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A GIANT X-RAY FLARE IN THE HYADES

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ABSTRACT

We have observed a giant stellar flare in the Hyades binary HD 27130 = VB 22 = BD +16°577 with the *Einstein Observatory*. The peak X-ray luminosity of the flare is greater than 10^{31} ergs s^{-1}, at least several thousand times brighter than the most intense solar flares. The ratio of flare peak to quiescent X-ray luminosity is ~ 35. The flare began shortly before 1980 September $19^d 06^h 13^m$ UT, and decayed with a $1/e$ time of ~ 2500 s.

HD 27130, first detected as an X-ray source in the central Hyades survey of Stern *et al.*, recently has been determined to be a double-lined eclipsing binary with a period of 5.6 days. The primary is a G dwarf, and the secondary is a K dwarf, as determined by McClure. The temperature estimated for the flare (~ 4×10^7 K) and the form of the flare decay suggest that it is solar-like; however, the size scales deduced ($\gtrsim$ 10% of the stellar surface area) are much larger than those observed for typical solar flares. We suggest that giant flares may be typical of young or rapidly rotating systems.

Subject headings: stars: atmospheres — stars: binaries — stars: coronae — stars: flare — stars: late-type — X-rays: sources

I. INTRODUCTION

There are only a handful of classical "flare stars" for which X-ray flaring has been observed. Prior to the launch of the *Einstein Observatory*, soft X-ray flares were detected on the M dwarf flare stars YZ CMi, UV Ceti (Heise *et al.* 1975), Prox Cen (Haisch *et al.* 1977), AD Leo, and AT Mic (Kahn *et al.* 1979). With *Einstein*, Johnson (1981) detected X-ray flaring on Wolf 630 and BD +44°2051. *Einstein* observations of X-ray flares on Prox Cen (Haisch *et al.* 1980, 1981) and YZ CMi (Kahler *et al.* 1982) have provided detailed X-ray light curves of such events. More recently, large X-ray flares have been detected in RS CVn systems (White, Sanford, and Weiler 1978; Pye and McHardy 1980) and in pre–main-sequence stars (Feigelson and de Campli 1981; Montmerle *et al.* 1983). Although it is generally believed that stellar flares are similar in origin to solar flares, the energy released in stellar flares is often many orders of magnitude greater than that of solar flares. For this reason and also because of the lack of spatial information about stellar flare regions, the values of physical parameters such as flare volume and magnetic field strength have been a matter of some controversy (Mullan 1976*a*, *b*; Vogt 1980; Kahn *et al.* 1979).

[1]Guest Observer with the *Einstein Observatory* (*HEAO 2*).

In a survey of the central region of the Hyades cluster with the *Einstein Observatory* (*HEAO 2*), Stern *et al.* (1981) detected coronal X-ray emission from 48 stars. Two of these were flare stars, but no X-ray flares were observed; however, this null result is partly due to the short (2000 s) exposure times for the original X-ray survey fields. To investigate X-ray variability and spectral parameters better for the strongest Hyades X-ray sources, follow-up observations with longer exposure times (10,000 s) were made for selected fields. During one of these longer duration exposures, a previously discovered X-ray source, HD 27130, underwent an X-ray flare.

II. OBSERVATIONS

We observed a 1° × 1° region in the Hyades with the *Einstein* Imaging Proportional Counter (IPC) centered at $\alpha(1950) = 4^h 15^m 29^s$, $\delta(1950) = +17°08'05''$. The observation lasted from UT $04^h 47^m$ to UT $11^h 03^m$ on 1980 September 19. Total time in the processed IPC image was ~ $2^h 50^m$. (Details of the IPC and *Einstein Observatory* operation may be found in Gorenstein, Harden, and Fabricant 1981 and Giacconi *et al.* 1979.)

The IPC count rate for HD 27130 shows a dramatic change in X-ray luminosity just after the source emerged from Earth occultation ($6^h 13^m$ UT). In Figure 1*a*, we plot the source count rate as a function of time. The

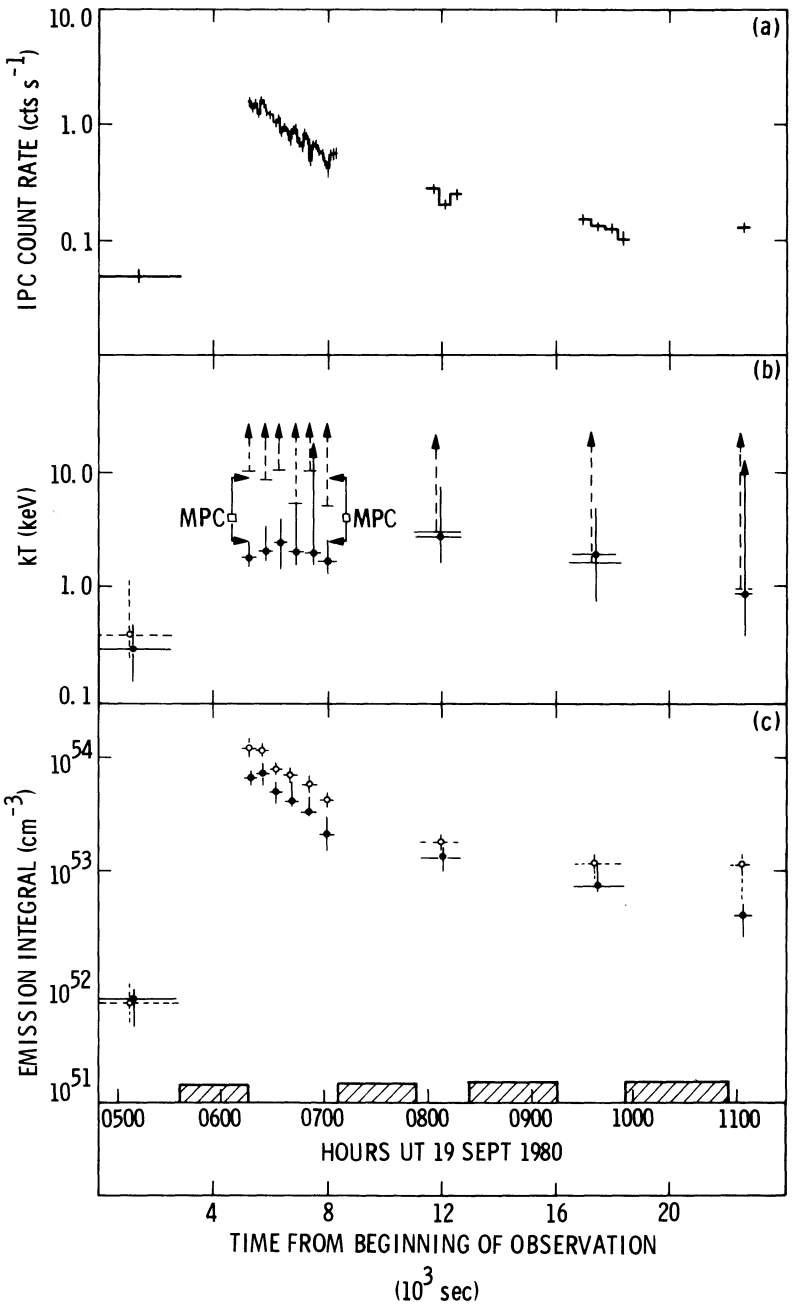

FIG. 1.—(*a*) IPC source count rate as a function of time. (*b*) Derived flare temperature in keV using Raymond's (1979) plasma emissivity model. Two values of the IPC gain and corresponding temperatures are shown, indicating representative values of the true gain parameter. Higher gain (16.3) indicated by filled circles, lower gain (14.3) by open circles (see text). Results from fitting MPC data to simple exponential models give best-fit values and limits indicated by "MPC." Error bars are 90% confidence limits for single parameter. (*c*) Emission integral derived from (*a*) and (*b*) (90% confidence limits). The hatched regions at the bottom of the figure indicate gaps in the data coverage due mostly to Earth occultations.

initial *e*-folding decay time is ~ 2500 s, with a clear increase in decay time toward the end of the flare. Because the flare began during a period of Earth occultation, we can only set an upper limit to the flare rise time of less than 2800 s. The peak IPC count rate is ~ 1.6 counts s^{-1}, or ~ 35 times that of the quiescent X-ray flux. The corresponding X-ray flux is ~ 4×10^{-11} ergs cm^{-2} s^{-1}, equivalent to an X-ray luminosity of 10^{31} ergs s^{-1} at the Hyades distance of 45 pc (Hanson 1980; McClure 1982). Since we failed to see the flare rise, this number represents a lower limit to the peak X-ray luminosity.

Determining the flare temperature and the emission integral ($n_e^2 V$) from the IPC pulse-height distribution is complicated by high spatial frequency variations in the IPC gain. We may, however, set bounds on these quantities for a range of possible IPC gains. Also, the time variation of the relative hardness of the X-ray spectrum can be derived from each gain value. The data were fitted using the thermal plasma emission models of Raymond (1979).

The results of this analysis are shown in Figures 1*b* and 1*c*. The hardening of the source spectrum after the onset of the flare is apparent, with a quiescent kT of less than 1 keV and a lower limit on the flare temperature of more than 1 keV. The emission integral changes by up to two orders of magnitude, reaching a peak of greater than 4×10^{53}–10^{54} cm^{-3}. Fortunately, we also detected harder X-rays from the flare using the coaligned Monitor Proportional Counter (MPC) of the *Einstein Observatory*, a nonfocusing, collimated detector sensitive to ~ 2–10 keV X-rays. Although the MPC is considerably less sensitive than the IPC to soft X-rays, by summing all the counts from the time interval at the peak of the flare (3300 s) and fitting the eight channels of MPC spectral information, we may derive a crude temperature, but one that is still better than the very uncertain IPC temperature. The MPC data yield a best fit temperature (for simple exponential models) of ~ 4 keV, with 90% confidence limits at ~ 2.5 and 9 keV. The corresponding X-ray flux at Earth (2–10 keV) is ~ 3.3×10^{-11} ergs cm^{-2} s^{-1}, comparable to L_x derived from the IPC data. The total flare energy in X-rays (0.2–10 keV) is thus $\gtrsim 3 \times 10^{34}$ ergs.

III. COMPARISON OF X-RAY RESULTS WITH OPTICAL OBSERVATIONS

In Table 1 we list the optical and quiescent X-ray properties of HD 27130 as given by McClure (1982) and Stern *et al.* (1981). HD 27130 has several characteristics in common with the RS CVn systems (Hall 1976, 1980). It is an eclipsing spectroscopic binary, the hotter star of the binary is a G dwarf; and strong Ca II H and K emission reversals have been detected (Eggen 1978). The quiescent X-ray luminosity is at the lowest end of the range observed for most RS CVn systems (Walter and Bowyer 1981) and is typical of G dwarfs in the Hyades (Stern *et al.* 1981). The secondary component, of lower mass and lower bolometric luminosity (McClure 1982), is clearly not evolved, unlike many RS CVn stars, and no photometric wave has been detected in visible light. As Hall (1980) has pointed out, however, the key characteristic of RS CVn or RS CVn like systems is probably the rapid synchronous rotation of one or both of the stars with well-developed convection zones. With our data, however, we cannot determine on which of the binary components the flare occurred.

TABLE 1

PROPERTIES OF THE HD 27130 SYSTEM[a]

Parameter	Value
Period	$5^{d}.61$
Inclination	$85° \pm 1°$
Primary mass	1.086 ± 0.018 $M_\odot$ (G0)[b]
Secondary mass ...	0.776 ± 0.015 $M_\odot$ (K0)[b]
Quiescent X-ray ...	~ 1×10^{29} ergs s^{-1}

[a] $V = 8.34$ (V primary = 8.59).
[b] Spectral types estimated from Allen 1973.

We infer from our observations that a class of X-ray flare stars may exist which are difficult to detect optically. Classical flare stars are detected in the *U* or *B* bands not only because of large flare energies, but also because of their low photospheric temperatures (~ 3200 K or less for dMe), which increase the contrast between quiescent and flare brightness at the shorter wavelengths of the photospheric spectrum. Thus, by "hiding" a flare star in the binary system with a hotter primary, the dramatic increase in *U* band luminosity characteristic of stellar flares (Mullan 1976*a*, *b*) can be effectively suppressed. In X-rays, of course, such flares are considerably easier to detect. This is a good argument for longer term X-ray monitoring of highly active stars likely to exhibit flaring behavior using the next generation of X-ray satellites such as the *European X-Ray Observatory Satellite* (*EXOSAT*).

Analysis of the remaining Hyades follow-up fields has indicated one or two more, smaller flares on other Hyades stars (Zolcinski *et al.* 1983, in preparation).

IV. COMPARISON WITH SOLAR FLARES AND FLARE MODELS

Is this Hyades flare fundamentally similar to solar flares, or is it a completely different phenomenon? Except for the large soft X-ray luminosity, the general features of the evolution resemble the decay phase of solar soft X-ray bursts, which are characterized by an initially rapid cooling phase, followed by a long-lived tail to the emission with a time scale, at least for very large solar flares, of several hours (Moore *et al.* 1980).

Assuming that the flare on HD 27130 is solar-like, we can infer the values of the basic flare parameters such as temperature, density, size scale, and magnetic field strength. From a detailed study of eight well-observed solar flares, it appears that the X-ray decay time near the time of flare maximum is characterized by the relation (Moore *et al.* 1980) $\tau \sim \tau_r \sim \tau_c$, where τ is the observed temperature decay time, and τ_r and τ_c are the cooling time scales by radiation ($\tau_r \sim 3kT/N_e\Lambda$) and conduction ($\tau_c \sim 3kN_eL^2/10^{-6}T^{5/2}$), respectively, inferred from observation of the flare temperature, T, density, N_e, and size, L. The radiative loss coefficient, Λ, is that for optically thin plasma. In any particular flare, processes such as cooling by mass motion may dominate, which would tend to invalidate the result of Moore *et al.*; however, it does appear to be valid for all the solar flares they studied. Using this result and the values 10^{54} cm^{-3} and $10^{3.4}$ s observed for the emission measure and the decay time, respectively, we deduce a flare temperature, $T = 10^{7.7}$ K, a density, $N_e = 10^{11.6}$ cm^{-3}, and a size, $L = 10^{10.2}$ cm, assuming a volume for the emitting region of $\sim L^3$. This value for T is consistent with that determined from the MPC data ($10^{7.5-8.0}$ K), which tends to support the assumption that the flare is solar-like.

The main difference between this Hyades flare and solar flares seems to be in the length scale. Compact solar flares can have as high, or higher, temperatures and densities, but only over much smaller regions. Although large two-ribbon flares often extend to heights of 10^{10} cm or more, the size scale of the soft X-ray emitting region during flare maximum is much smaller. This point is emphasized in Table 2, where we have listed the observed characteristics of solar and stellar flares for comparison with HD 27130. Note that the size deduced above is only that at soft X-ray maximum, and hence is a lower limit to the maximum extent of the flare. A large two-ribbon solar flare can exhibit a late decay phase with size scales an order of magnitude larger than those at X-ray maximum. There is evidence for a late decay phase in our data, Figure 1. Thus, the maximum extent of the flare on HD 27130 may be $\gtrsim 10^{11}$ cm.

The large size that we propose for the flare may at first seem unlikely because it implies that the flare covers a significant fraction of the total stellar surface, $\gtrsim$ 10%. However, we believe that this result is to be expected. The maximum area of a flare clearly is limited by the area of the active region in which it occurs. In the case of the Sun, an individual active region occupies a very small fraction of the solar surface, but there is now evidence that the fraction of stellar surface covered by active regions is much larger for young rapid rotators such as the Hyades stars. Observations of chromospheric Ca II emission (Vaughan *et al.* 1981) and our previous soft X-ray and UV observations (Stern *et al.* 1981; Zolcinski *et al.* 1983) indicate that the stellar surface of such stars may be completely covered by active regions. If this is the case, then it is not surprising that the area of a large flare on HD 27130 would approach the total stellar surface area.

Pursuing the solar analogy further, it is possible to obtain a lower limit on the magnetic field strength. Assuming that magnetic field annihilation is the flare energy source, we must have that $B^2/8\pi \gtrsim P$, where P is the pressure of the soft X-ray emitting plasma. For the values of N_e and T derived above, we obtain that $P = 10^{2.8}$ ergs cm^{-3} and $B \gtrsim 150$ gauss. Again, this value is not unusual for solar flares but only over a much smaller volume. It thus appears unnecessary to postulate regions of extremely high (> 10 kilogauss)

TABLE 2

SOLAR AND STELLAR FLARE THERMAL X-RAY PLASMA PROPERTIES

Log of	Sun[a,b,c]	Flare Stars[c,d,e,f]	HD 27130	Pre–Main-Sequence[g,h]	RS CVn[i,j]
τ_{rise}(s)[k]	2–3	2–3	< 3.3	2.4[g]	< 4
τ_{decay}(s)[k]	3–4	2–3	3.4	~ 3[h]	~ 4
L_x (peak, ergs s^{-1})......	≲ 27–28	27–31	≳ 31	30–34	31–33[l]
E_x (total, ergs) ...	≲ 30–31	31–33	> 34.5	≲ 34–36	35–38[l]
T_{max}(K)	7.0–7.5	7.1–7.6	7.5–8.0	7.0–7.3	> 7.5?[l]
EM(cm^{-3})	≲ 50	51–54	≳ 53.5–54	53–55	55–56[l]
N_e(cm^{-3})	10.5–12	11–11.6[m]	11.6[m]	10–11.5[m]	...
V(cm^3)	25–28	27–28[m]	30.6[m]	30–33[m]	...

[a] Sturrock 1980.
[b] Pallavicini, Serio, and Vaiana 1977.
[c] Kahn *et al.* 1979.
[d] Haisch *et al.* 1981.
[e] Haisch *et al.* 1983.
[f] Kahler *et al.* 1982.
[g] Feigelson and de Campli 1981.
[h] Montmerle *et al.* 1983.
[i] Pye and McHardy 1980.
[j] White, Sanford, and Weiler 1978.
[k] The *e*-folding decay times are given.
[l] Value for the 2–10 keV band; all others are ~ 0.2–10 keV.
[m] Model-dependent value is given.

field strengths for the site of stellar flare energy release as suggested by, e.g., Mullan (1976*b*). A crucial test of the solar model, which requires large energy storage volumes, would be observation in X-rays of the rise time for a large stellar flare. In the solar model, a strict lower limit for this time scale is L/V_A, where V_A is the Alfvén velocity in the preflare corona. Assuming a preflare coronal density of $10^{10.5}$ cm^{-3} yields a rise time $\gtrsim 10^2$ s for the flare in HD 27130, similar to solar values and well within our observational constraints.

In summary, we conclude that the X-ray flare on HD 27130, even though orders of magnitude larger than observed solar flares, can be understood using solar-like flare models, but with much larger size scales than for typical solar flares. Clearly, more observations of stellar flares are required to test this hypothesis. Such observations are likely to yield significant new insights into solar flares as well.

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REFERENCES

Allen, W. C. 1973, *Astrophysical Quantities* (3d ed; London: Athlone).
Eggen, O. J. 1978, *Inf. Bull Var. Stars*, No. 1426, Konkoly Observatory, Budapest.
Feigelson, E. D., and de Campli, W. M. 1981, *Ap. J. (Letters)*, **243**, L89.
Giacconi, R., *et al.* 1979, *Ap. J.*, **230**, 540.
Gorenstein, P., Harnden, F. R., and Fabricant, D. G. 1981, *IEEE Trans. Nucl. Sci.*, NS-28, 869.
Haisch, B. M., Linsky, J. L., Bornmann, P. L., Stencel, R. E., Antiochos, S. K., Golub, L., and Vaiana, G. S. 1983, *Ap. J.*, **267**, in press.
Haisch, B. M., Linsky, J. L., Harnden, F. R., Rosner, R., Seward, F. D., and Vaiana, G. S. 1980, *Ap. J. (Letters)*, **242**, L99.
Haisch, B. M., Linsky, J. L., Lampton, M., Paresce, F., Margon, B., and Stern, R. 1977, *Ap. J. (Letters)*, **213**, L119.
Haisch, B. M., *et al.* 1981, *Ap. J.*, **245**, 1009.
Hall, D. S. 1976, in *IAU Colloquium 29, Multiple Periodic Variable Stars*, ed. W. S. Fitch (Dordrecht: Reidel), Part I, p. 287.
______. 1980, in *Solar Phenomena in Stars and Stellar Systems, Proc. NATO Advanced Study Inst.*, ed. R. Bonnet and A. K. Dupree (Dordrecht: Reidel), p. 431.
Hanson, R. B. 1980, in *IAU Symposium 85, Star Clusters*, ed. J. E. Hesser (Dordrecht: Reidel), pp 71–80.
Heise, J., Brinkman, A. C., Schrijver, J., Mewe, R. Gronenschild, E., den Boggende, A., and Grindlay, J. 1975, *Ap. J. (Letters)*, **202**, L73.
Johnson, H. M. 1981, *Ap. J.*, **243**, 234.
Kahler, S., *et al.* 1982, *Ap. J.*, **252**, 239.
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.
McClure, R. 1982, *Ap. J.*, **254**, 606.
Montmerle, T., Koch-Miramond, L., Falgarone, E., and Grindlay, J. E. 1983, *Ap. J.*, submitted.
Moore, R. L., *et al.* 1980, in *Solar Flares*, ed. P. Sturrock (Boulder: Colorado Associated University Press), chap. 8.
Mullan, D. J. 1976*a*, *Irish Astr. J.*, **12**, 161.
______. 1976*b*, *Irish Astr. J.*, **12**, 277.
Pallavicini, R., Serio, S., and Vaiana, G. S. 1977, *Ap. J.*, **216**, 108.
Pye, J. P., and McHardy, I. M. 1980, *Bull. AAS*, **12**, 855.
Raymond, J. C. 1979, private communication.
Stern, R. A., Zolcinski, M. C., Antiochos, S. K., and Underwood, J. H. 1981, *Ap. J.*, **249**, 647.
Sturrock, P., ed. 1980, *Solar Flares*, (Boulder: Colorado Associated University Press).
Vaughan, A. H., Baliunas, S. L., Middlekoop, F., Hartmann, L. W., Mihalas, D., Noyes, R. W., and Preston, G. W. 1981, *Ap. J.*, **250**, 276.
Vogt, S. S. 1980, *Ap. J.*, **240**, 567.
Walter, F. M., and Bowyer, S. 1981, *Ap. J.*, **245**, 671.
White, N. E., Sanford, P. W., and Weiler, E. J. 1978, *Nature*, **274**, 569.
Zolcinski, M. C., *et al.* 1983, in preparation.

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