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DETECTION OF X-RAYS DURING THE OUTBURST OF SUPERNOVA 1980k

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ABSTRACT

We have detected X-ray emission from SN 1980k in NGC 6946 ~ 35 days after maximum light using the Imaging Proportional Counter on the *Einstein Observatory*. Previously the youngest supernova known to emit X-rays was ~ 300 years past maximum light. The absorption corrected X-ray flux of SN 1980k was ~ 0.03 μJy at 0.24×10^{18} Hz (1 keV), corresponding to a luminosity of $\sim 2 \times 10^{39}$ ergs s^{-1} (0.2–4 keV) at 10 Mpc. This is 3500 times weaker than the optical luminosity at that time. Fifty days later the X-ray source was marginally detected at $\sim \frac{1}{2}$ this flux. The data are compatible with a thermal X-ray spectrum with $kT > 0.5$ keV or a power-law energy spectrum with index > -3. The contemporaneous detection of radio emission from SN 1980k suggests the presence of relativistic electrons and of a magnetic field strength of $\lesssim 1$ gauss. Inverse Compton scattering of the copious optical photons on these electrons can explain the X-ray emission without additional ad hoc assumptions. However, other emission mechanisms are conceivable. None of the other four historical supernovae in NGC 6946 has detectable X-ray emission.

Subject headings: stars: supernovae — X-rays: general

I. INTRODUCTION

It has long been suspected that some fraction of the prodigious energy released in a supernova explosion should emerge as X-ray emission. However, previous attempts have failed to detect X-rays from either Type I or II supernovae shortly after outburst, setting upper limits of 10^{40}–10^{45} ergs s^{-1} to their X-ray luminosities (Bradt *et al.* 1968; Gorenstein, Kellogg, and Gursky 1969; Ulmer *et al.* 1972; Sprott *et al.* 1974; Canizares, Neighbours, and Matilsky 1974; Ulmer *et al.* 1974; Panagia *et al.* 1980*a*). Heretofore, the youngest supernova known to emit X-rays was the 300-year-old remnant Cas A (Brecher and Wasserman 1980).

We have detected X-rays from the Type II supernova SN 1980k in the nearby face-on spiral galaxy NGC 6946 ~ 35 days after it reached maximum light. The X-ray luminosity is below the previous upper limits and represents a small fraction of the bolometric luminosity of the supernova. We find that the X-ray emission is probably caused by inverse Compton scattering of optical photons on the relativistic electrons responsible for the observed radio emission of SN 1980k. Other X-ray emission mechanisms cannot be ruled out, but they require additional ad hoc assumptions, including a choice of parameters to suppress the inverse Compton mechanism.

II. SUPERNOVA 1980k

Supernova 1980k in NGC 6946 was discovered by Wild (1980) on 1980 October 28. It was classified as Type II by Kirshner, Kriss, and Berg (1980). Maximum light occurred around 1980 November 5, at a visual magnitude of ~ 11.5 mag. By 1980 December 4 the supernova had faded to 12.6 mag (Baroni and Cavagna 1980). On this same day, Sramek, van der Hulst, and Weiler (1980; also Sramek 1981 and Weiler 1981) detected radio emission from SN 1980k, although it had not been detectable at maximum light.

III. X-RAY OBSERVATIONS

The galaxy NGC 6946 was observed with the Imaging Proportional Counter (IPC) on the *Einstein Observatory* (Giacconi *et al.* 1979) on three occasions (see Table 1). The first observation was part of a survey of late-type galaxies (Fabbiano, Feigelson, and Zamorani 1982). The deconvolved X-ray image of SN 1980k on 1980 December 11, ~ 35 days after maximum light, is shown in Figure 1. The X-ray flux from the location of SN 1980k (with the NW quadrant excluded to avoid contamination by the nucleus) is listed in Table 1.

The positional agreement between the X-ray source and the supernova together with the apparition of the source sometime between 1979 May and 1980 December make us confident that the X-ray emission is indeed from SN 1980k. The detection ~ 35 days after maxi-

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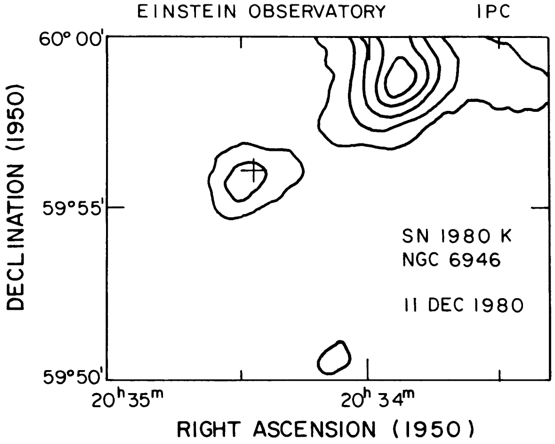

FIG. 1.—X-ray count rate contours showing SN 1980k and a portion of the nuclear emission of NGC 6946 after the deconvolution of the point source response. The observation was performed with the *Einstein Observatory* IPC ~ 35 days after SN 1980k reached maximum light. The cross is the radio/optical position of the supernova which agrees with the X-ray position within the ~ 1′ accuracy. The extended source to the NW is associated with the nucleus of NGC 6946 (Fabbiano, Feigelson, and Zamorani 1982).

mum light is significant at greater than a 5 σ confidence level. No emission was detected from the same region in the shorter, preoutburst observation; a source of the same strength as that seen postoutburst would have been detected at approximately a 3 σ confidence level, as verified by an analysis of the first 5130 s of the postoutburst data. The 1981 January observation gives a marginal 2 σ detection of the source. It suggests that during the intervening 47 days since discovery the X-ray flux of SN 1980k decreased by a factor of $\gtrsim 2$.

Despite the limited statistics of the 1980 December 11 observation and the systematic uncertainties in the IPC calibration, we can constrain the spectral parameters of SN 1980k. The values of color excess $E_{B-V} = 0.17$ for NGC 6946 (Sandage and Tammann 1975) or $E_{B-V} = 0.32$ for SN 1980k (Panagia *et al.* 1980*b*) imply column densities $N_{\rm H} \sim 1$ to 2×10^{21} cm^{-2} (Ryter, Cesarsky, and Audouze 1975; Gorenstein 1975). Fits to the IPC data of 1980 December 11 with this $N_{\rm H}$ indicate that a thermal spectrum must have temperature $kT > 0.5$ keV and a power-law spectrum must have $\alpha > -3$ (where the energy flux depends on the frequency ν as ν^{α}). Thermal spectra with temperatures $kT \approx 0.5$ keV are unacceptable unless $N_{\rm H} \approx 10^{22}$ cm^{-2}, but these are less plausible. Intermediate values of the spectral parameters were used to derive the absorption corrected fluxes and luminosities of Table 1. We adopt a distance of 10 Mpc (Sandage and Tammann [1975] quote 11 Mpc and de Vaucouleurs [1979] 5.1 Mpc, while Jacoby and Lesser [1981] set a limit > 4.8 Mpc).

Four previous supernovae have been observed in NGC 6946: SN 1917a, SN 1939c, SN 1948b, and SN 1968d (Sargent, Searle, and Kowal 1974). Each but the last of these is sufficiently far from the nuclear source to be detected if its X-ray luminosity were $\gtrsim 2 \times 10^{39}$ ergs s^{-1}, but none is visible in the IPC X-ray image.

IV. X-RAY EMISSION MECHANISM

There are several possible mechanisms for the X-ray emission of SN 1980k ~ 35 days after maximum light. Table 2 summarizes the data for that epoch. At maximum light, the photospheres of Type II supernovae have radii ~ 10^{15} cm and expansion velocities of ~ 8000 km s^{-1} (Kirshner and Kwan 1974, 1975), suggesting that the envelope has been expanding for ~ 15 days. Thus we adopt $t = 50$ days as the time between outburst and our X-ray detection.

In most of the following discussion we assume that the X-ray and radio emitting regions are outside the dense photosphere (as do Panagia *et al.* 1980*a*, Chevalier 1981*a*, and others). The alternative view, that the radiation emerges from the interior of the expanding envelope (e.g., Pacini and Salvati 1981), is considered briefly below.

a) *Nonthermal Mechanisms*

The existence of relativistic electrons and magnetic fields in SN 1980k can be inferred from the observed radio emission. With these ingredients, X-ray production can in principle arise from (i) inverse Compton scattering of the optical photons emitted at the photosphere off the electrons, (ii) direct synchrotron emission,

TABLE 1

EINSTEIN OBSERVATORY IPC OBSERVATIONS OF SN 1980k

Date	Days from Max. Light	Duration (s)	Count Rate (10^{-3} s^{-1})	Corrected Flux Density[a] (μJy at 0.24E Hz)	Luminosity[b] (ergs s^{-1})
1979 May 25 ...	−531	5,130	-0.83 ± 1.20	...	...
1980 Dec 11 ...	35	21,757	4.11 ± 0.73	0.03	2×10^{39}
1981 Jan 27	82	7,784	2.35 ± 1.15	~ 0.02	~ 1×10^{39}

[a] Corrected for absorption (see text); 0.24E Hz = 1 keV h^{-1}.
[b] 0.2–4.0 keV at 10 Mpc.

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TABLE 2

EMISSION OF SN 1980k ~ 35 DAYS AFTER MAXIMUM LIGHT

Band	Frequency (Hz)	Observed Flux Density (Jy)	Corrected Flux Density[a] (Jy)
Radio	4.8×10^9	0.7×10^{-3}	2×10^{-3}
Optical ...	5.5×10^{14}	35×10^{-3}	88×10^{-3}
X-ray	2.4×10^{17}	2×10^{-8}	3×10^{-8}

[a] Radio flux corrected for apparent absorption (Sramek, van der Hulst, and Weiler 1980; Sramek 1981; Weiler 1981); optical flux (Baroni and Cavagna 1980) corrected for $A_v \sim 1$ mag (Panagia *et al.* 1980*a*); X-ray flux corrected for $N_{\rm H} \sim 1\text{–}2 \times 10^{21}$ cm^{-2} (see text).

and (iii) "self-Compton" scattering of the radio photons off the relativistic electrons.

We find that the magnetic field strength in the radio emitting region must be $\lesssim 1$ gauss if there is approximate equipartition of energy between the magnetic field and the relativistic electrons. The energy in the field is $U_B \sim 10^{46}\ B^2 v_9^3$ ergs, where B is the magnetic field strength in gauss, and we take the emitting region to be a sphere expanding with velocity v_9 in units of 10^9 cm s^{-1}. The energy in electrons is $U_e \sim 3 \times 10^{44}\ B^{-3/2}$ ergs, assuming that the electron distribution with energy is a power law $\sim E_e^n$, that $n < -2$, and that the synchrotron emission extends from 10^8 to 10^{12} Hz (Tucker 1975; U_e is weakly dependent on these parameters). We have also assumed a 5 GHz radio flux of ~ 2 mJy, because the rapid rise of the radio flux to that value during 1980 December suggests that the lower flux observed on December 4 was affected by absorption (Sramek 1981; Weiler 1981). Equating U_e and U_B gives $B_{\rm eq} = 0.4\ v_9^{-6/7}$ gauss. Since $B_{\rm eq} \sim (U_B/U_e)^{2/7}$, only very large departures from equipartition can cause significant changes in the derived field strength. With $B_{\rm eq}$ the relativistic γ factor of the electrons responsible for the 5 GHz radio emission is $\gamma \sim 70$ or $E_e \sim 35$ MeV.

Compton scattering of optical photons is actually an inevitable X-ray production mechanism which can yield the observed flux. The electron energy required to boost the optical photons to the X-ray range is only $E_e \sim 10$ MeV ($\gamma \sim 20$), so the same electrons responsible for the radio emission produce X-rays. The X-ray flux can be calculated following Tucker (1975). Adopting an absorption corrected 5 GHz flux of ~ 2 mJy gives a Compton flux at 0.24 EHz of

$$F_c = 0.4 T_4^4 v_9^{12/7} f (B/B_{\rm eq})^{-2}\ \mu{\rm Jy} \qquad \text{for } n = -3,$$

$$F_c = 0.1 T_4^{7/2} v_9^{9/7} f (B/B_{\rm eq})^{-3/2}\ \mu{\rm Jy} \qquad \text{for } n = -2,$$

$$F_c = 0.014 T_4^3 v_9^{6/7} f (B/B_{\rm eq})^{-1}\ \mu{\rm Jy} \qquad \text{for } n = -1.$$

Here T_4 is the blackbody temperature of the photosphere in units of 10^4 K, and f is a dilution factor for the blackbody photon density, $f = (R_0/2R_r)^2$, with R_r and R_0 the radii of the radio emitting region and the optical photosphere, respectively (the calculation neglects any anisotropy of the photon flux; Blumenthal and Gould 1970).

The estimates of F_c are remarkably close to the observed X-ray flux for reasonable values of $f \lesssim 0.5$, $T_4 \sim 0.7\text{–}0.8$, and $B \sim B_{\rm eq}$ (Kirshner 1981). Since Compton scattering of the optical photons to X-ray energies will inevitably occur if our estimate of the magnetic field strength is approximately correct, other processes such as thermal emission can dominate the X-ray flux only if $f \ll 1$ or if $B \gg B_{\rm eq}$. Both T_4 and f should decrease with time, so the marginally significant decline in the X-ray flux from 1980 December 11 to 1981 January 30 can be explained by the inverse Compton model.

Direct synchrotron emission could produce the observed X-ray flux only if electrons of sufficiently high energy are present. The observed radio and X-ray fluxes of Table 2 can be connected by a power law in frequency of index $\alpha_{rx} = -0.6$, which would imply a power-law electron distribution with index $n = -2.1$ extending to electron energies $E_e > 500$ GeV ($\gamma > 10^6$).

Production of the X-rays by the self-Compton process is not plausible. Although the requirement on electron energy is modest ($E_e > 200$ MeV), the ratio of the self-Compton flux to the (extrapolated) synchrotron flux is $3 \times 10^{-3}\ v_9^{-2/7}\ (B/B_{\rm eq})^{-2}$ (Jones, O'Dell, and Stein 1974). This ratio is $\ll 1$ because v_9 is surely > 0.5 if the emitting region is outside the photosphere.

b) Thermal Mechanism

If the X-rays are emitted by a thin, hot plasma, the observed luminosity implies a volume emission measure $\langle n_e^2 \rangle V \approx 10^{62}$ cm^{-3}, where n_e is the thermal electron density and V the emitting volume, and we assume a plasma emissivity of 2×10^{-23} ergs cm^3 s^{-1}. This in turn gives

$$\langle n_e^2 \rangle^{1/2} \approx 2 \times 10^7 v_9^{-3/2}\ F^{-1/2}\ {\rm cm}^{-3},$$

where $F \lesssim 1$ is the fractional volume occupied by the thermal plasma (neglecting the possible occultation by the photosphere). We can estimate a mass,

$$M_x \approx 5 \times 10^{-3}\ v_9^{3/2} F^{1/2}\ M_\odot,$$

and column density,

$$N_x \approx 8 \times 10^{22}\ v_9^{-1/2} F^{-1/2} \left[1 - (1 - F)^{1/3}\right] {\rm cm}^{-2},$$

for the X-ray emitting gas.

Chevalier (1981*a*, *b*) and Fransson (1981) have suggested that such an X-ray emitting plasma could be formed as the supernova shock propagates through a circumstellar shell composed of the slowly expanding wind from the presupernova star. The plasma temperature behind the primary shock is $\sim 10^9$ K, and the total X-ray luminosity is $\sim 2 \times 10^{37}\ \dot{M}_{-6}{}^2 w_6{}^{-2} v_9{}^{-1} t_6{}^{-1}$. Here $\dot{M}_{-6}$ is the mass loss rate of the wind in units 10^{-6} $M_\odot$ yr^{-1}, w_6 is the presupernova wind velocity in 10^6 cm s^{-1}, v_9 is the shock velocity in 10^9 cm s^{-1}, and t_6 is the supernova age in 10^6 s. The plasma will cool with a time scale of months.

Clearly a significant thermal X-ray flux could be emitted if the proper amount of circumstellar matter is present. The marginally indicated decline in the X-ray flux between 1980 December 11 and 1981 January 30 could be naturally explained by the t^{-1} evolution of the model luminosity.

c) *X-Ray Reverberation*

Klein and Chevalier (1978), Falk (1978), and Lasher and Chan (1979) have concluded that a brief, intense burst of X-rays will be emitted by a Type II supernova when the initial shock emerges from the dense stellar envelope (see also Epstein 1981). If there is circumstellar material, Thomson scattering of the X-ray burst will cause a time-delayed "reverberation" which could, in principle, last many weeks. The time-delayed luminosity can be expressed as

$$L_{\rm rev} = 6.7 \times 10^{35}\, I_{46} \dot{M}_{-6} w_6{}^{-1} t_6{}^{-2}\ \text{ergs s}^{-1},$$

where I_{46} is the burst intensity (in 10^{46} ergs), t_6 the time (in 10^6 s), $\dot{M}_{-6}$ and w_6 are wind parameters as described above (see Canizares 1976). As $I_{46} \sim 2$–30 (Klein and Chevalier 1978), $L_{\rm rev}$ falls well below the observed luminosity.

d) *Other Mechanisms*

The material of the expanding supernova envelope will be opaque to 1 keV X-rays for many years (Bahcall, Rees, and Salpeter 1970). X-ray and radio emission could emerge from a newly formed pulsar inside the photosphere only if the envelope is sufficiently porous, as Pacini and Salvati (1981) suggest to explain the radio emission from SN 1979c.

If the envelope is porous, some fraction of the gamma-ray emission from the decay of radioactive elements in the supernova ejecta could be degraded to X-ray energies by Compton scattering. However, for the species synthesized in the 25 $M_\odot$ supernova model of Woosley, Axelrod, and Weaver (1981), a nearly 100% conversion of gamma-rays to X-rays would be required to give the X-ray luminosity we observe for SN 1980k.

V. DISCUSSION

The detection of X-ray emission from SN 1980k provides a spectral snapshot of the source that covers 9 decades of frequency. The luminosity of the supernova is dominated by the thermal emission of the expanding photosphere, which exceeds that in the X-ray by a factor of 3500. The radio emission indicates that $\sim 10^{-6}$ of the $\sim 10^{51}$ ergs released during the explosion appears as mildly relativistic electrons and a magnetic field of $\lesssim 1$ gauss. It seems most plausible that the X-rays arise from inverse Compton scattering of the optical photons on these electrons. However, we cannot exclude thermal emission from a circumstellar shell (some circumstellar material is indicated by the change in radio opacity in 1980 December to 1981 January; Weiler 1981; Chevalier 1981*b*). A detailed model that unifies all the observations and takes account of source geometry should now be constructed.

The X-ray luminosity of SN 1980k, the upper limits to the luminosity of the historical supernovae in NGC 6946, and the much smaller luminosity of the 300-year-old remnant Cas A ($\sim 10^{36}$ ergs s^{-1}; Gorenstein and Tucker 1976) suggest that, after a possible brief outburst, Type II supernovae are considerably less X-ray luminous than a bright binary X-ray source such as SMC X-1 (Blumenthal and Tucker 1974). Thus they probably constitute a minor fraction of the time-averaged X-ray output of a galaxy (e.g., see Fabbiano, Feigelson, and Zamorani 1982). Tucker (1970) and Silk (1973) showed that the X-ray output of supernovae could make a sizable contribution to the diffuse X-ray background if each supernova had an integrated energy of $\sim 10^{50}$ ergs. Our observations indicate that the X-ray output of Type II supernovae probably falls well below this value.

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