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SAS 3 OBSERVATIONS OF TWO X-RAY TRANSIENT EVENTS WITH PRECURSORS*

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ABSTRACT

SAS 3 has observed two unusual fast transient X-ray events from different sources, one lasting ~150 s and one ~1500 s. Both events were preceded by precursor pulses which lasted a few seconds and which rose and fell in less than 0.4 s. The precursors were separated from the "main" events by several seconds, during which no X-rays were detected. There are similarities between the two main events and X-ray bursts in both their temporal and spectral evolution. The spectra of the main events started out much softer than the spectra of the precursors, became harder as they approached maximum intensity, and softened as they decayed. In the ~1500 s event, X-rays with energies greater than 10 keV were delayed by ~80 s compared with 1.5–6 keV X-rays. A blackbody fit to the spectral data of the main event of ~1500 s duration gives a maximum temperature of 29×10^6 K and a radius for the emitting region of at least ~9 km (at a distance of 10 kpc); this is similar to the temperature and sizes found for several X-ray burst sources.

Subject heading: X-rays: bursts

I. FAST TRANSIENT EVENT OF 1977 FEBRUARY 2

At UT $20^h01^m14^s$ on 1977 February 7 the *SAS 3* observatory center slat detector (Lewin *et al.* 1976*c*) observed a transient X-ray event which lasted ~1500 s, shown in Figures 1*a*,*b*. No other *SAS 3* detector recorded this unusual event. The Earth was not in the center slat detector's field of view, and the satellite was well outside the South Atlantic Anomaly region. The possible locations of this event are shown in Figure 2. Some of its main features have already been reported by us (Lewin, Hoffman, and Doty 1977*a*).

The event has a narrow peak at energies below 6 keV, followed by a short period of rapidly decreasing intensity. The rate of decrease then lessens abruptly, and a long decay ensues, lasting ~1500 s. The decay is faster at higher energies, indicating an overall softening of the X-ray spectrum during the decay. At energies above 10 keV the event starts ~80 s later and reaches maximum intensity ~240 s later than at energies below 6 keV. The delayed rise at higher energies is particularly clear in Figure 1*a*, which has a logarithmic time scale. Figure 1*a* also shows the other unusual attribute of this transient event, a distinct precursor pulse lasting ~3 s. The precursor occurs simultaneously in all three energy channels, spanning the range 1.5–43 keV. Both the rise and fall times of the precursor are less than 0.4 s. The precursor is followed by a period of ~5 s during which there was no detectable emission at any energy. Throughout the rest of this paper, we refer to the "precursor" and the "main event" as the two components of the X-ray transients being reported.

The maximum observed intensities (1.5–43 keV) of the precursor and main event were ~0.4 and ~0.8 times that of the Crab, respectively. The total integrated energy flux (1.5–43 keV) was at least $\sim 6.0 \times 10^{-8}$ ergs cm^{-2} in the precursor and at least $\sim 1.2 \times 10^{-5}$ ergs cm^{-2} in the main event. The position of the source of this transient is not known, so no correction can be made for collimator transmission; the intensity and total energy flux of the event are thus lower limits.

Figure 3*a* shows the evolution of the spectral channel ratios. The initial hardening of the spectrum of the main event is followed by a prolonged softening during the decay. The rate at which the spectrum softens decreases as the decay progresses. The spectrum of the precursor pulse was harder than that during the onset of the main event but was softer than the spectrum of the main event when the radiation greater than 10 keV was near its maximum intensity (~150–350 s after the onset).

This transient event was observed only in three spectral channels, so any three-parameter spectral model will fit the data. Because the evolution of the spectral channel ratios resembled that of many X-ray bursts whose spectra have been well fitted by blackbody models (see § IV), we fitted the spectral data with a blackbody model. The maximum temperature of the transient event (assuming a blackbody spectrum) was $\sim 29 \times 10^6$ K, reached ~200 s after the onset; the temperature then decreased. We continued to fit the spectral points in successive time intervals with a blackbody model until there was no longer a significant signal in the highest-energy channel, ~650 s after the onset. By this time, the temperature had decreased to $\sim 13 \times 10^6$ K. The average value found for N_H was $(4 \pm 2) \times 10^{22}$ cm^{-2}. If the radiation was from a blackbody, the average radius of the emitting region, assuming isotropic emission, was ~0.9 D km, where D is the distance to the source in kpc. This number is a lower limit (as is the measured intensity), since the source's position is unknown, preventing any correction for the collimator

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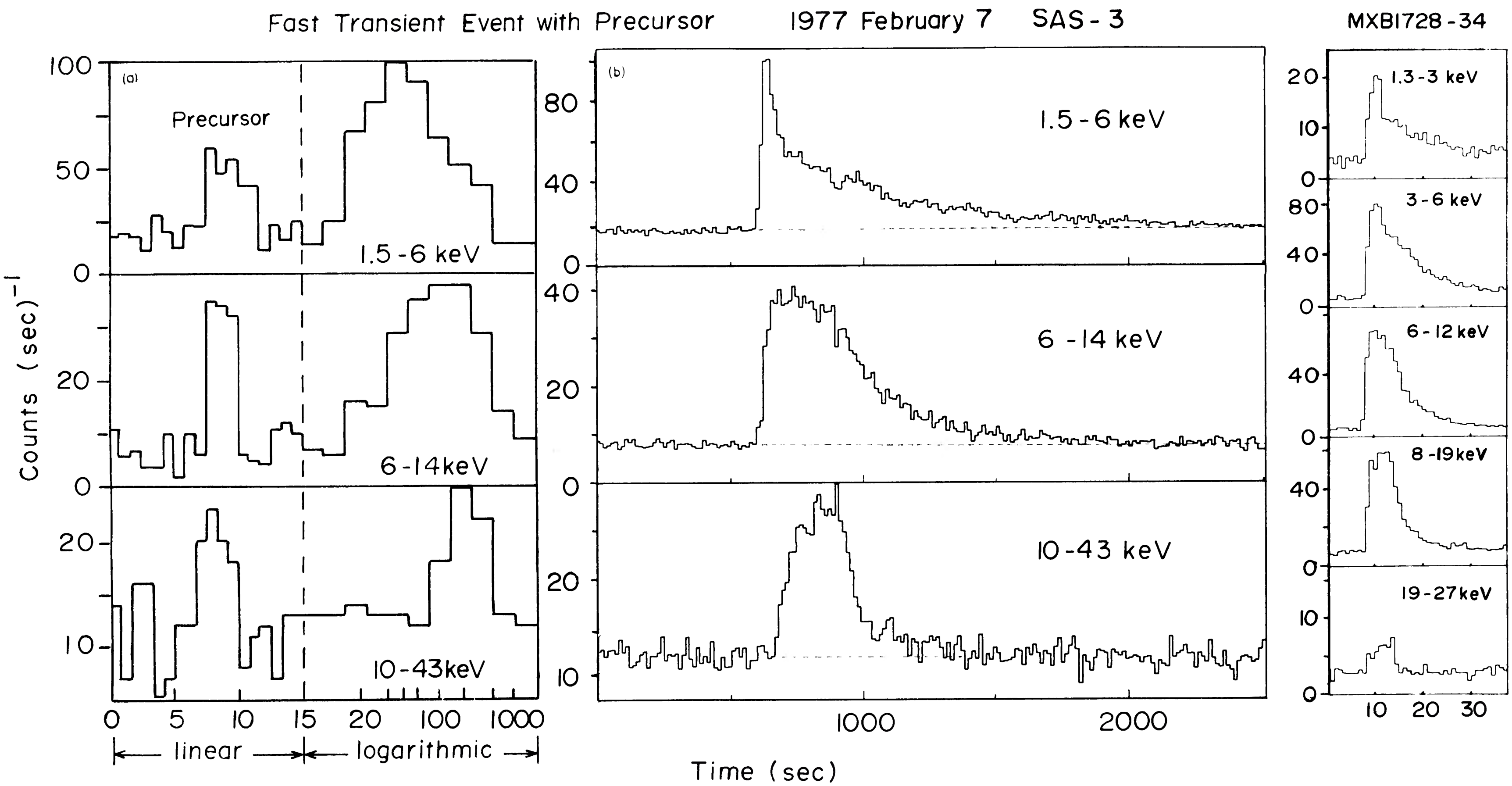

FIG. 1.—(*a*) Light curves in three energy channels of the 1977 February 7 fast transient X-ray event, as observed by the *SAS 3* center slat detector. The time scale of the first 15 s is linear and clearly shows the precursor. The time scale thereafter is logarithmic and shows the delayed rise at higher energies. (*b*) Light curves of the 1977 February 7 fast transient event. The ~13 s time scale of the binning washes out the precursor. (*c*) A composite X-ray burst from MXB 1728−34, as observed in five energy channels of the *SAS 3* horizontal tube detectors (from Hoffman, Lewin, and Doty 1977*a*).

transmission. The calculated size of the emitting region varies only as the square root of the observed intensity; so even if the actual peak intensity of the event were as high as 10 times that of the Crab, the radius of the emitting region would still be only $\sim$3 *D* km.

II. FAST TRANSIENT EVENT OF 1976 JUNE 28

At UT $14^h52^m05^s$ on 1976 June 28, the *SAS 3* rotating modulation collimator (RMC) system (Doxsey *et al.* 1976) observed a burstlike event lasting $\sim$150 s with a sharp precursor pulse lasting $\sim$2 s. Figure 4 shows the light curve of this event in the 2–6 keV and 6–11 keV energy channels. The precursor is clearly visible in Figure 4*b*, in which the beginning of the event is shown with a finer time scale. The modulation resulting from the motion of the spacecraft has been almost completely removed from these light curves in the manner described by Nishimura *et al.* (1977) and Haney (1977). A rectangular error box enclosing the possible locations of this event (Haney 1977) is shown in Figure 2. On a scale too fine to be shown in this figure, the 90% confidence rectangular region breaks up into numerous small "islands of possible locations" (Haney 1977). On this scale, MX 1716−31 (Markert *et al.* 1975) is the only known steady X-ray source consistent with the origin of this event. This source was the probable origin of a $\sim$10 minute flare observed by *OSO 7* (Markert, Backman, and McClintock 1976).

The maximum observed intensities of the precursor and main event were $\sim$0.6 and $\sim$0.8 times that of the Crab, respectively. The total integrated energy flux (2–11 keV) was at least $\sim 3 \times 10^{-8}$ ergs cm^{-2} in the precursor and at least $\sim 1.5 \times 10^{-6}$ ergs cm^{-2} in the main event. Since the location of the source of this event is not known, these numbers are lower limits. However, if MX 1716−31 produced the burst, then the energy flux was $\sim 6 \times 10^{-8}$ ergs cm^{-2} in the precursor and $\sim 3 \times 10^{-6}$ ergs cm^{-2} in the main event.

Figure 3*b* shows the evolution of the spectral channel ratios. The spectrum hardens as the main event develops and then softens as it decays. The rate of softening decreases as the decay progresses. The spectrum of the precursor is harder than that of the main burst at onset but softer than the spectrum during the

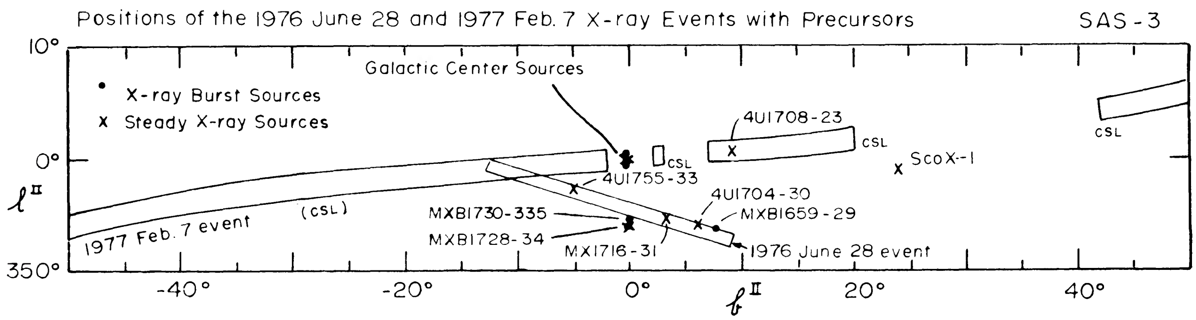

FIG. 2.—Possible locations of the two fast transient X-ray events with precursors discussed in this *Letter*. The rectangular region shown for the 1976 June 28 event actually is composed of numerous, small "islands of possible locations," too small to be shown here (see text).

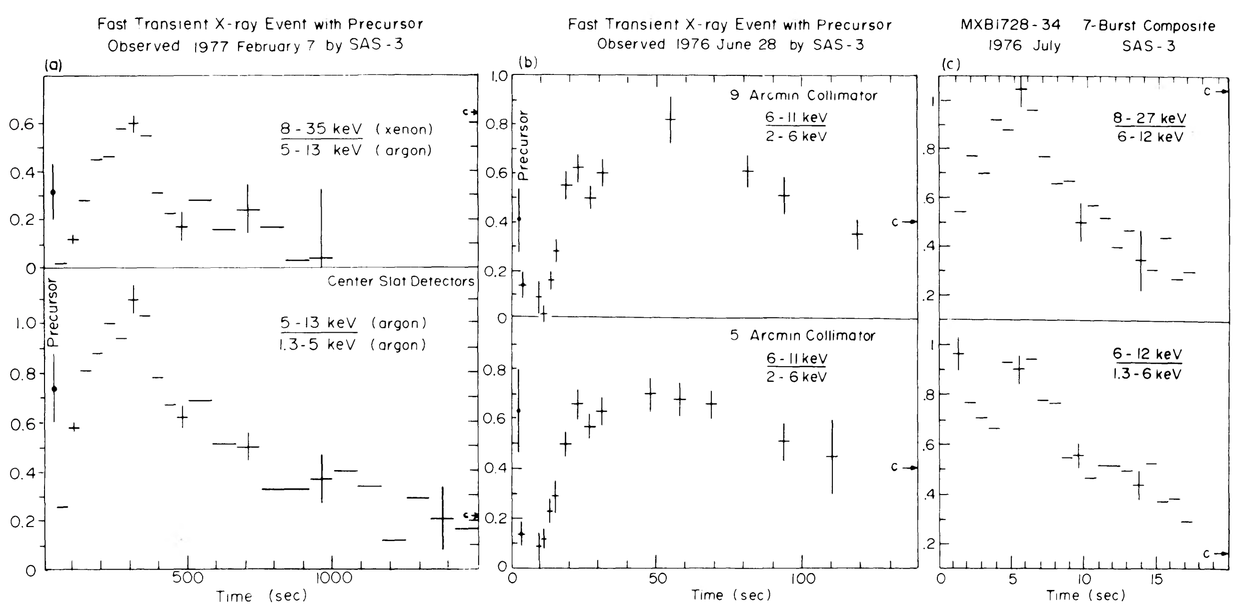

FIG. 3.—The evolution of spectral channel ratios with time for (*a*) the 1977 February 7 fast transient, (*b*) the 1976 June 28 fast transient, and (*c*) a composite X-ray burst from MXB 1728−34. All show initial spectral hardening and subsequent softening. The *c* with an arrow in each case represents the spectral ratio of the Crab Nebula.

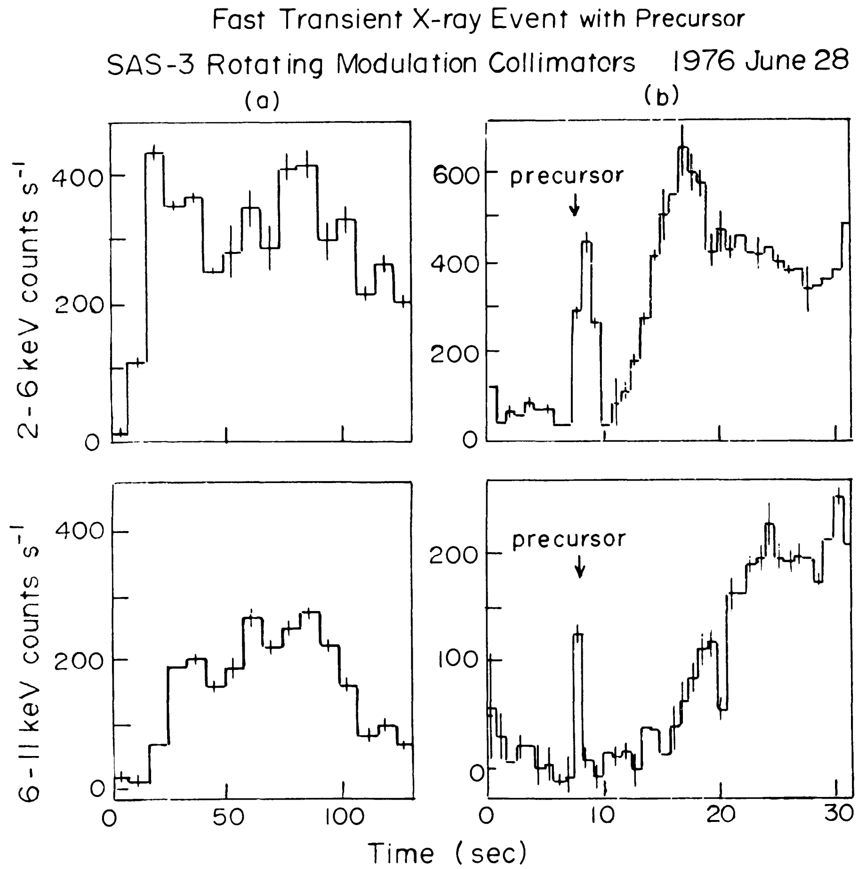

FIG. 4.—(*a*) Light curves of the 1976 June 28 long X-ray burst, in two energy channels of the *SAS 3* rotating modulation collimator detectors, with the collimator transmission response deconvolved. (*b*) The onset of the 1976 June 28 event, shown with an expanded time scale to make the precursor visible. The 1 σ error bars shown for each bin include both counting statistics and the uncertainty in the deconvolution of the collimator transmission.

peak of the main burst. This spectral behavior is similar to that of the ~1500 s 1977 February 7 transient event (Fig. 3*a*). The data for the 1976 June 28 event contain only two spectral channels; we made no attempt to fit any three-parameter spectral models to the data.

III. COMPARISON WITH X-RAY BURSTS

Figure 1 juxtaposes the 1977 February 7 event with the composite of seven bursts observed with the *SAS 3* *y*-axis detectors from MXB 1728−34 (Hoffman *et al.* 1976; Hoffman, Lewin, and Doty 1977*a*). The time scales are adjusted to make the events appear to have the same size in the figure, showing the strong resemblance. Figure 3*c* shows how the spectral channel ratios change during the seven-burst composite from MXB 1728−34. The similarity to the spectral channel evolution of the ~1500 s (Fig. 3*a*) and ~150 s (Fig. 3*b*) events is striking; the spectra all harden and then soften as the outbursts evolve. A burstlike event lasting several hundred seconds, observed by *OSO 8*, resembled the ~150 s event reported here and showed similar spectral behavior (Swank *et al.* 1977).

The main differences between the 1977 February 7 transient event and most X-ray bursts, aside from duration, are (i) the presence of the precursor, (ii) the delayed rise of the X-rays with energy greater than 10 keV, and (iii) the at least 100 times greater total integrated flux in the ~1500 s event. Precursors have never been reported to precede X-ray bursts lasting tens of seconds. A precursor with the same relative duration compared with the main event as that of the 1977 February 7 fast transient would last several tens of milliseconds in an X-ray burst lasting tens of seconds. We have searched *SAS 3* data for bursts from MXB 1728−34, MXB 1743−29 (Lewin *et al.* 1976*b*), and MXB 1916−05 (Lewin, Hoffman, and Doty 1977*b*) with 10 ms time resolution and have found no precursors. A several second delay in the rise of X-rays with energies greater than 6 keV compared with those less than 6 keV has been observed only in bursts from 4U 1820−30 (Grindlay *et al.* 1976; Clark *et al.* 1976). In bursts from other sources, the initial rise has been simultaneous to within a second at all energies (Hoffman *et al.* 1976; Lewin *et al.* 1976*a*,*b*,*c;* Li *et al.* 1977; Hoffman, Lewin, and Doty 1977*b*), although in some cases the maximum intensity was reached several seconds later at higher energies than at lower energies (Hoffman, Lewin, and Doty 1977*a*,*b*).

Typical integrated energy fluxes in X-ray bursts are between 10^{-8} and 10^{-7} ergs cm^{-2}, at least two to three orders of magnitude less than in the $\sim$1500 s event.

IV. COMPARISON WITH X-RAY NOVAE

The light curves of many galactic X-ray transient sources (X-ray novae) lasting weeks to months (see review by Pounds 1976) show a precursor peak preceding the main outburst. The relatively fast rise (observed from Cen X-4, A1524−62, A1118−61, A0535+26, and A0620−00; see references in Pounds 1976) and slow decay of these transients also resemble the light curves of the two events discussed in this *Letter*, except for a three to four order-of-magnitude difference in time scale. The relative intensity of X-ray transient precursors with respect to the main transient outbursts varies from $\sim$0.03 (A0535+26) to $\sim$0.4 (A1524−61), compared with $\sim$0.5 for the 1977 February event and $\sim$0.75 for the 1976 June event. There is no generally accepted explanation of the precursor pulses in bright galactic X-ray novae.

In those strong galactic X-ray novae for which spectra have been published, the spectrum was hardest at the peak of the precursor. In some transients, the spectrum stayed fairly constant during the rising phase of the main event (e.g., A1118−61), while in others (e.g., A0620−00) the spectrum softened markedly during the rise. This contrasts with the spectral evolution of the two events reported here, whose spectra hardened as the intensity rose in the main events (Figs. 3*a*,*b*).

The spectral evolution of the two events discussed in this paper resembles that of X-ray bursts much more closely than that of galactic X-ray novae. We therefore believe that the precursors of X-ray novae and those of these two events are different phenomena. They also differ from the precursors which are observed shortly before the light maximum of classical novae and which consist of a premaximum dip which does not decrease to prenova level.

V. DISCUSSION

We have recently classified X-ray bursts into types I and II (Hoffman, Marshall, and Lewin 1977). Except for their longer duration and greater integrated energy flux, both events reported here are similar to type I X-ray bursts.

Blackbody spectra have given the best fits of any simple, three-parameter model to bursts from MXB 1728−34 and MXB 1636−53 (Hoffman, Lewin, and Doty 1977*a*,*b*) and to a several hundred seconds long burstlike event from a source near $l^{II} = 356.^\circ4$, $b^{II} = 2.^\circ3$ (Swank *et al.* 1977). We think it is significant that, if a blackbody spectrum is assumed for the $\sim$1500 s 1977 February 7 event, then the temperature evolution and the implied size of the emission region for this event are the same as those found for type I X-ray bursts.

If our blackbody interpretation of burst spectra is correct, then we must explain a large range of durations in bursts which have similar maximum temperatures and which emanate from similar-sized emission regions. One explanation (Hoffman, Lewin, and Doty 1977*b*) is that the decreasing temperatures observed as most bursts decay result from radiative cooling of the blackbody burst emission regions, and that the cooling time scale determines the burst duration. An accurate analysis of cooling requires a detailed model of the density and temperature profiles in the burst emission region and is beyond the scope of this *Letter*.

Another interpretation, suggested independently by F. K. Lamb and R. Sunyaev (private communications), is that the temperature change (spectral softening) generally observed as bursts decay results from a change in the mass accretion rate (i.e., gradual "pinching off" of the mass flow into the burst region). In this interpretation bursts are produced by an accreting compact object, and the X-rays are emitted as thermal radiation from an optically thick region whose cooling time is short compared with the time scale of the burst decay. Thus the continuing energy input into the burst region following the burst onset maintains the emission region at the temperatures measured during burst decay. The temperature change is determined by the rate at which the energy input (accreting matter) is gradually choked off.

Our measured blackbody spectra and associated temperatures for various X-ray burst sources (Hoffman, Lewin, and Doty 1977*a*,*b*) are probably compatible both with magnetic instability accretion models (Lamb *et al.* 1977; Svestka 1976; Henriksen 1976; Baan 1977; Joss and Rappaport 1977; Wheeler 1977) and with thermonuclear flash models (Maraschi and Cavaliere 1977; Woosley and Taam 1976; Joss 1977).

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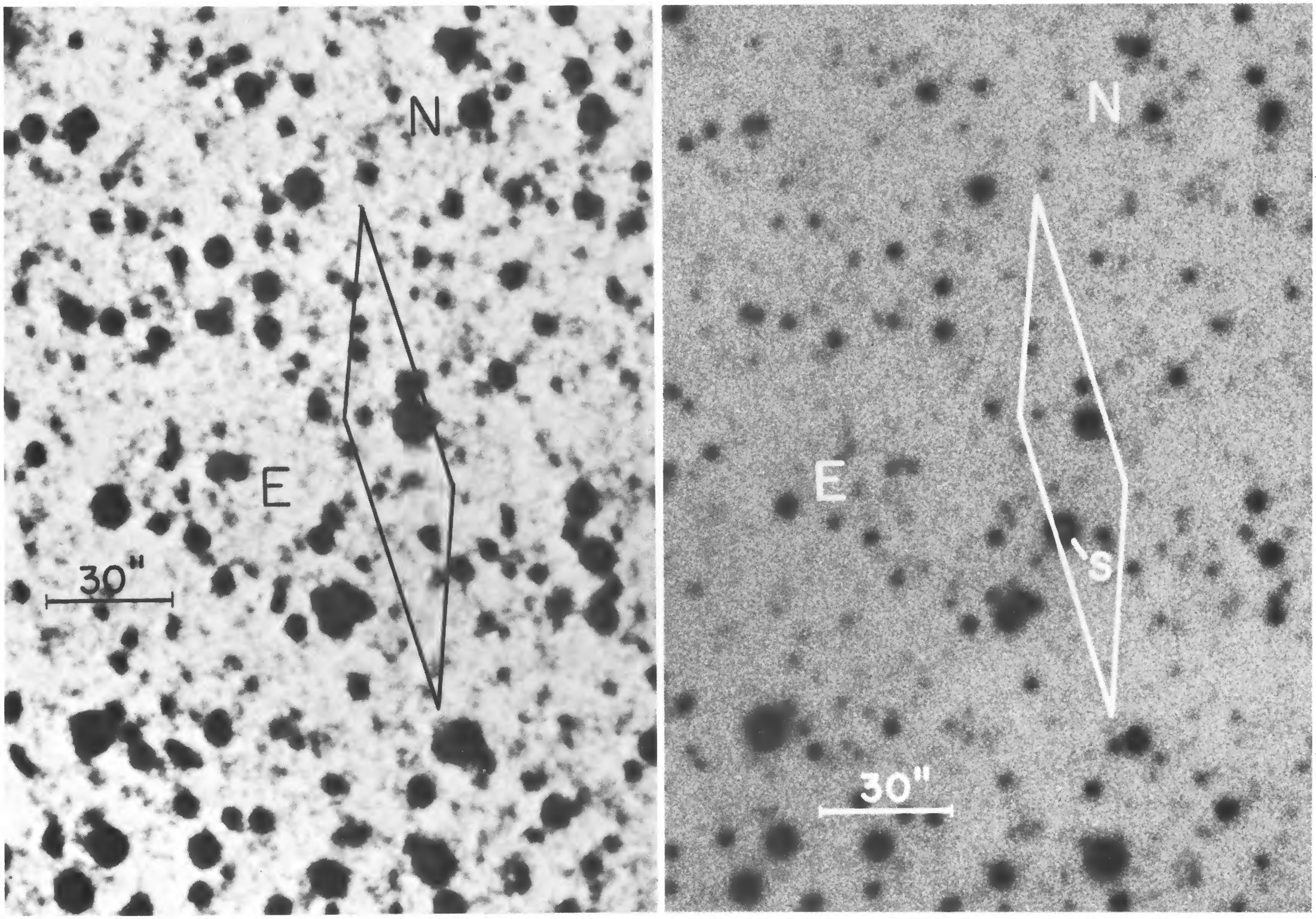

FIG. 2.—(*Left*) Reproduction of the red Palomar Observatory Sky Survey plate of the area near the nova. (*Right*) Print from the blue plate taken at the prime focus of the AAT on 1977 September 10 showing the optical nova, star S, and the error box for the X-ray transient (Table 1). A faint image at the position of S on the Sky Survey photograph can be seen on the original, although we do not expect it to be prominent on the printed reproduction.

GRIFFITHS *et al.* (*see* page L64)