Delta m/2.5} - 1)D/ST]\ , \qquad (2)$$

where T is the exposure time. We see that a 30 minute exposure for a triangular ($S = 2$) flash with $D = 1$ second will be barely detectable (say $\Delta m_{\rm OBS} > 0.2$) only if Δm is greater than 7.1 mag. A triangular flash with $\Delta m > 2$ mag will be barely detectable only if $T/D < 13$. This explains why flashes have not been detected on most photographic patrols or archival photographs.

Relatively few types of astronomical observations would detect a brief optical flash. One such program would be time series photometry of normal stars, for which, I crudely estimate that 10^6 hours of data have been analyzed. Another program would be flare star searches by chain photography, for which I crudely estimate that 10^2 stars have been monitored for 10^5 hr. In this monitoring time, 10^1 flashes have been observed (or at least reported), so the recurrence time scale for an average star is of order once every century.

Johnson (1959) has performed the only study which is capable of detecting rare flashes from normal field stars. His experiment was to take rapid sequences of short exposure plates on the Palomar 48 inch (1.2 m) Schmidt. When the plates were blinked, he found a total of 141 cases where a field star was significantly brighter (0.5 to 1.0 mag amplitude) on one plate. Unfortunately, the coordinates and colors of the

TABLE 2

FLASHES FROM "EXOTIC" STARS

Class	D (s)	Δm	λ[a]	Ref.
Flare stars	10–1000	<6.6	O, X, R	1–4
X-ray bursters	~30	1–2	O, X	5
Gamma-ray bursters	1–300	≳19	O, G	6–8
Cataclysmic variables[b]	50–3600	2.0–2.4	O	9–11
Symbiotic stars	<1200	0.4	O, R	12, 13
RS CVn–like stars	~2000	<0.5	O, R, U	14–21
W UMa stars	600–2000	0.1–1.7	O	22–27
Antiflare stars	3000	0.5	O	28–30
Peculiar stars	10–200	0.3–1.8	O, U	31–33

[a] The wavelength regions of observed flash activity are designated by O for optical, X for X-ray, R for radio, G for gamma ray, and U for ultraviolet.

[b] Note that the optical flashes discussed here are morphologically different from the usual flickering exhibited by cataclysmic variables.

REFERENCES.—(1) Gurzadyan 1980; (2) Gershberg and Petrov 1986; (3) Roizman and Shevchenko 1983; (4) Bond 1976; (5) Lewin and Joss 1981; (6) Schaefer 1981; (7) Schaefer *et al.* 1984*a*; (8) Moskalenko *et al.* 1987; (9) Szkody and Mateo 1984; (10) Imamura, Steiman-Cameron, and Middleditch 1987; (11) Schwarz and Heemskerk 1987; (12) Nha and Lee 1983; (13) Woodsworth and Hughes 1973; (14) Baliunas, Guinan, and Dupree 1983; (15) Simon, Fekel, and Gibson 1985; (16) Ramsey and Nations 1983; (17) Zeilik *et al.* 1983; (18) Wood 1957; (19) Cristaldi and Rodono 1971; (20) Patkos 1981; (21) Geyer 1977; (22) Kuhi 1964; (23) Huruhata 1952; (24) Eggen 1948; (25) Bakos and Tremko 1975; (26) Yang and Liu 1985; (27) Egge and Pettersen 1983; (28) Pugach 1975; (29) Kovalchuk 1984; (30) Karetnikov and Pugach 1973; (31) Chavarria-K. 1985; (32) Kartasheva 1972; (33) Darius 1978.

flashing stars were not recorded and no follow-up study has been done. Johnson calculates that an average field star has a flash once every 125 days. These frequent flashes may be just the low-amplitude end of some distribution for which flashes in Table 1 represent the high-amplitude end.

The possibility of a distribution in flash amplitudes is suggestive that the stars listed in Table 1 might show more frequent low-amplitude flashes. Unfortunately, most of these stars have very little accumulated observing time during which a small flash would be detected. I expect that only X Tri has more than a week or so of such data.

For our own Sun, better limits can be placed on possible flashes. It is unlikely that a flash with $\Delta m > 2$ mag would have been missed in the last century of scientific solar observations. It is plausible that any flash with $\Delta m > 4$ mag which occurred anytime during the last two millennia when the Sun was up in China would have been recorded in Chinese histories. The existence of a glazing on the top surfaces of lunar rocks has been used as a strong argument for a "solar outburst" where the Sun increased its luminosity by over 100 times for 10 to 100 s within the last 30,000 years (Gold 1969; see also Mueller and Hinsch 1970). Criticisms of this conclusion (Green 1970; Dietz and Vergano 1970; Greenwood and Heiken 1970; Morgan *et al.* 1971) have been answered by Gold (1970) who points out that much of the criticism discusses ordinary impact glasses and not the morphologically specific types of glazes on which the argument is based. Gold argues that all alternative hypotheses have difficulties explaining the glaze's distribution only on the tops of sometimes delicate rocks in the center of small craters. A sufficiently large flash will wreak havoc with Earth's environment (Niven 1971). The mode of impact on Earth will depend on the spectrum of the flash and may include damage by atmospheric heating and ozone destruction. I crudely estimate that a flash with log $(E) = 38$ (cf. Table 1) might result in a major extinction episode. (The Cretatious-Tertiary dinosaur extinctions cannot be explained by a flash since there is no mechanism for enhancing iridium.) The Sun could have undergone a few (at most) such super flashes in the last 10^8 yr. These data suggest that our own Sun may have a significantly lower event rate than average field stars.

To intentionally catch a rare flash, many stars must be simultaneously monitored. The best experiment for detecting flashes is the Explosive Transient Camera (Vanderspek 1985) and the associated Rapidly Moving Telescope (RMT, Teegarden *et al.* 1984). When completed, this combination will monitor 1.5 steradians for flashes brighter than 10th mag. Such a survey would monitor at least 10^5 stars for which a flash with $\Delta m > 2$ should be detected. If the average recurrence time scale is once a century, then a mere 10 hr of observations will reveal one flash. The difficulty will lie in distinguishing flashes from other triggers (Schaefer 1985; Schaefer *et al.* 1987*b*), a task for which the RMT is ideally suited.

IV. DISCUSSION

What are the causes of flashes on normal stars? The wide distribution of stars across the H-R diagram suggests that the mechanism may be related to some ubiquitous property of stars. One possible energy source is reconnection of a star's magnetic field. Another possible energy source could be the impact of a comet or asteroid onto an unobserved white dwarf companion.

In an analogy with solar flares and flare stars, it is possible that the flash energy source derives from the star's magnetic fields. The most efficient such process involves the annihilation of the field inside some volume. The surface magnetic field, B, needs to be sufficiently high so that the total energy in the field can provide the observed energy. The total magnetic energy available outside the star's surface of radius R_* will be $B^2 R_*^3/6$. If we assume that some fraction, f, of this available energy is released, then

$$B > 130 \text{ G } (E/10^{36} \text{ ergs})^{0.5} (R_*/R_\odot)^{-1.5} f^{-0.5} . \tag{3}$$

Another limit on B comes from the requirement that the emitting region (of density ρ_m) can be crossed by Alfvén waves in a time less than τ. I will take the characteristic size of the emitting region to be $R_* f^{0.5}$. This leads to

$$B > 8 \times 10^5 \text{ G } (\rho_m/10^{-11} \text{ g cm}^{-3})^{0.5} \times (R_*/R_\odot)(\tau/1 \text{ s})^{-1} f^{0.5} . \quad (4)$$

The combination of the conditions represented in equations (3) and (4) implies a lower limit on B for a typical flash which is typically around 10^4 G.

The total energy available from a comet accreting onto a white dwarf is

$$E = 8 \times 10^{35} \text{ ergs } (M_{\text{WD}}/M_\odot)(R_{\text{WD}}/10^{-2} R_\odot)^{-1} \times (R_c/10 \text{ km})^3(\rho/1 \text{ g cm}^{-3}) , \quad (5)$$

where M_{WD}, R_{WD}, R_C, and ρ are the white dwarf's mass, radius, the comet's radius and density, respectively. Much of this energy may be radiated as a blackbody with a photospheric radius comparable to R_{WD} (cf. Tremaine and Zytkow 1986) and a temperature

$$T = 70{,}000 \text{ K } (E/8 \times 10^{35} \text{ ergs})^{0.25}(D/100 \text{ s})^{-0.25} \times (R_{\text{WD}}/10^{-2} R_\odot)^{-0.5} . \quad (6)$$

It will be difficult to explain flashes with large E (especially in view of the large bolometric correction associated with the high temperature) because of the possibly unreasonably large size required for the comet. Comet–white dwarf collisions have been considered by Alcock, Fristrom, and Siegelman (1986) and Tremaine and Zytkow (1986). They find that significant numbers of comets will survive a red giant phase and even a supernova eruption (see also J. Katz 1986) and will then provide an impact rate of between several per year and once per 10 millennia (depending on the system's structure and history).

A search for the hypothesized white dwarf star can provide a test of the comet collision hypothesis. For the case of G99–47, we already know that a white dwarf is in the system. Wdowiak and Clifton (1985) have argued for a white dwarf companion of β Cam as an explanation of the observed He I line, although it is also possible to explain these lines as coronal recombination lines. Spectra from the *International Ultraviolet Explorer* (*IUE*) could potentially reveal the presence of a hot white dwarf companion. A search through the *IUE* merged log shows that long-wavelength spectra only are available for τ CrB and μ Cep, while short-wavelength spectra are available for ν Oph, 66 Oph, BW Vul, and ϵ Peg. For ν Oph and ϵ Peg, the flux from the white dwarf will be less than 1% of the primary star's flux for a white dwarf surface temperature of under 10,000 K. For the other four stars with *IUE* observations, the white dwarf light will be swamped by light from the primary star for all reasonable white dwarf surface temperatures. Hence, the current available *IUE* data do not test for the existence of white dwarf companions to the flash stars. However, future *IUE* observations may be able to reveal hot companions for the cool main-sequence stars in Table 1.

The magnetic reconnection model has the disadvantage that many classes of stars are thought to have only a very weak magnetic field. The comet accretion model has the advantage that white dwarf companions are common, hard to detect, and can occur around stars at any location in the H-R diagram. Neither energy source seems satisfactory for the most energetic flashes.

V. CONCLUSIONS

A pessimistic commentator would be frightened of making sweeping claims in light of the pedestrian nature of the Perseus Flasher (Schaefer *et al.* 1987*b*), the instrumental origin of the flash on G44–32 (Robinson 1980), the man-made cause for the potassium flares (Wing, Peimbert, and Spinrad 1967), and the coincidence involving the Hertzsprung object (Schaefer 1983). A pessimist might conclude that all 24 events are artifacts: the flashes on τ CrB, ν Oph, and α Cir are satellite glints. The flashes on β Eri, BD +26°870, and ζ Lyr are poorly documented. The reliability and photometric accuracy of all the visual observations are questionable. The flash on HD 160202 was a head-on meteor with a persistent train. The flashes on MT Tau, CF UMa, HD 97766, and HD 282773 demonstrate only that the normal flare star mechanism extends to G type stars. The flashes on X Tri (an Algol type eclipsing binary possibly with mass transfer, Mallama 1975), α Cir (a recently discovered 6.8 minute, 0.01 mag amplitude pulsator, Schneider and Weiss 1983; Kurtz 1982), BW Vul (a β Cepheid variable), SS Leo (an RR Lyrae variable), μ Cep (an irregular slow variable), and 66 Oph (a Be star) are merely examples of flashes on "exotic" stars (see Table 2). BD +31°1048 and BD +26°870 may also be Be stars. The conclusion that V654 Her is a giant is based on subtle spectral cues, so it is still possible that V654 Her is really just a normal flare star. The rotating disk used for the flash plate of CF UMa could have created the flash as suspected by Heintz (1984). The photometrically observed flashes could have instrumental problems similar to those of Robinson (1980). The Vidicon observations of β Cam have no control study to detect rare instrumental effects.

An optimistic commentator would tend to remember the histories of the serendipitous discoveries of flare stars (Gurzadyan 1980), flickering on cataclysmic variables (Walker 1954), and white light solar flares (Carrington 1985; Hodgson 1985). The optimist would respond to the specific criticisms of the pessimist as follows: The observations of S For are completely reliable because *three* independent observers in three different countries all detected the flash. The amplitude of the visual flashes range from 1.7 to 7, for which the eye is fully reliable in detecting the existence of an anomaly. The flash on ϵ Peg was confirmed over an 11 minute interval by both naked eye and telescopic examination. All experience with satellite glints (e.g., Schaefer *et al.* 1987*b*) shows that the >80 s duration of the flashes on ν Oph, ϵ Peg, S For, and β Eri is very difficult to explain by this means. A persistent meteor train cannot explain the presence of *two* bright flashes from HD 160202. Any claimed extension of the normal flare star mechanism to G5 stars is in itself an exciting result which is difficult to explain. There is no published evidence to suggest that either BD +31°1048 or BD +26°870 is anything other than a normal B-type star. The stars X Tri, BW Vul, SS Leo, μ Cep, and 66 Oph are not exotic in the sense that a substantial fraction of stars occupying the same regions on the H-R diagram share the same properties. Given the available high-quality spectra of V654 Her, the luminosity class is not really in doubt. W. Heintz (1988, private communication) admits that he can think of no plausible mechanism involving the rotating disk that will reproduce the flash on CF UMa. The light curves for HD 282773, V654 Her, SS 199II, UU CrB, μ Cep, and G99–47 have a time scale and shape totally unlike all known instrumental glitches in photometers. The fact that the smooth observed light curve for the UU CrB flash behaves differently in each color argues strongly against any instrumental effect.

Finally, the odds that a unique Vidicon "sparkle" should occur on only one out of $\sim 10^{7.5}$ frames at the exact position of a 4th magnitude star are small.

A realistic commentator (Kunkel 1975; Stencel 1983) would concede that some of the 24 flashes (especially the short visual flashes) may be artifacts. However, there are too many too well documented cases for the topic of bright flashes on normal stars to be dismissed. Indeed, even an understanding of flashes on most "exotic" stars is totally missing. Only further study will determine the existence and nature of this phenomenon.

I would like to end this paper with two appeals to the astronomical community. First, observers should promptly report any detected flashes in the astronomical literature. Second, flash search experiments should be designed to detect flashes from bright stars.

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