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UPPER LIMITS TO THE X-RAY LUMINOSITIES OF FIVE SUPERNOVAE

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ABSTRACT

We have examined data from the OSO-III X-ray telescope for evidence of X-ray emission from five optically detected extragalactic supernovae during the period 1967 March–1968 June. Upper limits to the X-ray emission in the range 7.7–113 keV near optical maximum (within 30 days) fall in the range 10^{-8}–10^{-10} ergs (cm^2 s)$^{-1}$. Reasonable estimates of the distances to these supernovae lead to upper limits on the total energies of from 10^{50} to 10^{51} ergs.

I. INTRODUCTION

Although it has been conjectured that near optical maximum, supernovae radiate large amounts of energy in the X-ray region, no X-rays have yet been observed (Bradt *et al.* 1968; Gorenstein, Kellogg, and Gursky 1969). Previous upper limits came from data accumulations during rocket flights, generally over periods of less than 1 minute. In view of this we examined the data from the OSO-III X-ray telescope (Schwartz 1969) for evidence of X-rays from optically observed extragalactic supernovae (table 1). From these data it was possible to set upper limits to the X-ray luminosity of a supernova, over the range 7.7–113 keV, for intervals as long as 26 days.

II. DATA REDUCTION

The OSO-III X-ray telescope consists of a NaI(Tl) crystal central detector 0.5 cm thick surrounded by a CsI(Tl) active shield and collimator. For this analysis we used five logarithmically spaced energy channels in the range 7.7–113 keV. The X-ray telescope points along a radius of the wheel of the satellite, and the telescope scans a 360° great circle as the satellite wheel goes through one revolution.

The data were accumulated in two different operational modes. The sector-rates data mode included directional information, allowing us to search for an X-ray flux from the direction of the supernova under consideration. The background, consisting mainly of diffuse cosmic X-rays, was subtracted from the observed counting rate in the known direction. No statistically significant positive excess was found in any case, and so we established upper limits based upon counting statistics.

The other operational mode of the X-ray telescope, the night-rates mode, provided data only during satellite night. These data consist of integrations of the total number of counts received by the X-ray detector over eight revolutions of the satellite wheel for all arrival directions. The appearance of an X-ray source anywhere within the scan circle of the telescope would cause an increase in the counting rates. In practice we used these data only for upper limits and to indicate interesting time variations for detailed analysis in the sector-rates data. For example, the night rates increased during the interval from March 25 to April 5 as shown in figure 1. The sector-rates data in figure 2 showed that a galactic X-ray source caused the increase. In this manner we showed that all of the statistically significant increases in the night-rates data came from sources in different directions from the supernovae.

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TABLE 1

OPTICALLY DETECTED EXTRAGALACTIC SUPERNOVAE SCANNED BY OSO-III

Variable	SN 1967j	SN 1968c	SN 1968h, Type I	SN 1968i, Type I	SN 1968j
Right ascension (1950)	$1^{h}08^{m}.3$	$10^{h}57^{m}.5$	$12^{h}55^{m}.9$	$13^{h}06^{m}.1$	$14^{h}04^{m}.1$
Declination (1950)....	32°58′	28°59′	27°24′	−6°31′	53°22′
Name and type of host galaxy............	Anonymous, type Sb	Anonymous, type Ir	Anonymous	NGC 4781, Sc or SAb^{+}–SBb^{+}	Anonymous, type S0
m_{pg} of host galaxy....	15.7	18.0	16.6	12.34 (corrected)	15.4
Adopted distance (Mpc)............	130	99	150	31	93
$A_{pg}=0.25 \csc b^{II}$......	0.25	0.25	0.30	0.25	0.29
Max. m_{pg} of supernova	≤17.5	≤17.8	16.65	≤13.5	16.6
Distance to supernova derived from absolute luminosity of galaxy:					
A[*] (Mpc).......	132 (Sb II)	84 (Ir IV–V)	...	31 (Sc II)	...
B[†] (Mpc).......	124	113	...	30	92.5
Distance derived from other methods (Mpc)............	≤71,[‡] ≤200[§]	≤227[§]	160,[‖] 133[§]	≤31[§]	≤128[§]
References other than Kowal (1971)......	IAU Circ. 2041; Zwicky (1968)	IAU Circ. 2058	IAU Circs. 2070, 2072	IAU Circ. 2070	IAU Circ. 2075

[*] Van den Bergh 1960*a*, *b*.

[†] De Vaucouleurs 1961.

[‡] If in Pisces cluster.

[§] If a Type I supernova.

[‖] From redshift of host galaxy.

The use of the night-rates data required an analysis of the background counting rates which varied with time according to the number of sources in the field of view. We used intervals with reasonable fit to constant rates at about the time of each supernova. Each scan of a supernova included some nonbackground features (see fig. 1). To obtain an upper limit we assumed that the supernova radiated X-rays over an interval no more than half the length of the segment of data used to determine the background level. Thus, the night-rates data were used to search for the short-duration X-ray emissions, while the sector-rates data were used to search for long-duration X-ray emissions and also to examine any significant increases in the night-rates data. Since the orbital motion of the satellite caused many interruptions in the data, we could only search for X-ray emissions of durations greater than 1 day.

III. RESULTS

From the list of optically discovered supernovae for the period 1967 March–1968 June (Tucker 1969) we chose all the supernovae scanned by the OSO-III X-ray telescope near optical maximum. Table 1 gives the optical descriptions. The 7.7–22-keV night-rates data for these supernovae appear in figure 1; no useful night-rates data are available for SN 1968j because Sco X-1, a very strong and variable galactic X-ray source, also lay in the scan plane. We found no evidence in the OSO-III data for X-ray emission from any of the supernovae on time scales of 1–26 days.

In order to convert the upper limits from X-ray flux to energy flux, it was necessary

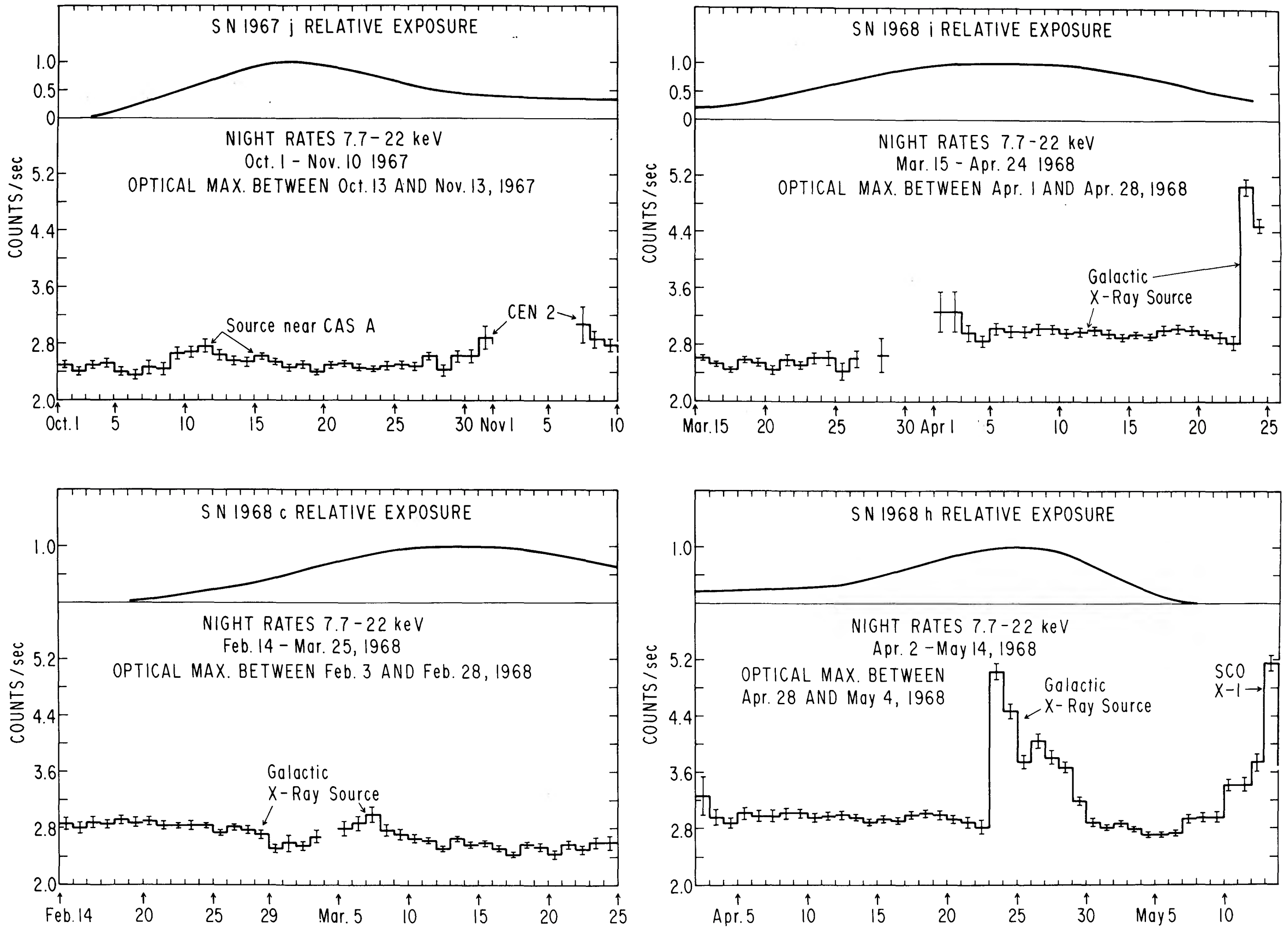

FIG. 1.—Counting rates from satellite eclipse (night rates), averaged over 1-day intervals for 7.7–22 keV, for the OSO-III X-ray telescope. Data are unavailable for the gaps shown near November 5, April 1, and March 5. The relative exposure represents the product of exposed area and accumulation time along the scan path of the X-ray telescope, normalized to a scan path directly intersecting the source. Point-source flux [counts $(cm^2\ s)^{-1}$] equals excess counting rate (counts s^{-1}) divided by (0.55 × relative exposure).

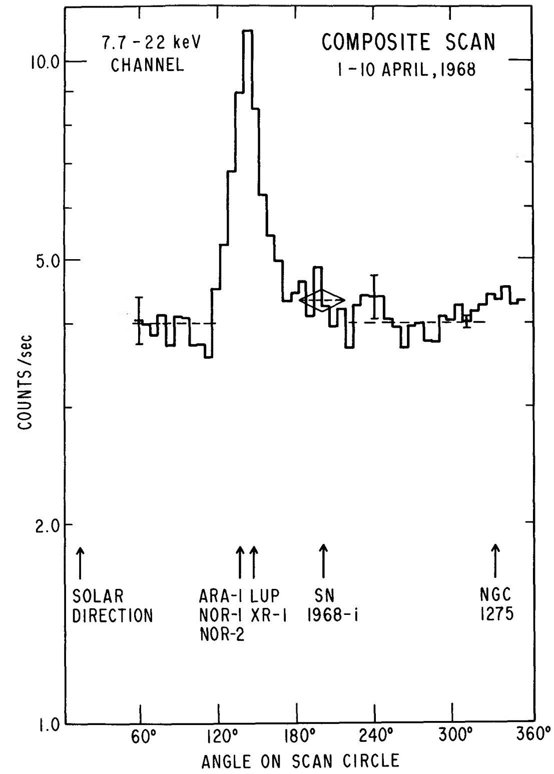

FIG. 2.—Sector-rates data for the high counting rates of 1968 April 1–10. Source of high counting rates clearly does not coincide with the supernova direction.

TABLE 2

SECTOR-RATES DATA: 2 σ UPPER LIMITS TO X-RAY FLUXES FROM EXTRAGALACTIC SUPERNOVAE

Date of Optical Max. of Supernova and Supernova Identification	Interval of Sector Rates Upper Limit	10^{9} ergs (cm^{2} s)$^{-1}$		10^{-45} ergs s^{-1}		10^{-50} ergs	
		7.7–22 keV	7.7–113 keV	7.7–22 keV	7.7–113 keV	7.7–22 keV	7.7–113 keV
SN 1967j, Oct. 13–Nov. 13...........	1967 Oct. 8–28	0.68	1.7	1.3	3.2	24	57
	Oct. 9–12	2.2	4.9	4.2	9.4	14	33
	Oct. 13–17	1.4	3.1	2.6	5.8	12	2.5
SN 1968c, Feb. 3–Feb. 28............	1968 Mar. 5–25	0.12	0.26	0.14	0.29	2.5	5.1
	Mar. 5–10	0.24	0.51	0.27	0.57	1.4	3.0
	Mar. 11–15	0.23	0.47	0.25	0.53	1.1	2.3
	Mar. 16–25	0.18	0.38	0.20	0.43	1.7	3.7
SN 1968h, Apr. 28–May 4............	1968 Apr. 17–30	1.3	2.7	3.2	6.8	39	82
SN 1968i, Apr. 1–May 4............	1968 Mar. 25–Apr. 19	0.79	1.8	0.085	0.19	1.9	4.2
SN 1968j, May 22.....	1968 May 3–18	1.1	2.8	1.1	2.8	18	39

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TABLE 3

NIGHT RATES: 2 σ UPPER LIMITS TO X-RAY FLUXES FROM EXTRAGALACTIC SUPERNOVAE

Date of Optical Max. and Supernova Identification	Interval of Night Rates Upper Limit	10^{9} ergs (cm^2 s)$^{-1}$		10^{-45} ergs s^{-1}		10^{-50} ergs	
		7.7–22 keV	7.7–113 keV	7.7–22 keV	7.7–113 keV	7.7–22 keV	7.7–113 keV
SN 1967j, Oct. 13–Nov. 13	1967 Oct. 19–22	2.3	7.4	4.4	14.0	15.0	50.0
SN 1968c, Feb. 3–Mar. 3	1968 Feb. 21–24	6.8	47	7.6	52	26	180
	Feb. 25–28	7.2	20	8.0	22	28	76
	Mar. 15–18	2.5	7.3	2.8	8.1	9.5	27
	Mar. 19–22	3.1	9.0	3.5	9.9	12	34
	Mar. 23–26	4.7	14	5.2	16	18	55
SN 1968h, Apr. 28–May 4	1968 Apr. 3–6	14.0	40	36	100	120	350
	Apr. 7–10	10.0	30	26	74	90	260
	Apr. 11–14	5.9	17	15	43	52	150
	Apr. 15–18	4.0	12	10	29	35	100
	Apr. 19–22	3.4	10	8.6	25	29	86
SN 1968i, Apr. 1–May 4	1968 Mar. 19–22	6.7	19	0.73	2.1	2.5	7.3
	Mar. 23–26	6.0	17	0.65	1.9	2.2	6.6
	Mar. 27–30	3.2	9.0	0.35	0.98	1.2	3.4
	Mar. 31–Apr. 3	2.6	7.3	0.28	0.79	0.97	2.7
	Apr. 4–7	2.3	6.5	0.25	0.71	0.86	2.5
	Apr. 8–11	2.8	7.7	0.3	0.84	1.0	2.9
	Apr. 12–15	5.1	14.0	0.55	1.5	1.9	5.2

to assume a spectral shape. We assumed the spectral shape $I_p = KE^{-2}$ photons (cm^2 s keV)$^{-1}$, which allows us to compare our results with the hypothesis that supernovae are the origin of the diffuse cosmic X-ray background (see, e.g., Apparao 1970; Tucker 1970; Silk 1971). We chose two energy ranges from the data: 7.7–22 keV, narrow enough to be relatively insensitive to the assumed spectral shape; and 7.7–113 keV. The 2 σ results appear in tables 2 and 3; the average upper limits to the X-ray intensity at the Earth range from 10^{-8} to 10^{-10} ergs (cm^2 s)$^{-1}$.

Estimates of the distances of the supernovae are needed to determine the upper limits to their total luminosities. We estimated the distances, shown in table 1, by four different methods: (1) Estimating the absolute luminosity of the host galaxy. (2) Estimating the absolute luminosity of the supernova. (3) Using the measured redshift of the host galaxy and assuming the Hubble constant $H = 75$ km (s Mpc)$^{-1}$ (Sandage 1968). (4) Identifying the host galaxy with a cluster of galaxies for which the distance from Earth had already been estimated.

For method 1 we used the absolute magnitude of the most common subtype of galaxy as determined by van den Bergh (1960*a*, *b*). We also used the absolute luminosities as determined by de Vaucouleurs (1961), and in both cases we allowed for differences in the choice of H. The absolute luminosities of supernovae as determined by Kowal (1968) were used for method 2, again adjusted for choice of H. We corrected for interstellar extinction in the Galaxy by using $A_{\rm pg} = 0.25 \csc b^{\rm II}$ but made no correction for the interstellar extinction of a supernova in its host galaxy. Except for the m_{pg} of NGC 4981, table 1 lists only raw photographic magnitudes.

Except for SN 1968i, multiple optical observations permitted estimates of the dates of optical maximum. For SN 1968i we estimated the time of optical maximum by first determining its absolute magnitude from estimates of the distance to the host galaxy. This magnitude differed by less than 0.5 mag from the average absolute magnitude of Type I supernovae (Kowal 1968). Allowing for some error in this method, we deduced that the supernova was within 2 mag of optical maximum and hence estimated the data of optical maximum by using the standard shape of a Type I supernova light curve (see, e.g., Minkowski 1964).

Using the distance estimates shown in table 1, we converted the upper limits on the X-ray flux at the Earth to upper limits on the absolute X-ray luminosities of the supernovae. The results shown in tables 2 and 3 are summarized below:

1. From all the data, the average 2 σ upper limit to the luminosity of a supernova ranging from $\sim$20 days before optical maximum to $\sim$10 days after optical maximum is $\sim 10^{45}$ ergs s^{-1} in the range 7.7–22 keV.

2. The lowest upper limits in terms of energy can be set for SN 1968i. The lowest 2 σ upper limits in the energy range 7.7–22 keV are $\sim 8.6 \times 10^{49}$ ergs over a 4-day interval, corresponding to $\sim 4.3 \times 10^{49}$ ergs over a 1-day interval, and $\sim 1.9 \times 10^{50}$ ergs over a 26-day interval.

In comparison, Bradt *et al.* (1968) reported an upper limit of 2×10^{42} ergs s^{-1} less than 34 days after optical maximum, and Gorenstein *et al.* (1969) reported an upper limit of 10^{45} ergs s^{-1} from a supernova less than 6 days after optical maximum.

IV. DISCUSSION

Several models have been proposed to explain the observed light curves of supernovae (see, e.g., Morrison and Sartori 1969; Colgate and McKee 1969; Grassberg, Imshennik, and Nadyozhin 1971, and references therein). Temperatures quoted for the region emitting the optical radiation, in these models, are in the range 10^4 °–10^6 ° K, too low to produce thermal continuum X-rays in the 7–100-keV region. Thus the results reported here cannot discriminate among supernova models of these types. Furthermore, the luminosity of Crab Nebula, the brightest galactic supernova remnant emitting X-rays, albeit with an age of $\sim$1000 years, is $\approx 10^{37}$ ergs s^{-1} (7–100 keV), well below the upper limits we can set here.

On the other hand, most discussions of the energetics of supernovae indicate an energy release between $\sim 10^{49}$ and 10^{52} ergs (e.g., Poveda and Woltjer 1968; Morrison and Sartori 1969). Minkowski (1964) integrated the light curve of a Type I supernova and estimated the energy radiated to be $\sim 3.6 \times 10^{49}$ ergs over optical and ultraviolet wavelengths. Therefore, the upper limits presented here imply that the ratio of energy radiated over the X-ray region (7.7–22 keV) to the ratio of energy radiated over optical and ultraviolet wavelengths is less than a factor of 10, near optical maximum for a Type I supernova. This assumes, of course, that the maximum X-ray emission takes place near optical maximum and over an interval of several days. In comparison, the Crab Nebula supernova remnant has a ratio of X-ray luminosity to optical luminosity of 2 (Bradt *et al.* 1968) and the pulsar NP 0532 has a ratio of X-ray luminosity to optical luminosity of $\sim 10^2$ (Apparao 1970). It should be noted, however, that the Crab Nebula radiates synchrotron emission, which does not dominate the supernova spectrum near optical maximum.

We now use our results to check the hypothesis that supernovae produce the diffuse X-ray background. We take the order-of-magnitude estimates by Tucker (1970) as a framework for this discussion. Tucker estimates that supernovae must radiate $\sim 3 \times 10^{50}$ ergs in the X-ray region in order to produce the diffuse X-ray background. Furthermore, since supernovae occur in galaxies, this hypothesis implies that galaxies have an average X-ray luminosity on the order of 10^{41} ergs s^{-1}. In addition, from the observed isotropy of the diffuse X-ray background (Schwartz 9170), Tucker showed that the radiating time scale of a supernova should exceed about 4 days in order to avoid producing a noticeable anisotropy. From our data the lowest 2 σ upper limit to the total energy emitted over a 4-day interval is $\sim 8.6 \times 10^{49}$ ergs (7.7–22 keV), and larger time intervals yield larger upper limits. The supernovae could therefore radiate sufficient energy over a timescale longer than 4 days or over somewhat different times relative to the optical maximum and remain undetected. Our data thus do not provide a conclusive test of the hypothesis that supernovae are the origin of the cosmic X-ray background.

V. CONCLUSION AND SUMMARY

In this paper we have presented results from the first long-period hard X-ray sky scan, which failed to detect X-rays from five extragalactic supernovae. The upper limits indicate that the energy released in the X-ray region (7.7–22 keV) near optical maximum is less than 10^{50}–10^{51} ergs. This is not more than a factor of 10–100 above the optical output, and it is less than the largest amounts of energy that are estimated to be generated in a supernova explosion.

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