Core-collapse Supernova Remnants in the Magellanic Clouds: 0453-68.5 and 0049-73.6

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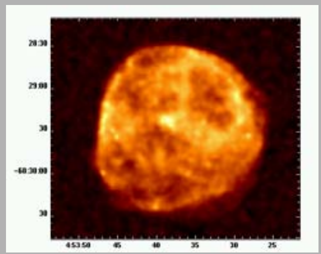


LMC SNR 0453-68.5

Angular Extent ~ 142"

Radius ~ 17 pc

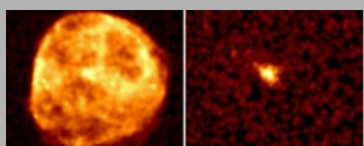
From Sedov fits to rim emission:

Shock Age ~ 13,000 yr

Swept Up Mass ~ 110 M_o

Explosion Energy ~ 5.0 x 10^{50} ergs

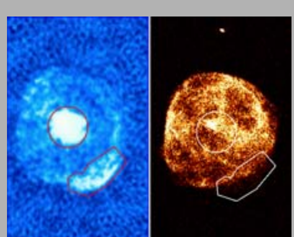
Hard versus Soft Emission



0.3-2.0 keV | 2.0-8.0 keV

PWN Detection

The hard emission in the central region is well described by a power-law spectrum with energy spectral index of –0.9. This prompted a radio observation with ATCA seen below. Embedded in the SNR shell is a compact central nebula producing both flat-spectrum polarized radio emission and nonthermal X-rays. We identify this source as a pulsar wind nebula (PWN) powered by an unseen central neutron star. The spectral index of the radio emission is –0.1.



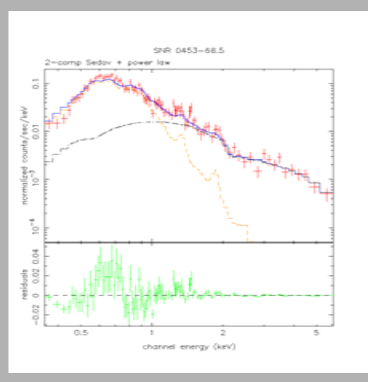
21-cm radio image with ATCA (left) compared to raw *Chandra* image (right). Besides the central source, the SW corner is brightened in the radio image. Unfortunately, there are not enough X-ray counts for spectral investigation.

SNR 0453-68.5 Summary

We find this SNR to be fully in the Sedov phase of evolution, with no evidence for ejecta within its center. Our investigation of the shell's X-ray emission shows no enhanced abundances beyond the levels in the LMC ISM swept up by the blast wave. 0453-68.5 is classified as the result of a core collapse progenitor due to the presence of a PWN in the interior. Our *Chandra* observation along with the ATCA radio observation leads us to conclude that this star was an initial rapid rotator with current properties similar to those of the Vela pulsar. As is the case for other similarly aged sources, there is currently an interaction taking place between the PWN and the SNR's reverse shock.

ABSTRACT

We present recent observations with the Chandra X-ray Observatory of SNR 0453-68.5 in the LMC and SNR 0049-73.6 in the SMC. We have determined that both SNRs resulted from core collapse explosions. In the case of 0453-68.5, we discovered a pulsar wind nebula (PWN) within the central region that pinpointed the origin. This is a large SNR, 17 pc in radius, with the outer shell emission well described by a Sedov model. Assuming Sedov dynamics we arrive at an age of 13,000 years for 0453-68.5 and 110 solar masses in swept-up material. 0049-73.6 in the SMC is quite a different object. The bright central emission in the central region does not show the presence of a PWN; rather we find evidence for ejecta. This remnant lacks the limb brightening seen in many remnants as an indication of swept up ISM material, as the central emission is much brighter than the outer regions. Spectral comparisons of these regions indicate enhanced abundances of O and Ne in the center consistent with a core collapse SNR. 0049-73.6 has a radius of 24 pc, an age of 15,000 years, and 180 solar masses of swept-up ISM. A standard SNR model with a power-law envelope and constant-density core ejecta cannot account for the observed ejecta emission. The presence of large amounts of O- and Ne-rich ejecta in 0049-73.6 may be contrasted with the lack of detectable ejecta emission in 0453-68.5. We attribute this to a higher initial mass of the SN progenitor in 0049-73.6, adding to growing evidence that explosions of massive progenitors generally do not produce classical Crab- and Vela-like pulsars.



Chandra integrated spectrum for 0453-68.5. The data (red crosses) are fit with a two component model (blue line). A Sedov model (orange line) accounts for the thermal emission of the shell, and a power law model (black line) for the excess of hard emission in the bright central region.

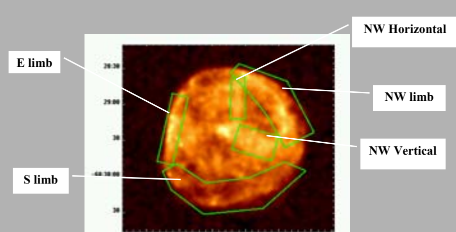


TABLE: Sedov Model fit results for the regions defined in the image above.

Param	NW	E	S	NW.H	NW.V
χ^2/ DOF	131/82	82/67	112/79	125/70	83/55
N_H $10^{21}cm^{-2}$	0.8	0.4	1.9	1.6	1.2
kT_s keV	0.24	0.34	0.34	0.34	0.34
kT_e keV	0.0	0.0	0.0	0.0	0.0
$\tau/10^{11}$ cm^{-3} s	19.5	4.76	15.3	5.4	4.2

INTRODUCTION

Supernova remnants (SNRs) in the Large and Small Magellanic Clouds represent a large sample of objects at known distances with relatively little obscuration, yet close enough that Chandra's imaging resolution allows spatially resolved spectroscopy. While the brightest and most compact objects have been well studied, many fainter ones are only poorly characterized. Imaging and spectral observations can allow the inference of remnant ages, energetics, and abundances. If ejecta emission can be identified, the supernova type can be determined by elemental abundance ratios. Fitted shock velocities and the location of ejecta emission may be able to constrain the evolutionary stage of the remnant.

SNR evolution comes in three stages:

Ejecta Dominated – Young remnants where the reverse shock heated ejecta accounts for the kinematics and X-ray emission.

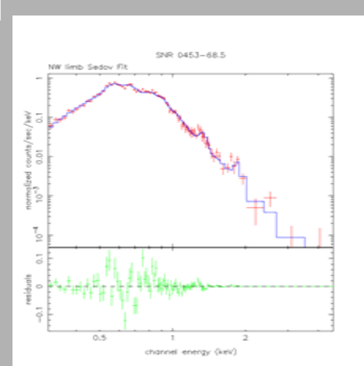
Sedov Phase – When the mass swept up greatly exceeds the ejecta mass, the remnant can be described as a point blast explosion.

Radiative Phase – Momentum conservation takes over.

X-ray Observations

The Magellanic Clouds offer an opportunity to study dozens of remnants at a known distance (we assume 50 kpc for the LMC and 60 kpc for the SMC), far from Galactic-plane absorption. In our Sedov fits we assume abundances of 0.4 solar for the LMC and 0.2 for the SMC.

Target	*Chandra* OBSID	Date	Exp. Time
0453-68.5	1991	2001-12-18	39.1 ks
0049-73.6	3907	2003-2-28	50.8 ks



SNR 0453-68.5 Shell Emission

The table to the left shows that each region is well described by a Sedov model with similar parameters. Although this was the expected result for the outer limbs, we were surprised to find Sedov emission in the inner NW features. Perhaps the expanding shell is encountering a higher-density region to the NW, with those features being brighter shell emission seen in projection.

Spectral Modeling

Sedov – emission calculated from Sedov dynamics parameterized by ionization timescale τ, the shock temperature T_s, and the electron temperature T_e.

Plane shock – an NEI model (vpshock in XSPEC) that assumes a plane shock--a good approximation when examining sections of a SNR. A full range of ionization timescales behind the shock are included along with a single electron temperature.

Heavy element shock -- a plane shock model that includes contributions to the electron density and electron temperature from ionized heavy elements. Shock speed and a range of ionization timescales are used to calculate how the electron temperature varies behind the shock.

For each model elemental abundances can be varied. Each fit includes a two-component absorption model for the Galaxy and the MCs.

TABLE: Plane shock fits to 0049-73.6 central region

Param	vpshock	Heavy Element
χ^2/ DOF	181/99	180/99
N_H $10^{21}cm^{-2}$	0.11	0.10
kT_e/ vs.	0.40 keV	424 km/s
O/Fe	24.5	20.7
Ne/Fe	9.53	5.32
Mg/Fe	1.47	0.95
Si/Fe	3.77	1.28
S/Fe	0.49	1.78
$\tau/10^{11}$ cm^{-3} s	1.56	3.13

Core Collapse vs. Type Ia

Type Ia – Explosive nuclear burning of a White Dwarf that exceeds the 1.4 M_o. Several solar masses of iron are expected.

Core Collapse (Type II, Ib, Ic) – Gravitational collapse of a massive star, accompanied by explosive nucleosynthesis. Large amounts of oxygen are expected. A compact object (neutron star or black hole) can be formed in the collapse. A pulsar may produce a distinct wind nebula.

Differences seen in ejected material:

Type Ia

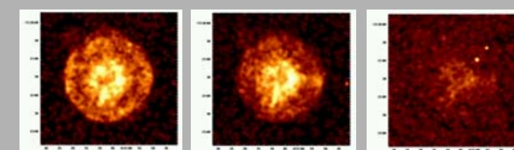
1.4 M_o of ejecta

O/Fe = 0.765

Core Collapse

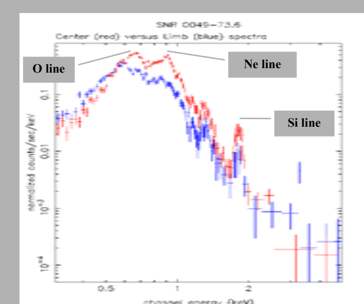
5-20 M_o of ejecta

O/Fe = 72.3



0.45-0.75 keV | 0.75-1.2 keV | 1.2-8.0 keV

SNR 0049-73.6 Limb vs. Center



SNR 0049-73.6 Central Emission

The table to the left shows plane shock model fits with high O/Fe, reflecting a relative weakness of Fe L-shell lines with respect to O lines. This is a strong indicator of a core collapse origin for this SNR. The heavyel spectral fit is presented to the upper right. Notice the poor fit to the Si line.

The fit to the lower right is a two-component fit, with one component containing O, Ne, Mg, Fe, and Ni, and the second heavyel model for Si and S. We used two vpshock models, as well as two heavyel shock models, and in both fits the ionization timescale is lower by an order of magnitude in the Si and S component. This is an indication that either Si and S have been shocked more recently, or that their density is much lower than density of O-rich ejecta.

SNR 0049-73.6 Discussion

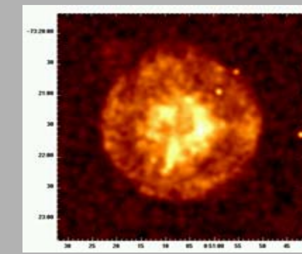
This SMC remnant contains evidence of ejecta, a surprising discovery considering our estimated age of 15,000 years. It is tempting to identify the inner edge of the SN ejecta as the reverse shock. We could then identify the following regions:

(1) the innermost central region of unshocked ejecta,

(2) shocked heavy-element ejecta bounded on the inside by the reverse shock,

(3) the shocked ambient ISM separated from ejecta by the contact discontinuity and bounded on the outside by the blast wave.

With this identification and for a power-law envelope + constant-density core ejecta expanding into constant-density ambient ISM (Truelove & McKee 1999), we find total ejecta mass of 7-8 M_o and a current reverse shock speed of 1500 km/s. This high shock speed is in conflict with our plane shock fits to the central region. The very short (< 10^9 cm^{-3} s) ionization timescales expected in this model are also in conflict with observations. We conclude that the standard SNR model cannot account for the observed ejecta emission. More realistic ejecta models, including inhomogeneous ejecta, are necessary to explain prominent ejecta emission in the interiors of old SNRs.



SMC SNR 0049-73.6

Angular Extent ~ 164"

Radius ~ 24 pc

From Sedov fits to rim emission:

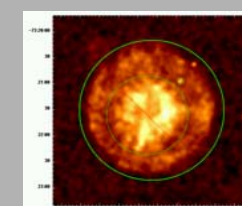
Shock Age ~ 15,000 yr

Swept Up Mass ~ 180 M_o

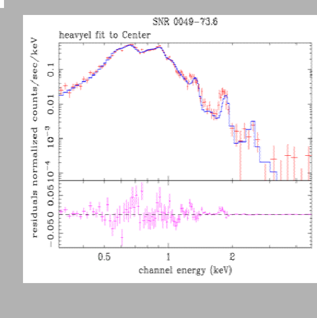
Explosion Energy ~ 8.6 x 10^{50} ergs

Images in Three Bands

We have extracted images of 0049-73.6 around the O-line (far left), Ne-line (middle), and hard emission including the strong Si-line (left). No hard central source is present, but the central structure indicates ejecta are being heated by the reverse shock.



The spectrum to the left shows the differences in emission between the two regions defined above. Prominent lines can be seen in the central region spectrum.



Chandra spectrum of 0049-73.6's central region. ABOVE: The data (red crosses) are fit with the heavyel model (blue line). BELOW: The same data fit with a two component model, one heavyel model for Si and S (green line) and another for the rest of the elements (light blue line).