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TWO FAST SOFT X-RAY TRANSIENTS AT HIGH GALACTIC LATITUDE

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ABSTRACT

Two soft X-ray sources appeared at a level 10 times the *HEAO 1* A-2 experiment's scanning sensitivity for $\sim 10^4-10^5$ s, and then dropped below detectability. Both sources were discovered at high galactic latitude. The transient designated H0850+13 appeared on 1977 November 4. In three consecutive observations made within 6 hours a softening of the source spectrum was observed, consistent with decline of temperature of $\sim 2\times10^6$ K to $\sim 1\times10^6$ K. The transient designated H0336−26 appeared on 1978 February 3 and had a temperature no higher than 10^6 K. The 90% confidence error boxes for these sources contain no convincing optical counterparts. Assuming a hypothetical distance to the sources of 10 pc, the observed intensity implies their luminosities are $\sim 10^{30}$ ergs s^{-1}. As the *HEAO 1* A-2 experiment's ability to detect such rapid transients is quite limited, the total rate of similar transients may be quite high. Assuming these two detections were random samplings of a population of transient sources isotropically distributed over the sky and occurring at a constant rate over time, we estimate there may be ~ 100 such transients per year.

Subject headings: X-rays: bursts — X-rays: spectra

I. INTRODUCTION

We report here the discovery of two transient soft X-ray sources. X-ray transients in general exhibit a wide range of behavior, but all are characterized by a relatively brief appearance above a limiting detector sensitivity. The transients reported here are distinguished by their short duration (10^4-10^5 s), extremely soft spectra ($T \lesssim 10^6$ K), and high galactic latitude.

The experiment used to detect the new sources is described in § II. The characteristics of the new sources are discussed in detail in § § III and IV. In § V the properties of these transients are compared with the properties of previously detected transients.

The possibility that the soft transients may belong to known classes of low-luminosity X-ray sources that exhibit flaring behavior is examined. Several other current models for the production of long burst-type behavior are also reviewed in an attempt to understand the nature of the new transients.

II. CHARACTERISTICS OF THE EXPERIMENT

These observations were carried out using the low energy detectors (LEDs) of the *HEAO* A-2 experiment.[2] The two LEDs are thin window gas flow proportional counters. Each LED has two collimated fields of view. Only the narrowest field of view of LED 1 (FWHM = 1°.55) was used to determine source position, but all fields of view were combined to extract source intensity.

During these observations the spacecraft operated in a scanning mode, spinning once every 33 minutes. A point source produces a triangular modulation in the data on an individual scan. Because the spin axis is shifted 1° per day, on successive days the source amplitude is modulated by a 2.95° FWHM triangular response perpendicular to the direction of scan.

The spectrum of the X-rays is determined from the LED 1 voltage pulse heights. The pulse height spectrum is integrated over broad bands and telemetered to the ground in 1.28 s intervals. Three pulse height bands (called scalers) are used in this analysis. Scaler 1 integrates all pulses which originate in the detector volume directly behind the window. Scaler 3 integrates pulses occurring in the central volume of the detector. Because X-rays must traverse the scaler 1 volume to be counted in scaler 3, the low energy sensitivity of scaler 3 is quite small. Scaler 5 includes those pulses in scaler 1 which correspond to X-rays of energy below 430 eV; but since the window absorption is very large above the carbon K-edge, the scaler 5 rate is almost totally due to X-rays with energy below 284 eV. Figure 1 shows the relative efficiency of the detector for these pulse height bands.

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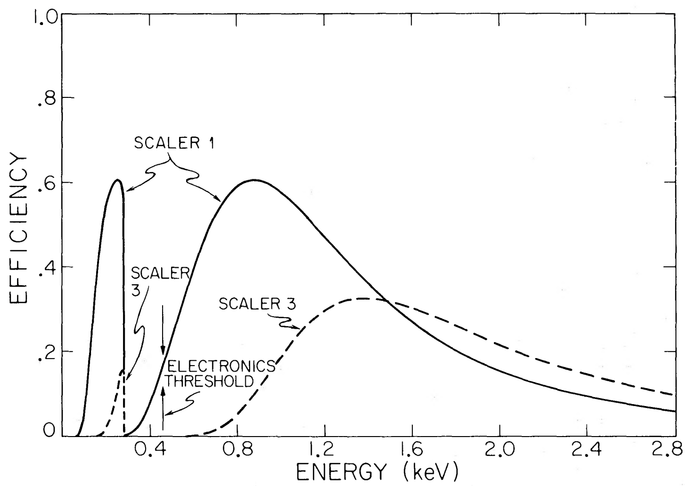

FIG. 1.—*HEAO 1* A-2 LED efficiency as a function of energy. The solid line is the detector efficiency of the front volume. All events occurring in the front volume are accumulated by Scaler 1 and telemetered to the ground in 1.28 s intervals. Those events with lower pulse heights than the indicated electronics threshold are accumulated in scaler 5. The broken line is the middle volume detector efficiency. Events in the middle volume are telemetered as Scaler 3.

We are confident that the transient events reported here result from celestial X-rays incident on our detectors. High-energy charged particle events are rejected by anticoincidence vetoing between cells in the detector volume. Low-energy charged particles can induce X-ray–like events without triggering the intercell vetoing, but such particles are characterized by a broad angular extent, unlike the point source response produced by the transients. A particle flux generally produces a flatter spectrum of events than that produced by X-rays. No increase in the higher pulse height channels was observed, further weighing against the possibility of particle contamination. As at least two observations for each source were made at greatly differing locations over the Earth and at different local zenith angles, geomagnetic effects and solar scattered X-rays are ruled out.

Although the LEDs have a small response to UV radiation ($\lesssim$2% window transmission for $\lambda = 1750$–1900 Å, Bowyer 1979), the observed response to the transients differs from that caused by UV pile up. As the counting gas, propane, is highly transmitting to UV in this range, UV contamination preferentially produces scaler 3 (middle counter volume) events via photon ejection from the ground plane wires of which there are twice as many as in the front layer. While the scaler 3 data show evidence for a source (Fig. 2), the ratio of scaler 3 to scaler 5 intensity is appropriate to an X-ray spectrum, simultaneously weighing against both UV and low energy particle contamination.

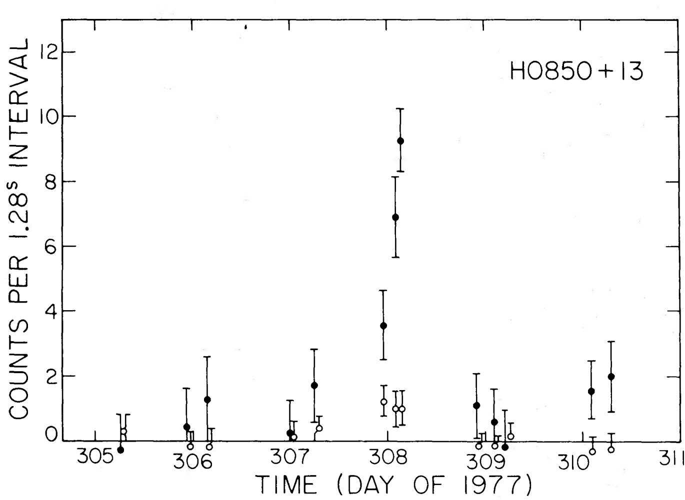

FIG. 2.—X-ray light curve for H0850+13. *Solid circles*, the scaler 5 ($\sim\frac{1}{4}$ keV X-rays) intensity. *Open circles*, the scaler 3 intensity.

For a more complete description of the *HEAO 1* A-2 experiment, refer to Rothschild *et al.* (1979).

III. H0850+13

a) *Observations*

A bright soft X-ray source was observed on three consecutive scans of the sky near ($8^h49^m.5$, 12°51′) between 23:09:41 UT 1977 November 3 and 03:50:15 UT 1977 November 4 at a peak flux level of 6.2×10^{-11} ergs cm^{-2} s^{-1}. Observations within a day before and after, as well as 6 months later, gave no indication of a source at this location down to a 2 σ upper limit of 6×10^{-12} ergs cm^{-2} s^{-1}.

The X-ray light curve of the transient is shown in Figure 2. The data during the three observations of the source in its high state are consistent with a single source at scan angle 184°.55 ± 0°.076. The X-ray intensity in Figure 2 is derived from a least squares fit of the X-ray data to a triangular point source response fixed at this scan angle. The dramatic increase in intensity must be intrinsic to the source as it cannot be explained by motion of the scan plane. Preceding and succeeding positions of the collimator differ in location on the sky by less than 0°.5, small in comparison to the 2°.95 collimator response in this direction. A constant source would require 3 days to rise to maximum, while the transient rises to maximum in less than a day.

The spectrum of the transient is quite soft, consistent with an incident flux entirely below 284 eV. Although detailed pulse height analysis is not fruitful due to the combination of low incident flux and the poor energy resolution of a proportional counter at low energy, we can use the weak sensitivity of scaler 3 to X-rays from ~250–284 eV to estimate spectral shape within the 150–284 eV scaler 5 bandpass. The scaler 3 rate is constant across the three observations while the scaler 5 rate more than doubles. The ratio of scaler 3 to scaler 5 intensity observed in the data is tabulated in Table 1 with the temperature at which a blackbody model spectrum with no interstellar absorption produces the same ratio.

TABLE 1

SPECTRUM OF H0850+13

Time (Day of 1977)	I_3/I_5	*kT* (eV)	LED 2/LED 1	*kT* (eV)
307.96	0.37±0.28	170	Not available	...
308.11	0.14±0.09	110	0.8 ±0.4	120
308.16	0.10±0.07	80	0.04±0.1	< 100

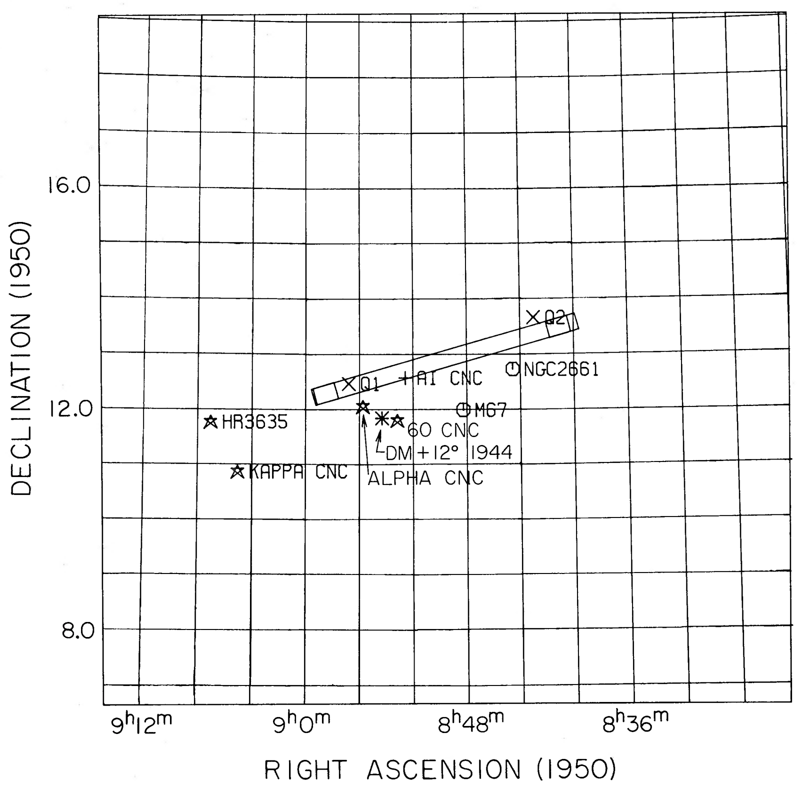

FIG. 3.—90% error region for H0850+13

A similar inference of the spectrum can be drawn from the ratio of scaler 5 in LED 2 to the same scaler in LED 1. As LED 2 operated at this time with low counter gain, many of the events produced by very soft X-rays fell below the lower electronic threshold in the detector and were not counted. The temperature of a model spectrum required to give the observed LED 2 to LED 1 scaler 5 ratio is also given in Table 1.

Both spectral indicators are consistent with a spectral softening. While we cannot determine the true spectral form, the softening is equivalent to a decline in the emitting temperature of a blackbody from 2×10^6 K to 1×10^6 K.

b) *Discussion*

The area on the sky in which the source lies (at the 90% confidence level) is plotted in Figure 3. Note that the area is tightly constrained in one direction by the daily scans, but is poorly constrained in the other because the intrinsic source variability overwhelmed the day-to-day variation expected from the collimator.

The error region contains no known X-ray sources, suggested RS CVn systems (Hall 1976), flare stars (Petterson 1976), white dwarfs (McCook and Sion 1977), or nearby stars (Gliese 1969). The brightest stars of any kind in the error region are eighth magnitude. We note that the fourth magnitude Am star α Cnc is not far from the error region. Another Am star, HR 976 (den Boggende *et al.* 1978), and a star of the similar Ap type, ϕ Her (Cash, Snow, and Charles 1979), have been reported as X-ray emitters at luminosities of a few times 10^{30} ergs s^{-1}.

The star α Cnc is offset from the error region in the direction of our maximum positional sensitivity, so that we can exclude it as the source of the transient event at the more than 5 σ level. Overall in this region there is evidence for a weak steady source of soft X-rays. Combining all our data, exclusive of the transient, we find it consistent with a point source of intensity 0.5 ± 0.23 counts s^{-1}, located at scan angle $185\overset{\circ}{.}45 \pm 0\overset{\circ}{.}37$. This location differs from the flare location by 2.4 σ, and includes α Cnc in its 90% error region. A possible explanation is that α Cnc is a weak, approximately steady X-ray source with luminosity $(4 \pm 2) \times 10^{29}$ ergs s^{-1}, but unrelated to the X-ray transient. However, *HEAO 2* observations have failed to detect α Cnc at this X-ray luminosity (Cash 1979).

The only variable star from the lists of Kukarkin *et al.* (1976) in the error region is the RR Lyrae variable AI Cnc. The star's apparent magnitude varies from 14.4 mag to 15.8 mag with a period of $0\overset{d}{.}564308$. Using the period-luminosity relation for RR Lyrae variables and assuming interstellar extinction of 0.5 mag, we estimate the distance to AI Cnc is more than 5 kpc. As RR Lyrae variables are not a known X-ray emitting class and the required X-ray luminosity is extremely high ($> 10^{36}$ ergs s^{-1}), we believe AI Cnc is unlikely to be the source of the transient.

Two proper-motion stars lie in the error regions (Giclas, Burnham, and Thomas 1971). G9–34, 12.2 mag, has a proper motion of $0\overset{''}{.}40$ per year. G9–26, 14.5 mag, has a proper motion $0\overset{''}{.}35$. No galaxy brighter than 15th mag lies in the error region. QSO 0856+124 (Burbidge, Crowne, and Smith 1977), 18 mag, with $z = 1.76$ also lies in the region. No evidence suggests that any of these objects produce X-ray transients.

From the observed intensity, correcting for counter efficiency, assuming the source radiates isotropically, and making no correction for interstellar absorption, we find the peak X-ray luminosity from 0.15 to 0.4 keV is at least 8×10^{29} $(R/10 \text{ pc})^2$ ergs s^{-1}, where R is the distance to the source. The size of the emitting region, assuming blackbody radiation, is at least 0.4 $(R/10 \text{ pc})$ km. Alternatively, assuming a thermal spectrum from a gas in collisional equilibrium (Raymond, Cox, and Smith 1976) the emission integral is at least 3×10^{52} $(R/10 \text{ pc})^2$ cm^{-3}.

IV. H0336–26

a) *Observations*

This transient appeared at a flux of 8.2×10^{-11} ergs cm^{-2} s^{-1} from 17:40:32 UT to 19:24:18 on 1978 February 2. Both observations were consistent with a source located at ($3^h36\overset{m}{.}5$, $-25°56'$). The light curve of the source in scaler 5 and 3 (Fig. 4) was derived from the data in the manner described for H0850+13.

Unfortunately, the limits on source intensity during nonflare observations are weakened by the presence of an apparent step function in the diffuse X-ray background near the source. However, no steady source is present at the location of H0336–26 down to a flux limit of 1.3×10^{-11} ergs cm^{-2} s^{-1}.

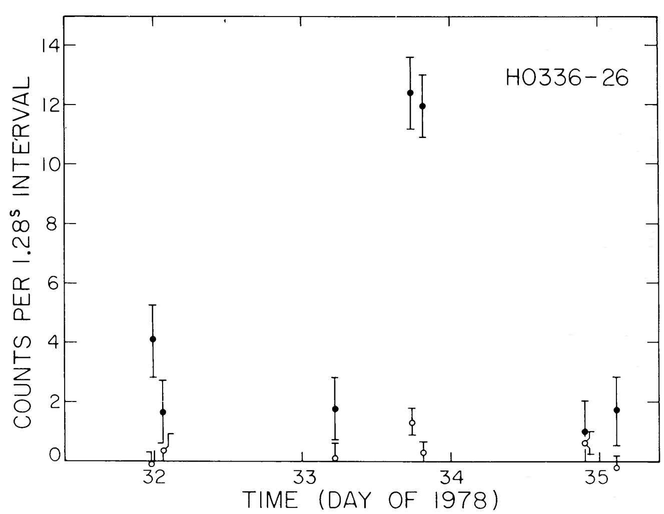

FIG. 4.—X-ray light curve for H0336–26. *Solid circles*, scaler 5 intensity; *open circles*, scaler 3 intensity.

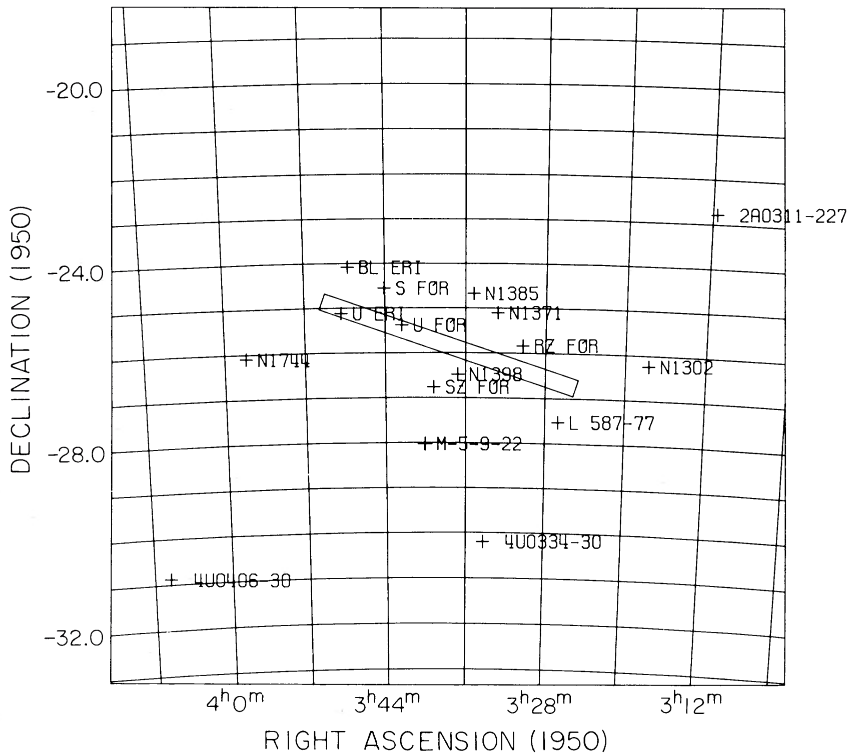

FIG. 5.—90% error region for H0336–26

TABLE 2

SPECTRUM OF H0336–26

Time (Day of 1978)	I_3/I_5	kT (eV)	LED 2/LED 1	kT (eV)
33.74	0.10 ± 0.04	80 ± 40	0.44 ± 0.08	70 ± 20
33.82	0.025 ± 0.03	$\lesssim 50$	0.43 ± 0.08	70 ± 20

H0336–26, unlike H0850+13, shows no increase in scaler 5 intensity with time. The second observation suggests a spectral softening because the scaler 3 rate declines while the scaler 5 rate is constant. Observations with LED 2 (again operating in a reduced gain state) do not require any softening, but large statistical uncertainties in all these rates allow a wide range of model temperature compatible with the data (Table 2). The spectrum is certainly soft (equivalent to a blackbody temperature of $\sim 10^6$ K) and is consistent with either a constant spectrum or a softening between the two observations.

b) *Discussion*

The error region for H0336–26 (Figure 5) contains no strong candidates. Klein and Chevalier (1978*a*) suggested a supernova observed 1978 August 14 in the nearby galaxy MGC–5–9–22 as the source for the transient H0336–26, but, as is apparent in Figure 5, the candidate galaxy is well removed from the error box.

No previously reported X-ray source falls in the error region. The following lists were searched without finding a candidate within the error regions: nearby stars (Gliese 1969), proper motion stars (Giclas, Burnham, and Thomas 1971, RS CVn stars (Hall 1976), flare stars (Petterson 1976), white dwarfs (McCook and Sion 1977), Yale Bright Star Catalog (Hoffleit 1964), and bright galaxies (de Vaucouleurs 1977). Two variable stars (Kukarkin *et al.* 1976), the Mira-type stars U Eri ($m_v = 8.5$ to 14.9) and U For ($m_v = 10.4$ to 12.5), fall inside the error region. Mira variables are quite common and have not been associated with X-ray emission, but we will discuss a possible emission mechanism in the next section.

The observed intensity implies a source luminosity of at least 10^{30} $(R/10 \text{ pc})^2$ ergs s^{-1} assuming an isotropic emission, but with no correction for interstellar absorption. A blackbody radiator of this luminosity at 5×10^5 K has a radius of 1.5 $(R/10 \text{ pc})$ km. The emission measure required for a thermal source is 5×10^{52} $(R/10 \text{ pc})^2$ cm^{-3}.

V. COMPARISON WITH PREVIOUS TRANSIENTS AND X-RAY PRODUCTION MODELS

In the absence of any strong candidate for these transients we cannot attempt to explain the cause of the transient phenomenon. We can, however, review the properties of previously reported transients in order to suggest possible models.

RS CVn systems are known to emit soft X-rays and exhibit flaring behavior (see Walter *et al.* 1980). While no known RS CVn systems lie in the error regions, noneclipsing RS CVn systems are difficult to identify. If an unidentified RS CVn system were responsible for the transient, the absolute optical magnitude of that system could not be less than $+3.2$ (the absolute magnitude of a K0 IV star, Allen 1973). As the brightest stars in the error box are eighth magnitude, the distance to the hypothetical RS CVn system must be at least 100 pc. At this distance, even without allowing for absorption, the transient luminosity must be at least 10^{32} ergs s^{-1}, comparable to the X-ray flare observed from the RS CVn system SAO 015338 = 2A 1052+606 (Walter *et al.* 1980). Although the luminosity of the transients is similar to an RS CVn flare, the transient's spectra are considerably softer than that seen in RS CVn systems. The spectra of RS CVn systems reported by Walter *et al.* exhibit $T \sim 10^7$ K, an order of magnitude hotter than these transients.

Another class of extremely variable soft X-ray emitters are the cataclysmic variables. In particular, the dwarf novae may appear as soft X-ray transients during optical outbursts. Prominent examples are SS Cyg and U Gem, both of which show very soft X-ray spectra equivalent to blackbody temperatures of order a few times 10^5 K, and exhibit intensity variability of a factor of 10 or more on a time scale $\leq 10^4$ s (Rappaport *et al.* 1974; Margon *et al.* 1978; Mason *et al.* 1978; Córdova *et al.* 1980). A difficulty with attributing the X-ray emission of the new transients H0850+13 and H0336–26 to a dwarf nova–like phenomenon is that any dwarf nova as bright in soft X-rays as these transients should be, by analogy with SS Cyg and U Gem, fairly bright optically (m_v in outburst < 10 mag). It is unlikely that an erupting dwarf nova this bright would have escaped detection. However, it has been suggested (Robinson 1980) that binary systems similar to dwarf novae, but having an early-type companion instead of a late-type companion, might escape optical detection. In such a hypothetical system the optical radiation from the dwarf nova–like accretion disk would be unimportant, even in outburst, compared to the light of the companion. At higher energies, i.e., EUV and X-rays, the accretion disk and boundary layer radiation would, during outbursts, significantly exceed the contribution from the companion. Thus this type of system might be a candidate for the new X-ray transients.

Flare stars are a third possible condidate for the new transients. Flares in the soft X-ray region have been reported in UV Cet and YZ CMi (Heise *et al.* 1975), Proxima Cen (Haisch *et al.* 1977), AT Mic, and AD Leo (Kahn *et al.* 1979). The X-ray luminosity during these flares is of order $10^{30}-10^{31}$ ergs s^{-1}, compatible with the transients if they are within 10–30 pc of the Sun. As flare stars have absolute magnitudes near $+15$, the apparent magnitude of the flaring star would be $\gtrsim 15^m$. Such a faint flare star could easily elude identification. (No M stars lie in either error region down to a limiting magnitude of 10.5 mag.) The proper motion star G9–34 (= LP 486–55) in the H0850+13 region exhibits colors ($m_R = 11.4$, $m_{pg} = 12.5$, Luyten 1973) suggestive of a flare-type star. The duration of the new transients is far longer than any flare observed in flare stars. The X-ray flare observed in UV Cet lasted only $\sim$200 s (Heise *et al.* 1975). Although an X-ray flare on Proxima Cen has been observed with a slower rise (Linsky 1980), no flare has been observed lasting more than 10^3 s, whereas both transients lasted at least 10^4 s.

A predicted, but so far unobserved, means of producing soft X-ray bursts on time scale of $\sim 10^3$ s is the collapse of a red giant star at the beginning of a supernova explosion. Predictions of the luminosity of the burst vary (Klein and Chevalier 1978; Falk 1978; Lasher and Cahn 1979). The highest soft X-ray luminosity predicted is $\sim 2 \times 10^{44}$ ergs s^{-1} over 10^3 seconds (Klein and Chevalier 1978*b*). At this luminosity, allowing for galactic absorption, the hypothetical supernova would be $\sim$40 Mpc distant. As no galaxies within the error regions are brighter than $m_v = 15$ mag, the hypothetical supernova would have occurred in a galaxy fainter than absolute magnitude $M_v = -18$ mag (comparable to the LMC).

While the time scale predicted for these bursts is shorter than that observed for the new transients, Lasher and Chan (1979) have pointed out that the duration of the burst will be longer if the ratio of the atmospheric scale height to the shock thickness is larger, or if the energy of the explosion is smaller, than that assumed in the standard model. However, if the time scale of the burst is lengthened, the peak luminosity is drastically reduced. Using Lasher and Chan's equations,

$$\tau_{1/2} \propto \left(\frac{E}{R_*^{\,3}}\right)^{-0.6}, \qquad F_{\max} \propto \left(\frac{E}{R_*^{\,3}}\right)^{1.22}, \qquad (1)$$

where $\tau_{1/2}$ is the half-power duration, $F_{\max}$ the peak luminosity, E the energy of the explosion, and R_* the stellar radius. To increase the duration by a factor of 10 reduces the peak luminosity by $\sim$100. For $\tau_{1/2} = 10^4$ s, the hypothetical supernova could be no farther than 4 Mpc and thus could reside in a galaxy no brighter than $M_v = -13$ mag (equivalent to a dwarf galaxy). In the absence of any reasonable galaxy in the error regions, it is highly unlikely that these transients are the result of precursor supernova X-ray bursts.

The X-ray production applied to supernovae might be expected in any extended stellar atmosphere subjected to a strong outward moving shock. We examine, for example, the case of a Mira-type variable because of the presence of U Eri and U For in the H0336–26 error region. The radius of a 1.5 $M_\odot$ Mira variable is about 5 times less than the giants considered by Lasher and Chan. Assuming the Mira atmospheric scale height is approximately the same as a red giant, then using equations (1), we find that a burst with duration 2×10^5 s (the longest consistent with the observations) requires an initial explosive energy input of 4×10^{45} ergs, or $5\times10^6\ L_\odot$ over the duration of the burst. Shell flash luminosities as high as $2\times10^7\ L_\odot$ have been modeled by Iben (1977), but for Mira periods $\sim300^d$ the flash luminosity is of order $5\times10^5\ L_\odot$. Based on these crude arguments, it appears difficult to obtain the energy required to produce an X-ray burst of the type seen in the transients from Mira variables, especially rapidly enough to form a shock in the atmosphere.

Whatever the source of these transients, they may be a fairly common phenomenon. The *HEAO 1* LED experiment surveyed no more than $\sim3\%$ of the sky during any one day. For most of the mission, a given sky location was observed about 3 times on nearly consecutive orbits, interspersed with long periods of no favorable observations. We estimate the efficiency of *HEAO 1* at detecting events with a time scale as short as 6 hours to be no higher than 1%. Short time scale soft X-ray transients like these are potentially occurring 100 times per year at the intensity detected here. A systematic search of the *HEAO 1* data is under way to locate additional transients from as little as a single sighting.

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