X-ray Polarization in Supernova Remnants

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Introduction

The rapid shocks and amplified magnetic fields in supernova remnants (SNRs) provide conditions for efficient acceleration of particles to high energies. Radio observations provide distinct signatures of this process in the form of synchrotron radiation for particles up to ~GeV energies. The emission is significantly polarized, providing important information on the structure of the magnetic fields. For many young SNRs, the overall field is predominately radial (Figure 1), although important exceptions exist.

X-ray observations of many young SNRs reveal synchrotron radiation associated with electrons with energies exceeding tens of TeV. The emission is often concentrated in thin filaments along the SNR rim, although considerable emission from interior regions is seen for Cas A, Tycho, and others. The conditions for particle acceleration to such high energies depend critically on the both the strength and the orientation of the magnetic field, with theoretical calculations and PIC simulations indicating higher efficiencies for fields that are roughly aligned with the shock velocity vector.

Studies of X-ray polarization from SNRs can provide crucial insights into the process of particle acceleration, including the effects of turbulence on acceleration efficiency, properties of synchrotron structures observing within SNRs, and the potential presence of particle acceleration at the reverse shock (RS)

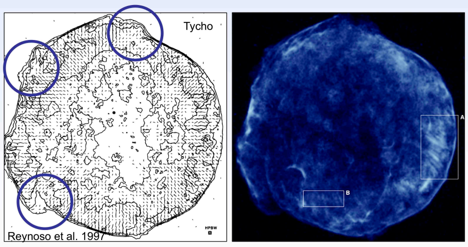

Figure 1: Left: Radio polarization map of Tycho's SNR (Reynoso et al. 1997) revealing radial magnetic field structure. Circles identify regions where evidence exists for a more complex field geometry. Right: Hard band (E > 4 keV) Chandra image of Tycho. Boxes identify magnetic structures discussed below.

Synchrotron Losses and Effective Resolution

The radio emission from particles behind the forward shock in SNRs extends back to the contact discontinuity (CD) that separates the ejecta from the swept-up ambient material. The magnetic field is compressed at the CD, resulting in bright radio emission. This is illustrated in the upper panel in Figure 2 (Cassam-Chenai et al. 2007), where models for the radio brightness are plotted for different acceleration efficiency parameters. The red line marks the forward shock (FS) for a case with $\eta = 10^{-3}$, and the cyan line marks the associated CD.

Because the CD is Rayleigh-Taylor unstable, filamentary structures can form that produce radial field structures that may be unrelated to the actual field geometry in the acceleration region.

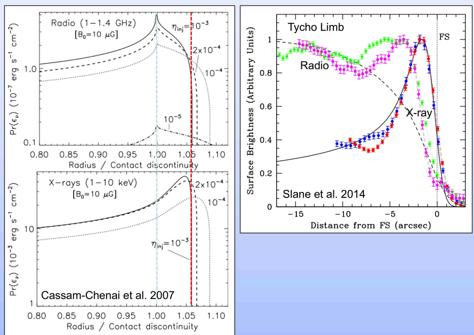

Figure 2: Left: Models of the brightness profiles for radio (upper) and X-ray (lower) emission being the shock of an SNR with efficient particle acceleration. Right: Comparison of observed and modeled radio and X-ray emission profiles from the rim of Tycho's SNR.

The X-ray emission for the same model is shown in the lower panel. Because synchrotron loss times are much shorter for the high energy particles that produce X-rays, the X-ray emission is concentrated just behind the FS. This is illustrated in the right panel of Figure 2 where X-ray and radio brightness profiles are shown for a limb of Tycho's SNR. The rapid synchrotron losses result in thin rims that are clearly observed in the X-ray images (Figures 1, 3).

Abstract

The fast shocks in supernova remnants are known to accelerate particles to extremely high energies. The acceleration process is closely tied to the magnetic field structure in the shock region. This, in turn, can be modified considerably by the shock. Synchrotron emission from the shock regions provides crucial details about the magnetic field strength and orientation through its polarization. Radio polarization studies of several SNRs have provided important maps of the field orientation, and these provide clues about the connection with particle acceleration. Due to the rapid losses of the highest energy particles, however, X-ray polarization measurements provide magnetic field information from particles much closer to the acceleration sites. Here I discuss how X-ray polarization observations can be used to investigate the magnetic fields in SNRs in order to address questions about acceleration efficiency dependence on shock obliquity, levels of turbulence in the fields, and acceleration of particles at the reverse shock.

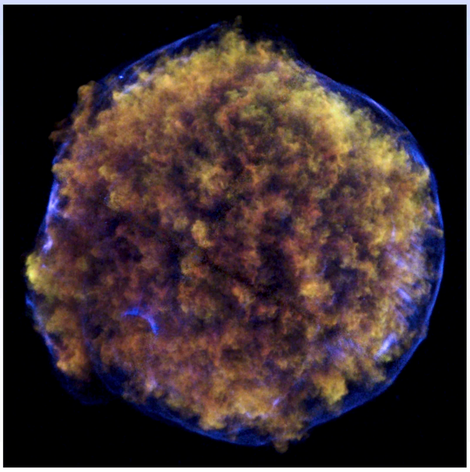

Figure 3: Chandra image of Tycho's SNR. High energy emission is shown in blue, and is dominated by synchrotron radiation. The central regions of the SNR are dominated by thermal emission from the ejecta.

Studies of the X-ray polarization provide information from the most energetic electrons in the SNR. Because the emission is confined to regions just behind the FS, X-ray polarization probes the magnetic field conditions much closer to the acceleration site.

Chandra images of thin synchrotron rims demonstrate that even for an X-ray polarimeter with more coarse angular resolution, the synchrotron losses provide an effective resolution that allows us to probe the shock region.

Simulations

For SNRs, several factors contribute to the measured polarization:

- Π and ψ, the polarization fraction and angle from the source
- Flux contributions from unpolarized emission
- Beam depolarization
- Energy-dependent instrument sensitivity to polarization

To analyze the polarization signal we must thus include a spectral model to properly assess the effect on the detector response and the contributions from the nonthermal emission.

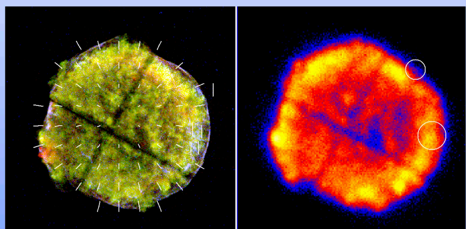

Figure 5: Left: Chandra image of Tycho. Dark cross structure is from the CCD detector gaps (and is imprinted on the resulting simulation). Arrows show the assumed polarization struture, which is radial except for in the western stripe region. Right: Simulated 1 Ms IXPE observation (single detector) with regions corresponding to polarization plots below.

Synchroton Structures in SNRs

The thin X-ray rims in young SNRs provide the best probes of the particle acceleration region. Measuring the polarization fraction and angle will provide a correlation between acceleration efficiency and field orientation in these crucial regions.

Because turbulence plays an important role in the amplification of magnetic fields, polarization measurements provide crucial information. In regions where the magnetic field is highly turbulent, we expect lower polarization fraction.

X-ray observations of Tycho reveal evidence for discrete "stripe-like" features that have been associated with regions where ions are accelerations to extremely high energies. The synchrotron emission from these structures is expected to be polarized, offering a direct comparison with the theoretical model predictions (Bykov et al. 2011).

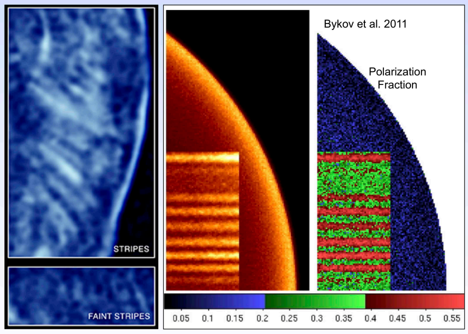

Figure 4: Stripe-like X-ray structures (left) in Tycho's SNR (Eriksen et al. 2011), along with model predictions for the emission and polarization structure (Bykov et al. (2011).

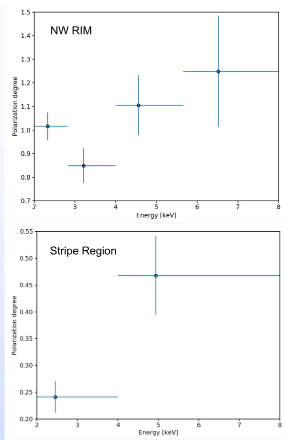

Figure 6: Recovered polarization fraction from simulations of NW rim and stripe region in Tycho.

To investigate the prospects of measuring X-ray polarization from SNRs with the upcoming IXPE mission, we have begun simulating the emission from Tycho's SNR. We began with a Chandra event file (Figure 5, left), to capture the full spectral properties of the emission, and have imposed a crude model consisting of radial polarization for the entire SNR except for the stripe region in the west, where polarization perpendicular to the stripes was assumed (Figure 5). For the NW region, we assumed a polarization fraction of 100% for all emission, as a test of sensitivity. For the stripe region, we assumed that the nonthermal emission comprises 90% (25%) of the flux above (below) 4 keV.

Figure 5 (right) shows the simulated image for one IXPE detector. Polarization fractions for the two regions indicated are reproduced with reasonable accuracy, where we expect to recover Π = 1.0 for the NW region, and Π = 0.45 (0.25) for E > 4 keV (< 4 keV) for the stripe region, in good agreement with results shown in Figure 6.

These preliminary simulations lay the groundwork for more detailed investigations of the overall sensitivity to variations in spectral and polarization properties within the SNR.