The X-ray Study of Small-Scale Shock Structures in the Non-thermal SNRs

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Abstract

The shock front of SNRs is the most probable acceleration site of high energy particles (up to, or more than TeV) as already confirmed by the hard X-ray observations of the synchrotron emission from accelerated electrons. The remarkable spatial resolution of the X-ray observatory *Chandra* enables us to investigate the small-scale structure of the spatial distribution of accelerated electrons close to the shock front, which may lead us to deep understanding of acceleration mechanism. We have found hard X-ray filaments having a sharp rise in upstream and rather slow decay in downstream from the shocked region of six SNRs (Cas A, Tycho, Kepler, SN 1006, RCW 86, and 30 Dor C) using the *Chandra* archive data. For all the SNRs, we found that the scale width of the filaments is significantly smaller than that of the thermal plasma derived from the Sedov solution, The scale width becomes larger as increasing radius of the SNR, which may be followed by the understanding of the history of acceleration and energy loss of electrons in the shock front.

1. Introduction

Supernova remnants (SNRs) are the most plausible acceleration sites of cosmic rays. Now synchrotron X-rays are the indicators of high energy electrons accelerated up to ∼TeV or more via diffusive shock acceleration mechanism since the discovery from the shell of SN 1006 (Koyama et al. 1995). However, the lack of spatial resolution of previous instruments prevents us from studying the spatial distribution of electrons, the structure of magnetic field, the injection efficiency, and so on.

Using the excellent spatial resolution of *Chandra*, Bamba et al. (2003) observed the shell of SN 1006 and found that the synchrotron X-rays concentrate on very thin "filaments" located at the outer edge of the SNR. The thickness is only about 0.04 pc in upstream and 0.1 pc in downstream, indicating that the magnetic field is almost perpendicular to the shock normal and highly turbulent in downstream under the assumption that the magnetic field in upstream is 10 μG,

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and that the injection efficiency is higher than previous estimations (Bamba et al. 2002b). In this paper, we report on our investigation whether the thin filaments are common among SNRs with synchrotron X-rays or not, and what correlation there is between the radius, which is the indicator of the age, and the filament width.

2. Observations

We use *Chandra* archive data of six SNRs (Cas A, Tycho, Kepler, SN 1006, RCW 86, and 30 Dor C), some of which have been already reported as the SNRs with synchrotron X-rays (Vink & Laming 2003, Hwang et al. 2002, Bamba et al. 2003, Rho et al. 2002, Bamba et al. 2002a). The satellite and instrument are described by Garmire et al. (2000) and Weisskopf et al. (2002), respectively. The data reductions and analyses were made using the *Chandra* Interactive Analysis of Observations (CIAO) software version 2.2.1. We used the Level 2 processed events provided by the pipeline processing at the *Chandra* X-ray Center.

3. Analyses

Fig. 1. shows the X-ray images of the SNRs in the 2.0–10.0 keV band. We can see sharp filaments on the outer edges of all the SNRs, with fast decay in downstream and even faster rise in upstream. The previous studies on these SNRs except for Kepler report that the photons above 2.0 keV in these filaments are almost non-thermal (in other words, synchrotron emission from high energy electrons), then we treat the all photons on the filament in the 2.0–10.0 keV band as synchrotron X-rays. Although the synchrotron X-rays from Kepler has not been reported, the sharp filaments in hard X-rays in this SNR are similar to those shown in other SNRs, then we assumed them to be synchrotron X-ray filaments.

For the filament analyses, we select one synchrotron X-ray filament as a template for each SNR, which are straight and free from other structures. To estimate the width, we defined a simple empirical model with exponential rise and decay in the same way as our previous study of SN 1006 (Bamba et al. 2003). The point spread function of *Chandra* is ignored. The best-fit parameters are plotted in Fig. 2. as the function of the radius (R: referred from the Green (2000)) and the width (w).

4. Discussion

As shown in Fig.2., the width in upstream is smaller than that in downstream for all SNRs. We can see positive correlation between R and w in both upstream and downstream. Cas A, Tycho, and Kepler have small angular radius

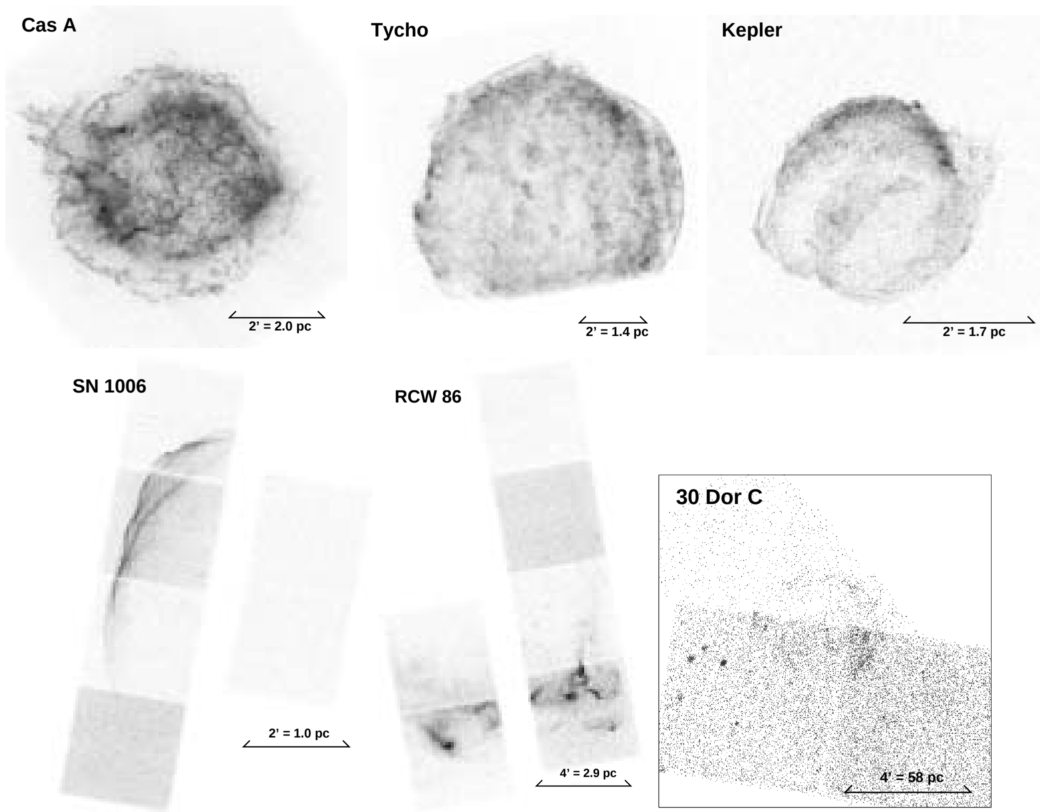

Fig. 1. The *Chandra* images of Cas A, Tycho, Kepler, SN 1006, RCW 86, and 30 Dor C in the 2.0–10.0 keV band.

and the structures of filaments, which can not be resolved even with *Chandra* spatial resolution. Then, their w may be smaller and the correlation must be stronger. The linear fitting tells us, although the statistics rejected this model, that summed w in downstream and upstream is about only 0.8% of R, which is quite smaller than the shock width expected from the Sedov solution.

The radius is an indicator of the age. Hence, Fig. 2. means that the filament becomes wider with the ages, keeping the scale widths much smaller than that of the thermal plasma by Sedov solution. Our result may be followed by the understanding of the history of acceleration and energy loss of electrons in the shock front. To discuss further, more detailed analyses are needed.

5. References

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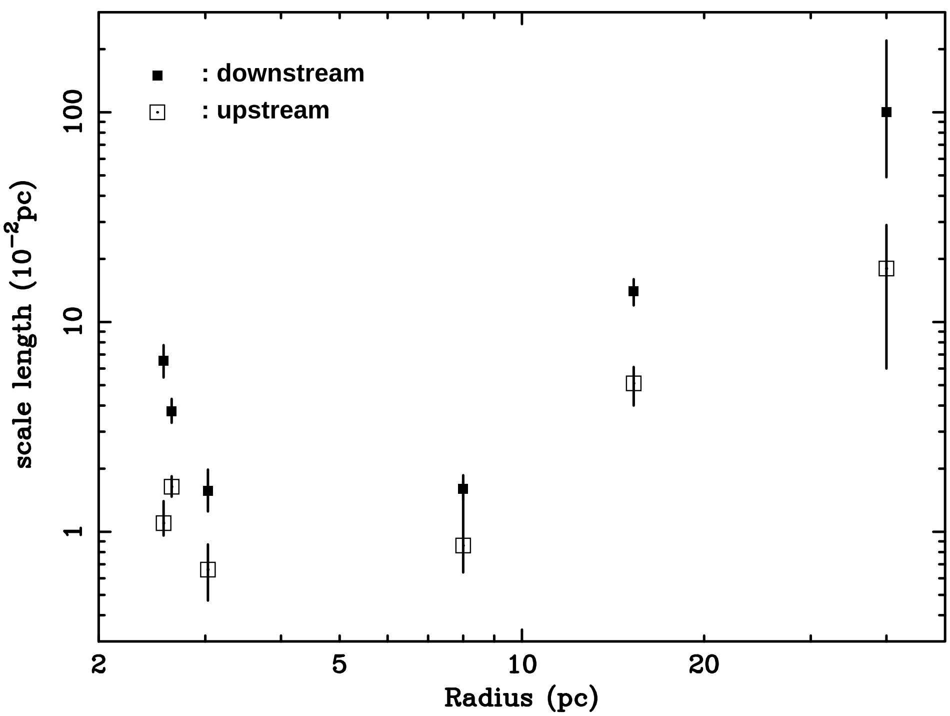

Fig. 2. The relation between the radius (R) and the width (w) of each SNRs. The filled and open box represent the width in downstream and upstream, respectively.

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