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Evidence for a possible black hole remnant in the Type IIL Supernova 1979C

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ABSTRACT

We present an analysis of archival X-ray observations of the Type IIL supernova SN 1979C. We find that its X-ray luminosity is remarkably constant at $(6.5 \pm 0.1) \times 10^{38}$ erg s^{-1} over a period of 12 years between 1995 and 2007. The high and steady luminosity is considered as possible evidence for a stellar-mass (∼5–10 $M_{\odot}$) black hole accreting material from either a supernova fallback disk or from a binary companion, or possibly from emission from a central pulsar wind nebula. We find that the bright and steady X-ray light curve is not consistent with either a model for a supernova powered by magnetic braking of a rapidly rotating magnetar, or a model where the blast wave is expanding into a dense circumstellar wind.

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1. Introduction

Kasen and Bildsten (2010) and Woosley (2010) have recently suggested that a class of Type IIL supernovae (SNe) may be powered by the birth of a magnetar during the SN event. These SNe include SN 1961F, SN 1979C, SN 1980K, and SN 1985L. In particular, Kasen and Bildsten (2010) argue that for a supernova with ejecta mass $M_{ej} = 5\,M_{\odot}$ that forms a magnetar with an initial period of $P_i = 10$ ms, the supernova can reach peak luminosities consistent with what was observed in these events. They also show that even brighter ($M_B = -21$) events can occur, such as the ultra-bright Type IIL SNe 2005ap and 2008es.

Motivated by Kasen and Bildsten (2010), Woosley (2010), we compared the time evolution of the X-ray luminosity of SN 1979C to the form expected from a magnetar-powered SN. In Section 2, we discuss SN 1979C and examine its X-ray luminosity. We find that contrary to the expectation of these papers, the evolution of this SN is not consistent with the magnetar model. Additionally, we show that the X-ray emission spectrum exhibits evidence for hard X-ray emission, possibly originating from a central source. We show that the X-ray luminosity has been steady over the lifetime of the SN evolution and argue that this is due to an accreting stellar-mass black hole remnant at the center of SN 1979C.

2. SN 1979C

The Type IIL SN 1979C, discovered on April 19 1979 by G. Johnson (Mattei et al., 1979) and its host galaxy NGC 4321 (M100, at a distance of 15.2 ± 0.1 Mpc; Freedman et al., 2001) have been extensively observed in the radio (Weiler et al., 1986; Montes et al., 2000; Bartel and Bietenholz, 2003, 2008; Marcaide et al., 2009), optical (Fesen and Matonick, 1993; Milisavljevic et al., 2009) and X-ray (Immler et al., 1998; Kaaret, 2001; Immler et al., 2005) bands. At optical wavelengths, the $H\alpha$ flux has decreased by ∼35% between 1993 and 2008, while forbidden line emission from lines such as [O III] has increased ∼50% (see Fig. 3 of Milisavljevic et al., 2009). The increase in the forbidden line emission is evidence of shock heating of the ejecta by the reverse shock. Similar to the $H\alpha$ emission, the radio emission also shows a decline of a factor of ∼5 over the lifetime of the SN (Bartel and Bietenholz, 2008), though early observations provided evidence for quasi-periodic oscillations that may be the result of a modulation in the progenitor's circumstellar environment by a binary companion (Weiler et al., 1992; Schwarz and Pringle, 1996).

Recently, Bartel and Bietenholz (2008) noted that in conjunction with a decrease in the radio luminosity the spectrum has begun to flatten. They note that the flattening spectrum would be expected for a supernova with emission from a compact remnant that is beginning to appear in the shell as the expanding remnant becomes increasingly transparent. They point out, however, that the flattened spectrum could also be due to synchrotron emission from the shell as electrons are accelerated to GeV energies. We note that in this scenario, it would be reasonable to expect an increasing hard X-ray flux as electrons are accelerated to TeV energies. More recently, Marcaide et al. (2009) presented a revised analysis of the radio expansion of SN 1979C and found that the expanding blastwave is in near free expansion with $m = 0.91 \pm 0.09$ for $R \propto t^m$. This seems contrary to X-ray observations which suggest that the blastwave has been strongly decelerated by a dense circumstellar

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Table 1
X-ray observations of SN 1979C.

Δt yr	Count rate 10^{-4} cps	F_X[a] 10^{-14} erg cm^{-2} s^{-1}	L_X[b] 10^{38} erg s^{-1}	Mission
0.7	<3.0	<2.3	<6.3	*Einstein* (HRI)
16.2	6.7 ± 0.7	3.0 ± 0.3	8.2 ± 0.9	*ROSAT* (HRI)
20.6	42. ± 2.0	2.5 ± 0.2	6.9 ± 0.6	*Chandra* (ACIS-S)
22.7[c]	...	2.3 ± 0.3	6.3 ± 0.7	*XMM–Newton* (MOS)
26.5[d]	8.0 ± 0.9	2.3 ± 0.3	6.3 ± 0.7	*Swift* (XRT)
26.9	40. ± 0.8	2.4 ± 0.2	6.6 ± 0.5	*Chandra* (ACIS-S)
28.0	43. ± 0.3	2.6 ± 0.2	7.0 ± 0.5	*Chandra* (ACIS-S)

[a] Unabsorbed 0.3–2.0 keV flux assuming a 0.5 keV thermal Bremsstrahlung model with Galactic hydrogen column density of 2.4×10^{20} cm^{-2}.
[b] Luminosity assumes a distance to M100 of 15.2 ± 0.1 Mpc (Freedman et al., 2001).
[c] Flux value taken from Immler et al. (2005).
[d] Values are from *Swift* XRT observations taken between 2005 and 2006, with the first observation performed on 2005–11–13.

interaction (Immler et al., 2005). While the optical and radio emission have showed evolution over ~25 years, X-ray observations of SN 1979C show a markedly different behavior. As seen in Table 1, the X-ray luminosity has remained remarkably constant over its 30 yr lifetime.

Kasen and Bildsten (2010) suggest that Type IIL SNe such as SN 1979C may have been magnetar powered. In the context of a magnetic dipole model, one can write the spindown luminosity as $L_p = 5 \times 10^{42} B_{14}^2 P_i^{-4}$ erg s^{-1} for a magnetar with magnetic field B_{14} (in units of 10^{14} Gauss) and period P_i (in units of 10 ms), or as

$$L_p = 2 \times 10^{42} B_{14}^2 (t/\mathrm{yr})^{-2} \ \mathrm{erg\ s^{-1}}. \quad (1)$$

The observed X-ray luminosity, L_X, can be expressed as some fraction, f_x, of the magnetar spindown luminosity, i.e. $L_X = f_x L_p$. In Fig. 1 we plot the evolution of the X-ray luminosity for a dipole magnetar-powered SN assuming that 1, 3, or 10% of the spindown power is transferred into X-rays, with $B_{14} = 1$ and $P_i = 1$. We also indicate the X-ray luminosity (from Table 1) as observed by the *ROSAT*, *XMM–Newton*, *Chandra*, and *Swift* observatories, as well as the early upper limit from the *Einstein* observatory HRI, where the model predicted X-ray luminosity is more than two orders of magnitude above the *Einstein* upper limit. As seen in Fig. 1 and also in Table 1, the observed X-ray luminosity[1] is remarkably constant over time, with $L_X = (6.5 \pm 0.1) \times 10^{38}$ erg s^{-1}.

Most importantly, even if the magnetar powered the SN only at early times, it would have likely resulted in a clear detection by the *Einstein* observatory. The above equation applies to a magnetic dipole spindown. More generally, the magnetar luminosity can be written as

$$L_p \propto \frac{(l-1)}{(1+t/t_p)^l}, \quad (2)$$

where t_p is the initial spindown time and $l = 2$ for magnetic dipole spindown. At late times, $L_p \propto t^{-l}$, and for all physical values of l the luminosity decreases with time. If the X-ray luminosity is some fraction of the spindown luminosity, the fraction will need to increase with time, potentially up to unphysical values greater than unity, in order for the observed X-ray luminosity to remain constant.

2.1. Spectral modeling

The combined *Chandra* ACIS-S spectrum of SN 1979C is shown in Fig. 2. Immler et al. (2005) fit the *XMM-Newton* observation to a two component thermal plasma model (MEKAL model in XSPEC[2]), with $kT_{low} = 0.77^{+0.17}_{-0.19}$ keV and $kT_{high} = 2.31^{+1.95}_{-0.66}$ keV. They did not

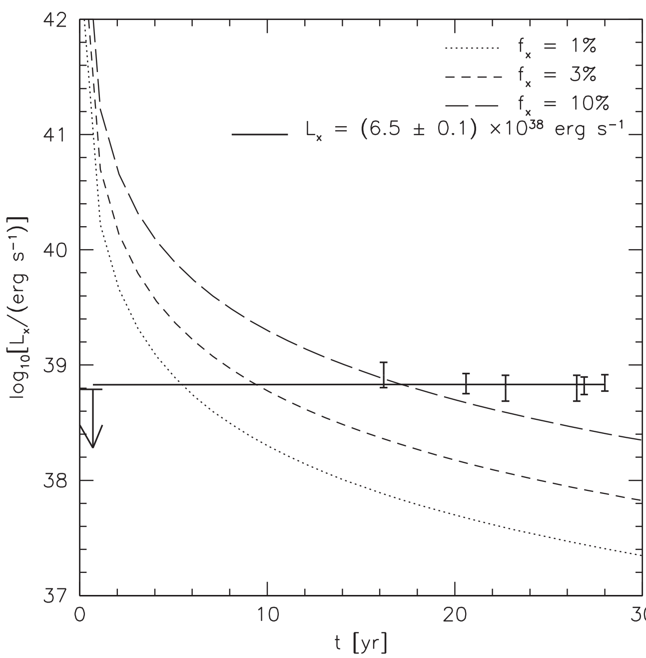

Fig. 1. Evolution of the X-ray luminosity of SN 1979C. The dotted, dashed, and long-dashed diagonal lines correspond to the evolution of the SN luminosity if it were powered by the magnetic dipole spindown of a central magnetar for various X-ray efficiencies, f_x. The data points correspond to the 0.3–2.0 keV X-ray luminosities with $1-\sigma$ uncertainties, assuming a distance of 15.2 Mpc. The upper limit from the *Einstein* observatory is depicted as an arrow. The heavy solid line corresponds to our best fit value of a nearly constant X-ray luminosity.

find any evidence for strong absorption, with a fitted hydrogen column density $N_H \approx 2.5 \times 10^{20}$ cm^{-2} (see also Dickey and Lockman, 1990), and attribute the low temperature component to recently shocked ejecta, and the high temperature component to emission from swept–up circumstellar material (CSM). In their model, the shocked circumstellar emission arises from a dense wind, with densities of $\lesssim 10^5$ cm^{-3} out to radii of 0.13 pc, yielding column densities $\lesssim 10^{22}$ cm^{-2}. Immler et al. (2005) argue that VLBI imaging at $t = 22$ yr show no evidence for clumping in the CSM, indicating that the CSM is remarkably uniform. If this were the case, then both the *XMM–Newton* and *Chandra* ACIS-S spectrum would show strong absorption at low energies. We fitted the *Chandra* ACIS-S spectrum to a two component thermal plasma model, and found that the spectrum can be described by two thermal plasmas with temperatures $kT = 0.75^{+0.2}_{-0.3}$ and $1.86^{+0.88}_{-0.72}$ keV, which shows no evidence for the level of absorption expected from the above properties of a hypothetical dense smooth CSM. We note that our fitted parameters and those of Immler et al. (2005) are consistent.

Recently, Bietenholz et al. (2010) reported on VLBI detection of a central source in SN 1986J. They argue that the small proper

[1] To convert from the observed count rates to source fluxes and luminosities, we assume an absorbed thermal bremsstrahlung model with $n_H = 2.4 \times 10^{20}$ cm^{-2} and $kT = 0.5$ keV.
[2] http://heasarc.nasa.gov/xanadu/xspec/.

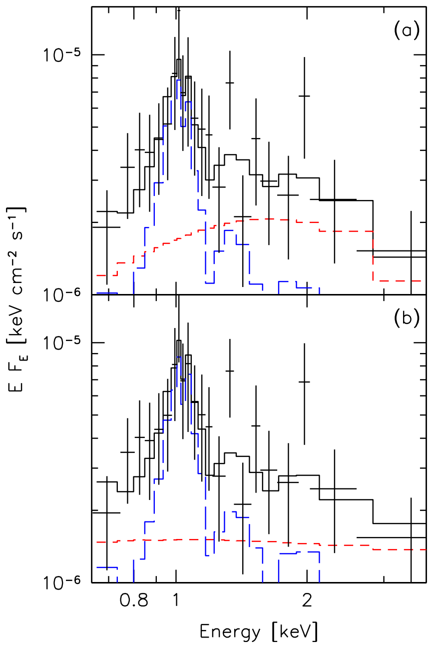

Fig. 2. The unfolded *Chandra* ACIS-S spectrum of SN 1979C. Panel (a) shows the data with its $1-\sigma$ error bars (crosses), which is fitted as a combination of a thermal plasma component (blue long-dashed line), and emission from a relativistic accretion disk around a Kerr black hole (red short-dashed line). For the thermal component, we infer a temperature of kT = 1.2 keV, and for the disk component, we infer a black hole mass of M_{BH} = 5.2 $M_\odot$. Panel (b) shows the same thermal plasma model as in panel (a) together with a power-law fit (red short-dashed line) with a spectral slope for the flux per unit energy $F_E \propto E^{-\Gamma}$ of Γ = 2.1. In both panels, the fitted absorption is consistent with Galactic foreground of a hydrogen column density, $N_H = 2.5 \times 10^{20}$ cm^{-2}. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

motion of the source (500 ± 1500 km s^{-1}) provides evidence that the source is either a central neutron star or black hole, but they do point out that it might also be a dense CSM condensate seen along the line of sight, as similar clumped regions appear in the northeastern region of the SN 1986 J shell. Additionally, as previously pointed out, Marcaide et al. (2009) showed that the blastwave of SN 1979C is still in free expansion, and Bartel and Bietenholz (2008) argued that the flattening radio spectrum could be evidence for emission from a central compact remnant. We thus chose to fit the X-ray spectrum of SN 1979C as a combination of shocked plasma, either arising from shocked CSM or ejecta, along with a component associated with a central source. The resultant fits are shown in Fig. 2. In both cases, we found that the thermal component is well described by a plasma with $kT = 1.1^{+0.14}_{-0.12}$ keV in collisional ionization equilibrium. We first modeled the hard emission as a power-law (bottom panel of Fig. 2), and found a power-law index for the flux per unit energy $\Gamma = 2.2^{+0.3}_{-0.4}$. We also fit the data to a model for an accreting central black hole, using the `kerrbb` model in XSPEC, shown in the top panel of Fig. 2. We found that the hard component of the spectrum can be well fit for a black hole mass of $\sim(5.2 \pm 0.8)\,M_\odot$. We do note, however, that while the X-ray spectrum is well described by a spectrum from an accreting black hole, we do concede that a powerlaw fit such as that shown in the bottom panel of Fig. 2 is still consistent with emission from either a central compact source such as a pulsar wind nebula, or from synchrotron emission arising from shock accelerated electrons.

2.2. A black hole remnant?

While a two component thermal model can describe the X-ray spectrum for SN 1979C, with the hard component having a $kT \gtrsim 2$ keV, as seen in Fig. 2, the data are equally well described by a thermal component, either from shocked CSM or shocked ejecta, and a hard spectral component, possibly from a central source. Immler et al. (2005) modeled the X-ray emission as arising from the expansion of the blastwave into a dense circumstellar wind, with values ranging from 10^4–10^7 cm^{-3} out to radii of 4×10^{17} cm. Ahead of the blastwave, the circumstellar density in their model is still 10^3 cm^{-3} at a distance of 1 pc (c.f. Fig. 6 of Immler et al., 2005), which would add an absorbing column density of $\sim 3 \times 10^{21}$ cm^{-2}, well in excess of the measured absorption in the spectrum of SN 1979C.

Additionally, in models for supernova remnant (SNR) evolution where the blast wave is expanding into a wind, the X-ray (and optical and radio) emissivity *from the expanding blast wave* should decrease with increasing blast wave radius. This is because the blast wave encounters the densest material at small radii, and sweeps over less dense material as it expands to a larger volume. At the late times of interest here, the ejecta is optically thin (Chevalier and Fransson, 1994). The free-free emission measure scales quadratically with the particle number density n and linearly with the volume $V \propto r^3$, so that for the typical $n \propto r^{-2}$ radial profile of a wind, $L_X \propto n^2 V \propto r^{-1}$ decreases with time. Other SN remnants (SNRs) do show evidence for a strong interaction with a circumstellar medium (c.f., SN 1994I and SN 1993J; Immler et al., 2002; Chandra et al., 2009). SN 1993 J was observed with *Chandra* in 2000 and again in 2008. Analysis of these data show that the X-ray luminosity has dropped from $\sim 6 \times 10^{38}$ erg s^{-1} in 2000 to $\sim 1.5 \times 10^{38}$ erg s^{-1} in 2008. This sharp drop in X-ray luminosity is inconsistent with the near steady X-ray emission from SN 1979C.

A plausible explanation for the constant luminosity would be to associate it with Eddington-limited accretion onto a central compact object of mass M_x. Based on the Eddington luminosity value,

$$L_{Edd} = 1.4 \times 10^{38} \left(\frac{M_x}{M_\odot}\right) \text{erg s}^{-1}, \quad (3)$$

with a modest bolometric correction (*e.g.* $L_{H\alpha} = 1.6 \times 10^{37}$, $L_{UV} = 9 \times 10^{36}$ and $L_{1.6GHz} = 1.6 \times 10^{36}$ erg s^{-1}; Immler et al., 2005; Bartel and Bietenholz, 2003), this implies that the accreting object has a mass of 5–10 $M_\odot$, which is within the typical range associated with stellar-mass black holes (McClintock, 2009). The hard component of the X-ray spectrum of the source shown in Fig. 2 is consistent with the spectrum of an Eddington-limited black hole in an X-ray binary such as LMC X-3 (see Fig. 1 in Davis et al., 2006), and our spectral fits to the data imply a black hole mass of $\gtrsim 5\,M_\odot$. It is plausible to expect that a black hole forms in a Type IIL SNe. According to Fig. 2 of Heger et al. (2003), solar metallicity stars with progenitor masses $\simeq 25\,M_\odot$ can follow a track that leads to black hole formation. Heger et al. (2003) also point out that 25% of low mass ($M \sim 20\,M_\odot$) progenitors with solar metallicity will produce black hole remnants by fallback. Since ~3% of core-collapse SNe are Type IIL (Smartt, 2009), this implies that some Type IIL's will form a black hole remnant, consistent with predictions for theoretical black hole mass distributions from core-collapse SNe (Fryer and Kalogera, 2001). Interestingly, Heger et al. (2003) also suggest that Type IIL/b SNe are produced in binaries, which would avoid the need for a fallback accretion disk in the SN (Perna et al., 2000; Wang et al., 2006) as the binary companion would provide the accreting material. There has been some evidence for a binary companion to the progenitor of SN 1979C, seen as a modulation of the early time radio light curve.

The existence of an accreting black hole remnant at the center of SN 1979C is consistent with the upper limit on the early X-ray luminosity established by the *Einstein* Observatory. For supernova models with 2–5 $M_\odot$ of ejecta and explosion energies of 2×10^{51} erg s, the expanding ejecta bubble becomes optically thin to keV X-rays on a timescale of 15 yr. The upper limit on the *Einstein* observation may reflect that early phase of the SNR evolution when the ejecta is optically thick or the time delay required to establish a stable accretion flow around the black hole remnant, which is calculated to be about twice the recombination timescale, $\sim$1 yr (Zampieri et al., 1998; Balberg et al., 2000).

Milisavljevic et al. (2009) note the presence of a Wolf–Rayet "bump" in the optical emission spectrum of SN 1979C which may be associated with the progenitor. They mention that several metal–rich H II regions in M100 have been observed to possess WR stars (van Dyk et al., 1999; Pindao et al., 2002), and *HST* imaging shows several young blue stars of age 4–6 Myr in the vicinity of SN 1979C. Photometry of the clusters' stellar population yields an estimate of the progenitor's mass to be $(18) \pm 3\ M_{\odot}$. This is consistent with the expected progenitors for Type IIL SN and with the required progenitor mass to form a black hole during the SN explosion, possibly from a fallback disk.

We have also analyzed *Chandra* and *ROSAT* observations of other two other Type IIL SNe, SN 1980K and SN 1985L. We have found that the X-ray luminosity of SN 1979C is more than an order of magnitude larger than that of SN 1980K ($L_X \approx 5.5 \times 10^{37}$ erg s^{-1}) and SN 1985L ($L_X \lesssim 4 \times 10^{37}$ erg s^{-1}). Interestingly, the latter luminosities from these Type IIL SNe are more consistent with a pulsar origin in young SNe, such as SN 1968D, SN 1941C, and SN 1959D (Perna et al., 2008; Soria and Perna, 2008), in line with Heger et al. (2003) who point out that not all Type IIL's will form a black hole remnant.

3. Conclusions

Our analysis of archival X-ray observations of SN 1979C indicate that the X-ray luminosity has been remarkably steady. We find that the X-ray light curve is not consistent with either a model for a supernova powered by a magnetar or a model where the X-ray emission arises from a blast wave expanding into a dense circumstellar wind. In the latter case, the observed decline in the optical and radio bands should be accompanied by a decline in the X-ray flux. The X-ray spectrum for SN 1979C can be modeled by a combination of a thermal X-ray component and emission from an accreting black hole with a mass $\sim$5 $M_{\odot}$. The accreting material likely originates from either a fallback disk after the supernova, or possibly from material accreted from a binary companion which is suggested by the radio light curve at early times (Weiler et al., 1992; Schwarz and Pringle, 1996). Finally, we note that the formation of a black hole in SN 1979C might have also imprinted a feature in the optical supernova light curve. Young et al. (2005) recently showed that the supernova light curve can be fit by a two component model which includes a GRB afterglow followed by supernova ejecta. They argued that the GRB optical afterglow is produced when a jet, from the formation of the central $\sim$2 $M_{\odot}$ black hole, penetrates through the stellar envelope.

We note that SN 1979C appears to be the first example of a historic supernova where there is possible evidence for a black hole remnant. A survey of Type IIL SNe observed at late times could reveal the existence of other accreting black hole remnants and constrain the statistics of black hole formation in core–collapse SNe. We note that a deep *Chandra* or *XMM–Newton* observation of SN 1979C could settle the issue, as it would allow for both a detailed spectral analysis of the emitted spectrum as well as a search for short term variations in the X-ray light curve, which could be seen as evidence for ongoing accretion.

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