# A *Chandra* Observation of the Mixed-Morphology Supernova Remnant W28

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## ABSTRACT

We present a Chandra observation of the archetypical mixed-morphology supernova remnant (SNR) W28. The observation was performed in the ACIS-S mode (4 ACIS-S and 2 ACIS-I chips) on board the Chandra X-ray Observatory for 89 ks. W28 has a diameter of 50 arcmin and our observation covered the central and southwestern parts of the remnant. While previous ASCA/ROSAT studies of W28 showed that the plasma conditions are different from other mixed-morphology SNRs, with spectral variations seen across the remnant, these Chandra data make this less clear by revealing hard point-like X-ray emission. This source is located on the I0 chip, 20′ southwest of the center and on the SNR shell. The spectrum of this hard emission is well modeled by a power law, suggesting non-thermal emission. We discuss possible physical explanations, such as an associated synchrotron nebula or an unrelated source such as a backgournd AGN. In the center of the SNR lies a bright X-ray region of a few arcmin in diameter, surrounded by fainter diffuse emission with filamentary structures. No strong spectral variations are found in the central region within one ACIS chip field of view.

## Introduction to Mixed Morphology SNR

Supernova remnants can be classified into four broad categories based on their radio and X-ray morphologies. The first class is those with shell-like radio and X-ray morphologies, as observed in Cas A, and their X-rays are thermal from optically thin plasma. The second class is Crab-like, with center-filled radio and X-ray morphologies, and the X-rays are non-thermal due to an active pulsar. The third morphological category is a composite of the former two, like CTB 80 and CTB 109. There is a fourth, new class of SNR, which show X-ray center-filled and radio shell-like morphology -"Mixed-morphology SNR" (MM SNR). The members include such bright remnants as W28 and W44. Two prominent distinctions of this new class are found using recent, ASCA and ROSAT data: their dominant X-ray emission mechanism is now confirmed to be thermal with dominant line emission, despite their X-ray morphological similarity to Crab-like SNR's, and their emission arises primarily from swept-up interstellar material, not ejecta (Rho & Petre 1998; Rho et al. 1994). The population represents at least 8 percent of all Galactic SNR's, and as much as 25 percent of all X-ray detected Galactic SNR's (Rho & Petre 1998). The temperature profiles across many of these remnants are nearly uniform, contrary to the standard Sedov model. Many of these remnants are interacting with molecular or HI clouds, as indicated in some cases by strong infrared line emission or OH masers (Reach & Rho 1996, 1998; Frail et al. 1996).

## W28: an Archetypical Mixed Morphology SNR

The supernova remnant W28 (G6.4-0.1) has been believed to be an archetype of "Mixed-morphology supernova remnants", showing center-filled X-ray and a shell-like radio morphology (Rho & Petre 1998; Rho et al. 1996, 2001). The radio spectral index is flat, $\alpha \sim 0.4$ (Kassim 1992). This remnant is suggested to be interacting with a dense molecular cloud (Wotten 1981; Arikawa et al. 1999), and we have recently confirmed the interactions using far-infrared lines (Reach & Rho 2000) and using detection of broad molecular lines with IRAM high resolution CO and CS data. We have found interaction evidence among other MM SNR using CO observations (Reach & Rho 1999; Koo et al. 1999), and the numbers among the MM SNR have been increasing dramatically, showing that there is a strong correlation between center-filled, thermal X-ray emission SNR and molecular interacting SNR.

A number of hypotheses have been proposed to explain how a remnant with a well-defined radio shell can appear X-ray center-filled. Two evolutionary scenarios – evaporation of many small interior clouds, and radiative shock model with thermal conduction – are competing to explain the isothermal temperature profile and cool HI shell. Both models require a reservoir of material with density higher than the typical intercloud ISM. The evaporation model is that dense clumps survive passage through a strong shock, subsequently providing a reservoir of material inside the remnant cavity (McKee 1981; White & Long 1991). The second scenario has been developed to explain the isothermal temperature profile and presence of the cool HI shell of some of these remnants: thermal conduction reduces the radial thermal gradient where radiative cooling is important (Shelton et al. 1999). The evaporating model is consistent with the remnants interacting with molecular clouds, which provide evaporating materials surviving behind the shock. The radiative shell model suggests that the MM SNR evolution occurs in an homogeneous medium, and thus it could not explain any properties related to cloud interaction. While the evaporating model is consistent with the remnants interacting with clouds, the radiative shell model did not require an interaction and thus it could not explain any properties related to cloud interaction. Recently Chevalier (1999) presented a combined version of the two: the radiative shell interacting with molecular clouds.

## References

### References


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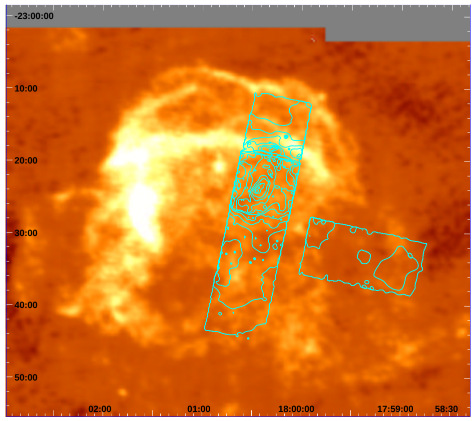
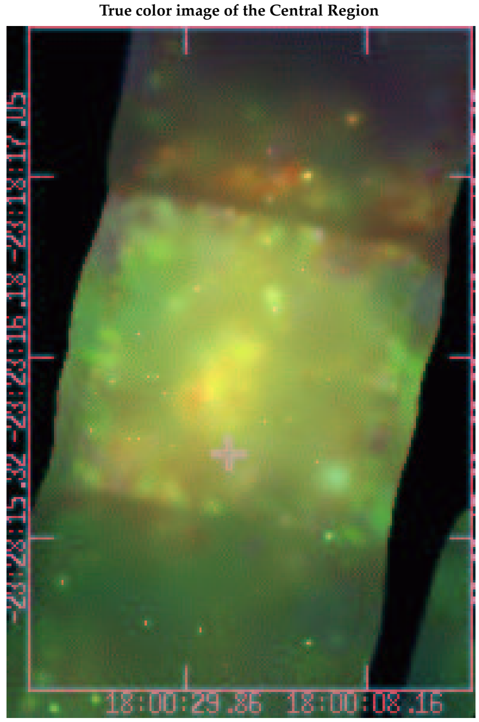
**Radio Image of W28 from Dubner et al. (2001) with the *Chandra* soft contours overlaid.**



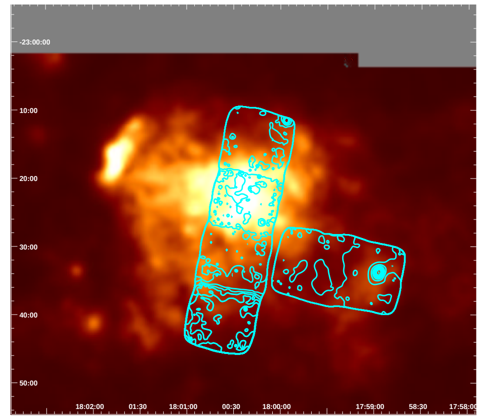
This VLA map, kindly provided by G. Dubner, shows W28's clear radio shell morphology. Overlaid is a contour plot of our Chandra soft emission. Note the compact radio point just outside our the Chandra field of view is believed to be an unrelated H II region.

**True color image of the Central Region**

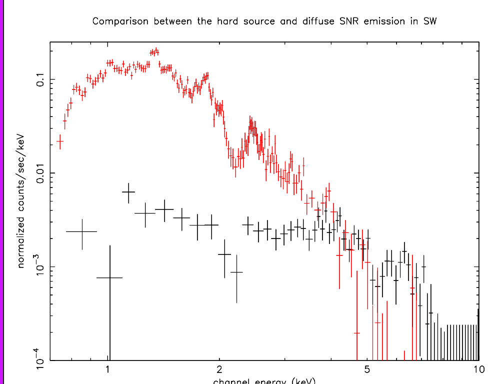


A true color, adaptively smoothed, exposure-corrected image of the X-ray bright central region of W28. The emission is primarily on chip #7 (S3). The cross denotes the location of the optical axis. Note the highly structured diffuse emission, and the variations in X-ray color. The soft, medium and hard cuts are as follows: Red (0.5-1.7 keV), Green (1.7-3.3 keV) and Blue (3.3-7.1 keV). The image was exposure corrected assuming monocrome emission in the middle of each bandpass.

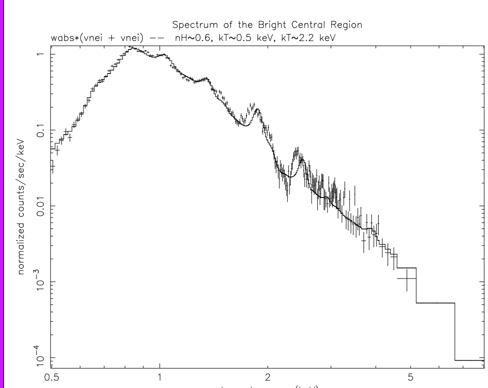
***ROSAT* PSPC image of W28 with Hard Chandra Contours Overlaid**



The *ROSAT* PSPC image of W28 of Rho & Borkowski (2002), with contours of the hard emission overlaid. Note the hard point source significantly off-axis on chip #0. The nature of this source is still uncertain, however it appears to be responsible for the harder emission as seen with ASCA.




Spectra of the hard source (black) and a much larger nearby region of the SNR from the same chip. The standard Chandra background spectra, for each corresponding region of chip #0, have been subtracted. We fit a thermal model to the SNR spectrum (in red), and then used this as a component (with all the parameters frozen including the absorption but excluding the normalization) for the background model for the hard source. The resulting spectrum has is then well-fit by an absorbed powerlaw of photon index of about 0.6 and an absorbing column density of about $3 \times 10^{22}$cm$^{-2}$. However these two values are highly interdependent, and are thus quite uncertain.




**Chandra Spectrum of the Central Region with a 2 Temperature NEI model similar to the one which fit the ASCA spectral data.**