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ABSTRACT

The first results from the ISEE-3 radiatively cooled Germanium Gamma-Ray Burst Spectrometer are presented. Spectra and time histories from two events on 1978 November 4 and 1978 November 19 are given. A significant difference in the continuum spectra for the two events was observed. Evidence is presented for two spectral features in the November 19 event, a broad one at ~ 420 keV and a narrower one at ~ 740 keV with a suggestion of an accompanying high energy tail.

I. INTRODUCTION

Since the initial discovery of gamma-ray bursts (Klebesadel et al. 1973) there has been a growing body of evidence on the spectral behavior of these events (Cline and Desai 1973, 1975; Wheaton et al. 1973; Imhof et al. 1974; Palumbo et al. 1974; Metzger et al. 1974; Kane and Share 1977; Sommer and Muller 1978; Mazets et al. 1979 a,b). As has been typical of early gamma-ray burst measurements most of these results came from instruments that were designed for other purposes. We report here the first results from the ISEE-3 Gamma-Ray Burst spectrometer, an instrument designed specifically to perform high resolution measurements of the energy spectra of gamma-ray bursts. Bursts were observed on 1978 November 4 and 1978 November 19. Both time histories and spectra for these events are given. Evidence is presented for the possible existence of structure in the November 19 spectrum and comparisons are made with other results that support this conclusion.

II. INSTRUMENTATION

The ISEE-3 Gamma-Ray Burst Spectrometer is a coaxial high purity Germanium crystal (35cm^3 vol.) cooled by radiation to a temperature of 130°K. It is a part of the Max Planck Institute-University of Maryland Charge Distribution Experiment system on the ISEE-1 and -3 spacecraft. The instrumental response is nearly isotropic over the southern ecliptic hemisphere. The northern ecliptic hemisphere is obscured by the spacecraft. The spacecraft orbits about the gravitational null or Lagrangian point some 200 earth radii sunward from the earth, an ideal location both for thermal performance of the cooler and low detector background. A two-stage radiative cooler developed by the Arthur D. Little Corp. for cooling infra-red sensors was modified to accommodate a Germanium crystal. The electronics contains a 4096 channel pulse height analyzer as well as a 10^5 bit memory capable of storing both temporal and spectral histories of the burst. Time histories are stored with an accuracy of better than 1 msec. Each detector photon pulse height is also stored and individually time tagged to an accuracy of 8 msec. A total resolution of $\sim$ 10 keV at 570 keV photon energy was achieved which is $\sim$ 5 times better than the best previous instrument. (Imhof et al. 1974). In addition the system is capable of monitoring the outputs of two other CsI detectors on the spacecraft and storing time histories from them. A more detailed description of the instrumentation is given in Hovestadt et al. (1978).

III. OBSERVATIONS

a. Temporal Structure

Plots of the ISEE-3 Germanium detector count rate as a function of time for the November 4 and November 19 events are shown in Figure 1. Both events last 10-20 seconds and display the complex temporal structure that is typical of most gamma-ray bursts. The November 4 event was independently detected by 8 other spacecraft: Pioneer Venus, Venera 11 and 12, Prognoz 7, and the four Velas. A preliminary ($\sim \pm 5^{\circ}$) direction of $\alpha = 301^{\circ}$, $\delta = -23^{\circ}$, $\ell^{II} = 19^{\circ}$, $b^{II} = -26^{\circ}$ for November 4 has been determined (Laros, private communication). The November 19 event was seen by all the above spacecraft as well as Helios-2 (for both events see Chambon et al. 1979; Evans et al. 1979; Mazets et al. 1979). Its direction, also preliminary ($\sim \pm 1^{\circ}$), is $\alpha = 19^{\circ}$, $\delta = 29^{\circ}$, $\ell^{II} = 229^{\circ}$, $b^{II} = -84^{\circ}$.

b. Spectral Continuum

The raw detector count spectra for the two events are presented in Figure 2. Data from 200 keV to 3 MeV are plotted; below 200 keV interpretation of the spectral shape is complicated by uncertainties in the amount of dead material in the path of the photon beam. Power law functions were fit to each of these data sets ($dN/dE = KE^{-\alpha}$) using the χ^2-minimization technique. For the November 19 event the candidate line features in the intervals 360-498 keV and 720-886 keV were removed from the data in order to permit a best estimate of the continuum to be obtained. The results of this fitting procedure are summarized in Table 1. It is evident that simple power laws adequately describe the detector continuum spectra for both events. It is also evident that there is a statistically significant difference in the slopes of the spectra for the two events. Monte Carlo simulations of the detector of the detector response have shown that, for the present statistical precision, over the 0.2-3 MeV range power-law detector spectra transform into incident photon spectra that are also power laws. Using the results of this simulation, the incident spectral indices can be inferred. These are also given in Table 1. Note that the indices of the two events differ significantly ($\Delta\alpha = 0.51$).

Metzger et al. (1974), using Apollo 16 data, have published a spectrum for the gamma-ray burst of 1972 April 27 covering the energy range 2.0 keV to 5.1 MeV. Two different power law functions are required to fit their data. Below $\sim$ 200 keV the slope is -1.38. Above 200 keV the spectrum softens to an index of -2.63. Cline and Desai (1975) have presented evidence for a single spectral shape for bursts which can be represented by an exponential (E_0 = 150 keV) at low energies and a power law (α = -2.5) at higher energies. Our data (see Table 1) are generally consistent with the power law behavior above $\sim$ 200 keV but strongly indicate that the slope varies from one event to the next. In addition the photon spectra for these events are significantly harder than those reported by Cline and Desai (1975) and Metzger et al. (1974).

c. Evidence for Structure

Features in the November 19 spectrum are present in the 360-500 keV and 720-900 keV intervals, although the evidence for the former is statistically marginal. To test for the existence of structure we have performed a χ^2 minimization using all of the November 19 data. We obtain χ^2_{min} = 38.8 with 27 degrees of freedom. The probability $P(\chi^2 > \chi^2_{min})$ is 6.6% that in succeeding experiments a larger value of χ^2 would occur. We regard this, by itself, as highly suggestive but not conclusive evidence for the existence of structure. It should be pointed out, however, that this test is blind to the fact that deviant data points may be associated in adjacent groups or features.

A commonly used alternative procedure is to find the number of standard deviations by which the feature in question exceeds the continuum. In our case, because of poor statistics, the continuum determination has a significant error which must be taken into account. Following the procedure outlined in Lampton et al. (1976), we have constructed a 68% confidence contour in parameter (K,α) space. This corresponds to that region over which $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ is allowed to vary up to a value of 2.3 (see Lampton et al. 1976), which is appropriate for two parameters. The upper and lower extreme values of the background flux under each candidate spectral feature over the 68% confidence region were then determined. These were taken as the $\pm 1\sigma$ error limits on the continuum. If the total number of counts in the feature is S and the background B, then the statistical significance of the feature is given by $\frac{S-B}{\sqrt{\sigma_S^2+\sigma_B^2}}$. Using the value for B derived from the best fit to the continuum described earlier we obtain 3.45σ for the statistical significance of the feature in the 720-900 keV region. Multiplying the probability of a 3.45σ event by the total number of trials, gives a probability of 0.7% that this could be a statistical fluctuation. This should be treated as a lower limit on the probability, since we cannot be certain that local deviations from the best fit to the continuum do not exist. We therefore regard the foregoing statistical analysis as limiting the probability that the 700-900 keV feature is a statistical fluctuation to the 0.7%-6.6% range. A similar analysis yields only a 1.4σ significance for the 360-500 keV feature, clearly not enough by itself to establish its validity. Additional corroborating evidence, however, will be presented in the following discussion.

The total energy in the 420 keV feature is 4×10^{-6} erg/cm^2 which is 1.5% of the total energy in the burst. For the 740 keV feature the total energy is 2.4×10^{-5} erg/cm^2 which is 9.2% of the total burst energy. It therefore appears that for the November 19 event line emission may be a significant contributor to the total burst energy. No significant evidence for line emission was seen during the November 4 event, however, it is curious that the data point at 420 keV lies 1.4σ above the continuum. The 2σ upper limits are: 4.6×10^{-6} erg/cm^2 (360-500 keV) and 8.0×10^{-6} erg/cm^2 (700-900 keV).

IV. DISCUSSION

Mazets et al. (1979a) have published a catalog of gamma-ray bursts observed on the Venera 11 and 12 spacecraft. Using a large area scintillator, they have measured the spectra of $\sim$ 30 different bursts, including both the 1978 November

4 and 1978 November 19 events discussed in this paper. Although the authors do not explicitly mention it in the text, there is strong evidence for the existence of a broad feature in the 400-500 keV interval in their 1978 November 19 data (see Figure 67 of Mazets et al. 1979a). Furthermore, the feature is not present in the later stages of the event, a behavior that we see also in our data. To the extent that it can be inferred from the data of Mazets et al. (1979a) the flux of their 420 keV feature is consistent with the ISEE-3 measured flux. Mazets et al. (1979a) however, do not show any evidence for the existence of the 700-900 keV feature that is prominent in the ISEE-3 data. It is possible, however, that because of the poorer inherent resolution of the Venera 11 and 12 scintillator system, it would not be possible for them to resolve this feature. Mazets et al. (1979a) also present data for the 1978 November 4 event. Their data do not show any evidence for the 420 keV feature during this event.

On 1979 March 5 an extremely intense burst of gamma rays was observed with an interplanetary network consisting of 9 different spacecraft (Cline et al. 1979, Evans et al. 1979) and with an independent directional experiment (Mazets et al. 1979b). It has been identified with a supernova remnant N49 in the Large Magellanic Cloud (Evans et al., 1979). Mazets et al. (1979b) have detected a broad 400 keV feature during this event that is qualitatively quite similar to the November 19 feature. It should be pointed out, however, that the 1979 March 5 event is very unusual in its temporal structure and intensity and is quite unlike a typical gamma ray burst (see Cline et al. 1979).

There are two other known examples of a gamma-ray line or feature in the vicinity of 400 keV. First, Leventhal et al. (1977) have reported a narrow line at 400 keV from the Crab nebula. Second, Jacobson et al. (1978) have given evidence for a complex 20-minute gamma-ray transient in which a family of lines was observed. Among these was a narrow line at 413.2 $\pm$1.8 keV. Lingenfelter et al.

(1978) have interpreted this family of lines as being from positron annihilation and neutron capture on hydrogen and iron. It is required that a subset of these lines are all redshifted by approximately the same value ($Z \cong 0.25$) which is consistent with surface production by a 1 $M_\odot$ neutron star. If we assume that the broad 400 keV feature in our data is, in fact, the redshifted 511 keV line, then we obtain redshifts anywhere in the 0-0.42 range. Similarly, if we assume that the 740 keV peak is the redshifted first excited state of iron (E = 847 keV) then we obtain Z = 0.10-0.18. The data, however, suggest that there is a high energy tail on the 740 keV peak which could allow redshifts all the way down to zero. It appears then, if this interpretation is valid, that rather large redshifts are required (up to Z = 0.42) to reproduce the broad 400 keV feature, or, alternatively, the temperature of the emission region must be very high ($T \cong 10^{8}$ °K). A further implication of this interpretation is the presence of additional lines from higher excited levels of iron (Ramaty et al. 1979). It is possible that the hard spectrum (α = 1.3) of the November 19 event could be a result of composite line emission at higher energies.

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FIGURE CAPTIONS

Figure 1. Time histories of 1978 November 4 and 1978 November 19 gamma-ray bursts. Both plots are from the radiatively cooled Germanium detector. Each point contains a fixed number of cts (32) with a variable time interval. Missing points are due to gaps in the spacecraft telemetry stream.

Figure 2. Raw spectra of the 1978 November 4 and 1978 November 19 gamma-ray bursts. Inset in 2(b) shows fine structure on a linear scale.

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TABLE 1

STATISTICAL ANALYSIS AND SPECTRAL PARAMETERS

EVENT	DEGREES OF FREEDOM	χ^2_{min}	$P(\chi^2 < \chi^2_{min})$	SPECTRAL INDEX DETECTOR COUNTS	SPECTRAL INDEX PHOTONS	TOTAL ENERGY (erg/cm^2)
1978 Nov. 4	25	20.6	.71	2.37 $\pm$.17	1.82 $\pm$.15	1.5×10^{-4}
1978 Nov. 19						
Lines Removed	20	23.7	.25	1.84 $\pm$.08	1.31 $\pm$.10	
All Data	27	38.8	.067			2.6×10^{-4}

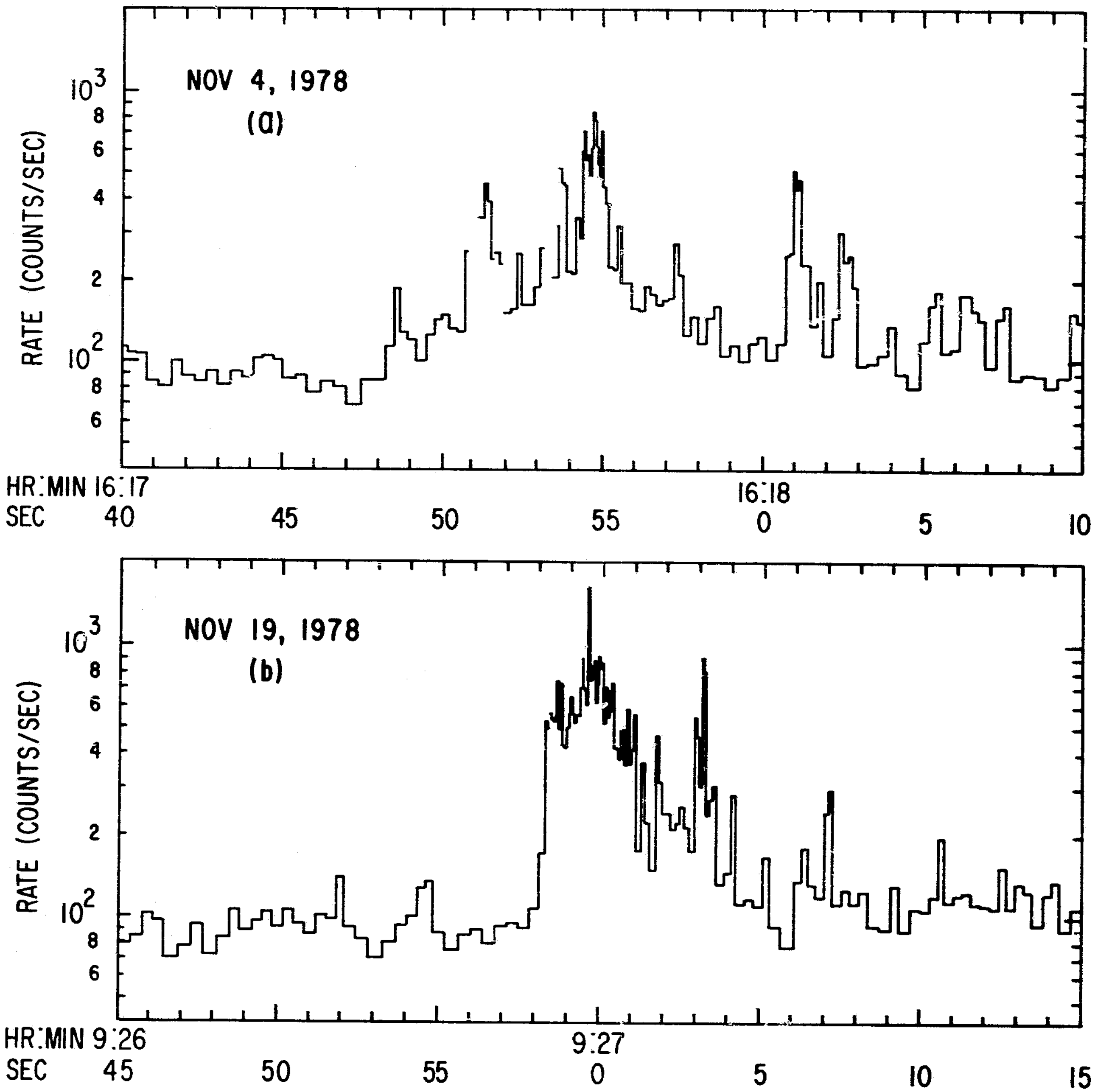
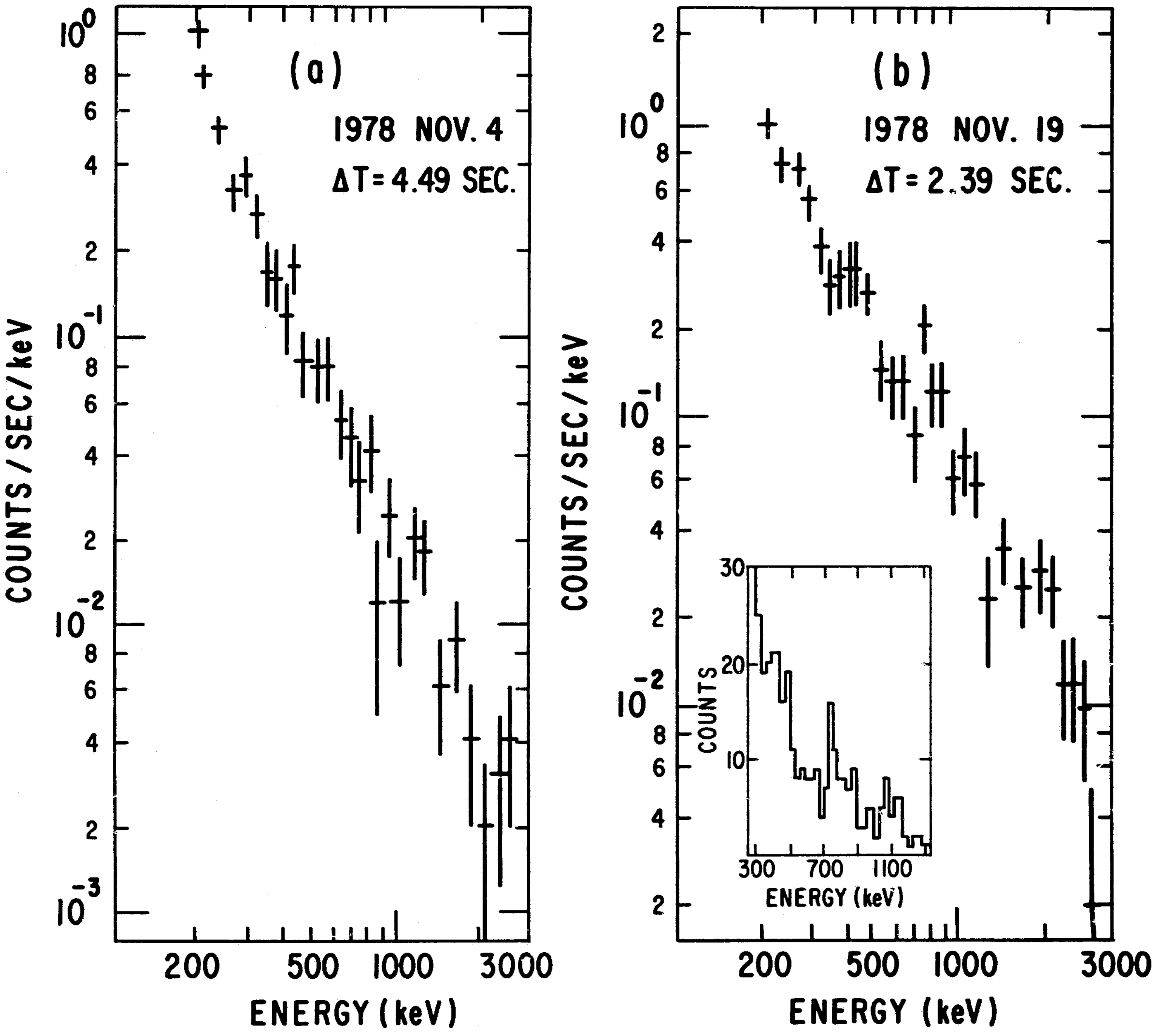

NOV 4, 1978
(a)
RATE (COUNTS/SEC)
10^3
8
6
4
2
10^2
8
6
HR:MIN 16:17
SEC 40
45
50
55
16:18
0
5
10
NOV 19, 1978
(b)
RATE (COUNTS/SEC)
10^3
8
6
4
2
10^2
8
6
HR:MIN 9:26
SEC 45
50
55
9:27
0
5
10
15

Fig. 1



(a)
1978 NOV. 4
ΔT = 4.49 SEC.
COUNTS / SEC / keV
ENERGY (keV)
(b)
1978 NOV. 19
ΔT = 2.39 SEC.
COUNTS / SEC / keV
ENERGY (keV)
COUNTS
ENERGY (keV)

Fig. 2