

Observational Study on Thermal and Non-thermal X-rays from
Shell-like Supernova Remnants

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Abstract

X-rays from shell-like supernova remnants (SNRs) are dominated by those of a shock-heated thermal plasma due to the progenitor explosions, while additional hard X-rays with a power-law spectrum have been found in some shell-like SNRs. This paper reports on the hard X-ray observations with Ginga and ASCA utilizing the capability of higher energy band and better energy resolution than previous instruments. We present the results of two selected shell-like SNRs: those of SN 1006 obtained with the Ginga and ASCA satellites, and IC 443 with the GIS detector on-board the ASCA satellite.

From SN 1006, we found strong X-rays from the two bright shells with energies extending at least to 20 keV, having a power-law spectrum of photon index of $\simeq 3$. This provides clear evidence that the emission is of non-thermal origin in the shell. The emission can be interpreted as a synchrotron radiation from high energy electrons of ~ 100 TeV.

At the same time, we detected, for the first time, strong emission lines of highly ionized Ne, Mg, Si and S from the whole region of SN1006. This gives firm evidence of the presence of thin-thermal plasma as well. Since the thermal emission was largely contaminated by stray lights of the non-thermal power-law emission from the bright shell, the inferred metal abundances may have possible ambiguity. Nevertheless, we can safely conclude that the abundances are significantly larger than the solar, hence suggest that SN 1006 is either in the phases of free expansion or in the early adiabatic stage.

From IC 443, we found hard X-rays of a semi-circular shell surrounding the center-filled thermal emission. The total hard X-ray flux in the ASCA field of view is only half of the Ginga hard component reported by Wang et al. (1992). This suggests that the hard X-rays are not confined only in the shell but some are extended larger than the ASCA field of view of about 1 degree diameter. The ASCA hard X-ray image contains the EGRET point-source position within 90% error contour (Thompson et al. 1995, Esposito et al. 1996). The spectral index are the same with each other, while are larger than that of radio band by about 0.5. Accordingly we infer that the hard X-rays and EGRET gamma-rays are emitted by the same electrons with a synchrotron and an inverse-Compton mechanism, respectively.

We also examined spatial structure of the thermal component with the non-equilibrium ionization plasma model, and found no systematic variation of the interstellar absorption.

If the hard components for both SN1006 and IC443 come from the non-thermal electrons accelerated by the shock wave, protons should be accelerated up to the same energy. Accordingly, present results provide strong supports for the cosmic-ray acceleration scenario in shell-like SNRs up to ~ 100 TeV in both free-expansion and adiabatic phases.

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Chapter 1

Introduction

Abundances of heavy elements and evolution of a thin thermal plasma produced by strong shock in supernova remnants (SNRs) are among the major subjects in the current X-ray astronomy. Studies of the metal abundances provides a key for the nucleosynthesis in stellar evolution and supernova explosions, which are dominant sources of heavy elements in the universe. The SNR plasma is a subject of far longer time scale evolution than any of the laboratory plasma, due to their extremely low density, hence enable us to study a time sliced plasma data: snapshots of various stages of the evolution and relaxation of a thin thermal plasma.

In addition to these major subjects, another aspect of SNRs would be a possible origin of cosmic ray production and acceleration. For the observational study of the cosmic ray acceleration, the electromagnetic radiation from the accelerated charged particles would be more useful than the cosmic particle itself, because the latter loses the information of the source direction due to the Lorentz force in the magnetized interstellar space of our galaxy.

The electromagnetic radiation from the charged particle has a wide range from radio to gamma-rays, with radiation processes such as synchrotron, Bremsstrahlung, inverse-Compton scattering and gamma-rays of the nuclear reaction. However, such a radiation from SNRs without the pulsar have been scarcely studied except for the synchrotron emission from electrons of energy below $\sim \text{GeV}$.

In the X-ray band, the dominant radiation from supernova remnants is of the optically-thin thermal plasma of a temperature of $\sim 1 \text{ keV}$. In several remnants, additional components which extend up to $\sim 10 \text{ keV}$ and possibly of non-thermal origin have also been detected. However, due to the confusion of bright thin-thermal X-rays, details of the hard X-rays have not been well studied.

A breakthrough is provided by the wide X-ray band imaging spectroscopy with ASCA and partly by the higher energy observation with Ginga.

Ginga has the large effective area detector with the sensitivity up to 35 keV which enable us to observe the hard component in the higher energy range than expected from the thin thermal plasma, typically less than a few keV of temperature. On the other hand, ASCA has an imaging capability of the spatial resolution of 3–5 arcmin with highest energy resolution so far, which can distinguish the hard component, both spectroscopically and spatially, from the soft thermal emission in the 0.5–10 keV band.

In this work, we analyze the data of the two shell-like supernova remnants, SN 1006 and IC 443, observed with these satellites. The former has been reported to exhibit an enigmatic spectrum of a strong power-law continuum coupled with very weak lines, while the latter has been known to have a strong thin thermal emission of center-filled morphology, with possible evidence of additional hard component. This paper reports, for the first time, that the hard components in these SNRs are spatially separated from the thin thermal plasmas: the former are confined in shell-like regions, while the later are prevailing in the whole SNRs.

Chapter 2

Review of SNRs

2.1 Supernova Explosion

Observationally, supernovae (SN) are classified into two types according the absence (Type I) or presence (Type II) of hydrogen line during the outburst.

Most of the type I have silicon optical emission line, and are sub-classified as type Ia, actually one of the major classes of SN. Light curves for all the SN Ia are very similar to each other, showing a rapid rise to maximum brightness at around $M_B = -18.2 + 5 \log h$ (Cadonau, Sandage and Tammann 1985), where h is the Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. SN Ia stay at maximum for only a short time, fading by 3 mag in just 30 days, and, after about 50 days, starting to decrease less rapidly with nearly a constant rate of $0.015 \text{ mag day}^{-1}$ starting at about day 50.

SN II are found only in spiral galaxies, preferentially in the spiral arms, where star formations are currently active, hence are the site of massive stars. They comprise an inhomogeneous group showing at least two distinct light curves. One group exhibits a halt or ‘plateau’ in the post-maximum phase (SN II-P), producing a nearly constant luminosity between days 30–80; the other exhibits little or no plateau, instead having a linear decline after the maximum with a rate $0.05 \text{ mag day}^{-1}$ (SN II-L). Generally, SN II show the peak magnitude of about $M_B = -17.5 + 5 \log h$.

2.1.1 Type Ia supernova

Absence of hydrogen line in the SN Ia means that the progenitor probably has no hydrogen envelope. The current model of SN Ia is due to the carbon deflagration of an accreting C+O white dwarf: the explosion mechanism is a thermonuclear explosion of the electron-degenerate white dwarf cores.

The scenario that a close binary system is lead to a SN Ia explosion is as follows: a close binary system consisting of two intermediate-mass stars ($M < 8M_\odot$) evolves to make the primary star to be a white dwarf composed of carbon and oxygen (a C+O white dwarf), after a mass transfer

with Roche-lobe overflow to the secondary star. Then the secondary star evolves, hence begins to transfer the hydrogen-rich envelope to the white dwarf.

If the accretion rate is small enough ($\dot{M} < \sim 1 \times 10^{-8} M_{\odot} \text{yr}^{-1}$), most of the accumulated hydrogen is ejected from the white dwarf with the flash ignited by the hydrogen shell burning. Since the mass of the white dwarf does not increase, no supernova event occurs. On the other hand, under the condition of higher mass transfer than $\sim 3 \times 10^{-6} M_{\odot} \text{yr}^{-1}$, the accreting matter becomes very hot, hence can not be accumulated on the white dwarf, but rather is lost from the system eventually. For the intermediate accretion rate of $1 \times 10^{-8} M_{\odot} \text{yr}^{-1} < \dot{M} < 3 \times 10^{-6} M_{\odot} \text{yr}^{-1}$, accreted hydrogen burns with moderate helium flashes and no significant ejection of hydrogen, thereby increases the C+O white dwarf mass to the Chandrasekhar limit. When the white dwarf mass becomes $1.4 M_{\odot}$ and the central density reaches $\sim 3 \times 10^9 \text{ g cm}^{-3}$, explosive carbon burning is ignited at the white dwarf's center.

Immediately after the ignition, the C+O in the whole white dwarf are explosively burned to iron-peaked elements releasing large amount of nuclear energy, under the central temperature of about $\sim 10^{10} \text{ K}$. As the result of the large energy release, the boundary between the burned and unburned layers becomes convectively unstable, and the hot internal material are mixed into the outer layer of fresh carbon. Thus, a carbon-burning front propagates outward on the time scale of convection (carbon deflagration). Since the speed of the deflagration wave is less than the sound speed, the white dwarf can expand during the propagation of the deflagration wave. Behind the deflagration wave, the material undergoes explosive nuclear burning of silicon, oxygen, neon and carbon, depending on the peak temperatures. In the inner layer, nuclear reactions are rapid enough to synthesize iron-peaked elements, mostly ^{56}Ni . When the deflagration wave arrives at the outer layers, the density it encounters has already decreased due to the expansion of the white dwarf. At such low densities, the peak temperature is not high enough to cause the silicon burning, hence only Ca, Ar, S, and Si may be produced. In the outermost layers, the deflagration wave is faded, hence C and O remain unburned. In the standard carbon deflagration model, $0.6 M_{\odot}$ of ^{56}Ni is produced with the total explosion energy of $1.3 \times 10^{51} \text{ erg}$. This huge energy explodes the whole white dwarf completely, with no compact star inside.

2.1.2 Type II supernova

Since SN II exhibits prominent hydrogen lines, they may have large hydrogen envelopes before the explosion. SN II are explained by the gravitational collapse after the evolution of massive stars. This scenario was confirmed by the detection of the burst of neutrinos from SN 1987A, because the neutrino burst is generated during the collapse of iron core to a neutron star; the iron core is

formed only in a massive evolved star.

In massive stars, at the end of silicon burning, iron cores of about $1.4 M_{\odot}$ are formed in the center, while surrounded by layers of the ashes elements of preceding burning with the outermost low-density hydrogen envelope. The mass fraction of helium plus heavier elements to the original mass of the star ranges from 1/4 (at $10 M_{\odot}$) to 1/2 (at $50 M_{\odot}$).

As the temperature of the iron core increases to $\simeq 10^{10} \text{ K}$, endothermic decomposition of ^{56}Fe occurs, since no nuclear energy can be provided from iron. Accordingly, the core can not be self-supporting but starts a gravitational collapsing. During the collapse, the electron increases its density, and finally are squeezed into the nuclei, leading to heavier neutron-rich isotopes and homogeneous neutron matter.

When the central density exceeds the density of the atomic nucleus ($2.7 \times 10^{14} \text{ g cm}^{-3}$), roughly half of the core still continues collapsing with supersonic speed, then bounces and produces an outgoing shock wave. If enough energy is provided to the shock, most mass of the star explodes with a kinetic energy near 10^{51} erg . The collapsed core becomes either a neutron star or black hole. As the shock passes through the shells of silicon and oxygen just outside the core, the temperature is increased to lead an explosive nuclear fusion; it produces a significant fraction of heavy elements from silicon to zinc. The shock finally loses the energy during the propagation in the outer shell, leaving the helium shells unburned. Consequently, the abundances of SN II are largely affected by those of the envelope, which depend on the mass of the progenitor.

2.2 Shell-like and Crab-like supernova remnants

The huge explosive energy of a SN makes a relic for a long time in the interstellar space. This has been usually found in the radio wavelength and is called as a supernova remnant (SNR).

From the appearance, SNRs can be classified into two types: 'shell-like' and 'prelions'. Examples of the former are Cassiopeia A (Cas A), Cygnus Loop and SN 1006. The prototype of the latter is the Crab nebula, hence also called as a 'Crab-like' SNR.

The energy source of the shell-like SNRs is a shock wave propagating either in the interstellar medium (ISM), circumstellar medium (CSM) or the ejecta. According the age (or evolutionary stage of the shock wave), the phase of the shell-like SNR can be divided into three: the free expansion, adiabatic (or 'Sedov') and radiative phases.

When the supernova explodes, the ejecta expands into ISM or CSM, and forms a discontinuity surfaces, where the shock waves stand in the ISM (CSM) and the ejecta (McKee, 1974), which are designated as forward and reverse shocks, respectively. The reverse shock is propagated inward

through the ejecta, but the expansion velocity of the ejecta of typically $\sim 10,000 \text{ km s}^{-1}$, which is determined from the Doppler shift of lines, is still far larger than the sound velocity. Therefore, the shock actually moves outward with respect to fixed coordinates. Accordingly, two nesting shock-wave shells appear, both expanding with time.

Behind the shock front, the temperatures of ions quickly increases depending on the shock velocity. Then the ion energy transfers to electron rather slowly but finally equalize the temperature of electron to that of ion. The electron temperature thus becomes high enough to emits X-rays by a thermal bremsstrahlung process, together with emission lines by electron collisional ionization or excitation of ions.

At the free expansion phase, the mass of the ejecta swept-up by the reverse shock exceeds that of the ISM (CSM) swept-up by the forward shock, hence the emission measure from the ejecta is larger than the ISM (CSM). In this phase, the X-ray spectrum is predominantly due to the emission from the ejected elements.

When the mass of the swept-up interstellar gas becomes larger than that of the ejecta, the SNR enters the adiabatic phase. The radiation energy is far smaller than the whole kinetic energy, hence we can regard that the energy of gas (kinetic + thermal) is conserved during this phase or adiabatic expansion. The expansion thus can be described by the theory of adiabatic blast waves (Sedov 1959; Landau and Lifshitz 1959). The radius of the shock front R is

$$R \simeq 13(W_0/10^{51})^{1/5} N_1^{-1/5} t_4^{2/5} \text{ pc}, \quad (2.1)$$

where W_0 , N_1 , and t_4 are the kinetic energy released in the explosion, the interstellar density, and the time since the explosion in units of 10^4 years, respectively. The velocity of the shock is $v = 2R/5t$ and the temperature behind the shock is

$$T \simeq 8 \times 10^9 (W_0/10^{51})/N_1 R^3 \quad (2.2)$$

(Gorenstein, Harnden and Tucker 1974). This phase lasts until radiative energy loss becomes large compared with the kinetic energy. This occurs when the radius of the SNR is equal to R_C , given by Cox (1972)

$$R_C \simeq 25(W_0/10^{51} N_1)^{5/17} N_1^{-2/17} \text{ pc}. \quad (2.3)$$

As the shock wave expands in time, due to the increasing mass of swept-up matter, the shock speed and, consequently, the temperature behind the shock decreases. Thus, the radiation is shifted to longer wavelengths in time.

When the SNR radius becomes greater than R_C , the radiation energy is not negligible compared to the kinetic energy: the radiative energy is so large that the pressure behind the shock drops,

leading a decreases of the shock velocity and a compression of the swept gas to a dense, relatively cool (10^4 – 10^5 K) shell.

By contrast with the shell-like SNRs, Crab-like SNRs are powered by neutron stars. The neutron stars are rapidly spinning, and gradually slowing down by supplying the energy to the surrounding nebulae.

The spectra of Crab-like SNRs can be described by a single power-law from radio to X-ray band. Accordingly, the whole radiations are believed to be synchrotron emissions, although details of the particle acceleration mechanism is still unclear.

2.3 Radiative processes in shell-like SNR

2.3.1 Shock wave

In the coordinates co-moving with the shock front, the shock wave is described by the following differential equations: in the case of the ideal gas, the conservations of mass, momentum and energy flux are described as

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v) = 0 \quad (2.4)$$

$$\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial x}(P + \rho v^2) = 0 \quad (2.5)$$

$$\frac{\partial}{\partial t}\left\{\rho\left(\frac{1}{2}v^2 + E\right)\right\} + \frac{\partial}{\partial x}\{Pv + \rho\left(\frac{1}{2}v^2 + E\right)v + Q\} = 0 \quad (2.6)$$

where ρ , v , P , E and Q are, respectively, the density, streaming velocity, pressure, energy per unit mass and heat flux density. Applying these equation to the upstream and the downstream of the shock wave (2.1), we get

$$\rho_1 v_1 = \rho_2 v_2 \quad (2.7)$$

$$\rho_1 v_1^2 + P_1 = \rho_2 v_2^2 + P_2 \quad (2.8)$$

$$v_1[P_1 + \rho_1\left(\frac{1}{2}v_1^2 + E_1\right)] = v_2[P_2 + \rho_2\left(\frac{1}{2}v_2^2 + E_2\right)] \quad (2.9)$$

where subscripts 1 and 2 correspond to the upstream and the downstream, respectively. With Bernoulli's theorem and the notation of the sound velocity, equation (2.9) is further transformed into

$$\frac{1}{2}v_1^2 + \frac{\gamma}{\gamma-1}\frac{P_1}{\rho_1} = \frac{1}{2}v_2^2 + \frac{\gamma}{\gamma-1}\frac{P_2}{\rho_2} \quad (2.10)$$

where γ is specific-heat ratio. With equations (2.7), (2.8) and (2.10), we get Rankine-Hugoniot relations,

$$\frac{\rho_2}{\rho_1} = \frac{v_1}{v_2} = \frac{(\gamma-1)P_1 + (\gamma+1)P_2}{(\gamma+1)P_1 + (\gamma-1)P_2} \quad (2.11)$$

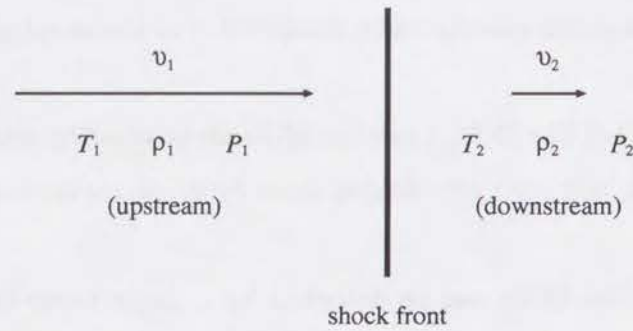


Figure 2.1: Discontinuity at the shock wave

$$\frac{T_1}{T_2} = \frac{a_1^2}{a_2^2} = \frac{P_1 (\gamma - 1) P_1 + (\gamma + 1) P_2}{P_2 (\gamma + 1) P_1 + (\gamma - 1) P_2}. \quad (2.12)$$

For the velocities of the gas across the shock front, we have

$$v_1^2 = \frac{1}{2\rho_1} \{(\gamma - 1)P_1 + (\gamma + 1)P_2\} \quad (2.13)$$

$$v_2^2 = \frac{1}{2\rho_1} \frac{\{(\gamma + 1)P_1 + (\gamma - 1)P_2\}^2}{(\gamma - 1)P_1 + (\gamma + 1)P_2}. \quad (2.14)$$

In the extreme case of a strong shock: $P_1 \ll P_2$,

$$\frac{\rho_2}{\rho_1} = \frac{v_1}{v_2} = \frac{\gamma + 1}{\gamma - 1}. \quad (2.15)$$

Under this condition, the velocities can be written as

$$v_1 = \sqrt{\frac{1}{2}(\gamma + 1) \frac{P_2}{\rho_1}} \quad (2.16)$$

$$v_2 = \sqrt{\frac{1}{2} \frac{(\gamma - 1)^2 P_2}{(\gamma + 1) \rho_1}}. \quad (2.17)$$

In the observer's coordinates where the shock velocity $v_s = v_1$, the post-shock velocity is $v_p \equiv v_1 - v_2$, while the post-shock pressure P_p becomes

$$v_p = \frac{2v_s}{\gamma + 1} \quad (2.18)$$

$$P_p = \frac{2\rho_1 v_s^2}{\gamma + 1}. \quad (2.19)$$

Using the equation of the state, we get the relation between v_s and the post shock temperature T_p as

$$kT_p = P_p \frac{\mu}{\rho_2} \quad (2.20)$$

$$= \frac{2(\gamma - 1)}{(\gamma + 1)^2} \mu v_s^2, \quad (2.21)$$

where μ is the mean atomic weight. In the case of the monoatomic gas, $\gamma = 5/3$, so that

$$kT_p = \frac{3}{16} \mu v_s^2. \quad (2.22)$$

2.3.2 Sedov solution

The propagation of the blast wave excited by the supernova explosion can be described as that of the shock induced by the large amount of energy release in a short time at one point, which is induced by Sedov (1959).

If the strong shock: $P_2/P_1 \ll (\gamma + 1)/(\gamma - 1)$, the evolution of the shock can be described only with the explosion energy E , the pre-shock density ρ_1 , the time since the explosion t , and the radius R . With them, a non-dimensional parameter ξ can be defined as

$$\xi = r \left(\frac{\rho_0}{Et^2} \right)^{1/5}, \quad (2.23)$$

then the distance of the shock front from the explosion center is written by

$$R = \xi_0 \left(\frac{Et^2}{\rho_1} \right)^{1/5}, \quad (2.24)$$

where ξ_0 can be determined from the equation of the energy conservation (Landau and Lifshitz 1959) and $\xi_0 = 1.17$ for $\gamma = 5/3$ gas.

From equation (2.24), we get the shock velocity as

$$v_s = \frac{dR}{dt} = \frac{2}{5} \xi_0 \left(\frac{E}{\rho_1} \right)^{1/5} t^{-3/5}. \quad (2.25)$$

Application to the shell-like SNR

If the ejecta or the ambient ISM (CSM) is exploded at the speed of v_0 , we get the initial velocity of the induced shock in the ISM (CSM) as

$$v_s = \frac{\gamma + 1}{2} v_0 = \frac{4}{3} v_0 \quad (2.26)$$

from the equation (2.18). The last term is attained for the ideal monoatomic gas. The shock propagates following the equation (2.24) and making the post-shock density $\rho_2 = (\gamma + 1)/(\gamma - 1) \rho_1 = 4\rho_1$. As a result, the shock propagates sweeping matters, of which thickness ΔR and temperature T can be calculated as

$$4\pi R^2 \Delta R \rho_2 = \frac{4}{3} \pi R^3 \rho_1 \quad (2.27)$$

$$\longrightarrow \Delta R = \frac{1}{12} R, \quad (2.28)$$

and

$$kT = \frac{3}{16} \mu v_s^2 \propto t^{-6/5}. \quad (2.29)$$

2.3.3 Emission from optically-thin thermal plasma

Electron heating with the shock

Immediately after the shock, ions and electrons are separately heated to high temperatures depending on their mass: the shock gives the velocity of $3/4 v_s$ to the plasma particle, hence the attainable energy of electron of $1/2 m_e (3/4 v_s)^2$ is roughly 2000 times smaller than that of ion gas $1/2 m_i (3/4 v_s)^2$. Then, the electrons in the post-shock region are gradually heated by the energy transfer from ions. Energy (temperature) transfer rate from ions to electrons, both in the Maxwellian velocity distributions with temperatures of T_i and T_e , respectively, is given as,

$$-\frac{dT_e}{dt} = \frac{T_e - T_i}{\tau_{eq}} \quad (2.30)$$

where τ_{eq} is the equipartition time constant. If energy is transferred through Coulomb collisions, τ_{eq} is given by (Spitzer 1962)

$$\tau_{eq} = \frac{3m_e m_i k^{3/2}}{8(2\pi)^{1/2} n_e e^4 \ln \Lambda} \left(\frac{T_i}{m_i} + \frac{T_e}{m_e} \right)^{3/2} s, \quad (2.31)$$

where $\ln \Lambda$ is the Coulomb logarithm.

Masai (1994) analytically estimated the equipartition process and found the post-shock temperature T_e to be

$$T_e \approx 0.21 (\ln \Lambda)^{2/5} (n_e t)^{2/5} T_s^{2/5} \text{ K} \quad (2.32)$$

for $t < 0.1 t_s$, where t_s is the equipartition time constant given as

$$t_s = \frac{3m_p (kT_s)^{3/2}}{8(2\pi)^{1/2} e^4 m_e^{1/2} n_e \ln \Lambda}. \quad (2.33)$$

Significantly higher temperature of electrons than that of the initial value of $\approx m_e/m_i T_s$, are obtained within extremely shorter time scale than t_s : $T_e \approx 0.1 T_s$ and $0.3 T_s$ for $t \approx 10^{-3} t_s$ and $10^{-2} t_s$, respectively.

Nonequilibrium ionization

In a collisional ionization equilibrium (CIE), and optical thin plasma of the electron temperature lower than 10^7 K and $Z \geq Z_\odot$, the X-rays are dominated by the line emission. The line flux from an ionizing plasma (non-equilibrium ionization: NEI) is generally larger at higher temperature than those expected in a CIE plasma.

In the NEI, 2γ -decay and free-bound processes, as well as line emission also become important. Ignoring the multiple ionization or the Auger transition, we get the collisional ionization rate equation for the element of atomic number Z as

$$\frac{dn_z}{dn_e dt} = S_{z-1} n_{z-1} - (S_z + \alpha_z) n_z + \alpha_{z+1} n_{z+1}, \quad (2.34)$$

where S_z and α_z represent the rate coefficients for ionization and recombination from ion of charge z to charge $z+1$ and $z-1$, respectively, while n_z and n_e are the number densities of the ions of charge z and electrons. Starting from a low initial ionization states, electrons in the outermost orbit are stripped (ionized) to inner orbit as time goes. Due to the electron shielding effects, higher ionization states has deeper effective potential, hence exhibit higher energy of a fluorescent line than those found in lower ionization states. Thus, we can obtain information of degree of ionization from the line energy. At the ionization parameter larger than $\sim 10^{12} n_e^{-1}$ s, no significant line energy shift from that of CIE is found in the wide range of the electron temperature and atomic number (Masai 1994).

Thermal Bremsstrahlung

The continuum emission from an optically thin thermal plasma is described by the thermal bremsstrahlung spectrum;

$$\frac{dW}{dV dt d\nu} = \frac{2^5 \pi e^6}{3mc^3} \left(\frac{2\pi}{3km} \right)^{1/2} T^{-1/2} Z^2 n_e n_i e^{-h\nu/kT} \bar{g}_{ff}(T, \nu), \quad (2.35)$$

or also given in the CGS units as

$$\epsilon_\nu^{ff} \equiv \frac{dW}{dV dt d\nu} = 6.8 \times 10^{-38} Z^2 n_e n_i T^{-1/2} e^{-h\nu/kT} \bar{g}_{ff}(T, \nu), \quad (2.36)$$

where $\bar{g}_{ff}(T, \nu)$ is the velocity averaged Gaunt factor. For energies at $10^{-4} < h\nu/kT < 1$, $\bar{g}_{ff}(T, \nu)$ is in the range 1 to 5. The $\bar{g}_{ff}$ values for high energies at $h\nu/kT \gg 1$ are virtually no importance, since the spectrum cuts-off at these energies. Thus, we get reasonable estimate within an error of a factor few, by setting $\bar{g}_{ff}(T, \nu)$ to unity. Thus, the dependence of ϵ_ν^{ff} on ν is

$$\epsilon_\nu^{ff} \propto \begin{cases} 1 & (h\nu \leq kT) \\ e^{-h\nu/kT} & (h\nu \geq kT); \end{cases} \quad (2.37)$$

Accordingly, the continuum flux is nearly constant to the energy of the given electron temperature.

2.3.4 Non-thermal emission

The radio spectrum of shell-like SNRs are generally described by a power-law of spectral energy index $\simeq 0.5$. The power-law shape suggests the existence of the electrons of a power-law distribution. As the acceleration mechanism, the Fermi acceleration in the shock (first-order Fermi acceleration) is widely supported.

Fermi acceleration in a shock wave

Suppose that upstream and downstream velocities of the nonrelativistic shock are, respectively, v_u and v_d , and that a relativistic particle of the kinetic energy E_0 passes along the flow from the

upstream to the downstream and vice versa. A particle scattered back elastically in the downstream change the energy to $E_{0'}$ from the initial value of E_0 as

$$E_{0'} \simeq \gamma_d^2 (1 - \beta_d)^2 E_0, \quad (2.38)$$

where $\beta_d \equiv v_d/c$ and $\gamma_d \equiv \sqrt{1 - \beta_d^2}$ ($\simeq 1$ if $\beta \ll 1$, i.e. the shock is nonrelativistic). Conversely, the energy change of a particle scattered in the upstream is given with the same notations as

$$E_1 \simeq \gamma_u^2 (1 + \beta_u)^2 E_{0'} \quad (2.39)$$

$$\simeq (1 + 2\beta_u)(1 - 2\beta_d) E_0, \quad (2.40)$$

where the suffix u means the value in upstream instead d in the downstream. Since $\beta_u > \beta_d$, the particle obtains the energy from the shock fluid by the round-trip between the two regions.

This process can be considered as the adiabatic compression of the particle by two flows: in a moving coordinate to give $\beta_u > 0$ and $\beta_d < 0$, we can easily understand this acceleration mechanism. Thus, a nonrelativistic particle also can gain the energy.

In the 3-dimensional case, the velocities of the particles scattered back have various directions, so the mean energy gain is eventually reduced. Bell (1978) showed the mean energy after n round trips is

$$E_n = E_0 \exp \left\{ \frac{4}{3} n (\beta_u - \beta_d) \right\}. \quad (2.41)$$

In the Fermi acceleration, the actual scattering mechanism is essentially important. In the SNR shock, the interstellar magnetic field frozen to the plasma in the downstream is randomized by the turbulence, therefore a charged particle is elastically and randomly scattered in many times: they do 'random walk'. Accordingly, some fraction of the particles coming from the upstream, for example, may return to upstream. In the upstream, the returning particles excite the MHD waves. Thus, the magnetic field in the upstream plasma is bent by the Alfvén wave, hence some particles are scattered back again to downstream.

We simply assume that the scatters make particles relax to a nearly isotropic angular distribution (*diffusive* approximation). Then the turbulent and the Alfvén wave make mean particle velocity equal to the stream velocity, so that all the upstream particles come back to the shock. In the downstream, Bell (1978) showed that the escape probability η by

$$\eta = 4 \frac{v_d}{v_p}, \quad (2.42)$$

under the assumption that the particles are injected at the shock into the downstream with the constant and that the downstream's is extending to $\gg v_p/v_d$ times of the mean free path, where v_p is the particle velocity.

Thus, the probability for the particle to make $\geq n$ times round trips is

$$P_n = (1 - 4\beta_d)^n \quad (2.43)$$

in a relativistic case.

Using equations (2.41) and (2.43), we can obtain the differential energy spectrum of the accelerated particles:

$$N(E) \propto \frac{dP_n}{dE_n} \quad (2.44)$$

$$\propto E^{-\frac{\beta_u + 2\beta_d}{\beta_u - \beta_d}}. \quad (2.45)$$

For a strong shock in the ideal monoatomic gas, $\beta_d = 1/4 \beta_u$, hence

$$N(E) \propto E^{-2}. \quad (2.46)$$

Synchrotron emission

The total power per frequency emitted from the moving electron in the magnetic field of strength B is

$$P(\omega) = \frac{\sqrt{3} q^3 B \sin \alpha}{2\pi m c^2} F \left(\frac{2mc}{3qB\gamma^2 \sin \alpha} \omega \right), \quad (2.47)$$

where $-q$, m and α are, respectively, the charge and the mass of electron and the pitch angle, while $\gamma \equiv 1/\sqrt{1 - v^2/c^2}$ and the function $F(x)$ is

$$F(x) \equiv x \int_x^\infty K_{5/3}(\xi) d\xi, \quad (2.48)$$

where $K_{5/3}(\xi)$ is the modified Bessel function. $F(x)$ has a peak at $x = 0.29$, so the synchrotron emission has a peak at

$$\omega = 0.29 \frac{3qB}{2mc} \gamma^2 \sin \alpha. \quad (2.49)$$

For relativistic electrons with a power-law energy distribution function with the form of

$$N(\gamma) d\gamma = C \gamma^{-p} d\gamma, \quad (2.50)$$

where C is the constant, the total power per unit frequency is

$$P_{\text{tot}}(\omega) = \frac{\sqrt{3} q^3 C B \sin \alpha}{2\pi m c^2 (p+1)} \Gamma \left(\frac{p}{4} + \frac{19}{12} \right) \Gamma \left(\frac{p}{4} - \frac{1}{12} \right) \left(\frac{mc\omega}{3qB \sin \alpha} \right)^{-(p-1)/2}. \quad (2.51)$$

In astrophysical cases, it is often assumed that the electron velocity is isotropic or the magnetic field is randomly oriented. Thus the spectrum averaged over the pitch-angle is conveniently used:

$$I(E) = \frac{\pi q^2 C h s^{-2}}{\sqrt{3} s c} \Gamma \left(\frac{3s+8}{6} \right) \Gamma \left(\frac{3s-2}{6} \right) \left(\frac{3qB}{8mcE} \right)^s \text{ photons sec}^{-1} \text{ erg}^{-1}, \quad (2.52)$$

where $s = (p + 1)/2$ and h are the photon spectral index and Planck's constant.

Using the equation (2.51) and the value $p = 2$ as shown in (2.46), the energy spectral index of the synchrotron emission from the electrons accelerated in the shock is estimated to be 0.5: a typical value observed from shell-like SNRs in radio wavelength.

2.4 Particle acceleration by a pulsar

The mechanism of particle acceleration by a rotating neutron star (pulsar) is roughly regarded two cases: one is that related to a pair (electron-positron) creation plasma inside the light cylinder, where the corotation velocity is smaller than the light velocity, hence the magnetic field line from a neutron star may co-rotate, and the other is MHD acceleration outside the light cylinder.

2.4.1 Pair plasma inside the light cylinder

The dipole magnetic field $\mathbf{B}$ and vector potential $\mathbf{A}$ (in Coulomb and Euler gauges) at a vector position of $\mathbf{r}$ from a neutron star with the magnetic moment $\boldsymbol{\mu}$ are given by

$$\mathbf{B} = \frac{3(\mathbf{r} \cdot \boldsymbol{\mu})\mathbf{r} - \boldsymbol{\mu}}{r^5}, \quad \mathbf{A} = \frac{\boldsymbol{\mu} \times \mathbf{r}}{r^3}. \quad (2.53)$$

In the simplest case of a rigidly rotating and perfectly conductive neutron star, the scalar potential is written as

$$\phi = -\frac{(\boldsymbol{\Omega} \times \mathbf{r}) \cdot \mathbf{A}}{c} = \frac{\Omega r \sin \theta A_\phi}{c}, \quad (2.54)$$

where Ω and (r, θ, φ) are the angular velocity of the star and the spherical polar coordinates referring to the rotation axis, respectively. For an oblique rotator,

$$\phi = \frac{\mu \Omega}{cr} (\sin^2 \theta \cos \alpha + \sin \theta \cos \theta \sin \varphi \sin \alpha) \quad (2.55)$$

where α is the angle between the magnetic moment and the rotation axis'.

Due to the strong electric field is thus created, electrons and ions at the surface of the neutron star are strongly accelerated and move following the strong magnetic field line toward the ambient space. Since the magnetic field line is not straight but have curvature, the electrons emit curvature gamma-rays; high energy gamma-rays are converted to electron-positron pairs. The pairs are then accelerated by the electric field and radiate again curvature gamma-rays. By the cycles of these process, a large numbers of electrons and positrons are created. The particles created on the magnetic-field lines move along the line out of the light cylinder; these are called the pulsar winds.

2.4.2 Pulsar wind

Although the Crab-like SNRs are believed to be powered by the rotational energy of the central pulsar, no consensus how to link the pulsar to the nebular synchrotron emission, how the energy supplied by pulsar is shared to magnetic dipole radiation and a relativistic stellar wind, nor how is the composition of elements in the plasma escaped away from the pulsar's magnetosphere.

Nevertheless, we can point out three major facts, which have become to be clear since the discovery of the pulsar in 1968. (1) The energy supplied by a pulsar is converted into nebular synchrotron radiation with extremely high efficiency of 10%–20%. (2) In the nebula, the pulsar provides magnetic field far stronger than that expected from a primordial field frozen into the expanding nebular. The pulsar and nebula therefore are strongly coupled hydromagnetically. (3) Equipartition of energy density calculated from the synchrotron radio emission leads the lower limit on the pressure in the nebula to that far exceed the interstellar medium. Thus, the energy from the pulsar, in any process, is confined inside the nebula, although little observational signature for the confinement mechanisms have been found until recently.

2.5 Origin of Cosmic Rays

Cosmic rays, comprising mainly relativistic protons and coming from all directions of our universe, were firstly observed with balloon-borne instruments. The observed proton energies ranges from $< 10^9$ eV to 10^{20} eV; the presence of low energy limit is due to confusion of the solar wind. The integral energy spectrum extends with a single power-law of the index of about -1.7 , to the energy of 10^{15} eV, then steepen (the 'knee') to an index of about -2.1 . The energy density of cosmic rays in the Galaxy is known to be about 1 eV cm^{-3} , a comparable value of other components.

The cosmic-ray flux of electron are lower than that of protons by about an order of two, and have been observed to the energy of about 10^{12} eV, above which the electron fluxes become lower than background noise level induced by proton.

The abundances (compositions) of heavy elements in the cosmic rays below 10^{10} eV are larger than that found in Population II, and are similar to those in Population I stars, except those elements such as Li, Be and B. These shows larger values than solar by about an order of 6 and have been considered to be produced by the collision of heavier nuclei in the cosmic rays to those of interstellar gas. With this assumption, we can estimate the mean column density along the path of cosmic rays to be about $4 \times 10^{24} \text{ cm}^{-2}$. The mean lifetime of the cosmic rays, on the other hand, can be also estimated from the flux of the radioisotope ^{10}Be produced by the same collision and is found to be about 20 million years. From the life time and the mean column density along the

pass of a cosmic ray particle, we can estimate the mean density of 0.02 cm^{-3} , which is significantly smaller than the typical value of the galactic plane. This may indicate that cosmic particles spend significant fraction of their lime time in the region of very ambient medium, such as in the hot bubble, or in the galactic halo.

Due to the Lorentz force by interstellar magnetic fields, cosmic rays can not travel straight in the interstellar medium. Therefore, we cannot identify the original position of the cosmic rays from its coming direction. With the typical magnetic field of $\sim 1\mu\text{G}$ in the Galactic plane, protons up to 10^{15} eV can be confined in the Galaxy. Above the energy, the Larmor radius of proton becomes comparable to or larger than the order of the thickness of the Galactic disk, hence begin to escape from the Galaxy, hence the spectrum slope becomes steeper than that determined by lower energies. Thus, the cosmic rays below the knee are believed to be of Galactic origin.

From the energy density and the mean lifetime of cosmic rays, we can estimate the energy injection rate to cosmic rays. Assuming that the Galactic disk has 30 kpc diameter and 300 pc thickness, the total energy of cosmic rays in the Galaxy is estimated to be $10^{66} \text{ eV} \sim 10^{54} \text{ ergs}$. Dividing by the mean lifetime, we get the energy injection rate as $\sim 10^{40} \text{ ergs s}^{-1}$.

This rate can be compared with the energy released by Galactic supernova explosions. Since the supernova rate in the typical spiral galaxy and explosion energy per one SN are, respectively $\simeq 30 \text{ years event}^{-1}$ ($\sim 10^9 \text{ s event}^{-1}$) and $\sim 10^{51} \text{ ergs}$, the mean energy generation rate is $10^{42} \text{ ergs s}^{-1}$. Thus, about 1% of the supernovae energy is required for the cosmic ray acceleration. The radio synchrotron emission from SNRs, which is radiated from $\sim 10^8\text{--}10^9 \text{ eV}$ electrons in $\sim 1\mu\text{G}$ magnetic field, partly support the idea that cosmic rays are accelerated in a shell of SNR.

Possible mechanism would be the first ordered Fermi acceleration in an expanding shock of SNR. Then, the differential energy spectrum of accelerated particles becomes power-law of number index 2, which is smaller than the observed value 2.7; the difference, however, may be within the range of fine tuning of escaping from the shock acceleration site and of the energy loss during the propagation in the space.

Thus, it is reasonable to address that SNR is the major source of cosmic rays. Since cosmic rays below 10^{15} eV is Galactic origin, it is naturally to assume that SNR can accelerate the cosmic particles to the same energy 10^{15} eV . However, the observational evidence of accelerations to energies less than $10^8\text{--}10^9 \text{ eV}$ has only been available until now.

Chapter 3

Review of SN1006

3.1 Historical story

SN 1006 is the remnant of the brightest historical supernova explosion in A.D.1006. Its explosion was recorded in wide area either as a new star or a 'guest star', from Europe, Egypt, Middle East, China to Japan, in diaries, chronicles or official histories. These records were firstly examined systematically by Goldstein (1965), then supplemented by Goldstein and Yoke (1965). The properties they corrected from more than 20 documents are as follows:

1. The supernova appeared on early May 1006, the earliest day being 1 May, in the constellation Lupus. It had been very bright for about $3\frac{1}{2}$ months, and re-appeared after about 7 months.
2. The apparent size of the event, as observed by naked eye of medieval astronomers, was $2\frac{1}{2}$ to 3 times of Venus, where apparent diameter of Venus was generally referred to be $\frac{1}{10}$ that of the sun, or about 3 arcmin. At the maximum, the brightness was equivalent to a quarter of the brightness of the full moon, or was as bright as the moon when a little more than a quarter of the surface is illuminated. The latter is consistent with the comparison to the size of Venus. A quarter-illuminated moon has a magnitude of -8 , and at quadrature it is -10 . These magnitudes are certainly the largest among the historical supernova.

From the records of Toktaga and Ouyang Haüan cited in Goldstein and Yoke (1965), Minkowski (1966) suggested that the supernova had remained visible for at least another year, and ruled out the possibility of type II event, which declines faster than this light curve. Furthermore, he suggested that the absence of the star between $3\frac{1}{2}$ and about 7 month after the explosion is due to its close vicinity to the sun. At the epoch of the disappearance, the angular separation between the sun and to the SN was about 70° . Accordingly, he estimated the magnitude of supernova was fainter

than $m_v = -4.5$ at +105 days. This gives the upper limit of the maximum brightness of the SN to be $m_v = -8$.

Using this value of $m_v = -8$, the average type I supernova maximum brightness of $M_v = 19.^m0$ (Minkowski 1963), interstellar absorption of $0.^m4$ (Sharov 1964) and the 11 cm radio image of the remnant (Gardner and Milne 1965), he estimated the distance and the linear radius of SN 1006 to be 1300 pc and 7.5 pc, respectively. The radius and the age of 960 yr (in 1965) give an average expansion velocity of 7600 km s^{-1} , which is not far less than that of Tycho's supernova, another type I SN candidate from its light curve (Baade 1943). Thus, he reached to the conclusion that SN 1006 was a type I supernova.

3.2 Previous Observation

SN 1006 (G327.6+14.6, PKS 1459-41) was firstly cataloged by Bolton, Gardner and Mackey (1964) as a radio source 1459-41. Following the suggestion by Goldstein (1965), Gardner and Milne (1965) regarded the radio source to the remnant of SN 1006. They made 11 cm image, revealing the shell-like structure. They also showed that the linear polarization and spectral index from each intensity maxima, respectively, exceeds 10% and $\alpha \sim 0.6$; the latter value is obtained with the comparison to the results of Bolton, Gardner and Mackey at 75 cm and Mills, Slee and Hill (1960) at 350 cm. Most of the single-dish works at frequencies from 408 to 5000 MHz are summarized by Milne (1971).

Recently, high resolution images in various radio wavelength have been accumulating. Reynolds and Gilmore (1986) gave 1370 and 1665 MHz images of $16'' \times 20''$ resolution with the Very Large Array (VLA). Two bright regions with extremely sharp outer edges dominate the total flux, while the fainter emission appears extending in the whole interior of the SNR. Several discrete filaments, unresolved in width, can be found near the outer diameter of the remnant diameter; one at near the remnant edge with almost a perfect quarter circle. The filaments' properties are consistent with being sheets seen edge-on, with widths of order 1 pc and thickness less than 0.1 pc.

Roger et al. (1988) gave 843 MHz image of $44'' \times 66''$ resolution with the Molonglo Observatory Synthesis Telescope (MOST). Similarly, the image shows a high degree of bilateral symmetry, both in intensity and in the shape of outer boundary. Near the symmetry axis, the flux is weak with no distinct boundaries.

Reynolds and Gilmore (1993), on the other hand, obtained the 1370 and 1665 MHz polarization images of $24''$ resolution with VLA. The gross morphology of the polarized intensity is "bipolar," similar to that the total (unpolarized+ polarized) intensity: two bright limbs across from one to the other. The SE quadrant, although is the faintest region in the total intensity, exhibits significant

polarized flux, while the extension to the NE, which is fairly bright in total intensity, shows no significant polarization. The integrated polarized fraction (measured polarized flux divided by total flux, taken from published single-dish observations) was about 13%, however locally, the ratios exceed 30%. By combining their observations with the previous observations, they inferred an intrinsic polarization position angle to be ordered with the magnetic field being primarily radial, as is the case of the other historical shell remnants.

Moffett, Goss and Reynolds (1993) measured the expansion velocity of the radio shell at 1370 and 1665 MHz comparing the images with those reconstructed from observations made in 1983-1984 by Reynolds and Gilmore (1986). They got the mean expansion velocity at this epoch to be $3.5 \pm 1 \text{ arcsec}$: the expansion rate to be $0.049\% \text{ yr}^{-1}$ or $R \propto t^{0.48 \pm 0.13}$, consistent with the Sedov expansion, or with a forward/reverse shock pair moving into constant-density material.

In the optical wavelength, an H α filament was detected by van den Bergh (1976) at the northwest edge of the remnant. Subsequent spectral observations by Schweizer and Lasker (1978) and Lasker (1981) revealed existence of Balmer-line only. Kirshner, Winkler and Chevalier (1987) discovered a broad component to the Balmer-line and inferred shock velocities in the range $2800\text{--}3900 \text{ km s}^{-1}$ using the non-radiative shock models of Chevalier, Kirshner and Raymond (1980). Long, Blair and van den Bergh (1988) observed the filament and, by comparing with the image taken by van den Bergh (1976), inferred the mean proper motion of the filament to be $0.30 \pm 0.04 \text{ arcsec yr}^{-1}$. Comparing this value with the shock velocity inferred by Kirshner, Winkler and Chevalier, they calculated the distance for SN 1006 to be 1.7-3.1 pc. Then the maximum visual magnitude and estimated to be between -6 and -9.5.

In the UV band, Wu et al. (1983) observed an sdOB star which had been found by Schweizer and Middleditch (1980) in the projected direction near the remnant center. They discovered strong Fe⁺ resonance absorption lines with zero radial velocity, but are broadened by $\sim 5\text{--}6 \times 10^3 \text{ km s}^{-1}$. These suggest that the bulk of the ejecta is iron, in agreement with the type Ia supernovae scenario. They also discovered redshifted Si^{+,2,3} lines, which indicates that the star is located behind, hence not physically associated to the SNR.

From the optical filament, Raymond, Blair and Long (1995) discovered H I , He II , C IV and O VI with the Hopkins ultraviolet telescope during the Astro-2 space shuttle mission. They found that the line widths are consistent with the $\sim 2300 \text{ km s}^{-1}$ width reported for H α , implying that the velocities of different ions are separately randomized in the shock and that ion temperature equilibration is not efficient. The faint continuum in the spectrum is consistent with relatively strong dust-scattered starlight along the line of sight. They also suggested that the line intensity ratios are, within ambiguity of factor 2, consistent with those of model predictions for a 2300 km s^{-1}

shock with cosmic abundance gas, which is 50% neutral gas ahead the shock.

In the X-ray band, Palmieri et al. (1972) first scanned the Lupus Loop including SN 1006 with a rocket-borne proportional counter of a $2.^\circ62$ FWHM collimator and of the 0.2–1.6 keV energy range. They detected an extended emission over about 8° with a peak at the position of SN 1006.

The X-ray image of SN 1006 was first obtained by Pye et al. (1981) with the IPC on the *Einstein* observatory. The image, with resolution of ~ 1 arcmin, shows a limb brightened circular nebula of $\simeq 15$ arcmin radius. The enhanced limb emissions found in the two quadrants are similar to the radio images.

Although the shell-like structure of the radio and the soft X-ray images of SN 1006, which is similar to those of Cas A, Tycho and Kepler, suggests that the bulk of the X-rays is attributable to a shock-heated plasma, the X-ray spectrum of SN 1006 has shown a featureless structure over a wide energy band. Thus, SN1006 has been regarded as an enigma in the X-ray astronomy. In fact, Becker et al. (1980) observed SN 1006 with the SSS on the *Einstein* observatory and the CXS (cosmic X-ray spectrometer) on *OSO 8*, and suggested that the X-ray emission is of non-thermal origin, based on the absence of X-ray emission lines and the fact that the X-ray spectrum was well represented by a single power-law with photon index 2.2, a similar value to those of well established synchrotron nebulae such as Crab and Vela X.

However, some pieces of information suggesting that X-rays are of thermal origin have been accumulating. Vartanian, Lum and Ku (1985), using an instrument with an improved energy resolution, detected K-emission lines from highly ionized oxygen atoms (O VII and O VIII), which is direct evidence for a thermal X-ray emission. Using Tenma-data, Koyama et al. (1987) reported that the spectral slope of the hard X-ray band was steeper than that of typical synchrotron nebula, after carefully subtracting the local background from the Lupus region. Combining the Tenma and SSS data, Hughes (1991) demonstrated that the wide-band X-ray spectrum favors a thermal spectrum rather than a non-thermal power-law model. Soon after, Leahy, Nousek and Hamilton (1991) reanalyzed the scanning data of the *HEAO-A2* LED (Low Energy Detector) instrument, and concluded that the low-energy X-ray spectrum can be explained by a two-temperature thermal plasma model. If the origin of the X-ray emission is of thermal, regardless multi-temperature or not, a critical problem is the lack of any prominent lines other than that from oxygen.

An important issue for the X-ray data analysis is an accurate determination of the local background from the Lupus Loop overlapping SN 1006. In fact, Koyama et al. (1987) have already reported an excess of diffuse hard X-rays from this region, which is described with either a power-law of a photon index of 2.2 or a thermal bremsstrahlung of $kT = 7$ keV temperature. Since the local background is diffuse and would not be spatially uniform, X-ray observations in a smaller

field of view, together with a high sensitivity to the low surface-brightness features is essential to derive reliable data for SN 1006.

The Lupus Loop is a very old supernova remnant of about $270'$ radius (Milne 1971). It has been observed in the X-ray and radio regions (Palmieri et al. 1972; Davelaar et al. 1979; Winkler et al. 1979; Toor 1980; Koyama et al. 1987; Leahy, Nousek and Hamiltont 1991). From the radio (Clark, Caswell 1976) and soft X-ray observations (Leahy, Nousek and Hamiltont 1991), the age and distance are estimated to be about 10^4 yr and about 500–1000 pc, respectively.

Since the surface brightness of the Lupus Loop is rather low and the statistical accuracy of previous observations has been limited, the reported temperature of the plasma are large scattered in the wide range of 60–1600 eV. In the hard X-ray band, Koyama et al. (1987) discovered an excess emission near to the Lupus region. The spectrum is described by a 7.5 keV thermal Bremsstrahlung model, which is considerably higher than that of the pervious soft X-ray spectrum. Although it shows no prominent iron K-shell emission line, the plasma temperature resembles that of the Galactic Ridge (Koyama 1989). However, since the galactic latitude of the Lupus Loop is far larger than the scale height of the Galactic Ridge, it is still unclear whether the hard X-ray excess is really associated with the Lupus Loop or due to a larger extended galactic ridge emission or else.

3.3 Previous Interpretations or Models of X-ray emission

As described above, SN 1006 exhibits apparent inconsistency between the image and the X-ray spectrum. Some scientists have tried to explain the inconsistency: the idea is roughly categorized into two depending on the assumption whether the spectrum is thermal or non-thermal. The X-ray energy index generally used in any models is $\simeq 2.2$, based on rather old observations.

3.3.1 Non-thermal model

Reynolds and Chevalier (1981) developed a self-consistent model for non-thermal radiation from supernova remnants in the Sedov phase, assuming that the shock accelerates electrons to an energy density proportional to the postshock pressure.

They assumed that an isotropic power-law electron distribution is created at the shock:

$$N(E)dE = KE^{-s}dE, (m_e c^2 \leq E \leq E_{\max}) \quad (3.1)$$

with the additional assumption that the accelerated electrons remain in the thermal gas, or no diffusion, but with no discussion for the detailed acceleration mechanism. For a given element of gas, K evolves behind the shock as a result of adiabatic expansion; it is proportional to $\rho^{(s+2)/3}$,

where ρ is the gas density given by the Sedov solution. They set the synchrotron emissivity to zero interior to the radius of the reverse shock, at which the Sedov extrapolation would have given an initial expansion velocity greater than $10,000 \text{ km s}^{-1}$ as appropriate for a type Ia explosion. For the evolution of the postshock magnetic field, they considered two cases: the field is swept up and compressed the interstellar field, and the field is turbulently amplified to the field energy density of a fixed fraction of the postshock energy. The former, however, was eliminated on the basis of X-ray data.

The upper limit of E_{max} is determined by the assumption of no diffusion, while the lower limit comes from the requirement that the acceleration time should be less than or of order of the radiative lifetime.

Since the amount of energy gain after a round-trip depends only on the initial energy and the shock velocity, the acceleration time scale is proportional to the mean round-trip path, or the mean free path, thus the lower limit of the acceleration rate is determined by the assumption that the mean free path is short enough to keep the electrons in the thermal gas. Accordingly, E_{max} is limited since the synchrotron radiative lifetime is proportional to E^{-1} .

They explained the X-ray power-law continuum of energy spectral index $\simeq 1.15$ shown by Toor (1980) and Becker et al. (1980) as the extension of the radio emission, steepened by synchrotron radiative losses; the photon index of the spectrum of a continuously injected power-law electrons increase by 0.5 above a critical energy. While their model do not fully satisfy this category exactly, they regarded the difference as minor. In order to fit the X-ray flux, they required the break frequency at $\sim 10^{14} \text{ Hz}$, hence required a high post-shock magnetic field of order $100 \mu\text{G}$. Under this magnetic field, the electrons with $\gamma \sim 10^8$ ($5 \times 10^{13} \text{ eV}$) emit the X-ray photons.

At frequencies where the energy losses become important, emission is confined to a thin shell behind the shock containing the most recently accelerated electrons; therefore, the radius of X-ray shell becomes larger than that of radio. They could not, however, find no signature of this. The resolution of the radio map would not be sufficient to support a firm conclusion.

3.3.2 Thermal model

Hamilton, Sarazin and Szymkowiak (1986) tried to compose the observed X-ray spectra by a combination of thermal emissions from the ejecta swept up by the reverse shock and that from ISM (CSM) with cosmic abundance swept up by the forward shock. They argued that the power-law continuum and absence of line emission are consistent with the spectrum of a reverse shock into the ejecta with a roughly uniform density and stratified layers structure of heavy elements.

They got satisfactory fit to the published X-ray spectra with a three-layer model of ejecta

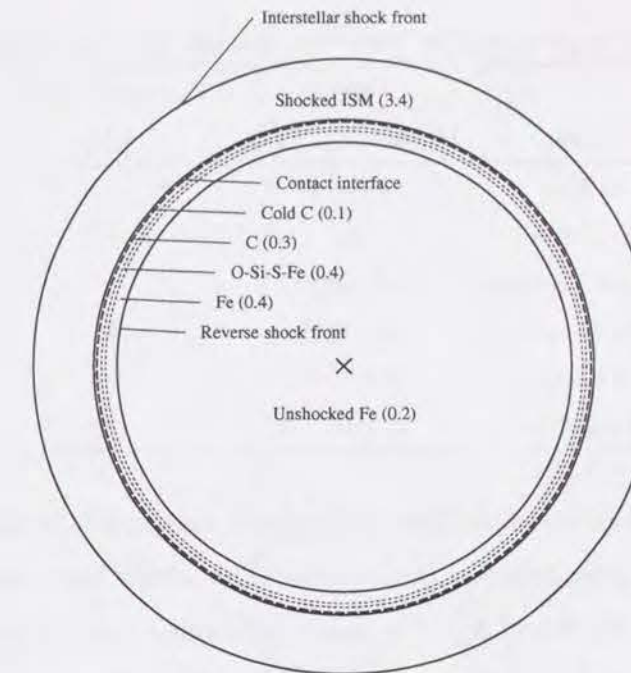


Figure 3.1: The onion-skin structure model of SN 1006 by Hamilton, Sarazin and Szymkowiak (1986). Numbers in brackets are masses in $M_{\odot}$.

consisting of an outer layer of pure carbon, a middle layer of processed heavy elements, oxygen, silicon, sulfur and iron, and an inner layer of pure iron. The free-free emission from fully ionized gas in the dense outer layers of the ejecta can produce a power-law continuum.

In detail for the power-law continuum, they proposed, assuming that the electron pressure in the remnant is constant, a power-law distribution of mass with temperature:

$$\frac{dM}{d \ln T_e} = \beta M_{\text{tot}} \left[\frac{T_e}{T_{e(\text{max})}} \right]^{\beta}, \quad (3.2)$$

with $\beta \approx 0.3$ in the hydrogen and helium dominant plasma, or $\beta \approx 0.5$ in the fully ionized carbon or oxygen plasma. Equation (3.2) assumes that β is positive and $T_{e(\text{min})} \ll T_{e(\text{max})}$.

The power-law distribution cannot be made by Sedov (1959) solution nor any individual component, blast wave or reverse shock, nor in any of Chevalier's (1982) similarity solutions. To make this power-law distribution, they adopted the early time reverse shock similarity solution for uniform density ejecta moving into an external medium (Hamilton and Sarazin 1984). Furthermore, to explain the weak oxygen K-line emission, they restricted the oxygen at the dense outer layers of ejecta, where the low energy X-rays are emitted.

Figure 3.1 shows the schematic illustration of the structure of the best-fit model, and table 3.1 gives the strengths of selected line features.

The spectrum is dominated by the reverse shock at low energies, and by the interstellar blast

Table 3.1: Line strengths predicted by Hamilton, Sarazin and Szymkowiak (1986) model.

Line	Flux [photons cm ⁻² s ⁻¹]	Equivalent width [eV]
C Ly α	0.1–0.2	—
O K-line	0.1	—
Si and S L-lines	0.1–0.2	—
Si K-line	3×10^{-4}	40
S K-line	2×10^{-4}	50
Fe K-line	5×10^{-5}	150

wave at high energies. In the dense outer layer of the ejecta, carbon is fully ionized and produces the soft X-ray continuum and strong carbon Lyman lines. The middle layer contributes line emission from heavier elements, O, Si, S and Fe. The low-density inner layer of iron produces negligible emission. Still this innermost layer is included in the model, in order to argue that a large amount of iron can be hidden without difficulty in the ejecta components. The equivalent widths of Si, S and Fe K-lines are 40, 50 and 150 eV, respectively, and are consistent with the observations they cited.

Chapter 4

Review of IC 443

IC 443 (G189.1+3.0, 3C157) is a shell-like SNR of about 45 arcmin diameter. The flux density at 1 GHz is 160 Jy and the radio spectral energy index from 20 MHz to 11 GHz is 0.36 (Erickson and Mahoney 1985).

While the association of supernova progenitors and their parent molecular clouds is expected, SNRs which show a clear-cut interaction of molecular cloud and blast wave are apparently rare. IC 443 is the unique SNR where the interaction between the shock wave and the molecular cloud is distinguished by the presence of clearly identifiable highly perturbed regions of molecular gas.

4.1 Previous Observations

DeNoyer (1979a,b) discovered three shocked OH and CO clumps with pointing observations where bright condensations of the shocked HI have been seen (DeNoyer 1978), and suggested existence of clumpy structures named A, B and C. The CO associates with the accelerated HI and OH clouds, and its lines have velocity width of 20 km s⁻¹ and appeared to be optically thin.

As the whole structure of IC 443 in radio and IR wavebands, Braun and Strom (1986) analyzed the IRAS all sky survey data of 12, 25, 60 and 100 μ m bands, and 327 and 1400 MHz and λ 21 cm HI line radio data. They argued that the SNR shock has encountered a pre-existing high density shell.

With the radio data, they showed that IC 443 consists of three interconnected $\sim$ spherical subshells of vastly different radii and centroids: two of them together define the usually assumed boundaries of IC 443, while the third includes the optical filaments which extend beyond the bright north-eastern rim. They showed that these filaments have well correlated non-thermal radio counterparts. They found the spectral index ($S \propto \nu^{-\alpha}$) for the bright north-eastern rim is $\alpha = 0.35 \pm 0.03$, while for the external filaments, $\alpha = 0.42 \pm 0.09$. These are in good agreement

with the value found by Erickson and Mahoney (1985) from integrated fluxes between 20 MHz and 11 GHz, $\alpha = 0.355 \pm 0.013$.

From the $\lambda 21$ cm data, they showed that the emission of negative velocities is dominated by an incomplete semi-circular arc which is coincident with radio continuum filaments in the east-central portion of the SNR, and of positive velocities at the bright north-eastern rim is seen as well as extended emissions in the south and south-east and long nearly linear features from the north-east to the south.

From the IRAS data, they extracted cool and warm dust emission images assuming the data as a linear combination of cool dust, zodiacal light and warm dust emission. The cool emission reveals shell-like image, while the warm emission shows more clumpy, centrally concentrated structure. They argued that the cool dust distribution suggests an outer skeleton which has been consumed from within by the action of the massive stars of the Gem OB1 association, and showed that the warm peak is coincident with the O9 Vp star HD256035 which is likely responsible for local heating and ionization. The brightest infrared emission regions are best spatially correlated with the shocked H α emission from the northeast and the molecular cloud.

Mufson et al. (1986) argued that the expansion of an initially symmetric SNR blast wave into an inhomogeneous ambient medium is sufficient to explain IC 443's H α , IR, visible and X-ray morphology.

Dwek et al. (1987) also analyzed the IRAS data and estimated the IRAS band luminosity to be 360 times the X-ray luminosity. They argued that approximately half of the infrared emission arises as thermal emission from shock-heated dust assuming a normal gas-to-gas ratio.

From the shocked clumps, other lines such as ^{13}CO and HCO^+ have been detected. Dickman et al. (1992) carried out systematic, high-resolution $J = 1 \rightarrow 0$ CO and HCO^+ mapping observations over whole IC 443. They found five new clumps of perturbed molecular gas and clarified their relations: together with the previous three clumps, the clumps outline a roughly elliptical ring whose major axis is ~ 9 pc across assuming the generally accepted distance of 1500 pc for IC 443. They showed a systematic variation in the distribution of the high-velocity molecular gas associated with the clumps: the southern part of the gas is blue shifted and the northern is red, which is the same trend as the $\lambda 21$ cm image (Braun and Strom 1986) and suggests that the clumps are distributed along the periphery of a tilted, expanding ring. They argued that the ring is a byproduct of the blast wave's interaction with a more homogeneous confining structure.

van Dishoeck, Jansen and Phillips (1993) observed various simple molecules in the shocked molecular gas. From CO 3–2 line profiles, they found that in the S–SE part of the ring (clumps A–C) the shock occurs mostly along the line of sight, whereas in the NE–NW part, the shock must

be mostly perpendicular (clumps D, E, G).

In the soft X-ray band, Petre et al. (1988) analyzed IPC, HRI and SSS of *Einstein* observatory, and ME of *HEAO-1* A-2 data. They found that there is little correlation between soft X-ray and optical or radio features, which is highly atypical of a supernova remnant in the adiabatic phase. The best-fit models of the low-energy X-ray spectrum of the brightest area suggested either that the remnant has not yet attained ionization equilibrium or that the X-rays arise in a multi-phase medium. They found that the X-ray hardness ratio map with IPC is well correlated with the surface brightness distribution of the CO line emission from a molecular cloud in the line of sight (Cornett et al. 1977), then suggested that the spatial structure of the X-ray absorption is globally explained by the molecular cloud.

Wang et al. (1992) observed IC 443 with *Ginga* satellite and found that the flux below 6 keV is consistent with the *Einstein* and *HEAO-1*, and the spectrum is smoothly extended to 20 keV. The extension could be fitted with a power-law of an energy index about one. They also found the iron K emission equivalent width about 0.25 keV.

Asaoka and Aschenbach (1994) analyzed ROSAT all-sky survey and pointing data, and found another overlapping SNR of $\sim 10^5$ yr, which they called G 189.6+3.3. They suggested that the high energy X-rays (> 2 keV) are emitted only from the smaller two shells (IC 443) but not from the large shell of G 189.6+3.3. From the spatially resolved spectroscopy of a ROSAT pointing observation, they suggested that G 189.6+3.3 and IC 443 are separated along the line of sight by the CO molecular cloud and only the IC 443 spectrum is affected by low energy X-ray absorption in the molecular cloud. They also suggested that the lane-like structure of reduced X-ray surface brightness across IC 443 is due to absorption of the background X-rays from IC 443 by a dense shell of cold matter associated with G 189.6+3.3 lying in front.

In the gamma-ray band, Esposito et al. (1996) studied the data from the EGRET instrument aboard the *Compton Gamma Ray Observatory*. The gamma-ray flux, $E > 100$ MeV, from 2EG J0618+2234, which is coincident with IC 443, is $(5.0 \pm 0.4) \times 10^{-7}$ photons $\text{cm}^{-2}\text{s}^{-1}$, and the spectrum can be fit by a single power-law of photon index 1.97 ± 0.07 . They showed that shock acceleration of cosmic rays gives consistent results with the data, and possibly for the origin of Galactic cosmic rays, although the pulsar origin cannot be precluded.

4.2 Interpretations for hard X-ray emission

For the origin of the hard tail observed with *Ginga*, Wang et al. (1992) discussed several possibilities: a shock-heated plasma, and other 3 possibilities of non-thermal origins, containing synchrotron

radiation, inverse Compton scattering and bremsstrahlung.

Here we quickly review their discussion. Suppose the synchrotron origin, the break frequency determined from extrapolations of the spectra of both the radio and X-ray comes at ~ 100 GHz. The half-life of the electrons having the peak synchrotron emission at this break frequency should therefore be shorter than the age of the SNR, probably shorter than 10^4 yr. Since the half-life is inversely proportional to the electron energy, a half-life of X-ray emitting electrons then is shorter than one year. Such an efficient mechanism of acceleration is unlikely. For an inverse Compton X-rays, the strong IR emission of a photon density comparable to that of the cosmic microwave background would be attributable to the inverse Compton X-rays. Since the energy index of the spectrum of the Compton scattered X-rays is the same as that of the synchrotron radio emission, the same electrons cannot be responsible for both X-rays and radio emissions. In addition, the hard X-ray flux become consistent with the radio flux, only if the magnetic field strength is unlikely weaker than 10^{-6} G, significantly weaker than the average of the galactic magnetic field.

If the mechanism is the bremsstrahlung from non-thermal electrons, the X-ray emitting electron is non-relativistic, hence the electron energy is lower than that of the radio emitting (synchrotron) electrons. The observed X-ray and radio spectral index can be explained by the electrons with a single spectral index. However, to explain both X-ray and radio flux, either the electrons or the magnetic field, both are responsible for the radio synchrotron, should be unreasonably high density or weak field.

Wang et al. (1992) thus suggested that a shock-heated plasma is most likely origin, and other 3 non-thermal origins are unlikely. In fact, after subtracting the soft component obtained by Petre et al. (1988), they got an acceptable fit to the hard component with a temperature higher than 8 keV. To explain the low equivalent width of iron K line, they proposed a low ionization time $n_e t$ for the plasma.

Such a high temperature for the hard component requires a shock velocity of $2500\text{--}3500$ km s $^{-1}$, then the crossing time for the shock wave over the radius of IC 443 is in the range of 1000-1400 yr. If the emission comes from about $\frac{2}{3}$ of the SNR, the hard X-ray flux and $n_e t$ required for the iron equivalent width become consistent. Thus, they suggested that the age of IC 443 is ~ 1000 yr instead of the previous estimation of 10^4 yr and that IC 443 is the remnant of a supernova in A.D.837.

Chapter 5

Instruments

5.1 Ginga

Ginga is the third Japanese X-ray observation satellite which was launched by the M-3SII-3 rocket from Kagoshima Space Center (KSC) on 5 February 1987. It was thrown into a slightly elliptical orbit with the perigee of 520 km, the apogee of 670 km and the orbital inclination of 31° . The orbital period is 96 min, which means 15 revolutions a day. The argument of perigee rotates in the orbital plane with a period of 37 days. It weighted 430 kg and consisted of $1000\text{ mm} \times 1000\text{ mm} \times 1550\text{ mm}$ body and four $760\text{ mm} \times 1755\text{ mm}$ solar paddles.

Ginga could contact KSC only for about 10 minutes each in 5 (or 6) consecutive orbits out of the 15. These orbits are usually called “contact orbits”, and the other ten “remote orbits”.

Ginga had three instruments; the large area proportional counter (LAC; Turner et al. 1989), the al sky monitor (ASM; Tsunemi et al. 1987) and the gamma-ray burst detector (GBD; Murakami et al. 1987). Figure 5.1 shows the configuration of these three instruments.

For the satellite attitude control system, *Ginga* had five different attitude sensors, (i) star trackers (STT) which are CCD cameras and detect the position of stars of > 6 mag., (ii) non-spin type solar aspect sensor (NSAS) of $\simeq 3$ arcmin accuracy, (iii) spin type solar aspect sensor (SSAS), (iv) inertial reference units (IRU) which detect the angular velocity around the X, Y, Z and S-axis which was arranged to form 54.7° angle to other three axis and (v) geomagnetic aspect sensor (GAS). The attitude was controlled in reference to four IRUs to an accuracy of $\sim 0.1^\circ$.

For maneuvering and stabilizing the attitude, *Ginga* had one momentum wheel (MW) to control around the satellite Z-axis slew, and three magnetic torquers (MTQ) to maneuver the Z-axis direction, as well as to release the accumulated extra momenta in the satellite body to the space maneuver. Figure 5.2 shows the definition of the satellite coordinates. The speed of the slew and the maneuver was 14°min^{-1} and 5°min^{-1} ; therefore, maneuverability around the Z-axis is about 170

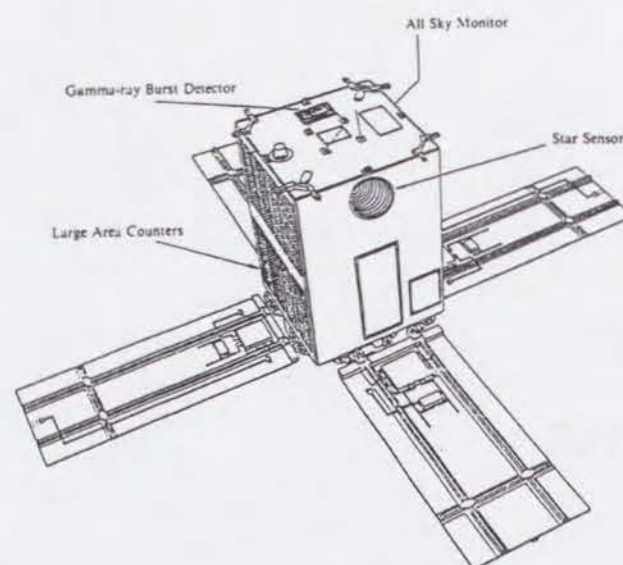


Figure 5.1: Instruments configuration of the Ginga satellite.

times more efficient than that around X and Y-axis. The satellite attitude is perturbed by the forces due to air between the earth atmospheric air drag, the solar light pressure and gravitational torque. The IRU attitude controller can compensate these small perturbations instantaneously.

If the angle between the sun and the Z-axis becomes small, the solar light on the solar paddles reduces much, hence the satellite lacks the power to operate. The attitude operations are therefore limited within the solar angle of $> 140^\circ$. For emergency when the solar angle becomes $< 135^\circ$ by some accident, the satellite was programmed to enter the power-save mode, and to move back to the attitude of the largest solar angle.

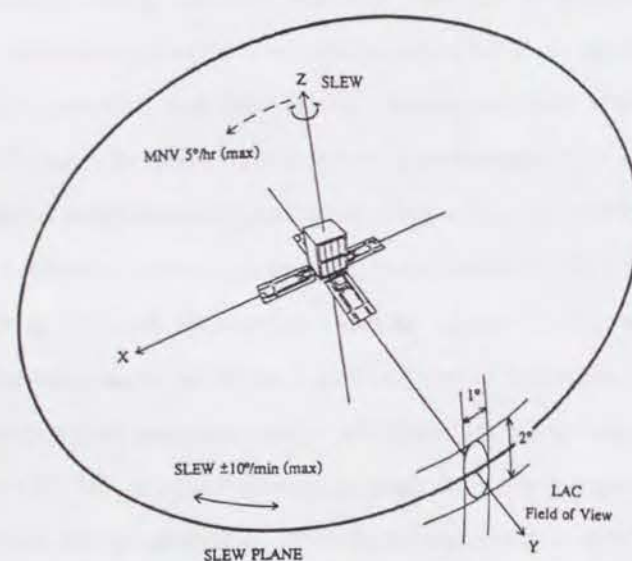


Figure 5.2: The definition of the Ginga satellite coordinates.

In addition to the ordinary pointing mode, the scanning mode was also available using the high speed maneuverability around the Z-axis, hence rotating the field of view of LAC along a great circle. The scanning mode was generally used (i) to determine the source position precisely, (ii) to examine whether or not any contamination sources are near the target of a pointing mode and (iii) to survey a wide sky region, either for the observation of surface brightness distribution of an extended source or that of diffuse background near the target.

The final attitude of the satellite and the aspect of the LAC were reconstructed on the ground using the IRUs and STTs data within a typical accuracy of $\sim 0.02^\circ$.

As the telemetry channel, *Ginga* used U-band (down-link 400 MHz) and S-band (up-link 2.1 GHz, down-link 2.3 GHz). On the contact path, the satellite transmits the stored and real-time data in S-band and U-band, respectively. The control commands are sent to the satellite in U-band. At the same time, the orbital elements of the satellite were obtained with the Doppler shift and loop-back time of the S-band signal. The daily operations were planned using thus accumulated orbital parameters.

The data are divided into three groups: scientific data from LAC, ASM and GBD, house keeping data such as battery condition and charged particle monitor, and data of the satellite attitude information. These data were processed by on-board processor (DP), then stored in the bubble data recorder (BDR) of 41.9 Mbits capacity when the satellite was out of contact, or transmitted to the ground station during the contact path.

Since the interval between contacts was variable depending on the phase of orbital cycle, and since the BDR capacity was limited, *Ginga* had three data processing bit rate, High, Med and Low. The recording time and time resolution depended on the bit rate. Each rate could record for 40 min, $5\frac{1}{2}$ and 23 hr with 16K, 2K and 512 bits s^{-1} , respectively. Therefore, bit-low was used in the remote passes and bit-med and -high were in the contact passes.

5.1.1 LAC

LAC consists of 8 proportional counters equipped with collimator blocks (figure 5.3) and a front-end electronics (LAC-S). All signals are fed into a signal processing part called LAC-E.

The collimator has semi-honeycomb structure shown in figure 5.4. It has the peak transmissivity of about 82% with a field of view of about 1° and 2° in X- and Z direction, respectively.

The counter is made of stainless steel of a 0.7 mm thickness which intercepts X-rays up to ~ 50 keV and electrons up to ~ 1 MeV. The gas chamber is divided into 4 layers, each consists of 13 multi-cell structure, with a center wire for an anode wire. These layers and cells are electrically separated by multiple ground wires. These wires also made of stainless steel with diameters of $40\mu m$

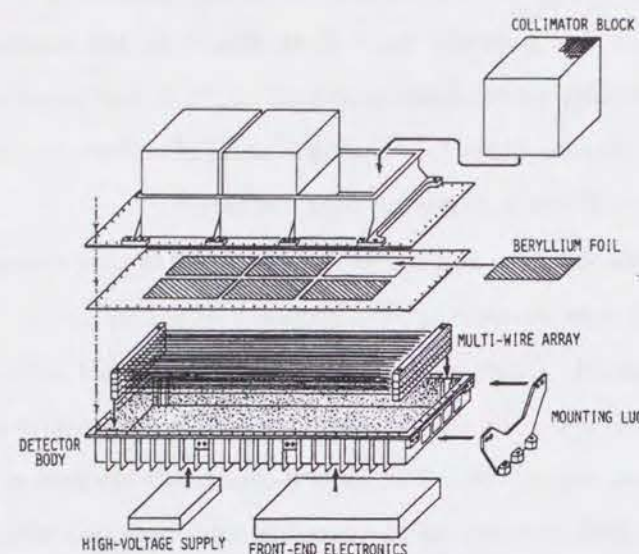


Figure 5.3: The schematic figure of the Ginga LAC.

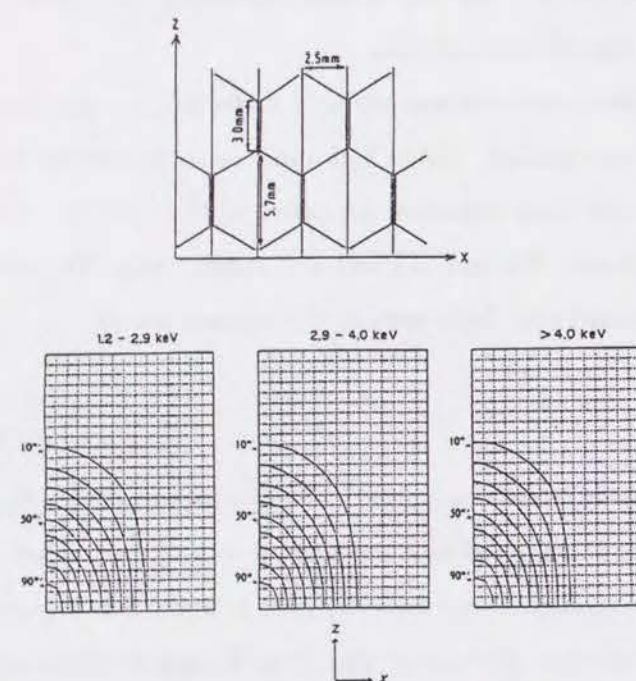


Figure 5.4: The structure and the angular response of the Ginga LAC collimator.

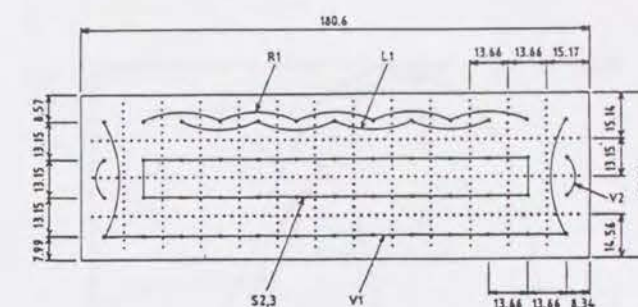


Figure 5.5: The wiring of the signal lines in a LAC.

for anode and $50\mu\text{m}$ for grounds. The signals from the first layer just behind the X-ray entrance window are mixed and called TOP layer, and those from the following two layers are called MID layer. Figure 5.5 shows the wiring of the signal lines in a LAC. The signals from the 4th layer, together with those from the aluminum plates called end-veto, which are set in front of the end-walls of the anode wire and provide veto-signals induced near end wall events, are mainly due to cosmic particles through the wall or electrons from the wall Compton scattered by gamma-rays.

The counter gas consists of 75% of Ar, 20% of Xe and 5% of CO_2 , and its total pressure is 1.86 torr at 0°C . As the counter has 56 mm depth, the upper energy of the detectable photon is about 35 keV. At the window, the gas is sealed by a beryllium foil of a $62\mu\text{m}$ thickness, which intercepts X-rays up to $\simeq 1$ keV and electrons up to ~ 100 keV. Behind the beryllium window, open area of 11 columns out of 13 excluding the both side cells are selected by the collimator. The central cells are thus guarded from the three-side walls by the cells in the right and left side and those in the 4-th layers. Therefore, signals from the guard cells are grouped all together and are, together with the end-veto signals, fed into the LAC-E, both proving the veto-signals for background rejection.

The open area of one proportional counter is 665 cm^2 . By multiplying the transmissivity of the collimator, the effective area becomes 545 cm^2 and the whole effective area of 8 LACs becomes 4360 cm^2 . In the actual operation, the effective area decreases to 4000 cm^2 because the additional anti-coincidence filtering of coincidence events between each adjacent two cells. Figure 5.6 shows the efficiency of the LAC.

LAC-E processes the signals from LAC-S: L1, R1, S23, V1, V2 and EV in figure 5.5 are converted to the pulse height and timing data, and sent to DP. Figure 5.7 shows the block diagram of LAC-E.

In usual observations, only L1, R1 and S23 signals are selected as a real X-ray data. The signals are filtered by the anti-coincidence: the signals are not processed if more than one line signaled at the same time, V1, V2 and EV signals inhibit the processing. With these selection, the charged-particle events that leave long tracks in the gas chamber and signals to more than one line are removed. The most of charged-particle background are removed by these filtering.

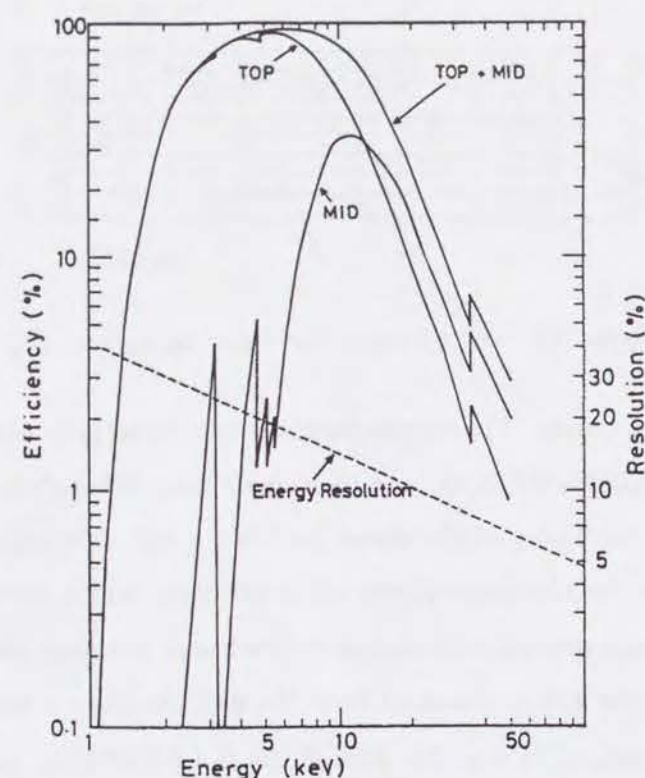


Figure 5.6: The detection efficiency and the energy resolution of the LAC for each layer.

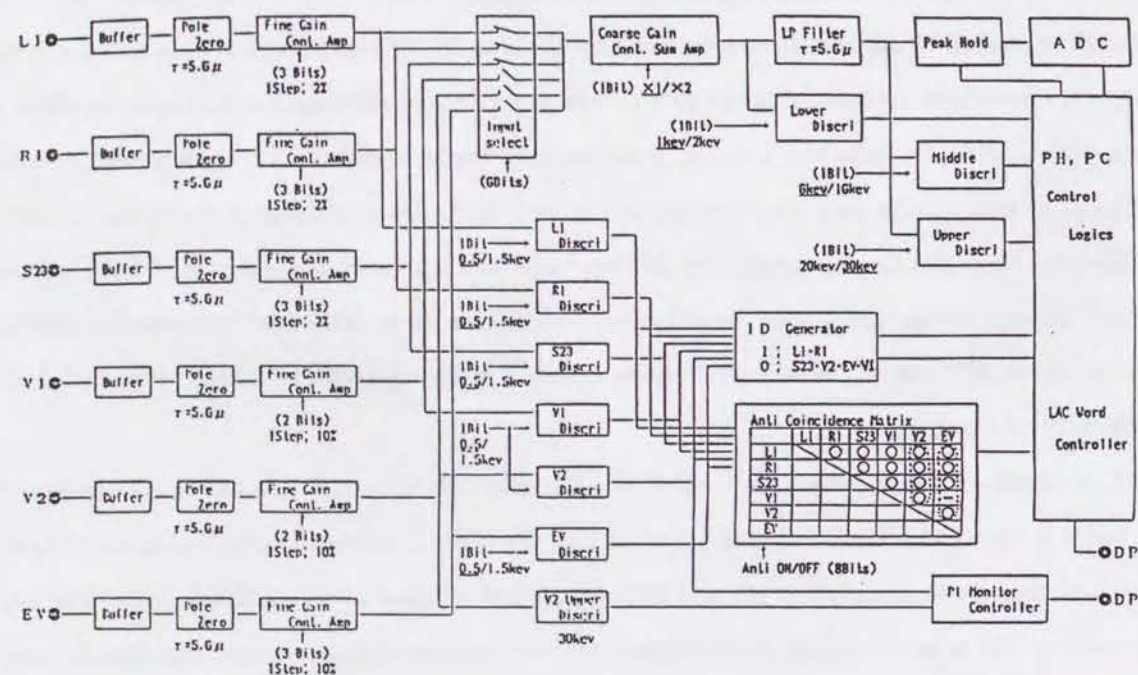


Figure 5.7: The block diagram of the LAC-E.

The pulse height corresponding to 0–37 keV is converted to 64 channels in LAC-E, then DP compresses them to 48 channels by rebinning the higher 32 channels into 16. At the same time, another 1 bit information to discriminate the event between lower and middle discriminator level (called PCL data) and between middle and upper (PCH) are sent to DP.

DP counts the number of events in each pulse-height channel using on-board memory in a fixed time interval and compile the resultant spectrum into telemetry format. Depending on the requirement of spectra or timing, data from each layers and detectors can be combined on board, providing four modes a for the LAC data:

MPC-1 Events are accumulated separately for the TOP and the MID layers of the 8 detectors, thus producing 16 separate spectra simultaneously. The energy corresponding to the lowest two channels are below the lower discriminator. This mode is mainly used for spectral study of faint sources.

MPC-2 Events from 4 counters and 2 layers are combined, thus 2 spectra are accumulated. In compensation for it, the temporal resolution becomes 8 times finer than MPC-1 mode.

MPC-3 Events from all counters and layers are combined into one. In addition, the pulse heights are rebinned into 12 channels: each energy channel corresponds to 4 consecutive channels in the MPC-1 and -2 modes. The temporal resolution becomes 64 times finer than MPC-1 mode. This mode is used mainly for fast timing studies with intermediate energy resolution.

PC In this mode, the ADC data is not used but discriminator data does. Events from all counters and layers are combined into one, then the temporal resolution of PCL and PCH data becomes 4096 or 2048 times finer than MPC-1 mode, respectively. This mode is used only for fast timing observation of the bright galactic objects.

Table 5.1 gives the number of energy channels and the maximum temporal resolution of these four modes for three recording bit rates.

5.2 ASCA

ASCA is the 4th Japanese X-ray observation satellite launched on 20 February 1993, by the M-3SII-7 rocket from KSC, the same rocket series and launching site as those of Ginga.

The satellite orbit is semi-circular with the perigee of 520 km, the apogee of 620 km. It weights 417 kg and is 4.7 m long along the telescope axis and 3.5 m wide across the solar paddles. Figure 5.8 shows the schematic view of ASCA in orbit.

Table 5.1: Temporal resolutions of the LAC data.

Mode	number of PH Channel	Bit rate		
		High	Medium	Low
MPC-1	48	500 ms	4 s	16 s
MPC-2	48	62.5 ms	500 ms	2 s
MPC-3	12	7.8 ms	62.5 ms	250 ms
PC	2	0.98/1.9 ms [†]	7.8/15.6 ms [†]	31.3/62.5 ms [†]

[†]: For PCL/PCH data.

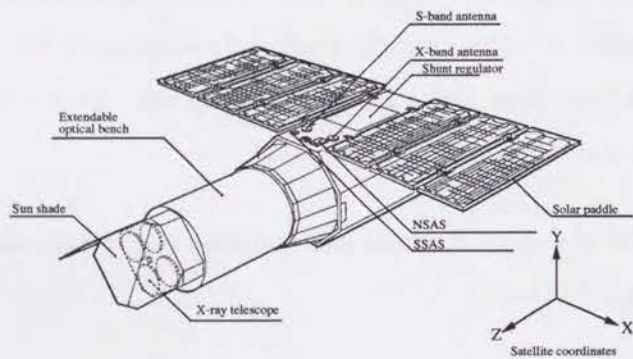


Figure 5.8: The schematic view of the ASCA satellite.

Since the orbit is similar to *Ginga*, up- and down-link operations are also the same, except that *ASCA* can do down-link, or receive the stored data to NASA DSN stations of Madrid, Canberra, Goldstone, Wallapase and San Diego. These reproduction is previously programmed in the KSC contact pass.

ASCA has four observation instruments; two Gas Imaging Spectrometers (GIS; Ohashi et al. 1996) and two Solid state Imaging Spectrometers (SIS). As these instruments have imaging capabilities, each has X-ray telescope of a 3.5 m focal length. Since M-3SII type rocket has no space to include the optical bench with the long focal length, the telescopes are mounted on the top plate of an extendable optical bench.

The satellite attitude control system is essentially same as *Ginga*, but has much improved capability with three-axis stabilization and the pointing accuracy of better than 10 arcsec and about $\simeq 30$ arcsec, respectively. To achieve them, *ASCA* is equipped with 4 plus one back-up gyros, four reaction wheels, two CCD stars cameras and 3 magnetic torques each with control electronics. The satellite attitude is limited to keep the direction of the solar paddle within 30° from the sun.

A biased and sun-direction angular momentum is always given in the 4 wheels, hence, in emergency, the satellite can automatically go into a safe-hold mode, which is a spinning mode around the sun vector. The maneuver is performed by changing the angular momentum balance among the reaction wheels. The slew rate is $\simeq 0.2^\circ\text{s}^{-1}$.

As the telemeter channel, *ASCA* uses X-band (down-link at KSC, 8.5 GHz) and S-band (up-link 2.1 GHz, down-link 2.3 GHz). Unlike *Ginga*, the stored data are reproduced in X-band with higher bit rate than the real-time data. The orbital elements are measured twice a day.

The data from the detectors and on-board instruments are processed by the data processor (DP), then stored in the bubble data recorder (BDR) of 134 Mbits capacity. DP has three bit rates, High of 32 Kbits s^{-1} , Med of 8 Kbits s^{-1} and Low of 1 Kbits s^{-1} ; thus the recording time is 68, 273 and 2185 minutes, respectively. Bit-High is mainly used in the contact orbits, and Bit-Med is in the remote orbits. Bit-Low is used to save the BDR capacity in case that the detectors cannot observe the target, i.e., the satellite is in the South Atlantic Anomaly (SAA) or the target is behind the earth.

5.2.1 XRT

ASCA has four identical conical foil X-ray mirrors which are weight saved versions of similar mirrors flown earlier on the Broad Band X-ray Telescope experiment (BBXRT) aboard NASA's Astro-1 space shuttle mission. Since the X-ray photon of a few keV is reflected only in a grazing incident

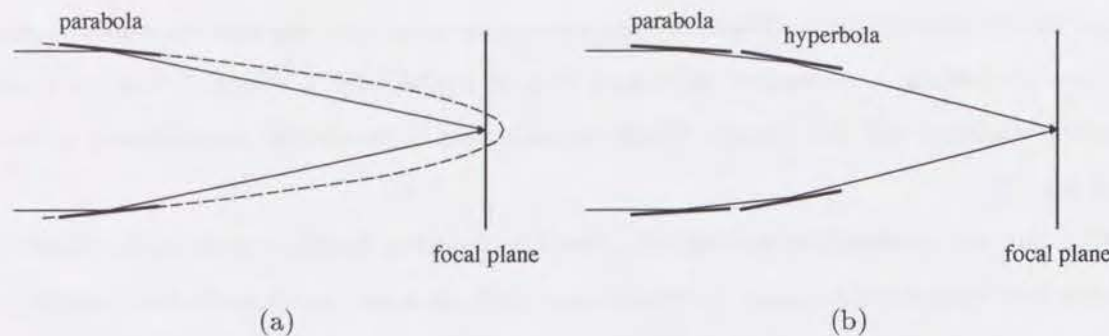


Figure 5.9: The schematic figure of the X-ray telescope. (a) The primitive model. (b) Wolter type I geometry, which is used in ASCA XRT.

angle, or the light pass is almost parallel to the mirror surface, effective area of the X-ray reflector is largely limited; see in the case of paraboloid (figure 5.9a), for example. To gain reflection area and to compensate aberrations, the X-ray mirror consists of multi-nesting tandem with aligned and co-focusing paraboloids and hyperboloids (Wolter type I geometry; figure 5.9b). *ASCA* XRT approximates this concept with a flat conical surfaces instead the parabolic and and hyperbolic surface. This simplification is crucially practical, allowing us to construct the multiple-nesting of 119 thin foils for one XRT. Nearly flat pieces of the aluminum foil of a $125\mu\text{m}$ thickness are first shaped into flexible conical segments having approximately the required curvature, then dipped in an acrylic bath to smooth the surface, deposited a $\sim 500\text{\AA}$ gold layer to increase X-ray reflectivity, then finally placed into a housing, constrained by supporting lags to fit the X-ray optics.

One XRT with 119 foils aligned by $\sim 1\text{ mm}$ pitch has a 558 cm^2 effective area, more than 50% of the geometric open area. A trade-off of this large effective area by the thin foil mirrors is found in less spatial resolution than the ideal Wolter type 1 optics. The half power diameter of XRT is about 3 arcmin. Table 5.2 gives the design parameters of XRT.

To maintain the best-performance of the mirror in orbit (i.e., to keep the reflecting surfaces free from contaminations and to minimize the mirror deformation by thermal stress), heaters and thin (0.22 and $0.54\mu\text{m}$ for the SIS and GIS, respectively) aluminized mylar covers were placed near and on the entire mirror aperture.

Since X-ray reflectivity depends on the grazing angle and photon energy, the efficiency and point spread function (PSF) of XRT also depend on the source position and energy. The efficiency and PSF are calibrated on ground in several points (in energy, mirror position, and incident angle), but overall features are simulated with the ray-tracing with appropriate optical constant (complex refractive index) of the mirror foils, including the real XRT structures.

The final response is supplied by the *ASCA* team with fine tunings to fit the standard sources: Crab for spectrum and Cyg X-1 for imaging.

Table 5.2: XRT design and performance parameters.

Design Parameters	
Mirror Substrate	0.125 mm aluminum foil
Surface	$10\mu\text{m}$ Acrylic Lacquer + $500\text{ \AA}$ Au
Number of Nested Cones	120 (back-to-back layers)
Outer/Inner Diameter	345/120 mm
Focal Length	3500 mm
Grazing Angle Range	0.24–0.70 deg.
Geometric Area	558 cm^2 (each)
Field of View	24/16 arcmin (@1/7 keV)
Number of Telescopes	4
Mirror Weight	10 kg (each)
Performance Parameters	
Effective Area	$\simeq 300/\simeq 150\text{ cm}^2$ @1.5/7 keV (each)
Size of Blur (Encircled Energy)	$\simeq 3$ arcmin Half Power Diameter (no energy dependence)
Reflector Surface Roughness	$\simeq 3\text{ \AA}$

Figure 5.10 shows the energy dependence of the XRT effective area. The values used to plot the graph is an integrated flux within the 6 arcmin circular area from the image center.

The effective area decrease rapidly as the off-axis angle increases. At higher incident energy, since the grazing angle should be smaller, only inner foils remain effective. Accordingly, effective area decreases much as energy increases. Figure 5.11 shows the off-axis angle dependence of the effective area.

Possible residual deformation of the foils worsens the angular resolution. While the half power

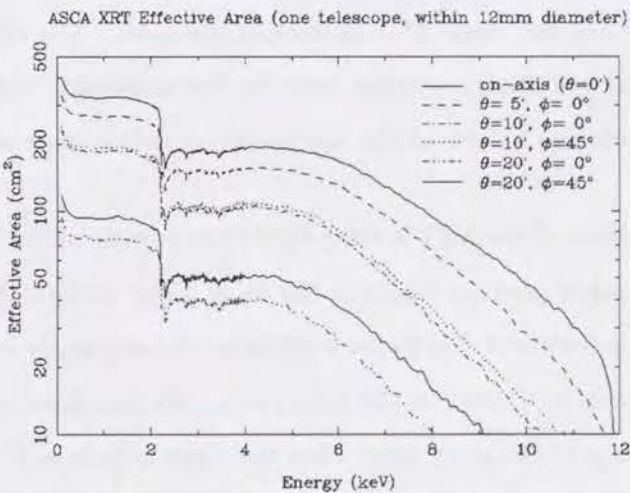


Figure 5.10: The energy dependence of the XRT effective area on-board *ASCA*.

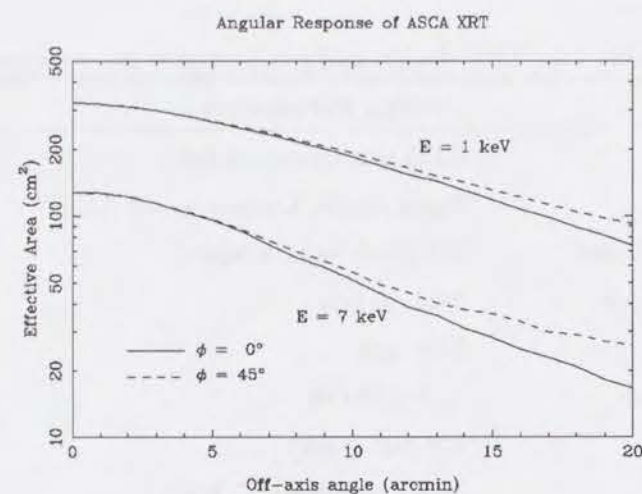


Figure 5.11: The off-axis angle dependence of the XRT effective area on-board ASCA.

diameter (HPD) of XRT is expected to be about 0.3 arcmin in the ideal case, the real value is about 3 arcmin.

Figure 5.12 shows the radial profile of the PSF. It can be approximated as a Gaussian in the central core of ($r < 1'$), followed by an exponential function outside. The quadrant mirror structure make the PSF to be Maltese cross shape (figure 5.13). As the off-axis angle increases, the PSF is largely distorted.

For the evaluation of the contamination of a bright source to the other regions, the encircled energy function (EEF) which is defined as the ratio of photons flux in a circle with given radius from a point source is useful. Figure 5.14 shows the EEF for different energies. It shows that the 80% of the flux drops within the circle of a 12 arcmin diameter. The difference of the encircled fraction between high and low energy become large as the increasing angular radius. Therefore, the apparent spectrum becomes harder as the accumulation radius increases.

Another practical problem of the XRT is stray light from outside of the field of view (FOV). The XRT geometry does not allow photons reaching the focal plane without being intercepted by the foils; however, the photons scattered due to the surface roughness, single or more than 3 reflection, or back-side reflected photon may come in the focal plane. We call these photon as the stray light. Figure 5.15 shows the image of the stray light when the Crab nebula is 1° offset from the detector center. The stray light, if strong source is nearby, is crucial for a weak source or extended emission, like the cosmic X-ray background (CXB).

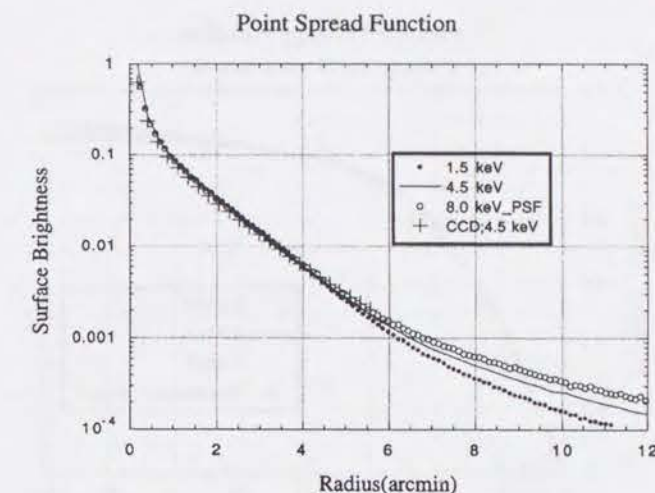


Figure 5.12: The point spread function of the ASCA XRT (Serlemitsos et al. 1995).

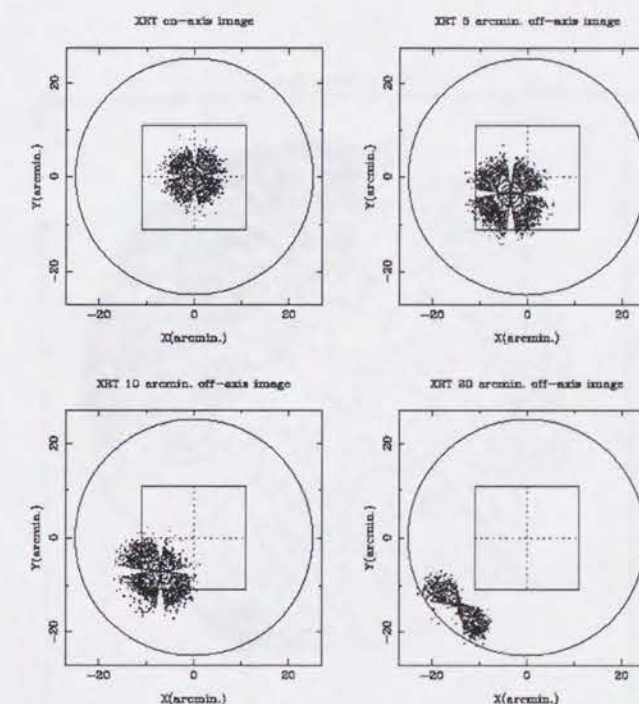


Figure 5.13: Point spread function of the ASCA XRT for four different off-axis angles. Approximate field of view is shown for GIS (circle) and SIS (square).

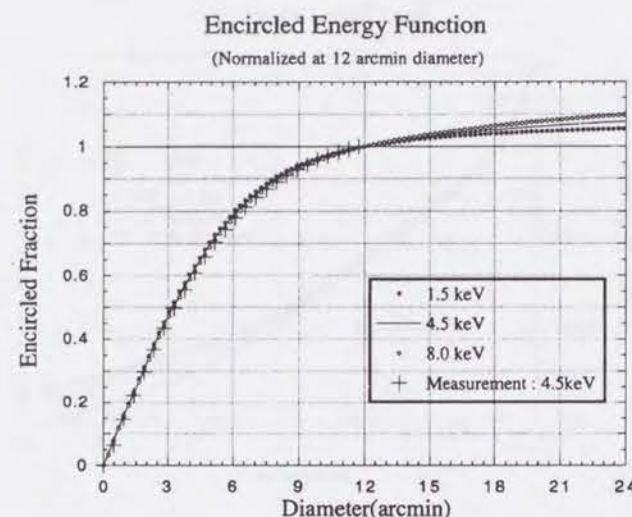
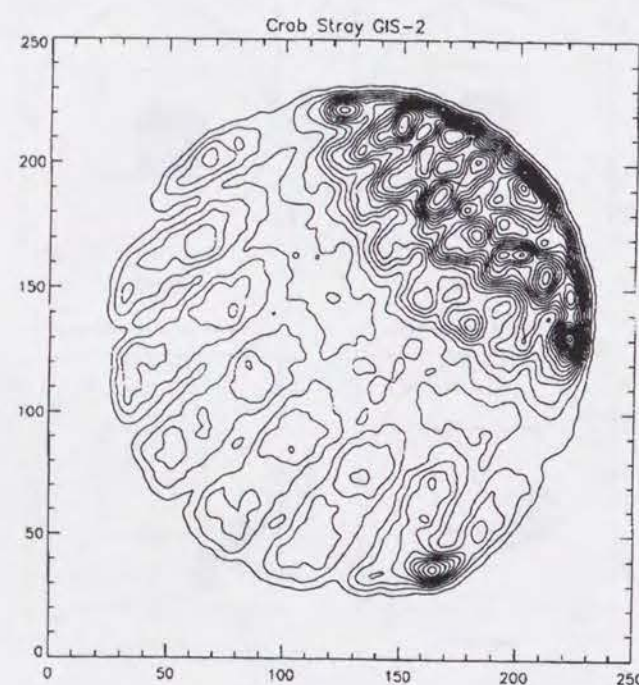


Figure 5.14: The encircled energy function of the XRT.

Figure 5.15: The stray light image of the Crab nebula at 1° offset from the detector center.

5.2.2 GIS

The GIS (Gas Imaging Spectrometer), which has been developed mainly by University of Tokyo, ISAS and Meisei Electric Co., Ltd., consists of two imaging scintillation proportional counters (GIS-S2 and -S3) and a signal processing part (GIS-E). Also the radiation belt monitor (RBM) is equipped.

Compared with the SIS (see next subsection), the GIS has larger efficiency (by a factor of 2 at 7 keV) at high energy, higher temporal resolution, higher signal saturation flux and a four-times wider FOV; however, it has a lower soft X-ray efficiency, a somewhat worse position resolution and a factor 2–4 poor energy resolution.

Each GIS-S consists of a gas cell, a position-sensitive phototube and high-voltage suppliers. Figure 5.16 shows the cross section of the GIS-S. The X-rays from the XRT are detected by the 25 mm-depth gas cell, which is filled with 96% of Xe and 4% of He to 1.20 atm pressure (at 0°C). The gas is sealed by a beryllium foil of a $10\mu\text{m}$ thickness and a 52 mm diameter supported by a stainless grid and fine mesh. The gas cell is divided into two, the drift region just inside the Be window and the following scintillation region. Each region is biased by 1 kV cm^{-1} and 4 kV cm^{-1} electric fields. To intercept the non-X-ray backgrounds, the GIS has the hood coated by a 0.2–0.5 mm thickness tin foil and partially by a 0.1 mm thickness molybdenum foil.

The X-ray photon is photo-absorbed in the drift region and creates free electrons. The electrons drift into the scintillation region guided by the bias field, then accelerated by the stronger field. The electrons are decelerated by the collision with the Xe atoms with exciting them. The excited Xe atoms return to the ground states by emitting UV photons of wavelength of $\simeq 170\text{ nm}$. This excitation and relaxation processes occur as the electrons pass the scintillation region in $2\text{--}3\mu\text{s}$; thus, there stands a scintillating column through the drift region. The number of UV photons becomes $\simeq 1.5 \times 10^5$ for a 6 keV X-ray photon. Since these process is not accompanied by secondary-electron multiplication, the energy resolution is kept 2–3 times better than the proportional counter. The scintillation UV photons are detected by a position-sensitive phototube set below the gas cell. Figure 5.17 shows the effective area of the combination of XRT and GIS.

The signals from the phototube are processed by GIS-E. The energy information is obtained from the final dinode signal. The energy resolution is about 8.0% (FWHM) at 5.9 keV, which scales as inverse square root of the energy. X and Y positions of a detected photon are calculated using outputs from 32 (16 for X and 16 for Y) multi-wire anodes. The position resolution is about 0.5 mm (FWHM), which corresponds to about 30 arcsec, at 5.9 keV, and scales as inverse square root of the energy.

To eliminate non-X-ray backgrounds, only the event of which rise time is within the window

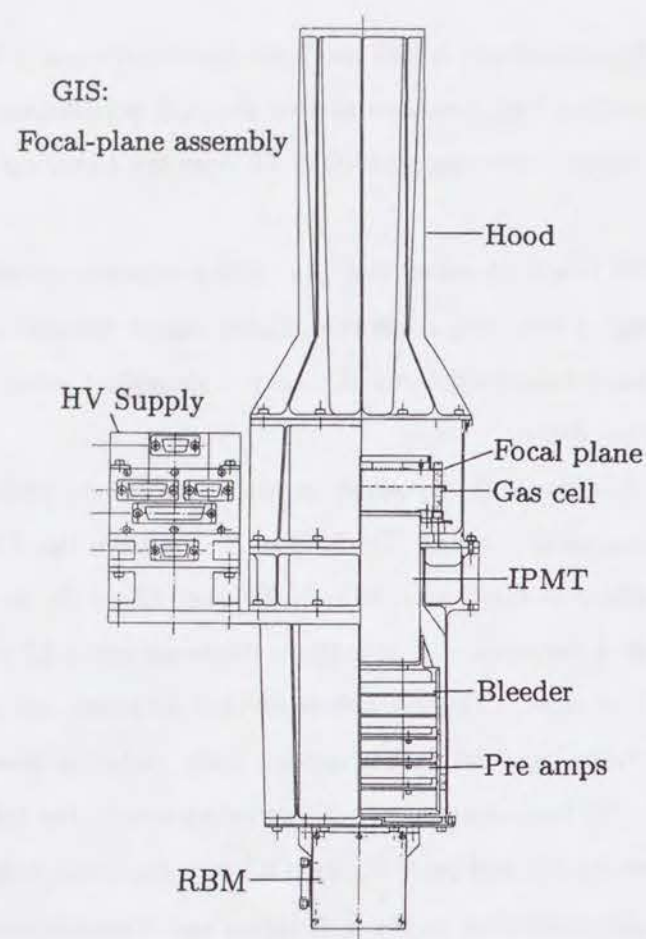


Figure 5.16: The cross section of the GIS-S.

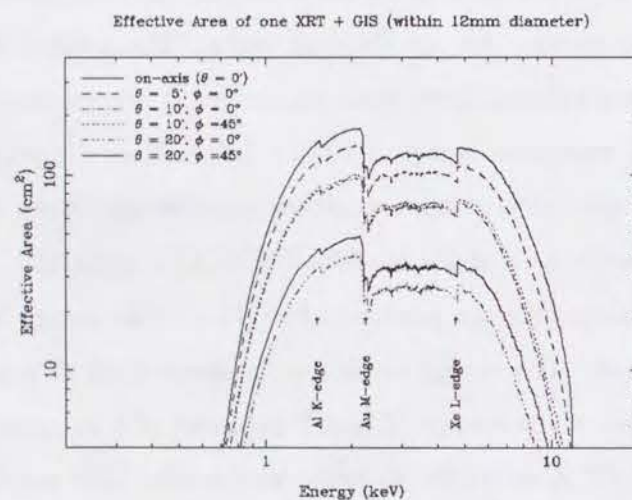


Figure 5.17: The effective area of the combination of XRT and GIS.

set by the command is passed to the on-board CPU. With this process, about 90% of backgrounds within 2–10 keV signal range are eliminated. In addition, on-board CPU eliminates the event of which position is outer than the certain radius or the spatial distribution of multi-anode output is larger than the certain length. This discrimination method is called SPRD. Without SPRD, it is known that the strong source near the edge of the GIS, such as the calibration source, makes a ghost image at the inner area if the event position is determined with the Fast Lorentzian Fitting, used for the usual data processing. With these discriminations, 99% of non-X-ray background is eliminated and the remained non-X-ray background in the 17 arcmin radius is 5×10^{-4} counts s^{-1} cm^{-2} keV^{-1} in 2–10 keV.

Since the telemetry capacity is limited, the GIS has four different telemetry modes:

PH (Pulse Height) For nominal observations, this mode is usually used. One event consists of the pulse-height, position, rise-time, event-spread and timing informations packed to 32 bits. The commandable bit-share are 10, 8, 5, 8 and 10 bits in normal operation. In this mode, all the data are processed by on-board CPU.

PH PCAL (Position Calibration) This mode is prepared for the calibration of the position calculation done by on-board CPU. All information including 32 anode signals are transmitted. Thus the maximum source intensity and the temporal resolution are reduced much from the PH mode. PCAL data, however, can be processed on ground in failure mode of on-board CPU.

MPC (Multi-channel Pulse Count) This mode transmits only the pulse-height and timing information. The pulse-height converted data are accumulated in on-board memory in DP. The maximum number of spectral bin is 256, which can be reduced to increase time resolution. This mode can be used for an extremely strong source or in the case that on-board CPU failure.

memory check This mode dumps the RAM image (32 KB $\times$ 2) of on-board CPU as it is. Usually, this mode is carried out once a day during the KSC contact to check whether on-board memory is lost or not.

Table 5.3 gives the temporal resolution and maximum source intensity of the GIS in each telemetry mode.

The gain of the GIS differs from position to position, hence the gain calibration by pointing Cas A in various positions has been performed. In addition, the gain changes with the pressure and the impurity of the counter gas and the phototube temperature. To correct these effects, the

Table 5.3: The temporal resolutions and the maximum source intensities of the GIS.

mode	Bit rate	Temporal resolution		Maximum Source Intensity [count s ⁻¹]
		0 bit	10 bits	
PH	H	62.5 ms	61μs	256
	M	500 ms	488μs	32
	L	2 s	1.95 ms	8
PCAL	H	31.25 ms		32
	M	250 ms		4
	L	1 s		1
MPC	H	0.5 s	1.95 ms	128 Crab [†]
	M	4 s	15.6 ms	16 Crab
	L	16 s	62.5 ms	4 Crab

†: 1 mCrab ~ 1 event s⁻¹

gain of the GIS is monitored by ⁵⁵Fe isotopes at the edges of the entrance windows of the each gas cell. These calibration data are accumulated by the ASCA team and distributed to the end users.

5.2.3 SIS

The SIS (Solid state Imaging Spectrometer) consists of three components — two cameras (SIS-S0 and SIS-S1), each with four CCD chips, the analog electronics (SIS-AE) and the digital electronics (SIS-DE). SIS-DE is equipped in the DP body The DP also has responsibility of a part of the SIS data processing. Figure 5.18 shows the signal block diagram of the SIS subsystem.

The CCD detector can be regarded as a cluster of solid state detectors (SSD) with a large number of square-aligned microscopic (27 × 27μm² in case of SIS) electrodes called ‘pixels’. The electron cloud induced by the X-ray photon are absorbed by the nearest pixels, then are carried by the driving external clock from pixel to pixel to the readout gate.

Since the charge is thus transferred from pixel to pixel, which have very small electric capacitance, the floating electric capacitance at the readout gate also very small. This extremely small capacitance makes a higher readout voltage than normal SSD, hence the readout noise can be very small. On the other hand, the temporal resolution is much lower than the normal single detector such as GIS, because the charges are read sequentially. In the case of SIS, the readout cycle of one chip is 4, 8 or 16 sec in 1-, 2- or 4-CCD mode, respectively.

Figure 5.19 shows the cross section of the SIS camera, and figure 5.20 shows the chip configuration of the SIS. In the normal operation, the CCD chip is cooled down to about -60°C by a

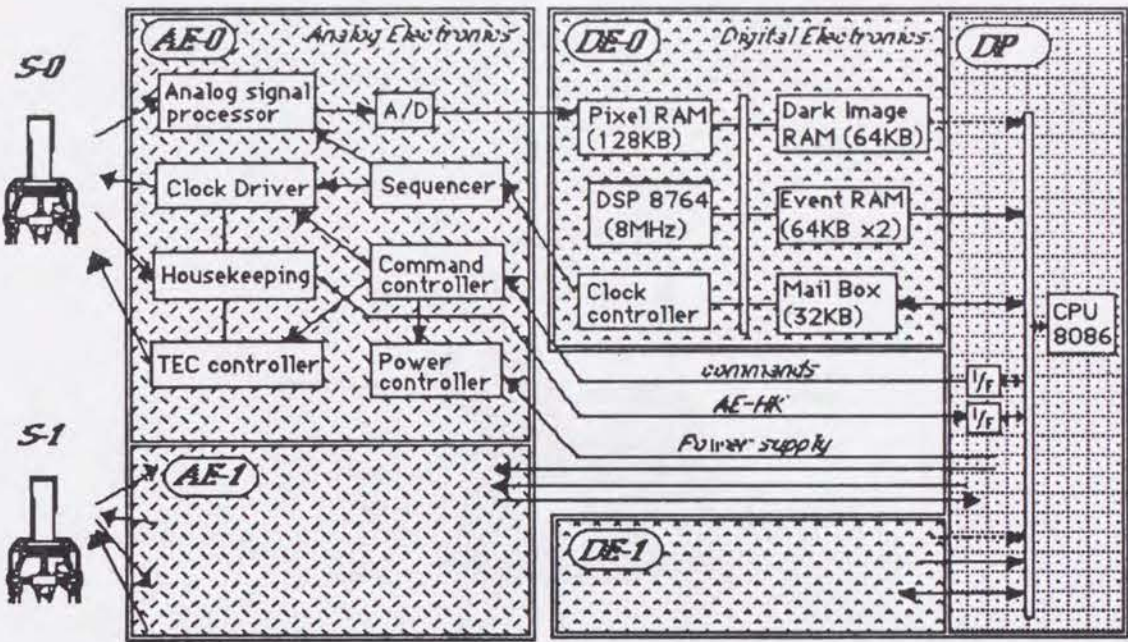


Figure 5.18: The signal block diagram of SIS.

Peltier device (TEC, thermal electric cooler) to reduce the dark current. The TEC dissipates the heat into the housing, which is cooled to -30-40°C with the radiator coupled to the heat pipe. The chip in the housing is covered by a multi-layer insulator and supported by Lexan columns in order to reduce the heat inflow. In front of the chip, a Lexan film of a 1000Å thickness coated with aluminum of a 400Å thickness at each side is placed to cut off the optical light.

The SIS-AE generates the chip driving clock, controls the TEC and converts the video signal from the SIS-S to the digital data (PH data). In contrast to GIS, SIS has no hardwired logic.

The SIS-DE receives the PH data from the SIS-AE and extracts the X-ray events. The X-ray photon of a 10 keV energy induces a primary electron cloud of a 1μm size by the photo-absorption process, with the size scaling as $E^{1.75}$ (Janesick et al. 1985). After drifting to the electrode of each pixel, the size is grown to be ~ 5μm. Since this size still smaller than the that of pixel, the electron cloud does not separate into larger than four pixels (figure 5.21). On the other hand, charged particle events leave long tracks (long cloud). Using this difference of the cloud size, SIS-DE can eliminate the non-X-ray backgrounds. The energy of the X-ray event is calculated from 3 × 3 pixels around the local maximum pulse height pixel.

The dark current level consists of ‘Dark level’ and ‘Bias level’. To save the on-board memory, the Dark level is taken from the average of the pixel group, which is typically in a $\frac{1}{16} \times \frac{1}{16}$ (default value) frame. This dark level is further time averaged and is updated using the event-free pixel

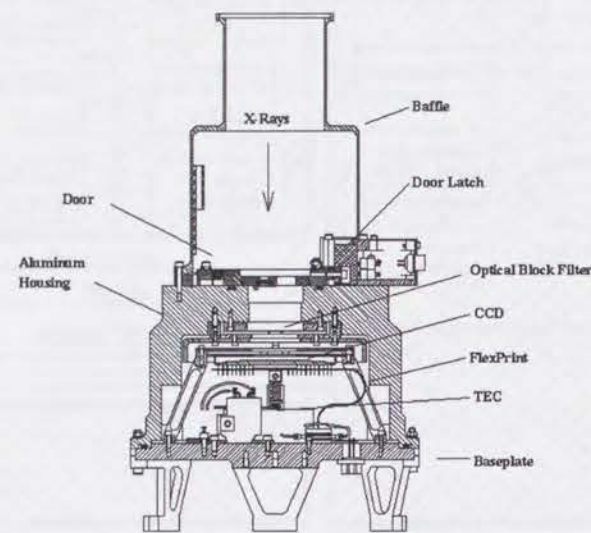


Figure 5.19: The cross section of the SIS camera.

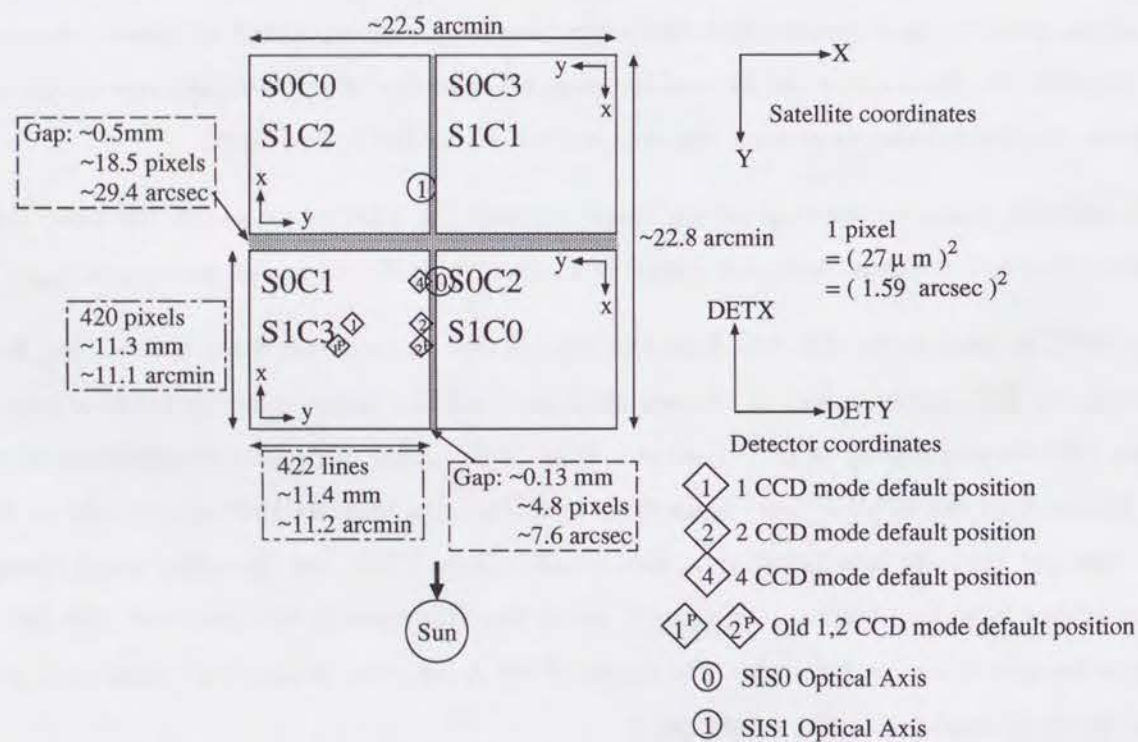


Figure 5.20: The chip configuration of the SIS.

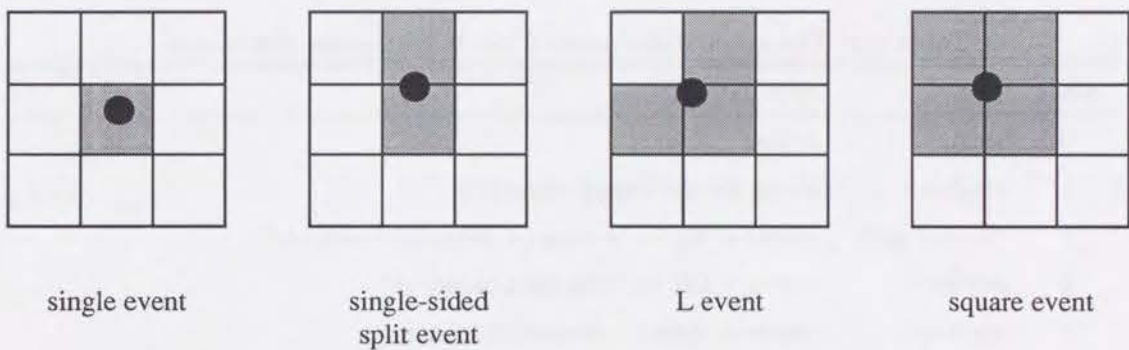


Figure 5.21: The X-ray event pattern of the CCD detector.

levels as:

$$\text{NewDarkLevel} = \text{OldDarkLevel} + \frac{\text{MeanPixelLevel}}{n} + 1, \quad (5.1)$$

where $n + 1$ is the history parameter and set as 1, 4, 8 or 16 on command. The set of Dark level is called the dark frame. The Bias level is the DC offset of the dark current level. This is obtained from the PH data of the overclock region, where there is no real electrode but only the driving clock is operated to these virtual pixels. Since the Dark level and the Bias level are the mean value in the grouped pixels, their possible variation within the group degrade the energy resolution essentially taken from multiple pixels. To take account or compensate this degradation, two approaches are currently used: (i) make the up-to-date response matrix including the long-term change of the resolution. This method can be applied for all the data, but needs the long term trend for pixel by pixel, which require a lot of work, hence has only been at a limited region. (ii) Since the dark level of each pixel is found to be rather constant in a short time scale (a few days), we can obtain the pixel-by-pixel dark template for the short time scale, by observing the night earth with frame mode or accumulating the event-free corner pixels of the faint mode data (see below). With this template, we can adjust the pulse height on the ground. This method can be applied for the faint mode data and the grade-0 bright mode data.

The SIS has three observation modes (faint, bright and fast) and four diagnostic modes (frame, dark frame, histogram and integration):

Faint The event information consists of the CCD ID, the addresses and 12 bit pulse heights of nine pixels. The size of each event is 16 bytes including the CCD ID. This mode can be used only for faint sources, but all the pulse heights relating with the event is obtained.

Bright The pulse heights of 9 pixels are summed, and the summed PH data and the Grade information are transmitted. Table 5.4 gives the definition of the Grades. The event data has 4 bytes and consists of the Grade, addresses and the summed pulse height binned up to

Table 5.4: The grade definitions of the Bright-mode SIS events.

grade	name	split pattern
0	single	center
1	single+	center (+ detouched corner(s))
2	vertical split	center + top or bottom (+ detouched corner(s))
3	left split	center + left (+ detouched corner(s))
4	right split	center + right (+ detouched corner(s))
5	single-sided+	single-sided split + touched corner pixel(s) (+ detouched corner(s))
6	L or square	L or square split (+ detouched corner(s))
7	Others	all others

11 bit scale; the original 1024–2047 channels are binned by a factor of two and 2048–4095 by a factor of four.

Fast In this mode, the chip is driven to project all the charge onto one dimension, so the spatial information is reduced: instead, the scan period of a frame becomes faster than other modes. The event data has 2 bytes and consists of the Grade, the reduced addresses and the pulse height binned as the bright mode. This mode is used for extremely strong point source for which each chip may be hit by X-rays more than the saturation level within accumulation time if we use the other modes.

Frame This mode sends the pulse heights of all pixels with 12 bit resolution.

Dark frame This mode sends a map of dark frame to ground with 8 bit resolution.

Histogram This mode makes the histogram of pulse heights of 4096 bins for all pixels and send to ground.

Integration This mode integrates the events in the chip for 160 s, read the resultant pulse heights and send them to ground with 12 bit resolution.

The SIS has three clocking mode for observation and frame modes — 1, 2 and 4 CCD modes. The exposure time for each clocking mode is 4, 8 and 16 s, respectively. Table 5.5 gives the summary of three observation modes.

As the SIS has no radio isotope, the relative gain between each chip was determined with the strong Fe-K emission line of supernova remnant W49B. It was pointed by all chips and the gains were determined within 0.5% errors. The absolute energy scale was determined with the strongest internal background emission line, Ni, which originate in the Kovar (an Fe-Ni alloy) frame-store shield.

Table 5.5: Observation modes of the SIS.

	Faint	Bright	Fast
Temporal resolution [†]	4/8/16 s	4/8/16 s	16 ms
Maximum event rate [‡]	128/16/4	512/64/16	1024/128/32
PHA bits	12	11	11
Spatial bits	9 × 9	9 × 9	1 (and 3 timing bits)
Number of grade	—	8	2

[†]: In 1/2/4 CCD mode for Faint and Bright.

[‡]: In bit High/Med/Low. The unit is [events/s/2sensors].

In the transfer of the charge, there exists the charge loss which is called charge transfer inefficiency (CTI). The CTI is periodically calibrated pointing Cas-A at the each corner of chips. The calibration data is accumulated by the ASCA team and released to the end user.

Chapter 6

SN1006 Study With Ginga

6.1 Observations and Data reduction

To study the spectral feature of SN 1006 up to 20 keV, we analyzed pointing data as well as those of two background pointing near the Lupus Region. As described in the section 3.2, SN 1006 data with large field of view (FOV) are the subject of significant contamination due to the emission originating from the Lupus Loop. Therefore, we further analyzed two scan data of Lupus Loop, in order to examine a large scale structure of the Lupus Loop. Figure 6.1 shows the observation points and scan paths, and table 6.1 gives the observation date and coordinates. All data were obtained with MPC-1 mode. Hereafter, we call two backgrounds and two scans BG 1, BG 2, scan 1 and scan 2, as designated in table 6.1.

The data selections were usually made with the following parameters. COR is the minimum momentum per unit charge, cosmic rays below which can not be arrive at the satellite orbit. Along the inclined and non-circular Ginga orbit in the bipolar magnetic field of the earth, COR is variable with the orbital phases. EELV is the elevation angle of the FOV from the horizon of the earth. SUD

Table 6.1: Field centers of pointing and scan paths.

Point/Scan	Coordinates (α , δ) in 1950			Observation date
	pointing center	scan from	scan to	
SN 1006	(224.7, -41.7)	—	—	30 July 1988
BG 1	(223.4, -38.6)	—	—	30–31 July 1988
BG 2	(226.4, -39.4)	—	—	7–8 March 1991
scan 1	—	(227.2, -31.8)	(225.4, -51.7)	30–31 July 1991
scan 2	—	(223.2, -33.0)	(214.3, -51.9)	4 August 1990

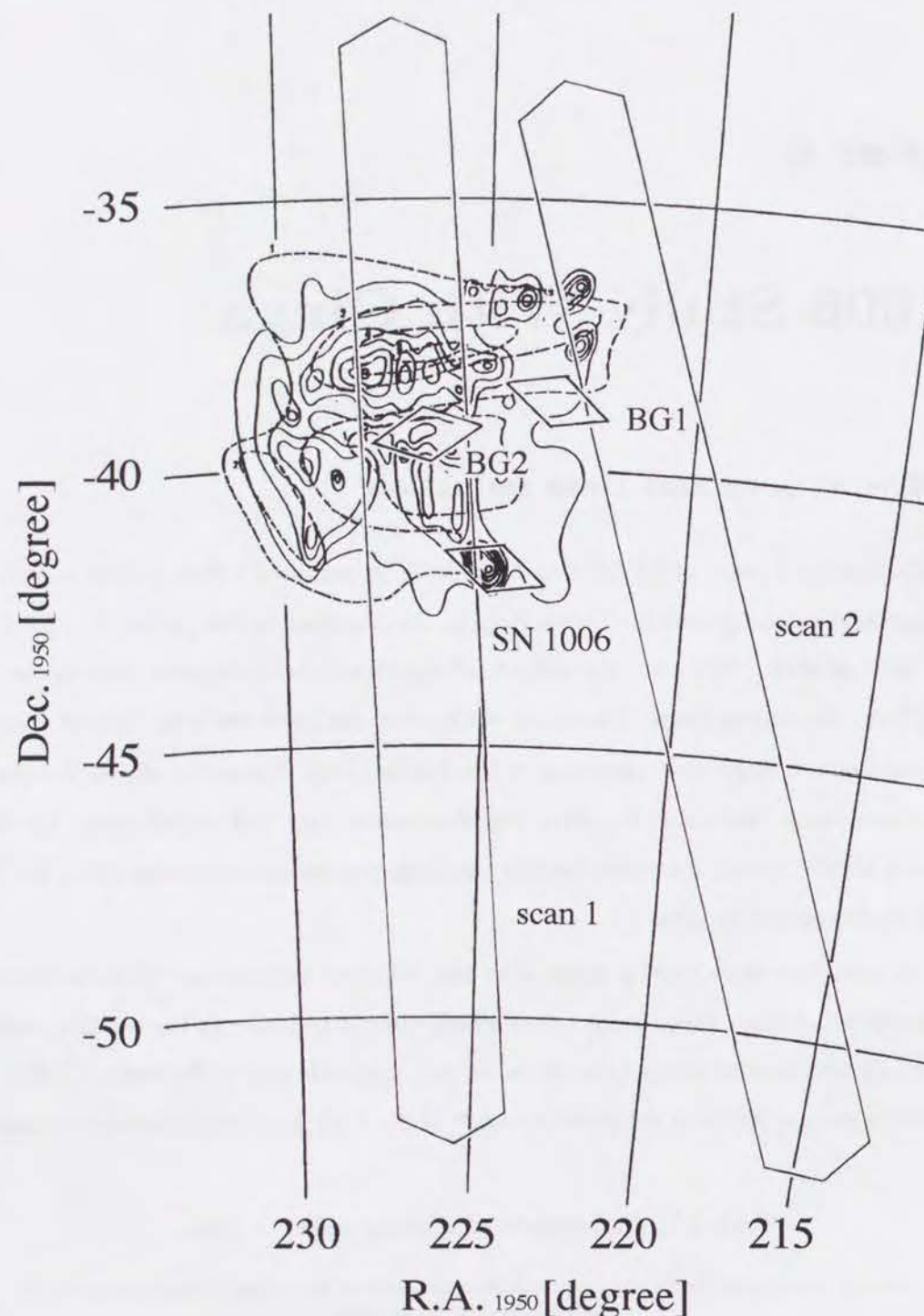


Figure 6.1: Pointing centers and scan paths with Milne's (1971) 1410 MHz surface brightness contour (solid line) and Toor's (1980) 0.2–1.0 keV feature (dashed line). Diamonds show the LAC fields of view and the long hexagonal boxes show FOVs of the scan paths.

and SSUD is the count rate above 24 keV and 37 keV, respectively. Since both the photon fluxes from the astronomical objects and the quantum efficiency of LAC decrease with increasing energy, while those for non-X-ray events are rather constant, SUD and SSUD can be good indices of the internal background. In the present case, we have screened with the criteria of $COR > 9 \text{ GeV c}^{-1} \text{Z}^{-1}$, $EELV > 10^\circ$, $SUD < 8000 \text{ counts (128s)}^{-1}$ and $SSUD < 6000 \text{ counts (128s)}^{-1}$. The resultant exposure times are 12.3, 12.8 and 12.0 ksec for SN 1006, BG 1 and BG 2, respectively. For the spectral analysis, we used only the Top-layer data to obtain the best S/N ratio. The CXB and non-X-ray backgrounds were subtracted from the three pointing data with the method described in detail by Awaki et al. (1991). The spectral analysis was performed on the FACOM M340 computer of The High Energy Physics Laboratory of Kyoto University with the software package developed in Nagoya University.

Since the collimator response has a cone shape, we extract the whole flux from SN 1006 by assuming the surface brightness of a uniform-disk of a 30 arcmin diameter. For the local excess near the Lupus Loop, we assumed the constant surface brightness, because the scan profiles shows the excess flux extends larger than the LAC FOV. The resultant flux, however, depends little on the assumed spatial shape.

6.2 Results

6.2.1 Lupus Region

Spatial distribution

Figure 6.2 shows the background-subtracted scan profiles in the 2–10 keV band. The errors shown are purely statistical, which dominate over the systematic error due to subtracting the particle background. Since the mean CXB has already been subtracted, the count rate should be 0 count s^{-1} on average if there was no local excess emission; however, as can be seen from the scan profile, there is a clear excess. The peak centered in scan No.1 corresponds to the position of SN 1006, which is located on the southern shell of the Lupus Loop; the smaller northern peak corresponds to the northern part of the shell. The other peak to the south of the main peak is a new X-ray source. Even if we exclude these peaks, we can still see excess emission extending over the Lupus region. The scan profile over path 2 shows more extended emission, although the largest enhancement appears near to the region of the Lupus loop. The fluctuations on spatial scales of 1 degree or so are probably due to uncataloged point sources or, equivalently, to fluctuations in the CXB.

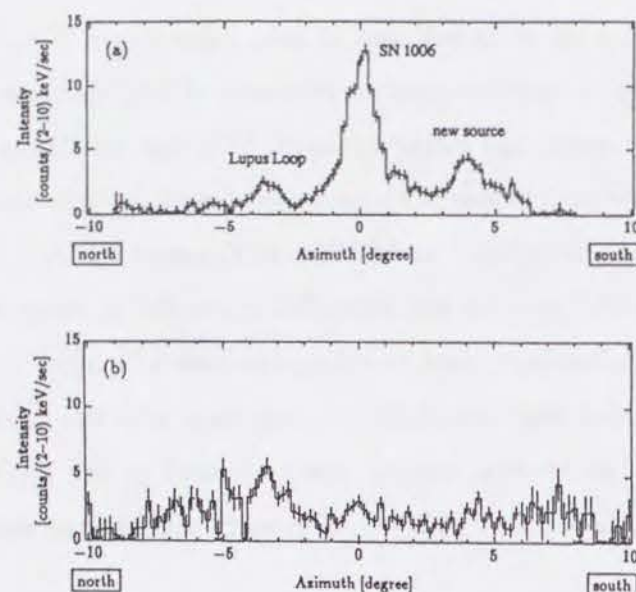


Figure 6.2: (a) Scan profile of path No.1. The horizontal axis shows the scan azimuth along the path. The zero level corresponds to the mean CXB level. Each error bar shows a $1\text{-}\sigma$ Poisson error. (b) The same as (a), but for path No.2.

Spectrum

Since the scan data are statistically poor, we performed the spectral analysis only for the BG1 and BG2 pointings. As the spectral model for them, we tried two: a thermal bremsstrahlung and a power-law for the continuum, both with Fe-K line and the interstellar absorption. With the first trial, the absorption column densities in each model became lower than that of the LAC window. Therefore, we tried the models again without the absorption.

Figure 6.3 shows the best-fit models with the spectra, and table 6.2 gives the best fit parameters. The parameters of the thermal model for BG 1 are consistent with the *Tenma* values, while the temperature for BG 2 is higher. The photon index of the power-law models are, on the other hand, smaller than the previous *Tenma* value, and their reduced- χ^2 values suggest that the model can be rejected. The new discovery with *Ginga* is the line emission near an energy of 6–7 keV. The best-fit energy and equivalent width of the emission lines are found to be 6.2–6.4 keV and 100–400 eV, respectively, depending on the positions and continuum models used. With rather large errors, the line energy is consistent with the K-shell transition from neutral to He-like iron (6.4–6.7 keV).

The background-subtracted count rates of BG 1 and BG 2 are 4.2 and 2.3 counts s^{-1} , respectively. These values are within reasonable range compared with the scan profiles. On the other hand, the background-subtracted count rate of SN 1006 is 23 count s^{-1} , which is much larger than BG 1 and BG 2; therefore, the possible ambiguity of the local background subtraction for the

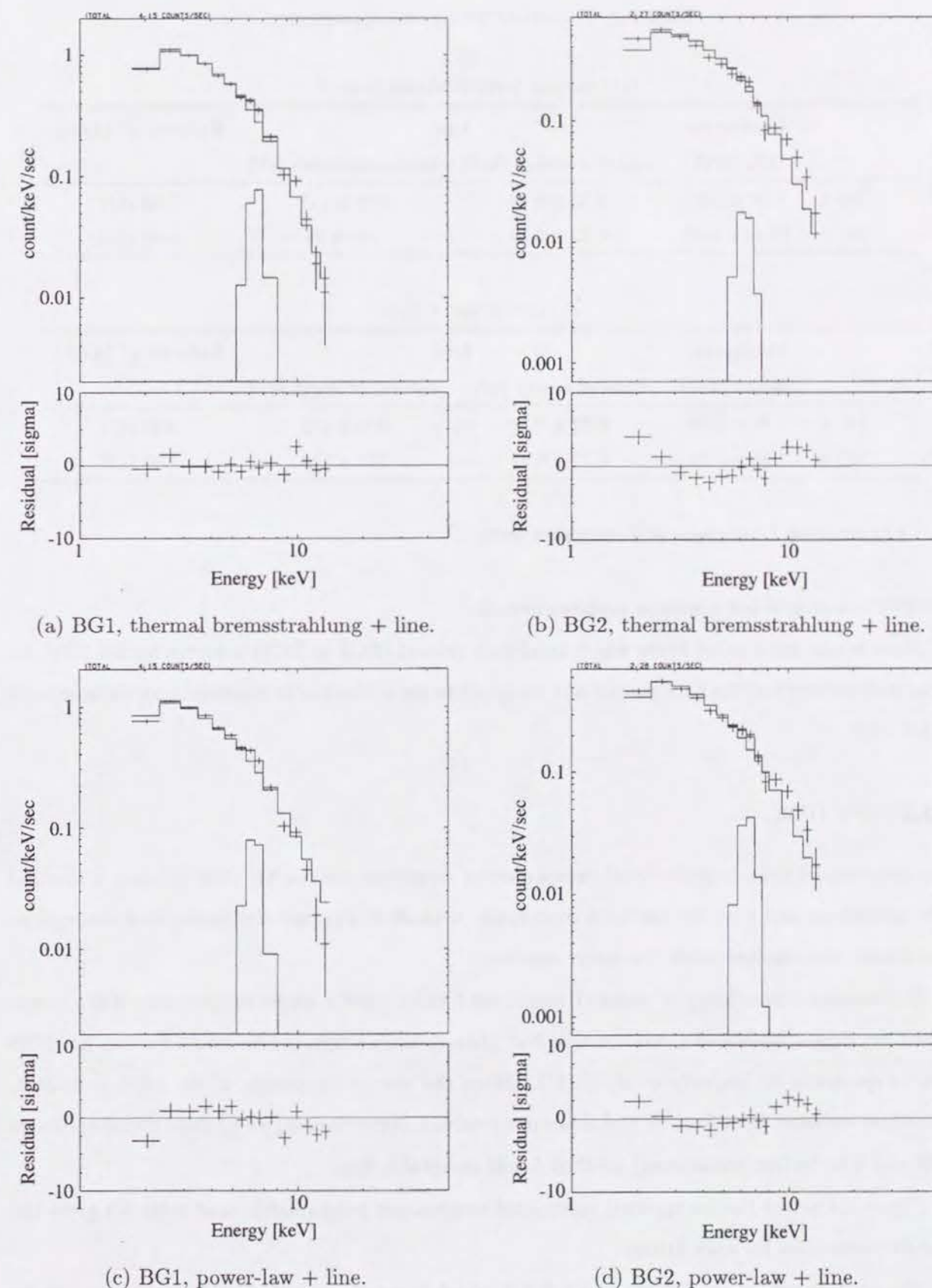


Figure 6.3: The Lupus Loop spectra with being subtracted the CXB and non-X-ray backgrounds and the best-fit models.

Table 6.2: Results of fitting of Lupus Region.

(a) (thermal bremsstrahlung + line)				
	Continuum	Line		Reduced χ^2 (d.o.f.)
	kT_e [keV]	center of energy [keV]	equivalent width [eV]	
BG 1	7.00 ± 0.61	6.33 ± 0.26	348 ± 147	1.23 (11)
BG 2	10.14 ± 0.59	6.22 ± 0.49	138 ± 95	4.46 (12)

(b) (power-law + line)				
	Continuum	Line		Reduced χ^2 (d.o.f.)
	photon index	center of energy [keV]	equivalent width [eV]	
BG 1	1.96 ± 0.05	6.22 ± 0.24	350 ± 133	3.25 (11)
BG 2	1.85 ± 0.09	6.37 ± 0.49	277 ± 223	2.00 (12)

* Errors show 1 parameter 90% confidence level.

SN 1006 pointing is not a serious problem overall.

Since we do not a priori know which local back ground (BG1 or BG2) is better for SN 1006, we separately subtracted the background and analyzed to set a reasonable constraint on the spectrum of SN 1006.

6.2.2 SN 1006

The same model fittings as the local excess spectra were done for the SN 1006 spectra: a thermal bremsstrahlung and a power-law for a continuum, with Fe-K line and the interstellar absorption. The former was rejected while the latter was not.

To examine a possibility of thermal origin, we further tried a single-temperature NEI plasma model developed by Masai (1984), which had already been suggested to be fit for the SN 1006 *Tenma* spectrum by Koyama et al. (1987). Since the energy resolution of the LAC is limited, individual emission lines from Si and S are not resolved. Nevertheless, we allowed the abundances of Si and S to be free parameters; we then found acceptable fits.

Figure 6.4 shows the background subtracted spectra and tried models, and table 6.3 gives the best-fit parameters for each fitting.

The photon indices are found to be 3.2–3.3, which is consistent with the *Tenma* value. While the energy range observed with *Tenma* is up to 12 keV, we confirmed that the continuum extends up to 20 keV with the present observation. The upper limit for the equivalent width of Fe-K line

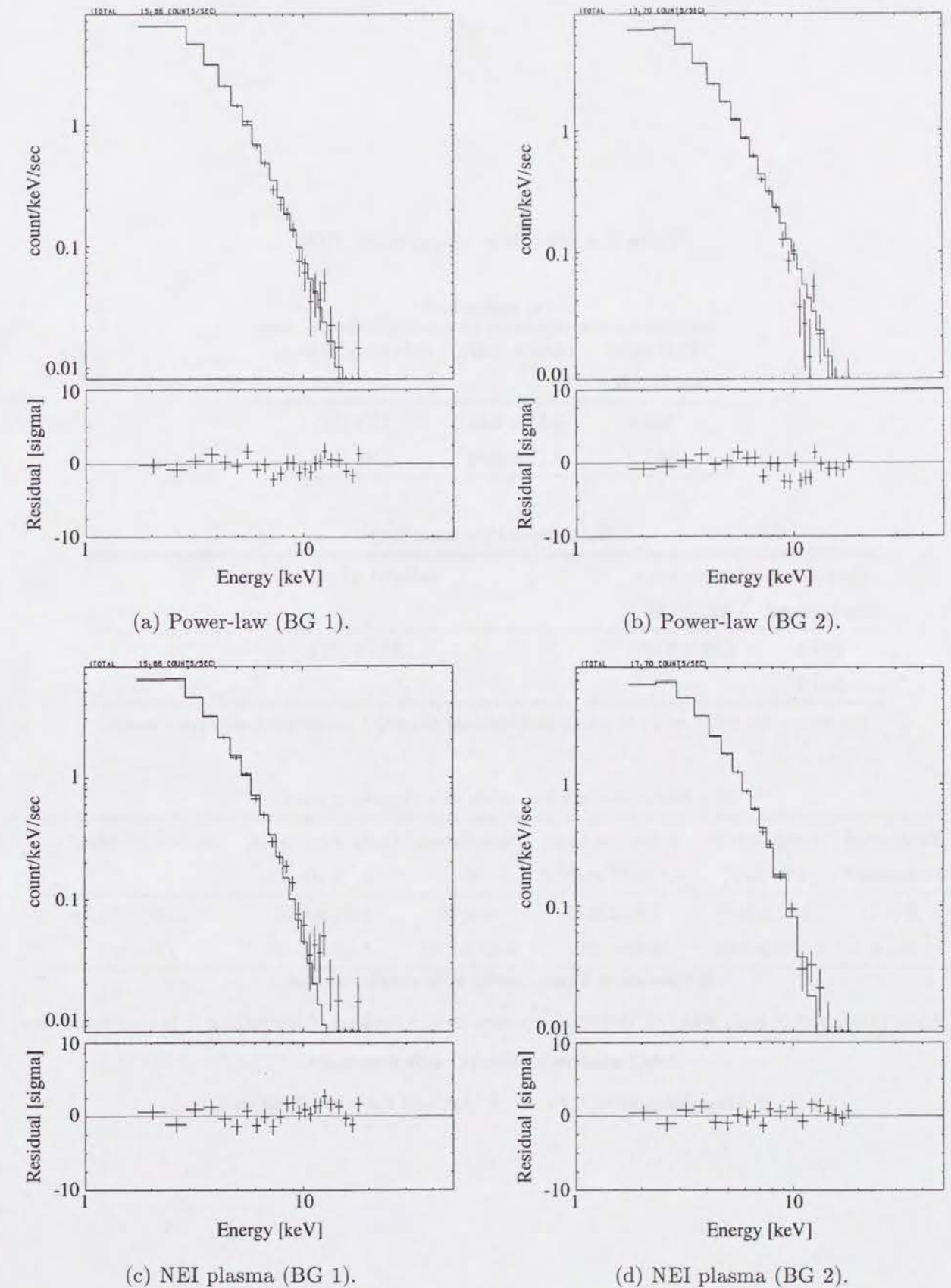


Figure 6.4: The SN 1006 spectra with being subtracted the backgrounds and the best-fit models.

Table 6.3: Results of fitting of SN 1006.

(a) power-law [†]		
Subtracted Background	photon index	reduced χ^2 (d.o.f.)
BG 1	3.31 ± 0.03	1.10 (22)
BG 2	3.17 ± 0.03	1.75 (22)

(b) thermal bremsstrahlung [†]		
Subtracted Background	temperature kT_e [keV]	reduced χ^2 (d.o.f.)
BG 1	1.78 ± 0.00	16.03 (21)
BG 2	—	—

The fitting for BG 2 was not performed because the BG 1 result gave very poor result.

(c) nonequilibrium ionization thin thermal plasma [†]					
Subtracted background	temperature kT_e [keV]	ionization time $n_e t$ [$10^{10} \text{ cm}^{-3} \text{ s}$]	abundances [‡] [solar abundance]		reduced χ^2 (d.o.f.)
			Fe	Si, S, Ar, Ca	
BG 1	2.91 ± 0.02	4.68 ± 0.57	< 0.10	0.61 ± 0.01	1.01 (15)
BG 2	2.60 ± 0.00	3.70 ± 0.07	0.07 ± 0.03	0.60 ± 0.00	1.98 (19)

Errors show 1 parameter 90% confidence level.

[†] Absorption component was not included because from previous observations it is suggested that

LAC window's absorption is dominant.

[‡] Abundances except Fe, Si, S, Ar, and Ca were fixed to 1.

is reduced to 120 eV.

The single-temperature NEI model survived the fitting. The most difference of the NEI model from the rejected thermal bremsstrahlung model is the existence of strong Si and S K-line around 2 keV. Becker et al. (1980), however, could fix only the upper-limit of Si-K line with SSS, which has sufficient energy resolution to recognize the line from the continuum. The LAC, by contrast, has no sufficient energy resolution to do so, therefore it is possible that the difference between the power-law continuum and the bremsstrahlung model is in appearance recovered by the lines.

Chapter 7

SN1006 Study with ASCA

7.1 Observations

We observed SN 1006 with ASCA on 19 August 1993 and 13 September 1993 during the PV (performance verification) phase, pointing at the center and the north-east rim of the remnant, respectively. Table 7.1 gives the coordinates and the attitude parameters. Table 7.2 gives the telemetry modes used in the observations. In these observations, no additional lower discriminator for SIS was set because the number of hot pixels due to the radiation damage was smaller than that of the telemetry saturation level. The Bright mode for Bit_Med was used to avoid the possible telemetry saturation. The Bit_Low mode was used only for the time that the target was occulted by the Earth; therefore, there is no Bit_Low X-ray data set in practice.

7.2 Data Reduction

The data were selected using the following indicators, cut off rigidity (COR), the earth elevation (ELV_MIN) and the radiation belt monitor count rate (RBM_CONT). In addition, the elevation angle from the bright earth (BR_EARTH), the time after day-to-night/night-to-day transition (T_DY_NT) and the time after the South Atlantic Anomaly (usually called SAA) (T_SAA) were

Table 7.1: The coordinates of SN 1006 ASCA observations.

ID	Pointing Center	Mean Euler Angle	Observation date
Center	(225.700, -41.930)	(-133.9237, 131.8816, 162.1723)	19-20 August 1993
NE	(225.880, -41.773)	(-133.7396, 131.7557, 155.9022)	13-15 September 1993

The coordinates and the Euler angles are in J2000.0 system.

Table 7.2: The telemetry modes of SN 1006 ASCA observations.[†]

Bit Rate	GIS mode	SIS mode
High	PH nominal (10-8-8-5-0-1) [‡]	4CCD Faint
Med	PH nominal (10-8-8-5-0-1) [‡]	4CCD Bright
Low	PH nominal (10-8-8-5-0-1) [‡]	4CCD Bright

[†]: Both observations used the same arrangement.

[‡]: Telemetry bits for pulse height, X position, Y position, rise time, light spread and timing informations.

Table 7.3: The event selection criteria for SN 1006 ASCA observation.

	SIS0	SIS1	GIS2/3
COR	> 6	> 6	> 7.5
RBM_CONT	< 275	< 275	< 275
ELV_MIN	> 10	> 10	> 6
BR_EARTH	> 30	> 20	—
T_DY_NT	> 4, < 0	> 4, < 0	—
T_SAA	> 4, < 0	> 4, < 0	—

used for the SIS data selection criteria, because the earth light leakage through the optical blocking filter, the rapid change of the dark level due to the light leakage and the non-X-ray event from the short-lifetime radio isotopes activated in the SAA, respectively, change the ratio of the event grade. Table 7.3 gives the criteria used in the selections, and table 7.4 gives the resultant exposure time for each observation and data mode. The exposure time for SIS is shorter than GIS mainly due to the more severe BR_EARTH selection. The event selection and the analysis below were performed on Unix workstations with the FTOOLS and XANADU packages released from the NASA Goddard Space Flight Center.

To make the statistics better, we converted the SIS Faint mode data to the Bright mode data format and treated the both mode data as one data set.

Table 7.4: The exposure times of SN 1006 ASCA observations after the event selection.

	SIS0/1 (Faint)	SIS0/1 (Bright)	GIS2/3
Center	17 ksec	7.5 ksec	35 ksec
NE	13/14 ksec	8.7/6.0 ksec	33 ksec

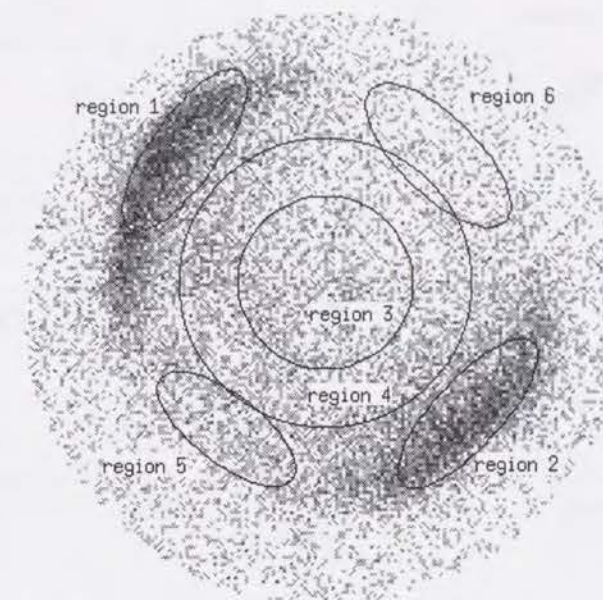


Figure 7.1: GIS2 image of SN 1006.

7.3 Analysis and Results

7.3.1 General property

GIS

Since the GIS FOV covered the whole remnant while the SIS covered only a limited region, we first made the GIS image and extracted the GIS spectra from region to region. Figure 7.1 shows the GIS image and the regions where we extracted the spectra, and figure 7.2 shows the corresponding spectra. The spectra can be divided into two groups; X-ray faint regions of SN 1006 including NW and SE edges, which are the regions where strong lines of Mg, Si and S were found, and X-ray bright NE and SW rims with no significant lines. The former provides the first detection of the emission lines from SN 1006, hence gives clear evidence that the emission from the whole remnant is of thermal origin. On the other hand, the latter (NE and SW rims) shows no strong line, and their continuums extend to higher energy than the former regions.

SIS

Referring the results of GIS, we have made two separate spectra: those from the two bright regions and interior region. Figure 7.3. shows the mosaic of the two pointing SIS images and the two regions where we extracted the spectra.

For nominal analysis, we usually use a response function with the relevant detector position, whatever the source is extended or point-like. For the presently combined spectra from a fixed sky

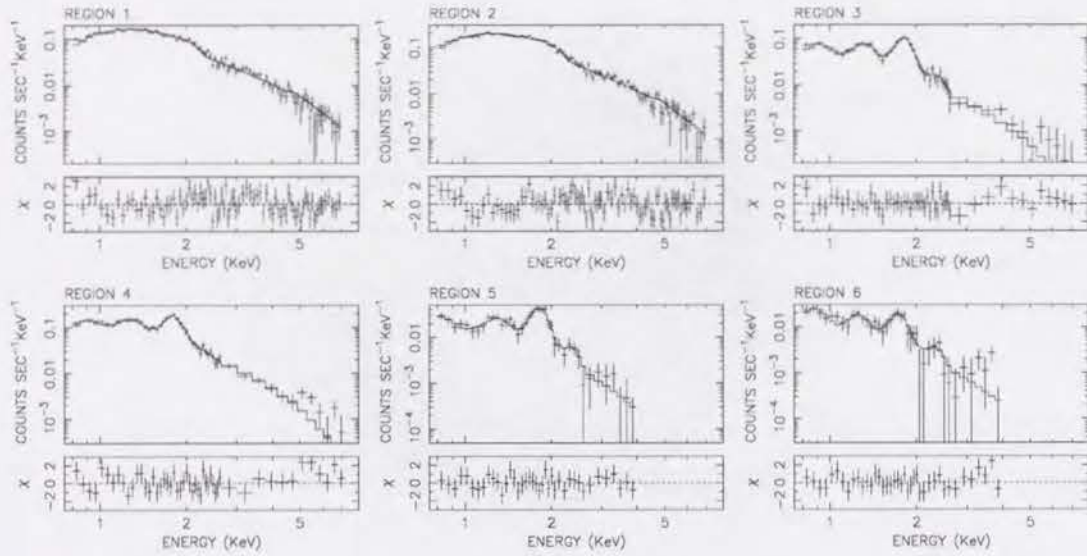


Figure 7.2: Spatially resolved GIS2 spectra of SN 1006 together with the model curves. Each panel corresponds to the region shown in Fig.7.2. Regions 1 and 2 are fitted by a power-law, and the others are by a thermal Bremsstrahlung with 4 Gaussian lines.

position, however, we have separately accumulated the data at different detector positions. Since the response function differs with different detector position, we need to reconstruct the effective response function. To make two response functions for the two-rims and interior spectra separately, we assume that the surface brightness S_j (here suffix j represents the energy bin) is uniform within the two separate regions (the bright rim and interior), as is roughly true for the present data, then we can get following equations:

$$C_{ij} = S_j t_i \Omega_i A_{ij}, \quad (7.1)$$

where C_{ij} , t_i , Ω_i and A_{ij} , respectively represent the counts of X-ray event, the exposure time, the detector area (or solid angle) and the detector efficiency, indicating pointing number by the suffix i .¹

Since the combined spectra consist of the two independent pointings with two SIS cameras (SIS 0 and 1), the number of the data set is 4: $i = 1$ to 4. Thus the total counts number of the X-ray event C_j is given as

$$C_j = \sum_{i=1}^{i=4} C_{ij} = S_j \sum_{i=1}^{i=4} t_i \Omega_i A_{ij}. \quad (7.2)$$

In other words, we can make the combined response and data as follows:

¹In practice, the detector efficiency for each pointing data is given as a matrix because the detector has finite energy resolution; however, we simplified the response as given in the text because the difference does not affect the essence of the discussion.

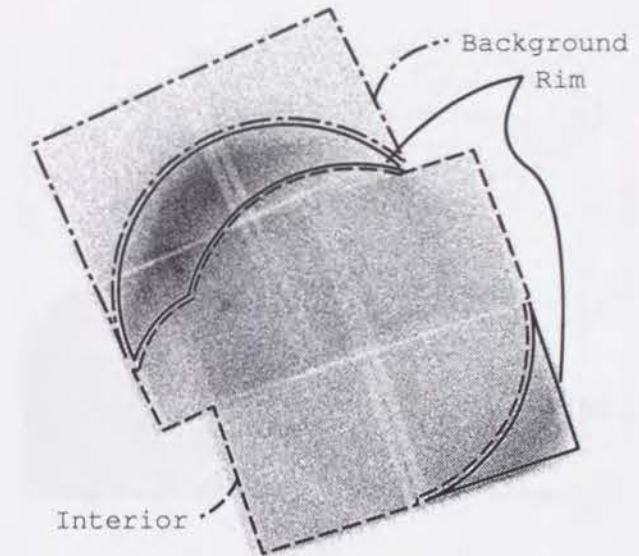


Figure 7.3: The whole SIS image and the regions where the spectra were extracted. As the background, we extracted events from the off-source region.

1. Summed all the data within the same spectral group.
2. Added the matrix element of the mirror and the detector responses for the relevant spectral data with weights of exposure times and the solid angles, then constructed new responses

This rather complicated procedure is essential for a precise subtraction of the nearby background, because the surface brightness of the interior region is as faint as the back ground region.

For the local background, we employed the off-source region of the NE pointing. Figure 7.4 shows the background-subtracted spectra of the Rim and Interior regions. We confirm the similar characteristics of the spectra difference found in the GIS spectra: strong line emission in the interior and almost featureless continuum in the two bright rims.

At first, we fitted the spectra from each region with a single-component NEI plasma model developed by Hughes and Helfand (1985). Figure 7.5 shows the observed spectra and the best-fit models for each region, and Table 7.5 gives the best-fit parameters. The fitting of the Interior is poor; the difference between the model and the data is mainly found in the line width; the data exhibit broader lines than the model. As the origin of the broadening, either a Doppler shift or a multi-ionization state can be possible. The former, however, requires the velocity of about 10000 km s^{-1} to explain the data, which is unreasonably large comparing to the any estimated shock velocities. Therefore, we interpret that the line broadening is attributable to the multi-ionization state. Investigations with this model will be given in section 7.3.3.

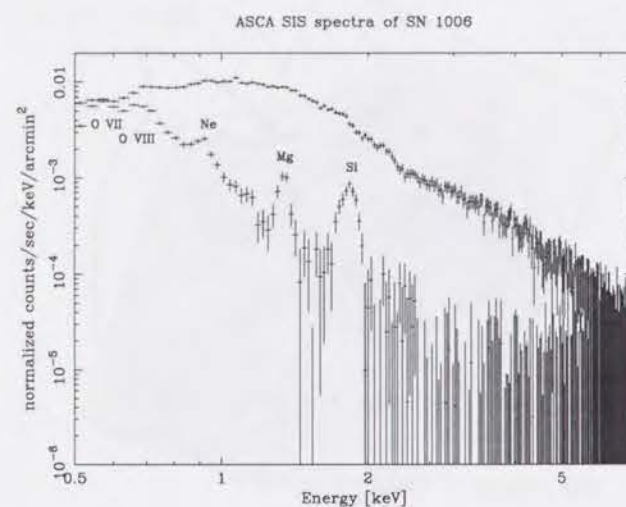


Figure 7.4: The rim and the Interior spectra. While the Rim is much brighter than the Interior, the lines are hardly seen except for oxygen lines around 0.6 keV.

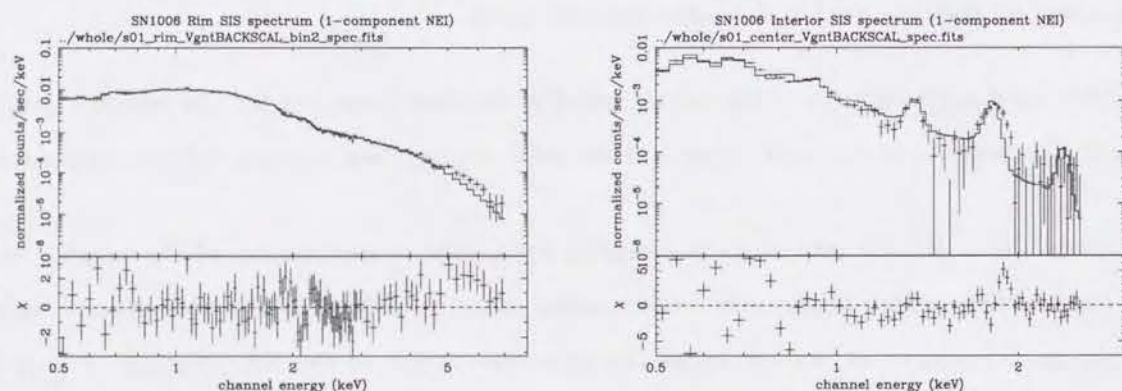


Figure 7.5: The spectrum and the best-fit single-component NEI model of each region. The model can represent neither the higher energy region of the Rim, nor the lines of the Interior.

Table 7.5: The best-fit parameters of the single-component NEI plasma fits for the SN 1006 SIS data.

Region	N_H [10^{21} cm^{-2}]	kT [keV]	$n_e t$ [$\text{cm}^{-3} \text{ s}$]	O	Ne	Mg	Si	S	Fe	reduced- χ^2 (d.o.f.)
				[relative to the solar value]						
Rim	0.13	1.67	9.46	7.59×10^{-3}	3.48×10^{-3}	3.87×10^{-2}	0.227	0.00	0.00	1.586 (97)
Interior	0.00	0.40	10.27	9.65×10^{-2}	7.14×10^{-2}	0.378	1.15	0.795	3.61×10^{-2}	7.288 (59)

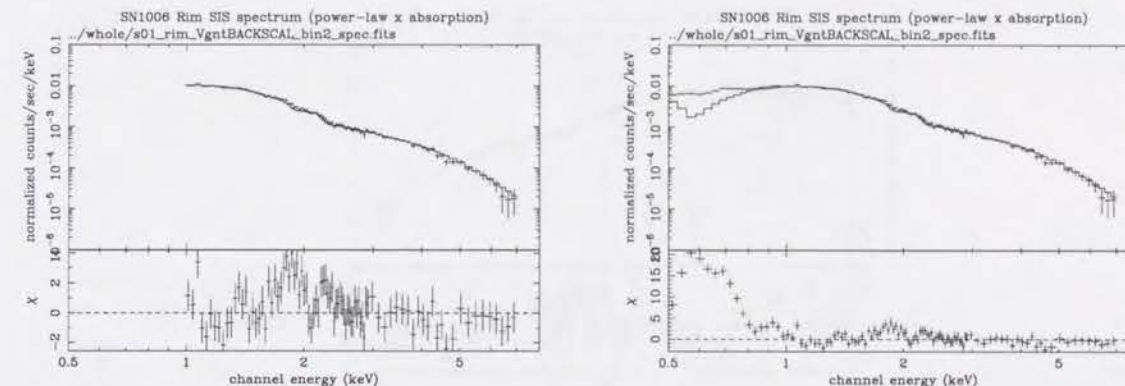


Figure 7.6: The Rim data and the power-law model which is the best-fit for the > 1 keV data. There remains structures below 1 keV and around 2 keV.

The fitting of the Rim is better than the Interior; however, the abundances are unnaturally smaller than those implied by the Interior fit or those of solar. Also the model above 5 keV is systematically comes below the data.

7.3.2 Rim emission

Spectrum

If the whole emission of SN 1006 is due to an NEI plasma, the Rim region should show stronger equivalent widths of lines than elsewhere, because the stronger continuum of the NE and SW rims than the NW and SE edges but similar geometry means that higher density plasma than elsewhere is prevailing in the bright Rims. Consequently, the ionization of heavy elements goes faster, hence gives stronger equivalent widths of emission lines than elsewhere. This prediction is, however, completely opposite to the observations. Thus, we suggest that the Rim emission is essentially of a non-thermal. Since non-thermal emission generally exhibit power-law spectra, we tried to fit the Rim spectra with a power-law and interstellar absorption. Figure 7.6 shows the best-fit model with the observed data. The model can represent the > 1 keV continuum well except for a weak line profile around 2 keV. The model however cannot represent the data at the lower band than 1 keV; there remains the line-like structure. The residual structure is similar to that of the Interior spectrum. To examine the origin of the line-like structure, we fit the data by the power-law and emission lines with the center energies, widths and flux as additional free parameters. The best-fit model is shown in figure 7.7.

Sine we found no systematic residuals by adding the lines which can be also found in the Interior spectrum, we infer that the Rim spectrum includes a part of the Interior spectrum. To examine this

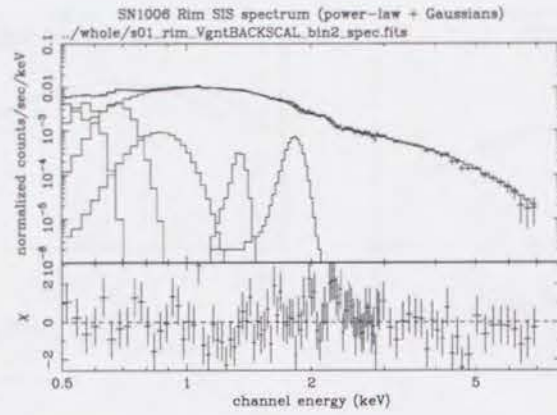


Figure 7.7: The Rim data with the power-law and emission-lines model. The structures in Fig.7.6 reduce or disappear.

Table 7.6: The center energy, width (σ) and the surface brightness of each Gaussian in the Interior and the Rim regions.

Number	Energy [keV]	σ [eV]	Interior count rate [10^{-7} count $s^{-1} cm^{-2} arcmin^{-2}$]	Rim count rate	Rim/Interior ratio
1	0.564	18.8	471^{+23}_{-19}	412^{+36}_{-37}	$0.87^{+0.08}_{-0.09}$
2	0.665	43.7	243 ± 9	221 ± 19	0.91 ± 0.08
3	0.839	96.7	$58.1^{+8.1}_{-4.3}$	$35.5^{+16.0}_{-14.6}$	$0.61^{+0.28}_{-0.27}$
4	1.342	0.00	$5.54^{+1.03}_{-0.82}$	$2.12^{+1.60}_{-2.12}$	$0.38^{+0.29}_{-0.39}$
5	1.835	54.7	$12.1^{+1.1}_{-1.0}$	10.4 ± 2.2	$0.86^{+0.19}_{-0.20}$

possibility in more quantitatively, we compared the count rate of each line between both regions as follows:

1. We extracted the line structure from the Interior, fitting an *ad hoc* model of a thermal bremsstrahlung continuum plus Gaussians.
2. We then fitted the Rim by a model of a low-energy absorbed power-law plus the Gaussians with the center energies and σ s were fixed to the Interior values.

Table 7.6 shows the center energy, width (σ) and the count rate of each Gaussian in each region, and figure 7.8 shows the best-fit surface brightness of the Gaussians and their ratios between both regions; each ratio is roughly constant from line to line with the mean value of 0.86. This fact gives a confirmation on the assumption that the line-structure found in the Rim is attributable to the Interior plasma.

Then, we subtracted the 86% of the Interior spectrum from the Rim and fitted the resultant

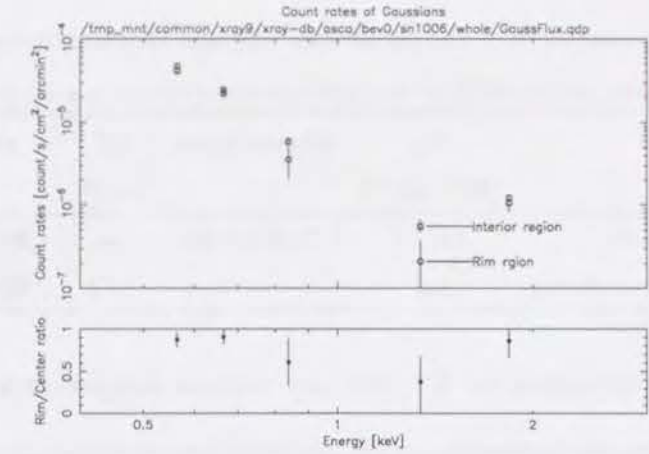


Figure 7.8: The surface brightness of the Gaussians of the Rim and Interior regions. At all energies, the Gaussians of both regions have almost equal surface brightness.

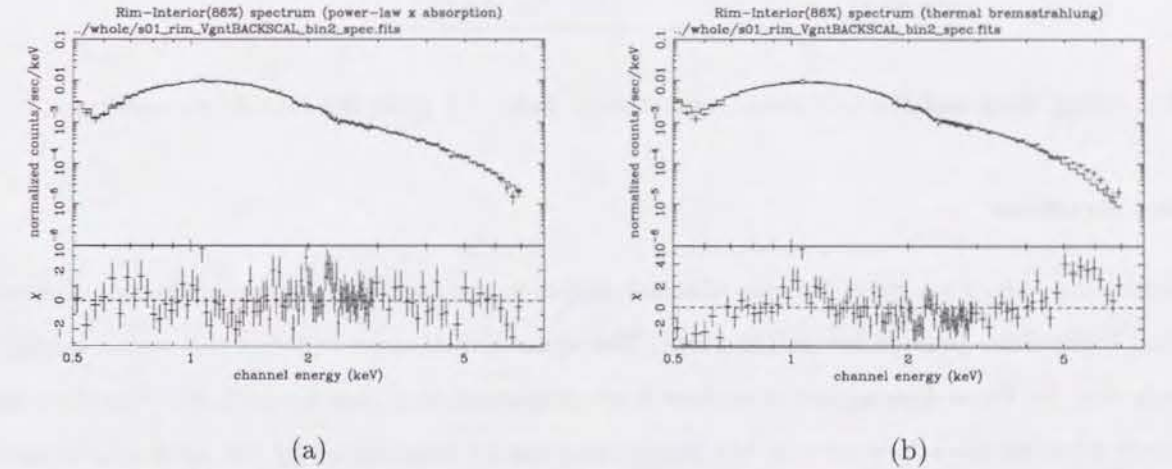


Figure 7.9: (a) The Rim spectrum after the subtraction of 86% of the Interior spectrum, and the best-fit power-law model. (b) The same spectrum and the best-fit thermal Bremsstrahlung model.

spectrum by two models: a power-law and a thermal Bremsstrahlung both with an interstellar absorption. Figure 7.9 shows the resultant spectra and best-fit models, and table 7.7 gives the best-fit parameters for both models. As we can see from the figure, the power-law model represents the data well, while the thermal continuum leaves a wavy residual over the whole energy band.

At the same time, we estimated the Fe K emission equivalent width in the Rim region, and obtained the 90% upper limit of 45 eV at 6.7 keV.

We estimated the flux of the non-thermal emission using the Center pointing GIS data and the Interior-free SIS spectrum. For the GIS data, we used only the > 3 keV band where the non-thermal emission dominates the spectrum; therefore, the photon index is decided by using both the SIS high energy and the GIS data, while the absorption and the normalization are decided by the

Table 7.7: The best-fit parameters of the power-law and the thermal Bremsstrahlung fits for the SN 1006 SIS Rim data from which 86% of the Interior component is subtracted.

model	N_H [10^{21} cm^{-2}]	Photon index	kT [keV]	reduced- χ^2
Power-law	$3.0^{+0.2}_{-0.1}$	2.96 ± 0.03	—	1.308 (105 d.o.f.)
Thermal bremsstrahlung	0.9	—	1.71	2.756 (105 d.o.f.)

Table 7.8: The best fit parameters for SN 1006 non-thermal component with both SIS and GIS data.

Photon index	2.97 ± 0.03
Absorption column density	$(3.1 \pm 0.1) \times 10^{21} \text{ cm}^{-2}$
Flux (2–10 keV)	$3.4 \times 10^{-11} \text{ ergs s}^{-1} \text{ cm}^{-2}$
(Flux density at 5 keV)	$3.6 \times 10^{-12} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ keV}^{-1}$
reduced- χ^2	1.072 (590 d.o.f.)

SIS low energy data and the GIS data, respectively. Table 7.8 gives the best-fit parameters.

Spatial structure

To discuss the energy source of the non-thermal emission, the spatial structure of the non-thermal emitting region may provide key information. The symmetrical appearance of the region strongly suggests that its three-dimensional structure is of axial-symmetry (see figure 7.10). We therefore examined whether the appearance of the bright rims can be reproduced by the axial-symmetrical structure.

For simplicity, we studied two extreme cases; a barrel structure and a pair of polar-cap structure, both have 0 thickness skin with symmetrical axis perpendicular to the line of sight. We made the surface brightness profiles along three strips: one is that crossing the remnant from NE to SW and the other two are those overlapping the bright rims (figure 7.11), using the vignetting-corrected GIS image of the Center pointing in the 2–4 keV band, where the non-thermal component dominates the emission (actually, there exist Si $k\beta$ and S $K\alpha$ lines in 2.0–2.7 keV, but they do not affect the Rim-profile analysis because they distribute in a wide region while the Rims are spatially confined). We then made models of surface brightness in the same strips taking account of the PSF and compared with the data. As the models, we assumed a 0-thickness cylinder for the barrel, and 0-thickness disk for the cap. The PSF we used is of the 2.0–3.0 keV energy band and of the positions at $\theta = 17.0$ arcmin and $\phi = 39$ deg, which is supplied by the ASCA team. Figure 7.12 shows the employed PSF and its projected profiles along the radial and azimuthal directions of the

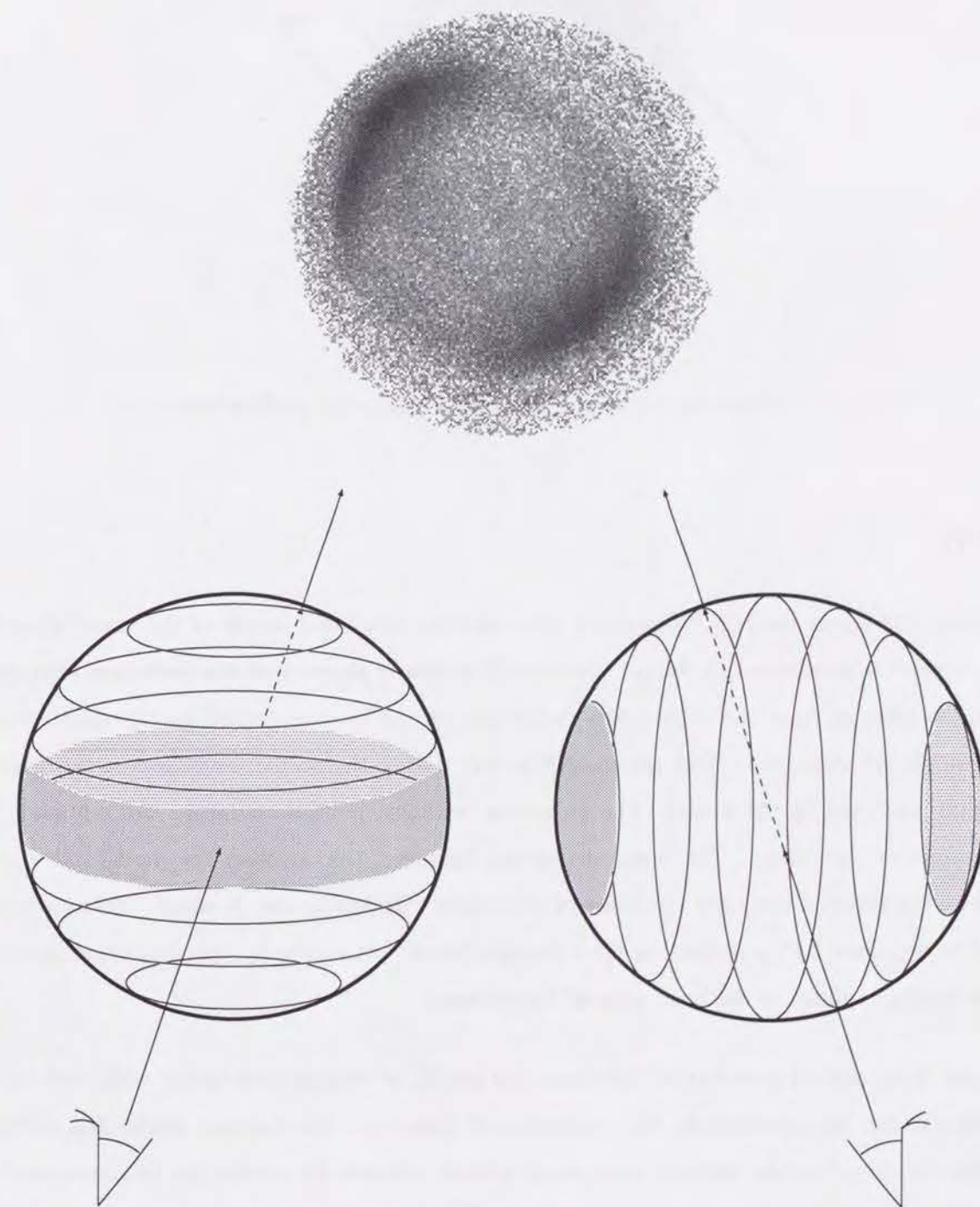


Figure 7.10: The candidates of the 3-D structure which can reveal the observed image of SN 1006 qualitatively.

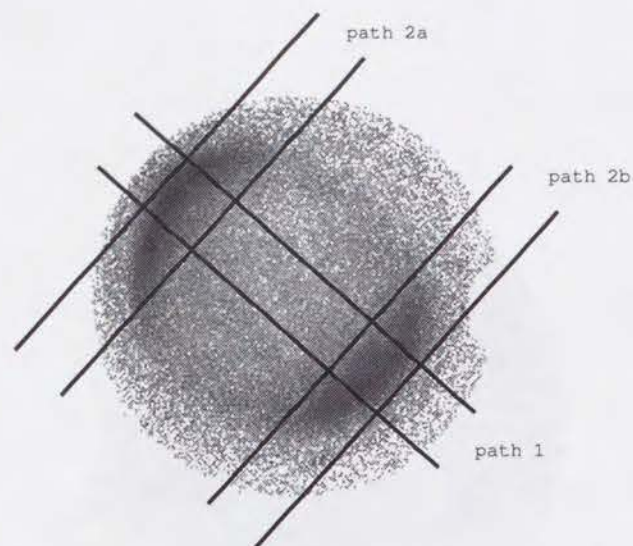


Figure 7.11: The regions where the surface-brightness profiles were made.

GIS FOV.

Figure 7.13 shows the NE-SW crossing strip with the simulated profile of the barrel structure whose bottom is normalized to that of the data. It is clearly shown that the each rims have quite different brightness from the other, thus the profile cannot be represented by the simple barrel structure. In addition, even if we see the NE or SW half of the profile, each peak is far brighter than that predicted by the model. The polar-cap (actually, polar-disk) model can represent the outer slopes of each rims. The inner slopes are, however, thicker than the model; we should introduce the disks of the finite thickness or thin disks with curvature. In short, the data profile cannot be explained by the projection effect of a thin barrel, but can be by the two distinct emitting regions locally confined in the both sides of the remnant.

Apart from the relative flux of the rims, the profile is roughly symmetric with each other. Therefore it can be explained by the projection of disks with the common center but different emission measures. As the simplest case, we examined whether the profile can be represented by single disk of an uniform emission measure. Figure 7.14 shows the data and the simulated profiles; it seems that the surface brightness can approximately be explained by this simplest assumption. Since the rims extend along a few pc, they should have fine spatial structure in addition to the disk. Still, the data cannot be well fitted by the simple model, perhaps requiring fine structure in the model. However, the spatial resolution of *ASCA* and the data statistics are not good enough to resolve the finer structure, hence we did not tried more complicated model.

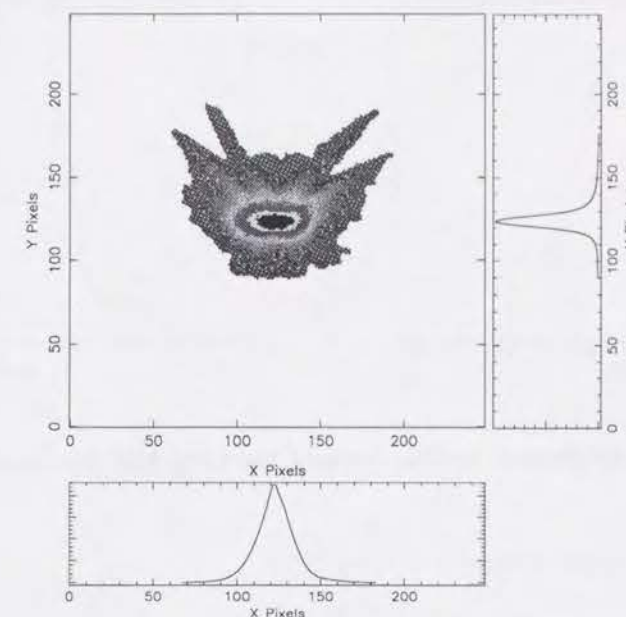


Figure 7.12: The XRT+GIS PSF (17.0 arcmin apart from the optical axis) used in the SN 1006 spatial analysis and the projections along the radial and azimuthal directions. The optical axis is toward the upper of the figure.

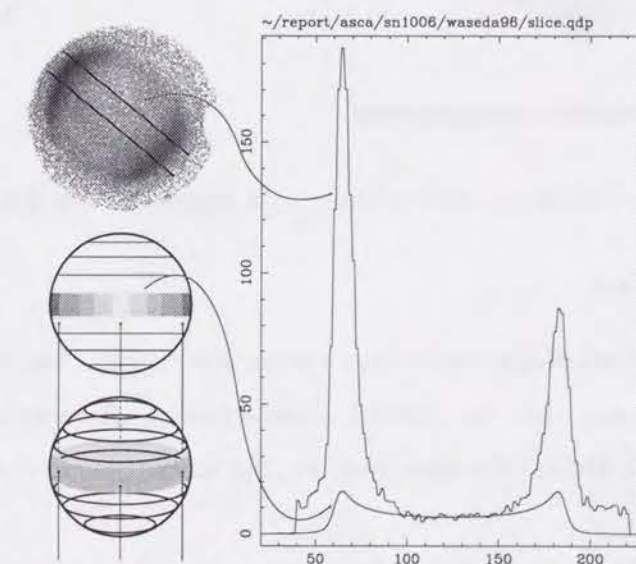


Figure 7.13: The remnant-crossing surface-brightness distribution (path 1) and the simulated profile of the barrel-like structure normalized at the interior of the remnant. It is clearly shown that the each rims have quite different brightness from the other and the contrasts between the rim and the interior cannot be represented.

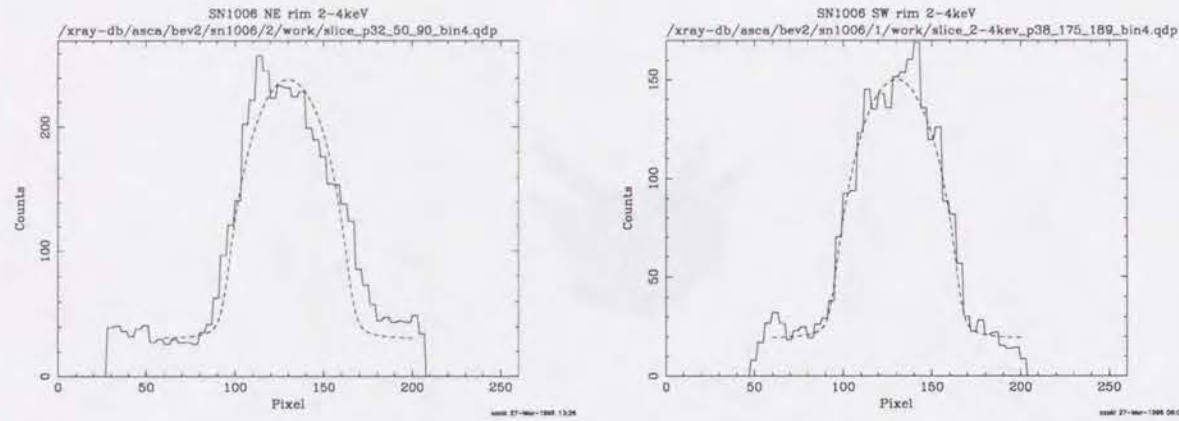


Figure 7.14: The surface-brightness profiles grazing the rims and the emission models from disks of uniform emissivity.

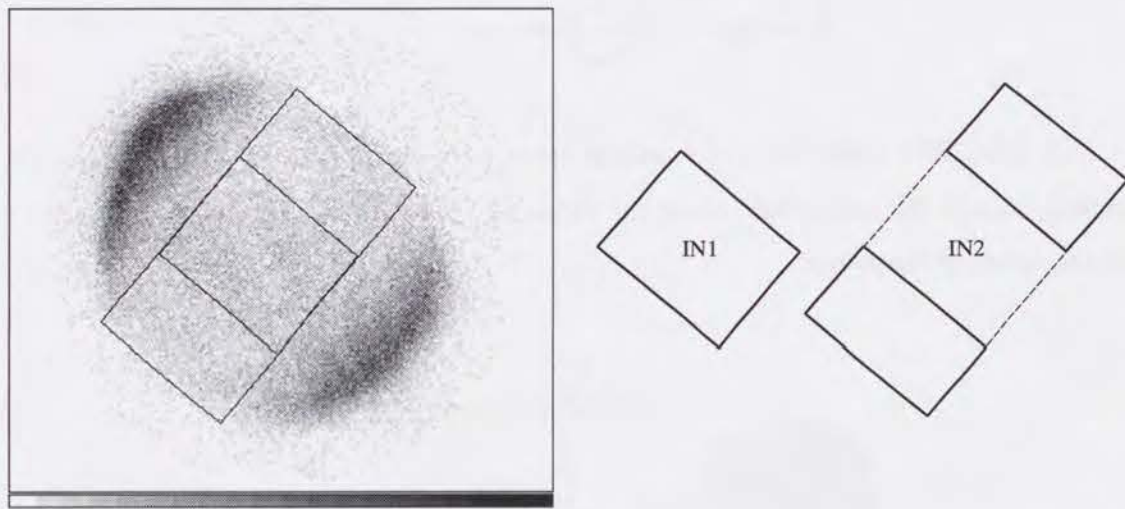


Figure 7.15: The GIS image and the integrated regions for the Interior analysis.

7.3.3 Interior emission

For SIS analysis, we re-extracted the events from the smaller regions than the Interior: figure 7.15 shows the regions. Assuming that the thermal plasma can be characterized by the spherically symmetric distribution, we divided the data into two; the inner (IN1) and outer (IN2) regions.

Background estimation

Since the Interior emission is very faint compared with the Rim, we have to consider three background components: CXB (blank sky), the local background coming from the Lupus Loop and the leak from the strong Rim component. While the first and the second ones should be considered in any observation or analysis, the last one is an issue for the ASCA XRT, of which PSF has a sharp peak but with a widely-spread tail (see the encircled energy function shown in figure 5.14). The

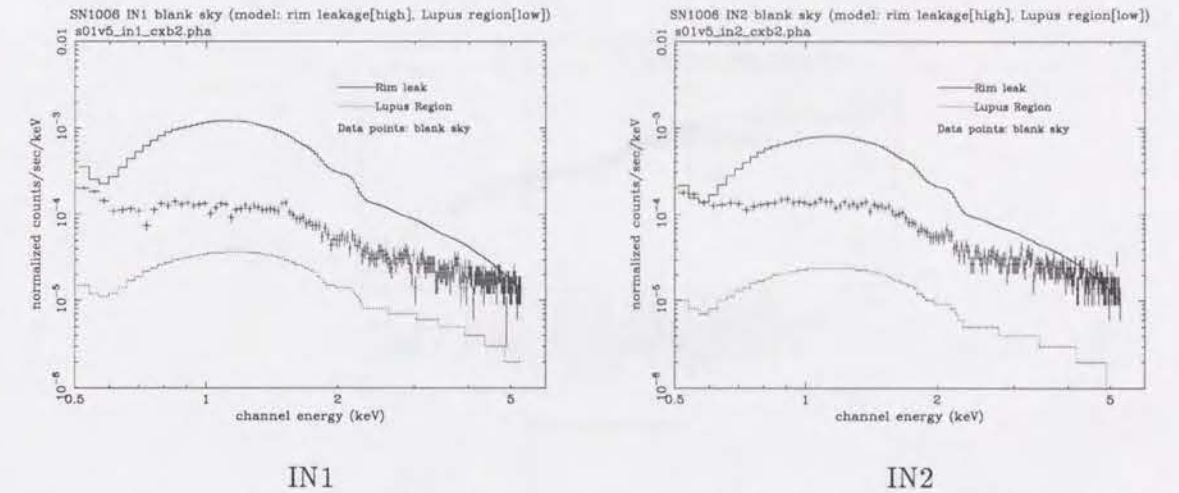


Figure 7.16: The model spectra of the leak component and the local component detected by Ginga with the blank-sky data for each region. In each panel, the model with larger flux is the leak component and the weaker one is the local component.

leakage is not a matter unless a neighboring source is not strong. In the present case, however, the neighbor or the bright Rim is far stronger than the other backgrounds below 5 keV. Figure 7.16 shows the model spectra of the leak and the local components detected by Ginga with the blank-sky data corresponding to the Interior regions; the leak is computed using the XRT response, and the local is done using the spectral parameter obtained in the Ginga analysis. In case of the ASCA Interior data, the local component is negligibly small compared to the large contribution of the leak component, hence we did not include this in the relevant background.

To estimate the background spectrum, we used two methods; one is that we represent the background from the raw data of the SIS BG region, which locates in the opposite side of the NE rim to the Interior region so that the leak is expected to be similar to the Interior, and the other is that we composed the background spectrum adding a simulated leak component and the blank-sky contribution (hereafter, we call these at the fitted- and simulated- BGDs, respectively). In the former method, we essentially require two component for the Interior spectra, one is that for the background, in which we beforehand fit the whole background spectrum and use the best-fit parameters. If we subtract the raw BG data from the Interiors, the statistics becomes very poor due to the poor statistics of the BG.

In the other method, we subtract the blank-sky data supplied by the ASCA team from the Interiors and use the simulated leak spectrum as a local background component: the reason that the blank-sky is not given by a model is that it has already good statistics.

As the fitted-BGD model, we used a Raymond-Smith plasma with the solar-abundance and a power-law continuum: figure 7.17 shows the spectra with the best-fit model. For the fitting, we

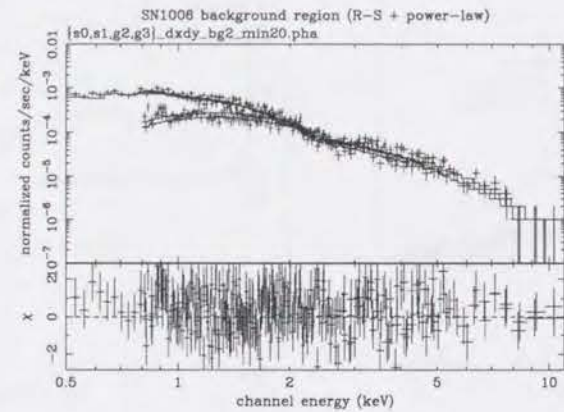


Figure 7.17: The BG region data and the ‘fitted BGD’ model.

used the 0.8–5 keV band for the SIS0, 0.5–5 keV for the SIS1 and 0.8–10 keV for the GIS data; the 0.5–0.8 keV for the SIS0 data were excluded because they are polluted by the optical-light leakage. The > 5 keV SIS data were excluded due to the intrinsic background limit; it does not affect the analysis below because only the < 2.7 keV data is used. The best-fit values of the temperature and the photon index are $kT = 0.19 \pm 0.01$ keV and $\Gamma = 2.24 \pm 0.05$, respectively (with reduced- $\chi^2 = 1.083$ for 312 d.o.f.). The power-law index represents the composition of the CXB of a photon index $\simeq 1.5$ and the leakage of the Rim emission of the index $\simeq 3$. The Raymond-Smith can be interpreted as the leak of the Interior component judging from its temperature and the surface brightness.

The leak component of the simulated-BGD for each region is obtained as follows:

1. We made the mirror response, where the source image was the Rim-component image and leakage is integrated over the regions of the IN1 and IN2. The response was made for GIS to make enable the large-area source image. Although the analysis was carried out with SIS data, we simulated the leakage with GIS because the simulation was purely of the mirror and each mirror is identical. Since each region data set consists of multiple pointings and detectors, the responses were made separately for each component.
2. We made the simulated spectra with the same exposure time as the observation using the responses above.
3. We combined the fake spectra as the same manner as the observation data.
4. We made the spectral model for the combined fake data convolved by the response for the observation. The fitted model is a power-law with an interstellar absorption using the Rim analysis results.

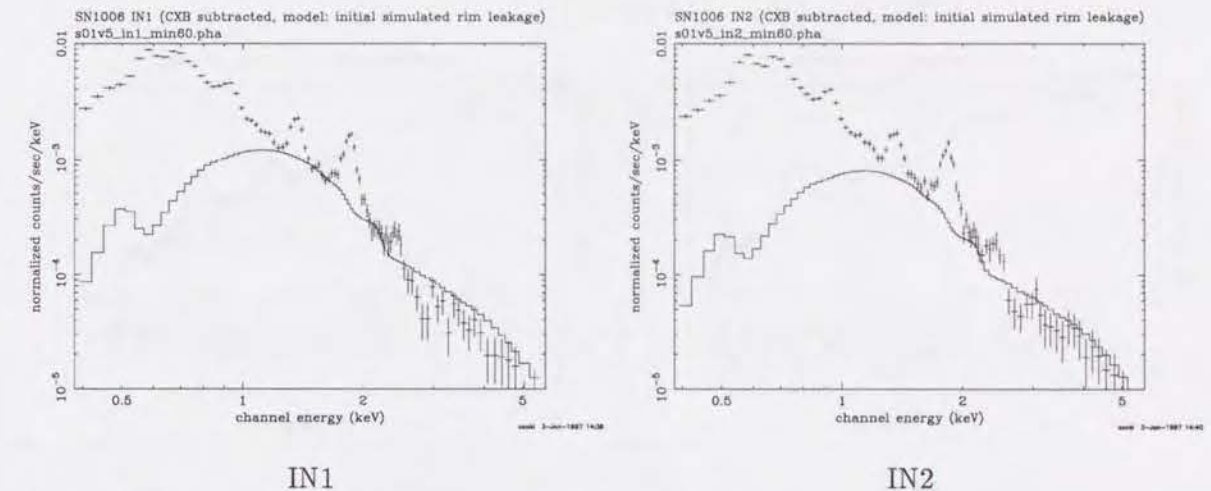


Figure 7.18: The simulated Rim-leak components and the Interior data after the subtraction of the blank-sky components. The models above 3 keV represent the spectral shape, but its flux exceeds the data. In the actual fittings, we renormalized the model to the > 3 keV data points in each region.

Figure 7.18 shows the simulated leak-components with the Interior spectra after the subtraction of the blank-sky. As can be seen from the figure, spectral shape at > 3 keV seems to follow the data; however, the model seems to be larger than the data in the same band. It may be attributed to the fact that since the used-image is after the convolution with response of XRT and GIS, the observed image does not precisely describe the true source distribution and that the XRT response is not precisely calibrated for such a large off-angle leakage. In the present analysis, therefore, we renormalized the model by fitting to 3–5 keV data. The renormalization factor of IN1 and IN2 are 65% and 78%, respectively.

Analysis and Results

In the present analysis, we used the 0.5–2.7 keV band SIS data. Above $\simeq 2.7$ keV, the Rim-leak component becomes dominant in both the background models.

We fitted a single-component NEI model to the data, but could not represent the line profiles of the data as already found in the spectrum of the whole Interior region. Therefore, we fit a two-components NEI plasma model with no interstellar absorption, because we found that the single-component NEI requires no absorption. For the two-NEI model, we used that developed by Masai (1984), because the coding of the Masai model is nicely organized for the present particular purpose.

Any two-components NEI model, however could not represent the data well, neither. Nevertheless, we show figure 7.19 and table 7.9, the best-fit models with data and the best-fit parameters,

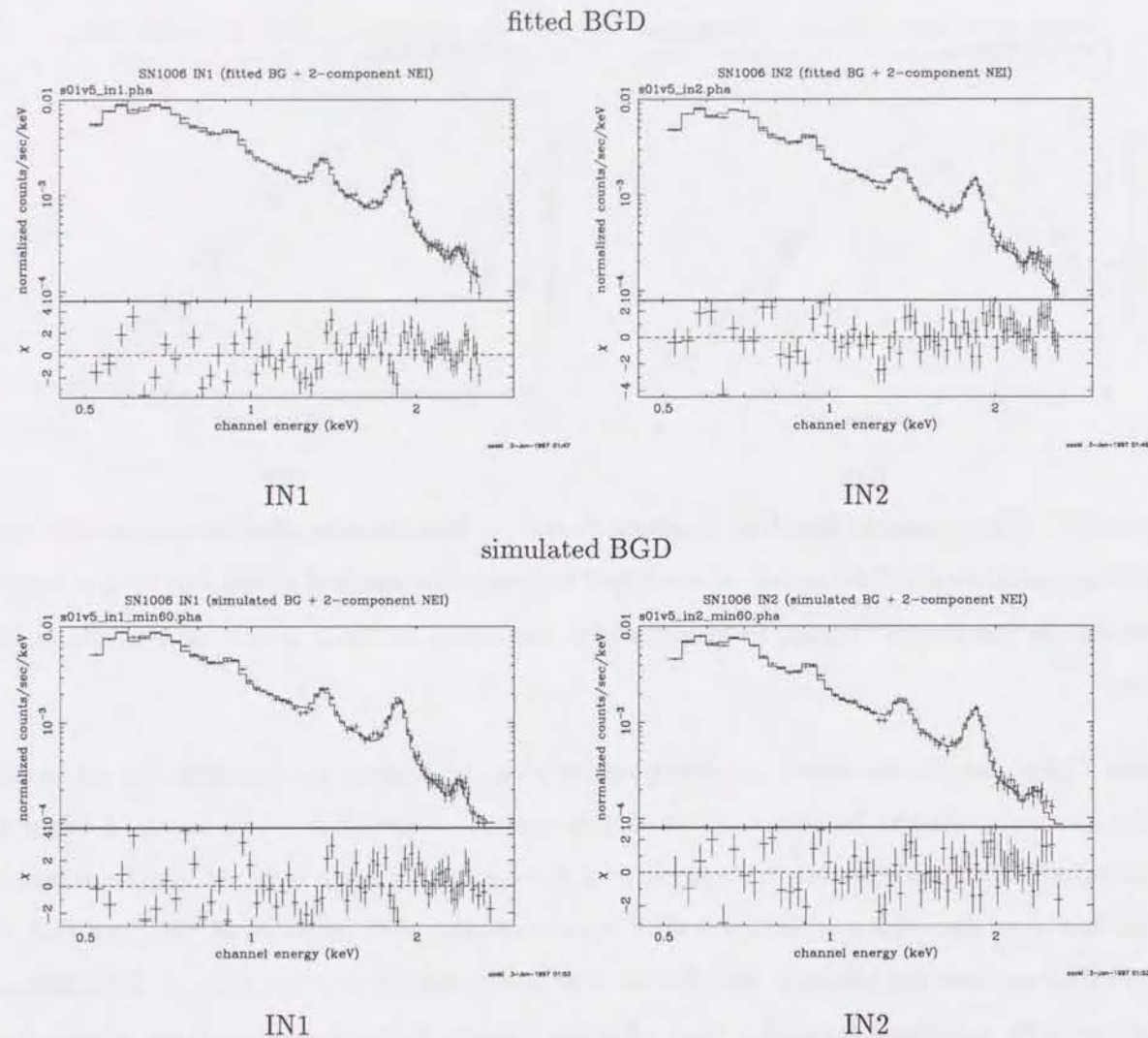


Figure 7.19: The 0.5–2.7 keV SIS data and the best-fit two-component NEI models.

and try to infer semi-quantitatively the discrepancy between the data and model.

The residuals scatter significantly below 1 keV, in particular for the profile profile between OVII (0.574 keV) and OVIII (0.654 keV).

Since there is no other strong atomic line candidate in this band, the large residual in this band is a serious problem. Probably, we need further precise calibration of the response particularly in this band. In addition, the 0.7–0.9 keV profile could not be represented well, neither; the model predict smoother curve than the data. This can be attributable to the Fe-L complex, in which lines emissivity in the NEI plasma are not well known.

Above 1 keV, the Mg- and Si-line profiles also failed to represented the data, but less extent than found in < 1 keV.

Since the model could not particularly represent the < 1 keV spectra, we divided the spectra into two energy bands: those of > 1 keV and < 1 keV, and fit the NEI models to these bands

Table 7.9: The best-fit parameters of two-component NEI model for SN 1006 0.5–2.7 keV Interior spectra. All fittings are clearly rejected statistically.

(a) fitted BGD										
Region	Component	kT [keV]	$\log(n_e t)$ [10^{21} cm^{-2}]	O	Ne	Mg	Si	S	Fe	reduced- χ^2 (d.o.f.)
IN1	NEI1	3.35	9.5	0.88	0	0.10	2.11	3.71	0	3.668
	NEI2	0.27	11.7	0	4.58	23.3	133.7	0	1.25	(54)
IN2	NEI1	1.36	9.3	1.20	0	0	5.37	17.1	791.5	2.315
	NEI2	0.27	11.0	0	8.16	35.4	288.0	0	2.54	(54)
(b) simulated BGD										
Region	Component	kT [keV]	$\log(n_e t)$ [10^{21} cm^{-2}]	O	Ne	Mg	Si	S	Fe	reduced- χ^2 (d.o.f.)
IN1	NEI1	2.05	9.6	1.18	0	0	3.64	7.44	0	3.305
	NEI2	0.26	11.6	0	3.05	16.6	92.0	0	1.00	(54)
IN2	NEI1	1.36	9.3	1.65	0.19	0	7.70	20.6	303	2.101
	NEI2	0.23	11.3	0	4.88	26.3	221	0	1.95	(48)

The definition of the solar abundances is from Allen (1973).

separately. For the < 1 keV band fittings, we performed only with the fitted-BGD case because the all the < 1 keV backgrounds are smaller than the errors of the data; the difference of the two backgrounds is negligible.

Figure 7.20 and figure 7.21 show the best-fit models with < 1 keV and > 1 keV data, respectively, and table 7.10 gives the best-fit parameters. Contrary to the whole-energy band fitting, the > 1 keV band fittings gave acceptable results. On the other hand, the < 1 keV band fittings is unacceptable again. Table 7.11 gives the emission measures for each the > 1 keV band fitting.

As another approach, we evaluated the equivalent width of each line.

Since we could not represent the O-line profiles well, and since the Fe-L complex energy range does not show significantly line profile as well, we evaluated above the 0.85 keV band. As the continuum component, we used a thermal bremsstrahlung continuum; although we tried two-component continuum fit but gave no statistical improvement. Table 7.12 gives the fitted lines and their equivalent widths with 90% errors. Most of the line profiles can be represented with no Doppler shift nor line broadening, except the Mg line showing a hint of energy shift and broadening of line.

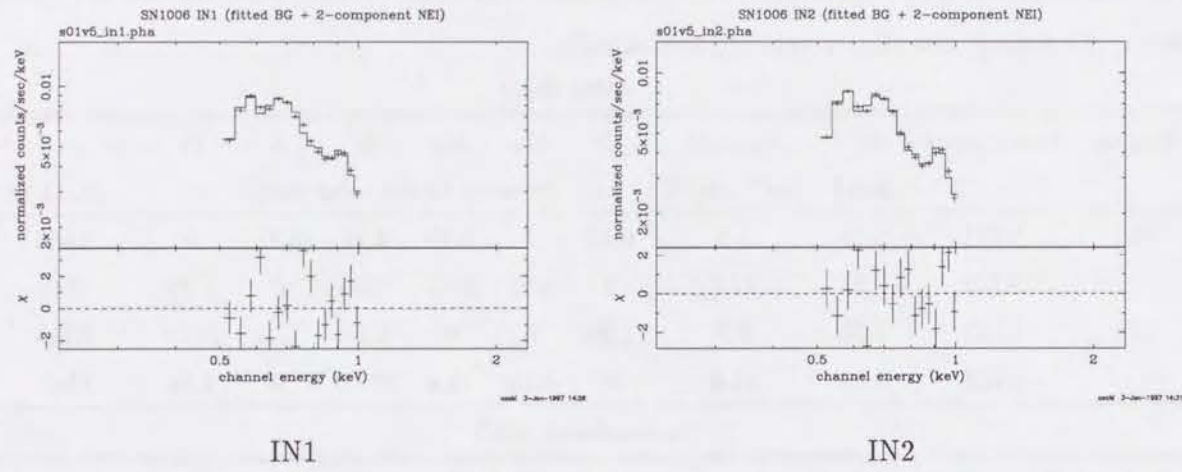


Figure 7.20: The 0.5–1.0 SIS data and the best-fit two-component NEI models. The background components are fitted BGDs.

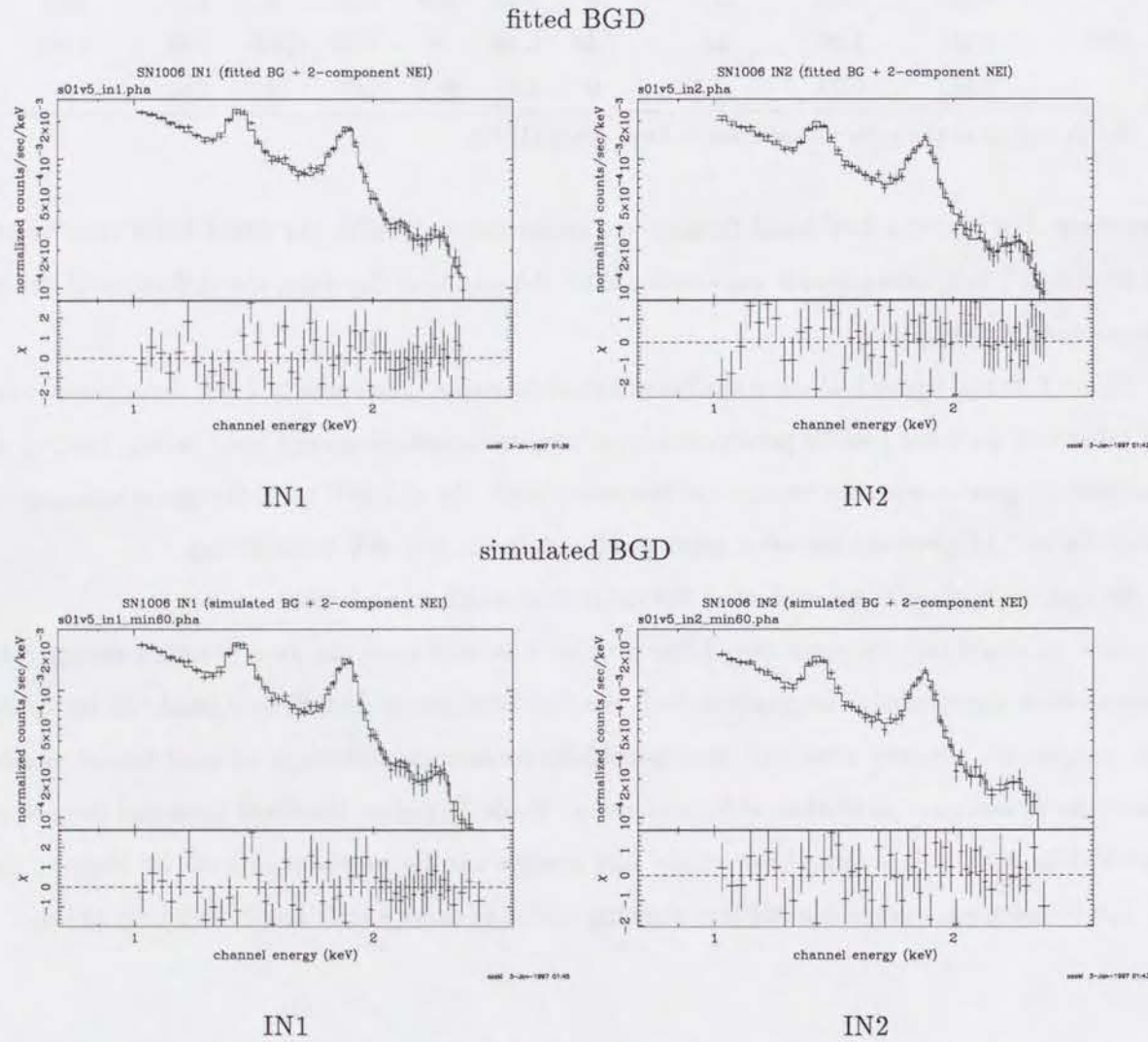


Figure 7.21: The 1.0–2.7 keV SIS data and the best-fit two-component NEI models.

Table 7.10: The best-fit parameters of two-component NEI model for SN 1006 Interior < 1 keV and > 1 keV spectra. We did not carry out < 1.0 keV fitting for simulated BGD because the fitted BGD gave poor results and the backgrounds below 1 keV do not affect the result in practice.

(a) fitted BGD								
	IN1 (0.5–1.0 keV)		IN1 (1.0–2.7 keV)		IN2 (0.5–1.0 keV)		IN2 (1.0–2.7 keV)	
	NEI1	NEI2	NEI1	NEI2	NEI1	NEI2	NEI1	NEI2
kT [keV]	1.80	0.17	$1.63^{+0.58}_{-0.45}$	$0.61^{+9.39}_{-0.34}$	1.23	0.16	$1.65^{+0.78}_{-0.51}$	$0.58^{+0.57}_{-0.18}$
$\log(n_e t)$ [cm ⁻³ s]	9.42	12.36	$10.21^{+0.09}_{-0.08}$	$< 9.25^\dagger$	9.50	11.75	$10.17^{+0.11}_{-0.1}$	$< 9.05^\dagger$
O	0.16	0.00	—	—	0.34	0.00	—	—
Ne	0.00	2.01	—	—	0.27	0.59	—	—
Mg	—	—	$7.14^{+3.79}_{-1.36}$	< 5.54	—	—	$8.20^{+6.55}_{-2.65}$	< 0.73
Si	—	—	$15.4^{+11}_{-4.8}$	$17.5^{+982.5}_{-15.84}$	—	—	$17.8^{+19.3}_{-8.3}$	$8.17^{+13.23}_{-4.39}$
S	—	—	$9.69^{+9.73}_{-4.53}$	$59.2^{+940.8}_{-58.0}$	—	—	$17.1^{+22.8}_{-9.4}$	$33.4^{+135.2}_{-26.0}$
Fe	0.00	10.1	$1^\ddagger$	$1^\ddagger$	2.49	14.8	$1^\ddagger$	$1^\ddagger$
reduced- χ^2 (d.o.f.)	12.58 (4)		1.215 (43)		7.729 (4)		1.336 (43)	

$\nearrow$ s show that each value is bounded by the model limit.

† : The best-fit and the lower limit became 9.00, which is the bounded value by the model.

‡ : Iron abundances in 1.0–2.7 keV fittings were fixed to the solar value.

(b) simulated BGD				
	IN1 (1.0–2.7 keV)		IN2 (1.0–2.7 keV)	
	NEI1	NEI2	NEI1	NEI2
kT [keV]	$1.46^{+0.50}_{-0.31}$	$0.28^{+9.72}_{-0.09}$	$1.11^{+0.62}_{-0.46}$	$0.48^{+9.52}_{-0.26}$
$\log(n_e t)$ [cm ⁻³ s]	$10.21^{+0.10}_{-0.09}$	$9.56^{+0.87}_{-0.56}$	$10.22^{+0.23}_{-0.15}$	$9.35^{+1.10}_{-0.35}$
Mg	$9.02^{+12.83}_{-3.92}$	< 1.11	$5.4^{+5.91}_{-1.98}$	< 82.0
Si	$21.2^{+28.4}_{-10.1}$	$71.1^{+928.9}_{-53.4}$	$12.5^{+14.3}_{-4.8}$	$69.1^{+930.9}_{-66.4}$
S	$15.0^{+20.5}_{-8.9}$	764^{+236}_{-656}	$12.1^{+18.4}_{-7.5}$	237^{+763}_{-236}
Fe	$1^\ddagger$	$1^\ddagger$	$1^\ddagger$	$1^\ddagger$
reduced- χ^2 (d.o.f.)	1.213 (43)		1.082 (37)	

$\nearrow$ s and $\searrow$ s show that each value is bounded by the model limit.

‡ : The lower limit is bounded by the model to 9.00.

‡ : Iron abundances in 1.0–2.7 keV fittings were fixed to the solar value.

Table 7.11: The emission measures par area of each component in 1.0–2.7 keV fittings. The values are in unit of $[10^{53} (\frac{D}{1 \text{ kpc}})^2 \text{ cm}^{-3} \text{ arcmin}^{-2}]$, where D is the distance toward the remnant.

Background	IN1 (1.0–2.7 keV)		IN2 (1.0–2.7 keV)	
	NEI1	NEI2	NEI1	NEI2
fitted BGD	0.38	1.8	0.36	9.1
simulated BGD	0.30	12	0.70	2.1

Table 7.12: The equivalent widths of lines of SN 1006 Interior spectra.
(a) fitted BGD

Line	Lab	IN1			IN2		
Name	Energy [keV]	Energy [keV]	σ [eV]	E.W. [eV]	Energy [keV]	σ [eV]	E.W. [eV]
Ne He α	0.923	0.923	0	$88.1^{+9.3}_{-9.7}$	0.923	0	113^{+11}_{-10}
Na He α	1.127	1.127	0	$16.6^{+12.5}_{-15.36}$	1.127	0	$30.8^{+13.5}_{-13.7}$
Mg He α	1.352	1.365 ± 0.004	$15.1^{+9.5}_{-13.2}$	953^{+67}_{-50}	$1.359^{+0.005}_{-0.006}$	$23.2^{+6.8}_{-12.5}$	534^{+46}_{-35}
Mg Ly α	1.473	1.488	0	< 179	1.480	0	$94.7^{+44.3}_{-67.6}$
Mg He β	1.580	1.596	0	747^{+123}_{-188}	1.588	0	426^{+92}_{-83}
Si Be–O α	1.756–1.821	$1.763^{+0.025}_{-0.005}$	0	$4.25^{+0.51}_{-0.41} \times 10^3$	$1.777^{+0.011}_{-0.004}$	0	$3.08^{+0.28}_{-1.40} \times 10^3$
Si He α	1.865	1.865	0	$27.3^{+1.70}_{-1.40} \times 10^3$	1.865	0	$8.79^{+0.63}_{-0.64} \times 10^3$
Si Ly α	2.006	2.006	0	$6.87^{+1.98}_{-1.85} \times 10^3$	2.006	0	$2.62^{+0.71}_{-0.72} \times 10^3$
Si He β	2.183	2.183	0	$13.6^{+4.30}_{-3.86} \times 10^3$	2.183	0	$5.80^{+1.39}_{-1.35} \times 10^3$
Si Ly β	2.375	2.375	0	$69.9^{+14.3}_{-16.9} \times 10^3$	2.375	0	$20.6^{+4.70}_{-4.90} \times 10^3$
S He α	2.460	2.460	0	$78.0^{+29.0}_{-26.4} \times 10^3$	2.460	0	$24.0^{+7.20}_{-7.00} \times 10^3$

(b) simulated BGD							
Line	Lab	IN1			IN2		
Name	Energy [keV]	Energy [keV]	σ [eV]	E.W. [eV]	Energy [keV]	σ [eV]	E.W. [eV]
Ne He α	0.923	0.923	0	$85.2^{+9.4}_{-9}$	0.923	0	120^{+11}_{-11}
Na He α	1.127	1.127	0	$24.5^{+19.8}_{-13.3}$	1.127	0	$44.3^{+19.2}_{-14.2}$
Mg He α	1.352	$1.364^{+0.004}_{-0.005}$	$18.0^{+5.7}_{-18.0}$	$1.23^{+0.08}_{-0.10} \times 10^3$	1.359 ± 0.006	$22.5^{+8.0}_{-12.3}$	912^{+76}_{-75}
Mg Ly α	1.473	1.488	0	< 197	1.480	0	< 164
Mg He β	1.580	1.596	0	880^{+320}_{-153}	1.588	0	603^{+217}_{-218}
Si Be–O α	1.756–1.821	$1.77^{+0.014}_{-0.009}$	0	$7.27^{+1.14}_{-0.74} \times 10^3$	$1.788^{+0.01}_{-0.005}$	0	$9.48^{+1.02}_{-0.99} \times 10^3$
Si He α	1.865	1.865	0	$51.5^{+2.70}_{-3.30} \times 10^3$	1.865	0	$26.8^{+2.40}_{-2.20} \times 10^3$
Si Ly α	2.006	2.006	0	$13.1^{+4.60}_{-4.23} \times 10^3$	2.006	0	$5.77^{+3.07}_{-3.09} \times 10^3$
Si He β	2.183	2.183	0	$27.5^{+11.1}_{-10.3} \times 10^3$	2.183	0	$16.1^{+7.50}_{-7.40} \times 10^3$
Si Ly β	2.375	2.375	0	$188^{+44}_{-55} \times 10^3$	2.375	0	$112^{+33}_{-35.5} \times 10^3$
S He α	2.460	2.460	0	$232^{+74}_{-100} \times 10^3$	2.460	0	$117^{+54}_{-56.2} \times 10^3$

The line energies of Ne, Si, and S are fixed to be the laboratory-value, while those of Mg are blue-shift corrected value, which is determined by the observed energy of He α .

Chapter 8

IC443 Study with ASCA

8.1 Observations

We observed IC 443 with ASCA on 14–15 April 1993 and 9–10 March 1994 during the early PV and AO1 phases, respectively. The former observation pointed the brightest NE subshell of the remnant, and the latter did the SW subshell. Figure 8.1 shows the FOVs of the observations overlaid on the Palomar Observatory Sky Survey image. Table 8.1 gives the coordinates and the attitude parameters, and table 8.2 gives the telemetry modes used in the observations. In these observations, no additional lower discriminator for SIS was set because the number of hot pixels of the radiation damage origin was smaller than the telemetry saturation level. The Bit_Low mode was used only for the time that the target was occulted by the earth, hence no Bit_Low X-ray data are available.

Since the PV data of IC 443 were obtained at the very early phase and the spread discriminator (see section 5.2.2) had not been applied yet, the data contains more non-X-ray background events than the late PV and AO observations. There also exists a ghost image of the calibration source at the image area. The AO GIS3 data are degraded by the on-board data processing trouble happened on February 10, 1994, between 22:05 and 22:35 UT, after passing through the SAA; the three least significant PHA bits were stuck in the pattern 101, resulting in a loss of the digital resolution.

Table 8.1: The coordinates of IC 443 ASCA observations.

ID	Pointing Center	Mean Euler Angle	Observation date
PV	(94.1304, 22.4818)	(94.6377, 67.1966, 177.8991)	14–15 April 1993
AO1	(94.1304, 22.4818)	(94.3579, 67.4463, 174.5171)	9–10 March 1994

The coordinates and the Euler angles are in J2000.0 system.

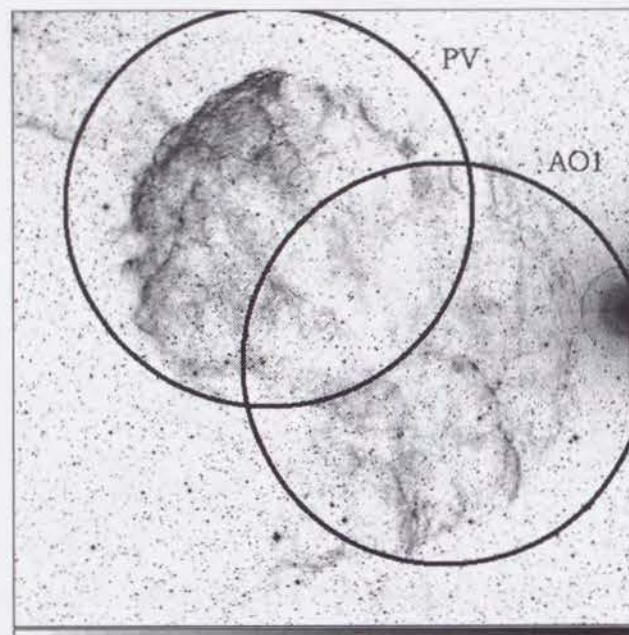


Figure 8.1: The GIS FOV of the IC 443 observations over the Palomar Observatory Sky Survey image.

Table 8.2: The telemetry modes of IC 443 ASCA observations. In the both observations, the same arrangements were used.

Bit Rate	GIS mode	SIS mode [†]
High	PH nominal (10-8-8-5-0-1) [‡]	4CCD Faint
Med	PH nominal (10-8-8-5-0-1) [‡]	4CCD Bright
Low	PH nominal (10-8-8-5-0-1) [‡]	4CCD Bright

[†]: In the present analysis, we did not use the SIS data (see text).

[‡]: Telemetry bits for pulse height, X-position, Y-position, rise time, light spread and timing informations, respectively.

Thus, some of the IC 443 GIS data are less qualified and suffered larger background than those of the other observations like SN 1006.

8.2 Data Reduction

In this paper, we focus on the study for the large scale characters of the remnant in order to make clear the spatial distribution of the Ginga hard component. Consequently, we analyzed only the GIS data which cover the larger area and have higher sensitivity in the hard band than SIS.

The data were selected under the same criteria as applied to the SN 1006 data, which are described in section 7.2. In short, these are $COR > 6$, $RBM_CONT < 275$ and $ELV_MIN > 7.5$. The resultant exposure time for PV and AO1 observations are 53 ksec and 42 ksec, respectively.

Since the IC 443 pointing have no region which can be used as the background, for the AO1 data analysis, we used the blank sky fields and night earth data accumulated by the ASCA team as the standard background. For all the PV data analysis, on the other hand, we have made the blank sky data set accumulated when the spread discriminator was off.

Since the AO1 GIS3 data were degraded by the on-board trouble, we truncated the 2 least-significant energy bits (2 LSB), as to have no practical trouble for the spectral analysis.

8.3 Results

8.3.1 General property

Figure 8.2 shows the GIS images of IC 443 in 0.8–10 keV and 4–10 keV bands. While the former appears a center-filled morphology, which is similar to the Einstein and ROSAT images, the latter appears as a bright spot and an incomplete semi-circular structure surrounding the NE part of the remnant and including a bright bar-like structure at the southern edge of the PV FOV. The positions of the bright spot and the bar-like structure are approximately (06h17m04s, 22d22m)J2000 and (06h18m01s, 22d26m)J2000, respectively.

8.3.2 Hard component

To study the hard component, we extracted the spectra from three regions; the bright spot, the bar-like structure (hereafter, hard-spot and hard-bar, respectively) and the whole region.

For comparison of the spectra of the hard-spot and the hard-bar with the soft component prevailing over the whole remnant, we also extracted the spectra of the hard-component-free regions, of which surface brightness in the whole energy band and the distances from the pointing centers

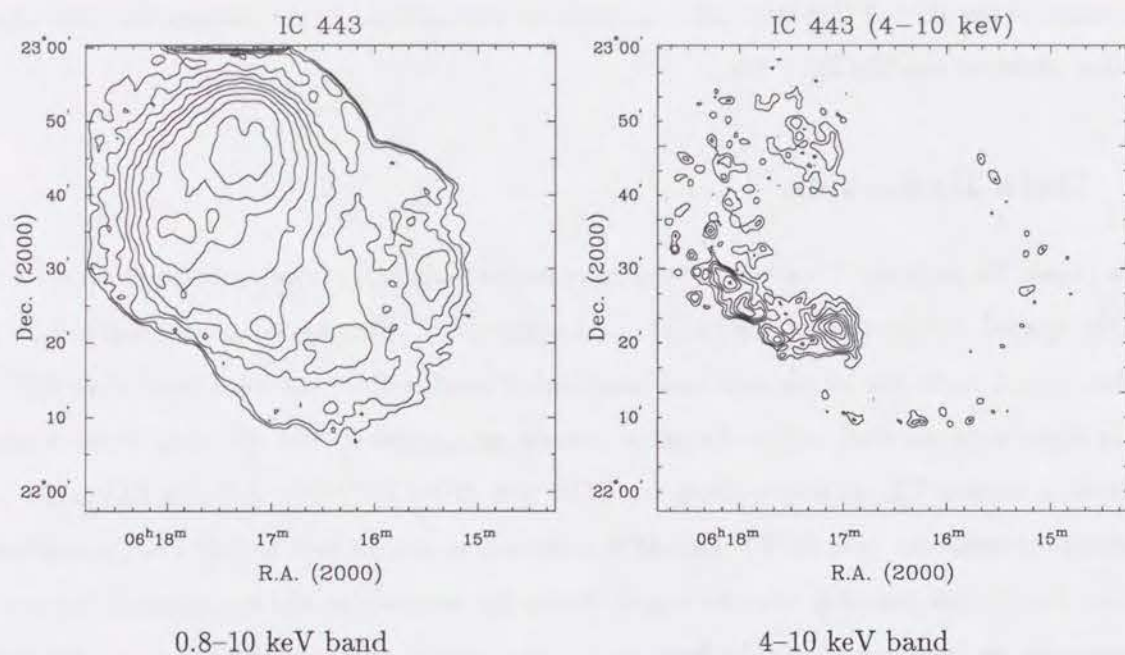


Figure 8.2: The GIS image contours of IC 443 in 0.8–10 keV and 4–10 keV bands. Each panel is drawn in log-scale.

are similar to the hard regions. Figure 8.3 shows the regions where we extracted the spectra of the hard regions and their backgrounds.

Hard-spot

For the hard-spot, we extracted the spectrum from the AO1 data and subtracted the surrounding annular region data as the background. In the spectral fitting, we tried two models; one is a single-component NEI plasma and the other is a power-law, both with the interstellar absorption. Both models can represent the data well, hence we could not discriminate these models from the shape of the continuums. Figure 8.4 shows the spectrum and the best-fit models, and table 8.3 gives the best-fit parameters. The flux and the flux density of the best-fit power-law model are $4.7 \times 10^{-12} \text{ ergs s}^{-1} \text{ cm}^{-2}$ (2–10 keV) and $3.8 \times 10^{-5} \text{ photons s}^{-1} \text{ cm}^{-2} \text{ keV}^{-1}$ (at 7 keV), respectively.

Hard-bar

For the hard-bar spectrum taken from the PV phase, we subtracted the black sky spectrum. The resultant spectrum is shown in figure 8.5. Note that this spectrum include local background, mainly attributable to the soft X-rays from IC443. Therefore, we also made a local background spectra from the region named BGD for hard-bar and subtracted the relevant blank sky data. As already noted, the blank sky data in the PV phase case is that when the spread discriminator was off, as it was in the first IC443 observation.

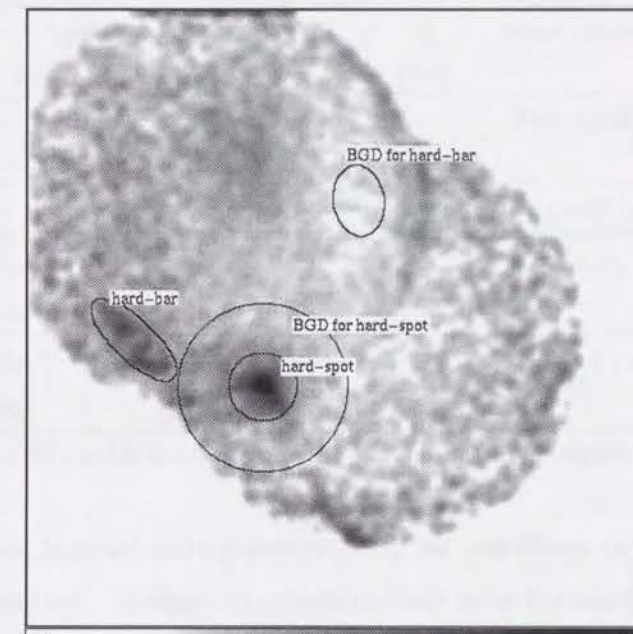


Figure 8.3: The regions where the hard component events and the corresponding local-background (or soft component) events were extracted.

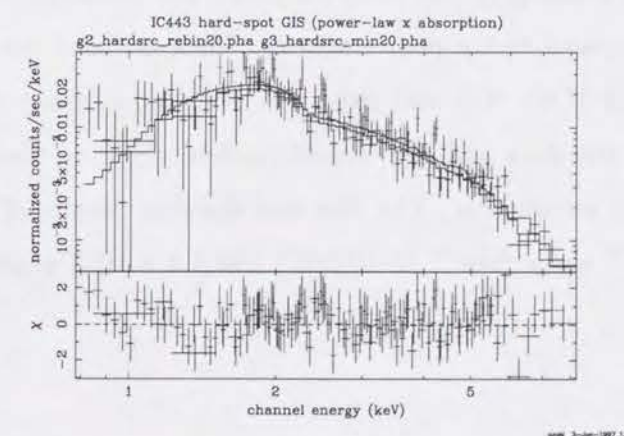


Figure 8.4: The hard-spot data from which the soft component are subtracted and the best-fit power-law models.

Table 8.3: The best-fit parameters of the IC 443 hard regions spectra.

(a) The hard spot at (06h17m04s, 22d22m) J2000.

Model	N_H [10^{21} cm^{-2}]	photon index	kT [keV]	$\log n_e t$ [s cm^{-3}]	Ne	Mg	Si	S	Fe	reduced- χ^2 (d.o.f.)
Power-law	$9.7^{+2.9}_{-2.6}$	2.12 ± 0.18	—	—	—	—	—	—	—	0.9301 (247)
NEI	$6.4^{+4.6}_{-2.5}$	—	$8.67^{+5.65}_{-2.55}$	$9.85^{+0.28}_{-0.30}$	< 0.73	< 0.17	< 0.40	$0.80^{+0.46}_{-0.40}$	< 0.29	0.9095 (241)

(b) The hard bar around (06h18m00s, 22d27m) J2000.

Model	N_H [10^{21} cm^{-2}]	photon index	kT [keV]	Fe [Solar abundance]	soft-component normalization	reduced- χ^2 (d.o.f.)
Power-law	25^{+19}_{-14}	$2.35^{+0.65}_{-0.53}$	—	—	$0.97^{+0.03}_{-0.05}$	0.9715 (260)
R-S	20^{+15}_{-12}	—	$4.17^{+4.11}_{-1.59}$	$0.27^{+0.57}_{-0.27}$	$0.96^{+0.04}_{-0.05}$	0.9654 (260)

The definition of the solar abundances is from Allen (1973).

To the local background spectrum, we fit an optically-thin thermal plasma containing heavy elements (Raymond-Smith model) with the interstellar absorption. We linked all the abundances of the elements and assumed the ionization equilibrium not to make the model too complicated. The best-fit temperature, abundance and the absorption column density were $kT = 0.66^{+0.06}_{-0.05}$ keV, $Z = 0.10^{+0.07}_{-0.05}$ solar abundance and $N_H = (4.6^{+1.4}_{-1.6}) \times 10^{21} \text{ cm}^{-2}$, respectively, with the reduced- χ^2 of 1.236 (211 d.o.f.). As for the spectrum of the hard-bar, which include the local background, we tried the same two models as the hard-spot, but adding the local background model. In the fitting, we fixed the whole parameters of the local background, except only normalization, to those determined independent fitting as given above.

The fitting for the NEI model to the hard-bar could not converge, due possible to the too many free parameters compared to the poor statistics. Thus, we used the model of an ionization equilibrium plasma instead of the NEI and fixing the abundances except for iron to the cosmic values. Figure 8.5 shows the data and the best-fit models including the local background, and table 8.3 gives the best-fit parameters. The flux and the flux density of the best-fit power-law component are $1.9 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ (2–10 keV) and $1.2 \times 10^{-9} \text{ photons s}^{-1} \text{ cm}^{-2} \text{ keV}^{-1}$ (at 7 keV), respectively.

Whole region

Since the position dependence of the response function differs between different energy band, to re-construct the overall response function for a largely extended emission is complicated when the extended source has different energy spectra from position to position. This is true for the case of IC443, because, as we already noted, that the soft and hard components exhibit quite different

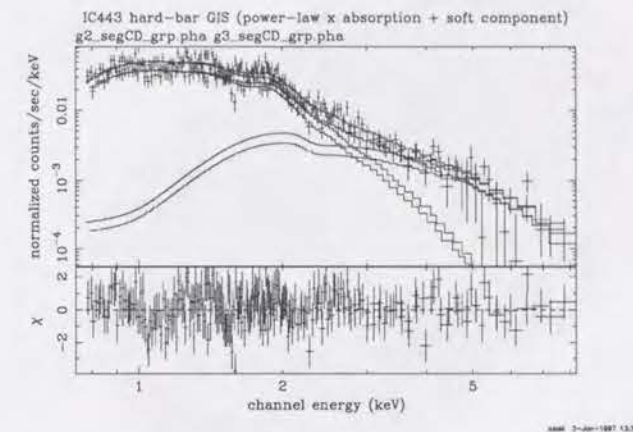


Figure 8.5: The hard-bar data with the best-fit power-law models (hard components) and the soft thermal components of GIS2 and 3.

spatial structures with each other.

To estimate the hard component flux from the whole FOV, we accordingly assume the surface brightness of the hard component follows the limited energy band >4 keV, in which the spectral does not differ much from position to position, because contribution of the soft component is almost disappears. Then reconstruct a response function for the particular purpose of the flux estimation of the hard components from the whole region of the SNR. Note since the response thus made does not reflect the low-energy band surface brightness, we cannot determine the flux of the soft components precisely with this particular response function.

We fitted the model consisting of a thermal bremsstrahlung, a power-law and a line of which energy is near 6.5 keV to the >4 keV band spectrum from PV and AO1 (except for the overlapping PV) region, fixing the temperature and the photon index to the Ginga value reported by Wang et al. (1992). Figure 8.6 shows the regions where we estimated the flux. The flux density at 7 keV is estimated to be $2.1 \times 10^{-5} \text{ photons s}^{-1} \text{ cm}^{-2} \text{ keV}^{-1}$ for each region. The equivalent widths of the iron lines of the PV and the AO1 region are $1.33^{+0.51}_{-0.36}$ keV and <63 eV, respectively. The center energy and the flux of the iron line in the PV region are $6.60^{+0.08}_{-0.14}$ keV and $3.4^{+1.3}_{-0.9} \times 10^{-5} \text{ photon s}^{-1} \text{ cm}^{-2}$, respectively.

8.3.3 Soft component

In the soft component fitting, we did not use AO1 GIS3 data because the energy bin is not fine enough to use the NEI plasma fitting, due to the instrument trouble.

We divided the PV GIS data into 12 regions as is given in Figure 8.7, and extracted the spectra region by region. For each spectra, we subtracted the blank sky background at the same detector

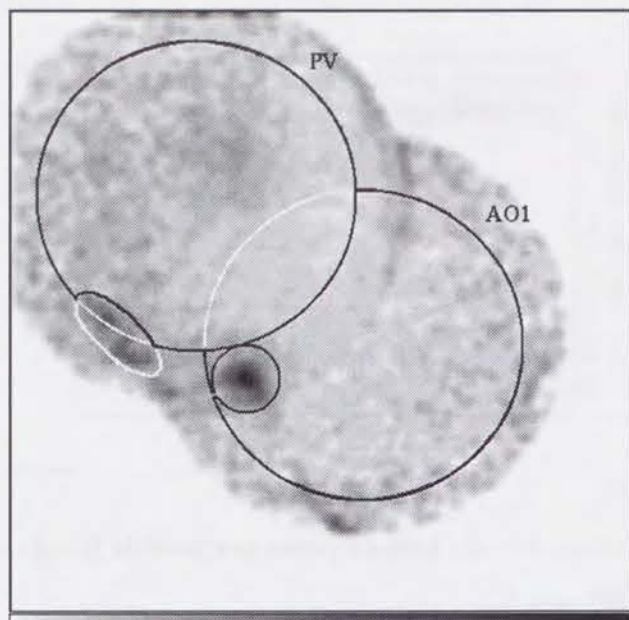


Figure 8.6: The region where we estimated the whole hard-component flux.

coordinates as the relevant source region.

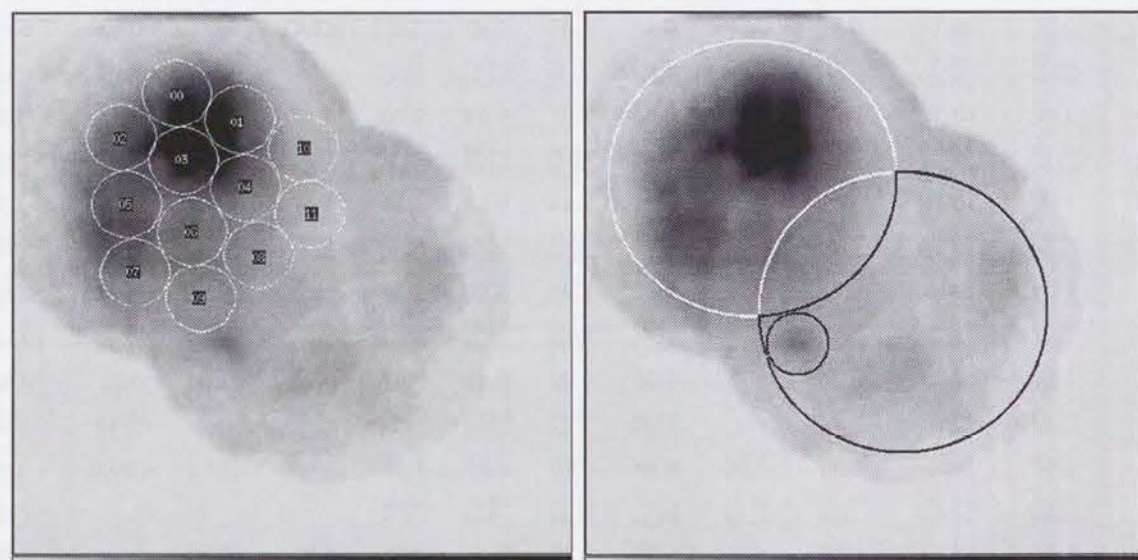
We used an NEI plasma with the interstellar absorption for each region. Figure 8.8 shows the spectrum with the best-fit model for each region, and table 8.4 gives the best-fit parameters.

Since the surface brightness of the AO1 region is too faint to make spatial sorted analysis with sufficiently small errors to make a comparison of the fitting parameters from position to position, we analyzed only the whole AO1 spectrum excluding the PV and hard-spot regions. The spectrum can be represented by an NEI plasma with the interstellar absorption. Figure 8.9 shows the best-fit models with the data, and table 8.4 gives the best-fit parameters. The flux of the AO1 diffuse component is 5.8×10^{-12} ergs s $^{-1}$ cm $^{-2}$. In particular, a good fit is obtained below 3 keV. In the > 3 keV energy band, however, the model could not represent the data well: there remains undulating residuals. No additional hard-tail component can improve the fitting.

Table 8.4: The best-fit parameters of the NEI fittings for IC 443 soft components

Region	N_H [10^{21} cm $^{-2}$]	kT [keV]	$\log n_e t$ [s cm $^{-3}$]	Ne	Na	Mg	Al	Si	S	Ar	Ca	Fe	reduced- χ^2 (d.o.f.)
							[solar abundance]						
00	4.2 +0.4 -1.1	1.22 +0.19 -0.14	10.26 +0.41 -0.20	0.80 +0.21 -0.52	<3.16	0.77 +0.19 -0.17	1.25 +1.37 -0.66	0.55 +0.14 -0.10	0.81 +0.54 -0.36	0.68 +1.23 -0.68	5.56 +11.30 -5.56	0.33 +0.31 -0.16	1.076 (156)
01	5.5 +0.4 -0.6	1.10 +0.08 -0.07	10.10 +0.10 -0.11	0.82 +0.16 -0.13	<2.03	0.63 +3.11 -0.09	1.03 +0.47 -0.42	0.66 +0.14 -0.10	1.53 +0.51 -0.37	2.43 +1.20 -0.97	12.30 +10.52 -8.47	0.38 +0.27 -0.15	0.8937 (197)
02	4.9 +0.7 -0.7	1.01 +0.27 -0.13	10.13 +0.28 -0.32	0.77 +0.26 -0.77	<4.04	0.84 +0.32 -0.21	1.46 +0.81 -0.77	0.46 +0.44 -0.14	1.05 +1.04 -0.52	<1.47	6.50 +27.60 -6.50	0.43 +2.90 -0.24	0.7949 (135)
03	6.0 +0.4 -0.4	1.03 +0.06 -0.05	10.22 +0.11 -0.10	0.77 +0.14 -0.12	<1.07	0.64 +0.09 -0.08	1.27 +0.39 -0.36	0.52 +0.08 -0.06	1.08 +0.32 -0.24	1.67 +0.80 -0.66	5.21 +6.39 -5.21	0.24 +0.09 -0.07	1.205 (210)
04	7.4 +0.6 -2.3	1.07 +0.07 -0.06	10.11 +0.13 -0.11	1.01 +0.23 -0.39	<4.48	0.64 +0.09 -0.18	1.15 +0.37 -0.45	0.53 +0.11 -0.10	1.24 +0.38 -0.34	1.87 +0.97 -0.83	9.71 +8.75 -7.12	0.23 +0.17 -0.23	1.104 (207)
05	4.7 +0.6 -0.6	1.18 +0.14 -0.12	10.07 +0.30 -0.27	0.78 +0.22 -0.78	<4.91	1.02 +0.25 -0.19	2.26 +0.92 -0.86	0.56 +0.37 -0.15	1.36 +0.96 -0.68	<1.26	<9.43	0.46 +2.06 -0.46	0.8691 (149)
06	4.3 +1.4 -1.5	1.15 +0.09 -0.08	10.69 +0.09 -0.15	0.25 +0.27 -0.21	<1.11	0.58 +0.16 -0.12	1.99 +0.68 -0.57	0.42 +0.08 -0.07	0.67 +0.13 -0.12	0.40 +0.32 -0.29	<1.64	0.30 +0.10 -0.09	0.9692 (183)
07	0.9 +4.0 -0.9	1.40 +0.29 -0.19	9.57 +0.50 -0.17	0.30 +0.67 -0.09	4.04 +1.83 -1.48	0.90 +0.37 -0.18	0.86 +1.37 -0.86	1.07 +0.24 -0.60	1.52 +0.68 -0.71	<0.78	<17.1	<20.2	1.069 (140)
08	3.1 +2.6 -1.6	1.41 +0.23 -0.18	10.70 +0.08 -0.16	0.07 +0.45 -0.07	<2.63	0.74 +0.25 -0.17	2.71 +1.19 -0.92	0.46 +0.13 -0.10	0.63 +0.20 -0.17	0.31 +0.40 -0.31	<2.37	0.34 +0.18 -0.18	0.7517 (149)
09	2.5 +1.6 -1.1	1.93 +0.44 -0.29	10.57 +0.06 -0.09	<0.35	<1.88	0.96 +0.31 -0.22	2.62 +1.48 -1.10	0.53 +0.16 -0.14	0.63 +0.24 -0.19	0.19 +0.47 -0.19	<1.95	0.51 +0.25 -0.18	0.8144 (145)
10	4.5 +2.6 -4.0	1.29 +0.48 -0.31	10.54 +0.27 -0.34	0.74 +0.92 -0.63	2.06 +5.46 -2.06	0.75 +0.50 -0.37	2.88 +2.06 -1.59	0.41 +0.19 -0.15	0.39 +0.32 -0.21	<1.11	<11.1	0.22 +0.37 -0.22	0.8036 (120)
11	5.4 +1.2 -4.0	1.45 +0.38 -0.32	10.01 +0.63 -0.33	0.68 +0.46 -0.68	<7.76	0.82 +0.41 -0.36	2.72 +2.33 -1.37	0.57 +0.51 -0.23	1.14 +0.95 -0.68	<1.63	1.52 +28.21 -1.52	0.53 +5.48 -0.53	0.7757 (111)
12	3.5 +1.4 -1.5	1.09 +0.13 -0.11	10.77 +0.09 -0.12	0.22 +0.29 -0.22	<0.96	0.78 +0.20 -0.15	2.31 +0.86 -0.69	0.36 +0.09 -0.07	0.40 +0.12 -0.11	<0.13	<2.13	0.39 +0.14 -0.12	0.9384 (132)

The definition of the solar abundances is from Allen (1973).



PV data

AO1 data

Figure 8.7: The regions where the NEI fittings were performed.

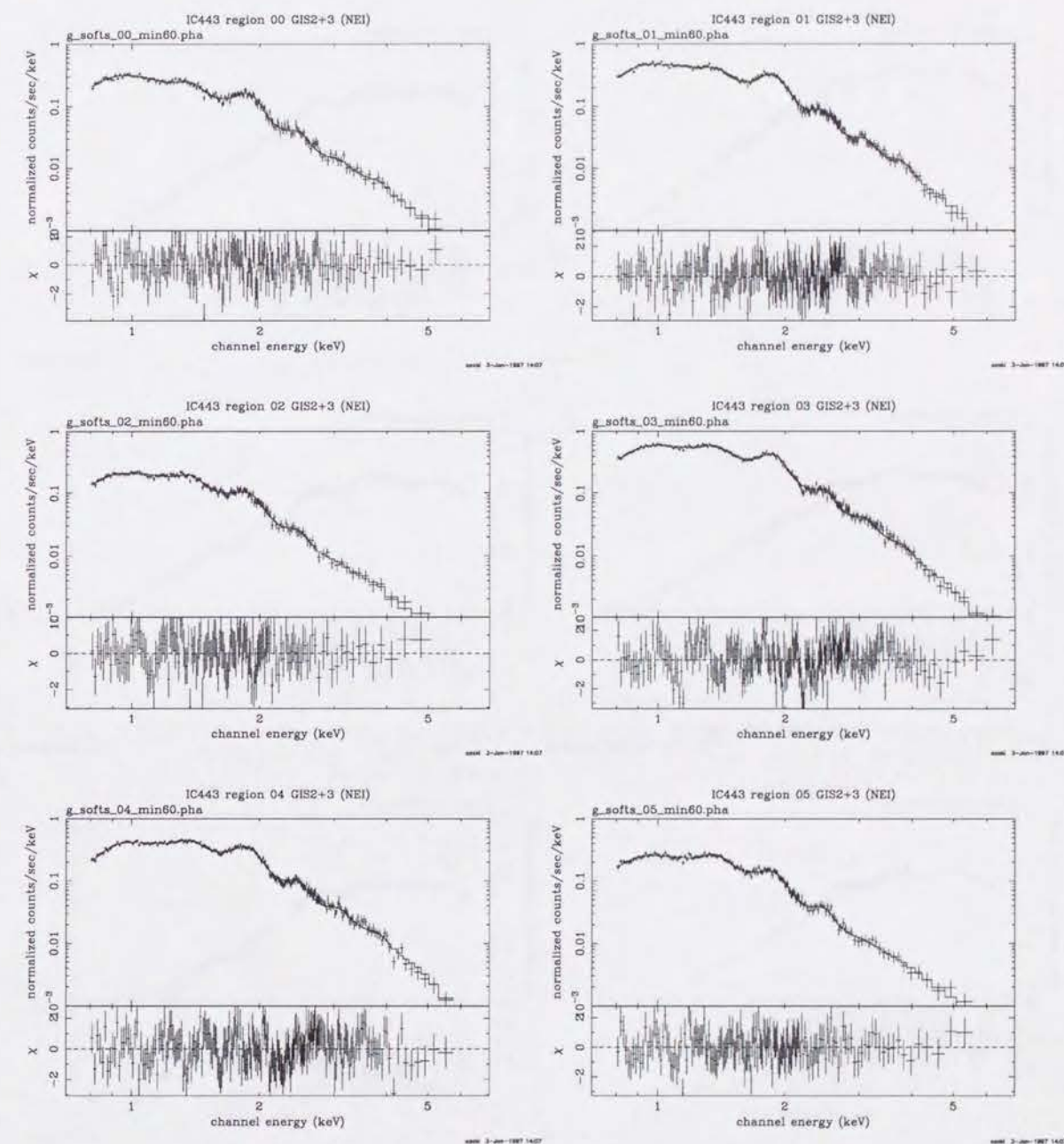


Figure 8.8: The data and the best-fit models of PV-region fittings.

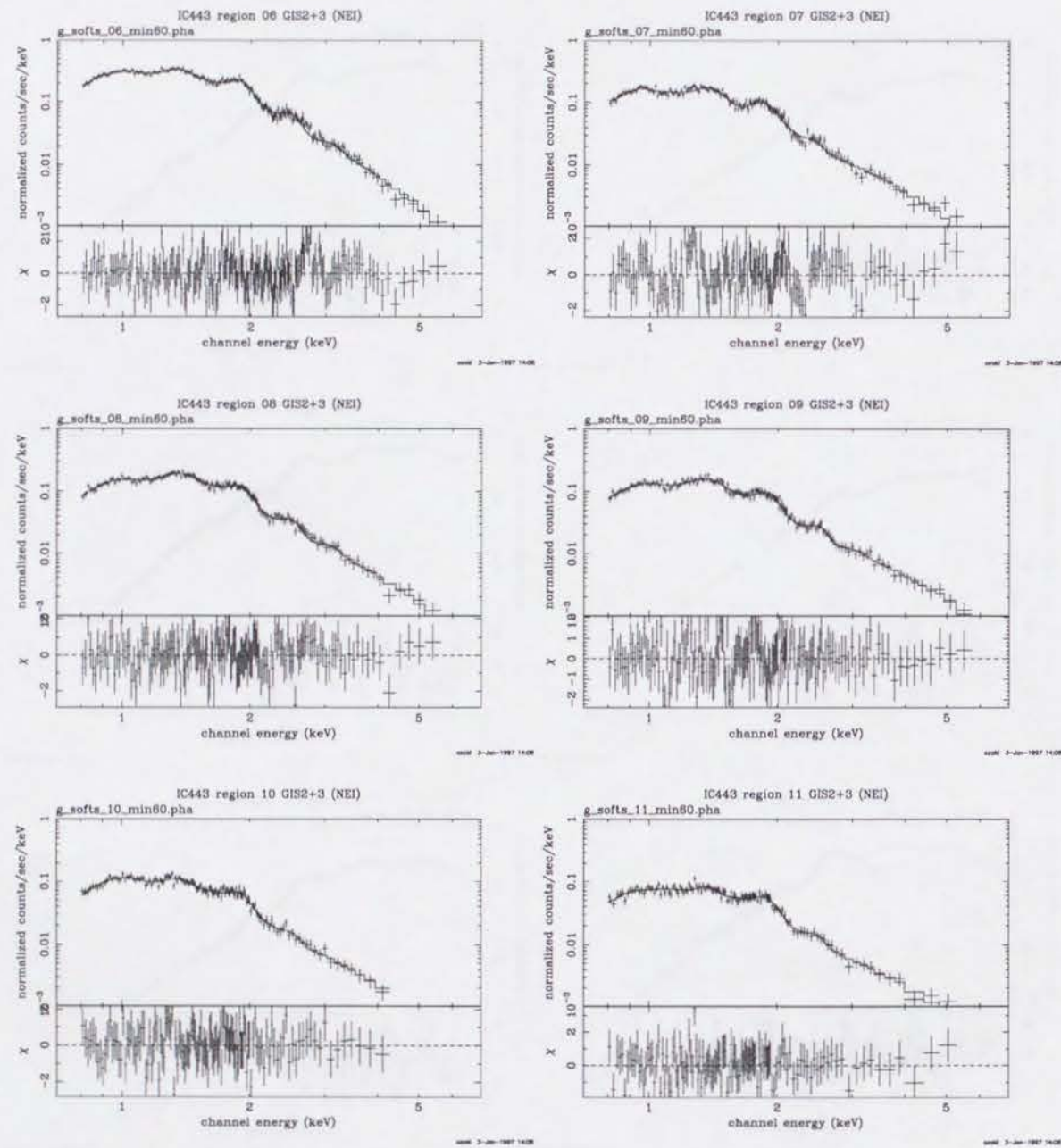


Figure 8.8: (continue) The data and the best-fit models of PV-region fittings.

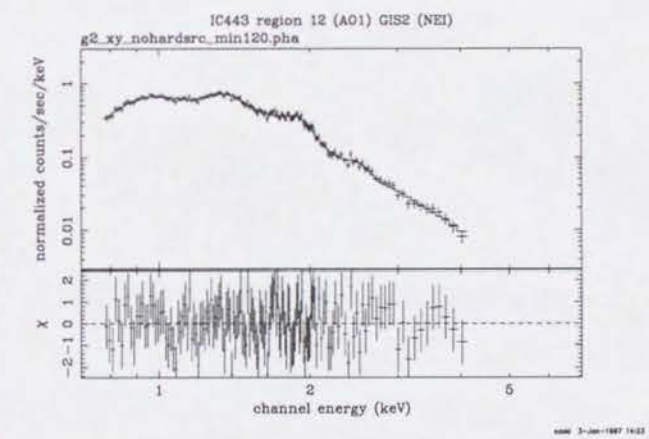


Figure 8.9: The data and the best-fit models of AO1-region fitting.

Chapter 9

Discussion

9.1 SN 1006

In the present analysis, we succeeded to separate the SN 1006 emission into two qualitatively different parts; one is the weak and uniform soft emission which contains strong fluorescent lines from highly ionized atoms, and the other is strong power-law emissions without the line confined in two distinct rims which is bright in the radio band as well. The lines in the uniform emission show that the emission is thermal plasma origin, which is commonly seen in shell-like SNRs. Among the lines, OVII and OVIII have been reported previously, but the others, Ne, Mg, Si and S, are first detected in the present analysis.

The strong power-law reveals a photon index $\simeq 3$, which is steeper than most of the previous observations, up to 20 keV. The difference seems to come from the high temperature plasma of the Lupus region, which is spread more widely than the Lupus Loop so that the major component at the higher energy with large FOV of the previous non-imaging instruments. In the present, on the other hand, the local background contribute little to the SN1006 data because of the small FOV.

In summary, the geometry of SN 1006 can be described as follows: in the whole region of the remnant, there exists the optically-thin NEI thermal plasma, and in the NE and SW rims, there confined strong power-law regions of which shape can be described by a uniform thin disk as the first order approximation (figure 9.1).

9.1.1 Interior emission

Reliability of the background estimation

Since the Interior region is contaminated by various complex backgrounds, we estimated the whole background with two methods; one is to re-construct an *ad hoc* model from the GIS and SIS data

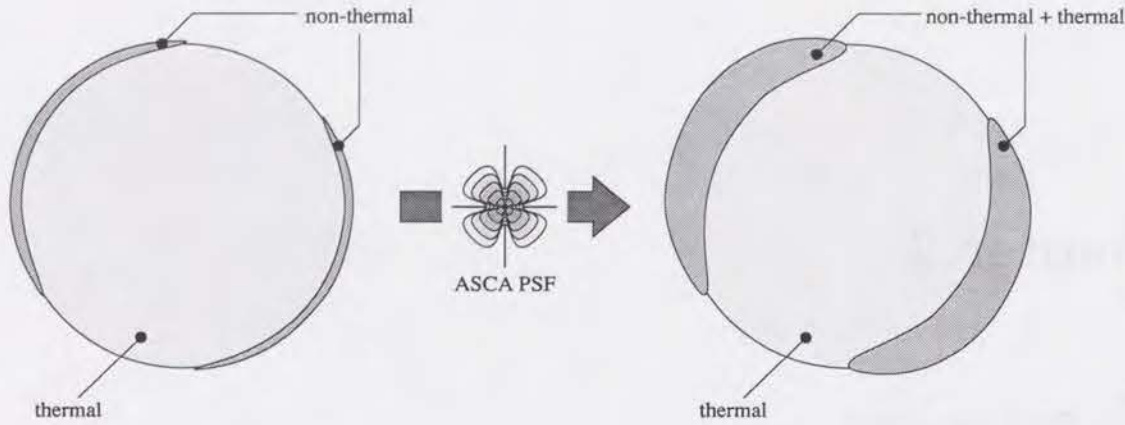


Figure 9.1: The schematic structure of the SN 1006 emission components.

of SIS-BG region outside the remnant, and the other is to de-compose the background into the known components, standard blank sky, the local diffuse emission and the Rim component leakage coming from the loose XRT PSF, estimate them separately and compose again. The former has the advantage that the model is constructed from the real data, and the latter has that each component of the model has the legitimate origin. On the other hand, the former has the disadvantage that the included Rim leakage spectrum may be different from that in the Interior region which should contain larger leakage from the SW rim, and the latter has that the XRT PSF has not been calibrated precisely for such a leakage estimation and there may be components other than those listed above. Since the Rim emission leakage is found to be the dominant background in the present analysis, the disadvantages relating to the leakage may affect the strength and the shape of the background model, which immediately affect the source analysis because the estimated backgrounds occupy a considerable ratio of the whole data. The essential solution for the background problem is to carry out further observation with the mirror of a much sharper PSF, which should be available in the future mission.

Although the backgrounds have uncertainties shown above, they agree with each other in the following points:

- The each power-law, which is dominant component in each model, has similar slope with each other, although they were made from completely different approach. The slope determined by the data fitting is flatter than the simulated ones, but it can be qualitatively understood as the result of the mixing with the CXB component, which has a photon index $\simeq 1.5$, at the higher energy band.
- With both backgrounds, we can regard the power-law component can well represent the SN1006 data in the same energy band, ≥ 2.7 keV. Since the simulated-BGs were renormalized

with the real SN1006 data at the hard band, it may be seen artificial; however, the simulated-BGs can explain the the slope, of > 2.7 keV of the SN1006 data.

On the other hand, the uncertainty of the background cause some difficulties in the analysis; as the background level above 1.5 keV is close to the continuum level from SN1006, even a little change of the background largely affects the continuum level, then the equivalent widths of lines above 1.5 keV, i.e. Si and S, differ much depending on the background model we used.

NEI fitting

The results of the whole energy band fitting showed similar trend of the kT - $n_e t$ relation to the < 1 keV fittings while the > 1 keV fittings showed the opposite trend; the higher kT gives, respectively, lower and higher $n_e t$, for the former and the latter. The former trend comes from the large data residuals below 1 keV data. Since only the > 1 keV fittings gave acceptable results, we continue the discussion below based on them.

The > 1 keV results, however, have some abnormal best-fit parameters in low kT - $n_e t$ components: extremely low $n_e t$ and very large abundances for some elements both in the two components. The former is extreme with the fitted-BGD, and the latter is with the simulated-BGD. The former can be explained as follows; after subtraction of rather flat background, the appearance of the low-energy tail of lines is enhanced, while the slope of the continuum changes little, hence gives lower ionization temperatures. The latter comes predominately from the larger flux density of the simulated-BGD, which makes the continuum flux smaller, hence gives larger abundance.

We can see the trend that the lower $n_e t$ components have higher abundance except for IN2 with the fitted-BGD. It can be qualitatively understood as follows; if the $n_e t$ is very low, the emissivity of each line becomes low, requiring the high abundances of the components

The abundances found in the present analysis are extremely larger than any other SNRs so far observed with ASCA; other SNRs abundances are reported as typically < 0.3 cosmic value (Miyata et al. 1994 for Cygnus loop, Hayashi et al. 1994 for E0102-72), while the present fittings show typically 10-100 solar abundances. It suggests that X-rays come primary from the ejecta which consists of the synthesized heavy elements in the supernova explosion. Accordingly, we infer that SN1006 is still in the free expansion or early of the adiabatic phase.

We cannot determine the emission measure of the whole thermal component precisely because the fittings with different backgrounds deduced inconsistent values in each area. However, the mean value between two areas for each backgrounds showed similar values, $\simeq 6$ or $7 \times 10^{53} \times \left(\frac{D}{1 \text{ kpc}}\right)^2 \text{ cm}^{-3} \text{ arcmin}^{-2}$, where D is the distance toward the remnant. Assuming that the thermal component is uniform all over the remnant of the circle of a 15 arcmin radius and the numerical

factor of the emission measure is 6.5×10^{53} , we can roughly evaluate the shocked mass as

$$M_{\text{sh}} \simeq 0.6n_e^{-1} \left(\frac{D}{1 \text{ kpc}} \right)^2 M_{\odot}. \quad (9.1)$$

If we assume D as 1.7 kpc or 3.1 kpc (Long, Blair and van den Bergh 1988), M_{sh} becomes $1.7n_e^{-1}$ or $5.8n_e^{-1}M_{\odot}$, respectively.

On the other hand, we can estimate the total mass inside the remnant as

$$M_{\text{all}} \simeq 14n_e \left(\frac{D}{1 \text{ kpc}} \right)^3 M_{\odot}. \quad (9.2)$$

If we assume D as 1.7 kpc or 3.1 kpc, M_{all} becomes $69n_e$ or $420n_eM_{\odot}$, respectively. Therefore, if $n_e < 0.16$ or 0.12 cm^{-3} , respectively, all the matter inside the remnant should have already been shocked.

We cannot infer, however, how much matter inside the remnant has been still unshocked, because we do not know the precise value of the density, and the shocked-matter ratio scales as the inverse square of the electron density. Even if we use the best-fit $n_e t$ values with the assumption that the age of the plasma is 997 yr, we cannot evaluate the density because of the large errors. It is still possible that there remains much unshocked matter inside the remnant. It is consistent with the fact of no detection of iron line together with the existence of the strong low-ionized Fe absorption in the UV band, which suggests that the remnant contains much unshocked iron inside it (Wu et al. 1993).

Equivalent widths estimation

In the equivalent widths estimation, we introduced the Doppler-shift and line-broadening into the Mg K-line in each region and background. The center-energy shifts correspond to the velocity of 1500–3000 km s^{-1} , and the broadening widths are equivalent to 3000–4000 km s^{-1} . Since they are similar to each other and are consistent with the shock velocity determined from the optical observation (2800–3870 km s^{-1} ; Kirshner, Winkler and Chevalier 1987), they are attributable to the shock velocity and the turbulence induced by the shock, respectively. However, there remains a problem; the Doppler velocities are directed toward us in both regions while the disk appearance of the thermal component and the ROSAT low-energy study (Willingale et al. 1996) suggests that the shock is of spherical symmetry. Since H α line at the NW edge of the remnant shows no Doppler shift (Kirshner, Winkler and Chevalier 1987), the possibility that the whole remnant is moving toward us is obviously rejected.

It is unclear whether lines except for Mg are Doppler-shifted or not; the equivalent width fittings did not require this for other lines.

It is still unclear how much iron exists in the remnant, which is the very strong key to determine the supernova type. The K fluorescent line, which is the strong probe of iron in the X-ray band, is still unseen all over the remnant. Neither the line nor the thermal continuum above 2.5 keV were detected; thus, we had to estimate the iron abundance from the L fluorescent line. However, the insufficient ASCA energy resolution to distinguish each L-line from strong O and Ne lines near iron L line energy makes the estimation impossible in practice.

9.1.2 Power-law emission

Emission mechanism

For the dominant emission mechanism of SN 1006, thermal and non-thermal have been suggested. With the present Ginga observation, we clearly rejected the possibility of the simple thermal spectrum and showed that the emission can be represented by a power-law up to 20 keV, and with the present ASCA observation, which has enough capability to distinguish emission lines from the continuum with high accuracy, we made clear that the lines, including the previously reported oxygens, in the strong rims can be wholly explained by the uniformly-distributed thermal component. If the emission comes from the complex of thermal plasmas of various temperatures, each component should have a temperature of a few keV to construct a steep power-law (see the emitting spectral form, equation (2.37), of which shoulder energy is near the plasma temperature), thus there should be much stronger lines because the stronger thermal-bremsstrahlung continuum means higher density or higher temperature which lead the plasma to more effective line emission. Thus we strongly suggest that the power-law component is non-thermal origin. The photon indices of Ginga and ASCA observations do not agree with each other; Ginga showed the steeper slope than ASCA. This can be attributable to the difference of the energy range; Ginga band is 2–20 keV, while ASCA is 0.5–10 keV. This difference and the fact that the ASCA power-law component needs much larger absorption than the Interior region suggests that the slope becomes gradually steeper in higher energy.

In the X-ray band, there are three candidates of the non-thermal emission mechanism; bremsstrahlung, inverse-Compton scattering and synchrotron radiation. In each mechanism, the emitting electrons have power-law energy distribution formed by the shock acceleration. We will discuss the possibility of each mechanism below.

Bremsstrahlung The bremsstrahlung spectrum from the nonrelativistic and monochromatic energy of electron becomes

$$F(E) \propto \ln \left(\frac{\sqrt{\epsilon} - \sqrt{\epsilon - E}}{E} \right) \quad (9.3)$$

for $E < \varepsilon$, where ε is the electron energy (Asvarov et al. 1990). In case of the relativistic electron, the spectrum becomes $F(E) \propto \ln(E^{-1})$ for the low energy limit, $E \ll \varepsilon$ (Rybicki and Lightman 1979). This function is almost flat (i.e. spectral index $\simeq 0$) below $\sim 0.1\varepsilon$ and becomes 0 at ε . Therefore, X-rays come mainly from electrons of the energy similar to the emitted photons. Accordingly, if the electrons have a steep power-law distribution, the X-ray emission also shows a steep power-law such as SN 1006. In such a case, the ionization should progress like a thin-thermal plasma of a few keV; thus, strong emission lines should be present as the Interior thermal region. However, such a line does not present. Thus, we can reject the bremsstrahlung model.

Inverse Compton Since the Rim emission from the SN 1006 is only the radio power-law, of which photon densities are much smaller than the 3 K microwave background, the dominant source for the inverse-Compton scattering is the 3 K microwave background. Since the mean output photon energy by the inverse-Compton process is $\sim \gamma^2 E_i$, where γ and E_i are the electron's Lorentz factor and the initial energy of the photon, The Lorentz factor of electrons which can kick up the 3 K photon to a few keV (10^7 – 10^8 K) X-ray is $\gamma \sim 10^{3.5}$.

Using the fact that the synchrotron radio spectrum has the same spectral index as that of the inverse-Compton if the original electrons is the same (Rybicki and Lightman, 1979), we can set the limit of the magnetic field strength. Since the synchrotron emission has its peak at the frequency given by equation (2.49), the peak frequency from the inverse-Compton electron of $\gamma \sim 10^{3.5}$ becomes

$$f \sim 10^7 \left(\frac{B}{1\mu\text{G}} \right) [\text{Hz}], \quad (9.4)$$

where B is the magnetic field strength. At this frequency, the power-law spectrum should have a photon index of 3, or a spectral index of 2. Since the radio emission, which is strongly confined at the same position as the X-ray, up to 10 GHz has the spectral index of $\simeq 0.5$, the frequency shown above have to be larger than 10 GHz. Thus we can obtain the limit of the magnetic field strength to be $B > 1$ mG, which is far larger than the mean Galactic magnetic field strength, $\sim 1\mu\text{G}$. Thus, we reject the inverse-Compton model.

Synchrotron emission If the emission is synchrotron origin, the X-ray spectrum should smoothly connect with the radio spectrum of the same origin. Figure 9.2 shows the whole SN 1006 spectrum from radio to X-ray frequencies; the two spectra cross at the frequency $\simeq 8 \times 10^{17}$ Hz, or $\simeq 0.3$ keV. In fact, as we already pointed out, the ASCA spectrum, together with those of ROSAT and Ginga suggest that the power-law index becomes smaller (flatter) in the lower energy than in higher energies. This also supports the assumption that the radio and X-ray

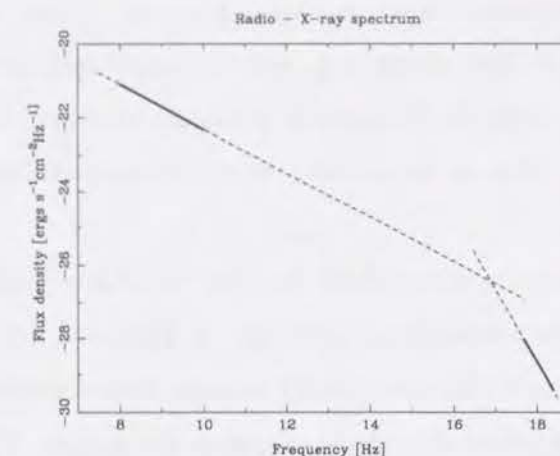


Figure 9.2: The spectra of SN 1006 from radio to X-ray frequencies. The radio data are cited from Reynolds and Ellison (1992).

spectra have the same origin, synchrotron emission.

Energetics

If the emission is synchrotron origin, we can estimate the electron energy which produce the synchrotron photon from equation (2.49), if the magnetic field strength is given. While there is no measurement of the strength for any type Ia SNR, the best estimate is thought to be 6 – $10\mu\text{G}$ (Reynolds and Ellison 1991). Since the power-law continuum extends up to $\simeq 20$ keV, the electron energy becomes ≥ 200 TeV.

The total energy of the synchrotron-emitting electrons becomes 3×10^{47} erg, which is about 0.1% of the kinetic energy released by the explosion.

Acceleration source

As the traditional source of synchrotron electrons in the X-ray band, pulsars, or rotating neutron stars, have been discussed. If the energetic electrons are supplied from a pulsar, it should be near the center of the remnant because the two power-law regions are located at the opposite sides of the remnant symmetrically. While pulsars usually have center-filled morphology, which is thought to come from the positronic pulsar wind, no corresponding point-like source has been discovered in SN 1006 from the radio to Gamma-ray band.

Even if the neutron star is invisible by some reason, there remain problems; the power-law shells are thinner than that of W 50, which is thought to be supplied the accelerated electrons from the central source SS 433 (Yamauchi, Kawai and Aoki 1994). In addition, there seems no significant

emission originating from the electron flows inside the remnant. To make such a geometry, the matter density and the magnetic field strength of both the inside and the outside of the remnant should be much lower than the shell. It is unnatural to assume that only the shell has far stronger magnetic field than elsewhere. Thus as far as the energetic electrons in SN1006, the pulsar origin is unlikely.

More likely mechanism, with conjecture of the fact that the X-ray shells well coincide with the radio, is the first-order Fermi acceleration in the shock. In this case, not only electrons but also protons should be accelerated up to the same energy because ultrarelativistic electron and proton, except it charge, are essentially identical in the acceleration mechanism. Therefore, the power-law component can be interpreted as a support of the cosmic-ray (proton) acceleration in SNR up to ≥ 200 TeV.

The efficiency of the first-order Fermi acceleration should change position by position depending the reflecting angle between the shock-propagating direction and the magnetic field; it is generally thought that the larger angle makes the efficiency larger because the mean free path of charged particle of which flight direction is perpendicular to the magnetic field is expected much shorter than that parallel to the field. Therefore, the strong emission is expected to distribute near the great circle of the shock shell if the remnant is in nearly uniform magnetic field; however, the emission is confined in two polar regions, where the radio polarization implies that the magnetic fields cross the shock front with small incident angle (Reynolds and Gilmore, 1993). These observational facts implies that the acceleration efficiency is higher in the parallel shock.

Possibility of the Gamma-ray observation

If the emission is of synchrotron, the X-ray emitting electrons should kick up the 3 K background to a few TeV by the inverse-Compton process. If such a emission is detected by EGRET on-board the Compton Gamma-Ray Observatory (30 MeV–10 GeV) or CANGAROO air Čerenkov experiment (~ 100 GeV–), we can determine the magnetic field strength at the rims with comparing it and the X-ray synchrotron flux which is determined by the number of the electrons and the magnetic field strength, because the inverse-Compton photon flux is determined only by the number of the scattering electrons and the source photon density.

9.2 IC 443

In the present analysis, we first obtained the IC 443's large scale structure with high energy and moderate spatial resolutions up to 10 keV. With these feature, we discovered an incom-

plete semi-circular structure in high energy band which is seen in other wavelength, and analyzed the previously-known thermal components under the condition that the continuum shape and the line profiles, from which we can determine the absorption column density and the abundances, respectively, can be distinguished from each other.

9.2.1 Soft component

We analyzed the large-scale spectral trend over the bright part of IC 443. It is the first time that such a analysis is done with enough high energy resolution and good statistics to distinguish each abundance up to $\simeq 5$ keV. Figure 9.3 shows the plot of the best-fit parameters with 90% errors for each region.

We could represent the each spectrum with the single-component NEI plasma model. Most of the parameters do not largely differ from position to position. In particular, the absorptions do not show the systematic change suggested with Einstein IPC (Petre et al. 1988) and ROSAT PSPC (Asaoka and Aschenbach 1994); though the previous observation suggested that the southern parts of the PV FOV (region 05–09) have higher absorption than the northern parts, the present analysis did not show such a tendency.

The ionization time $n_e t$, however, shows systematic change; in the region 06, 08 and 09, they are significantly higher than other region. For the region 08 and 09, this can be attributable to the molecular clouds seen in IRAS 60 μ m band and H₂ 1-0 S(1) line. Since the molecular clouds and the surrounding regions have higher density than the other regions, the ionization near the clouds should goes faster than the others. The region 06, however, has no active counterpart, suggesting no interaction between the molecular cloud and the shock in radio or IR band. In this region, the density would not be high enough to form the molecular cloud.

Abundances of the most elements, except for silicon and iron with significantly smaller than the solar, are not largely differ from the solar. This suggests that the X-ray emitting materials are mainly interstellar gas which is heated by the shock in the adiabatic phase.

9.2.2 Hard component

With the present analysis, we found that the hard component has an incomplete semi-circular form which lies along the previously known molecular clouds. Within the region, there are two especially bright spots which are near to but do not just coincide with the known CO molecular cloud clumps.

The photon indices of the hard components found with ASCA agree to that of the Ginga result within the 90% error. However, the 7 keV flux of the total ASCA hard component of $\simeq 9.6 \times 10^{-5}$ photons s⁻¹keV⁻¹cm⁻² can account only 30% of the Ginga flux at 7 keV of $\simeq$

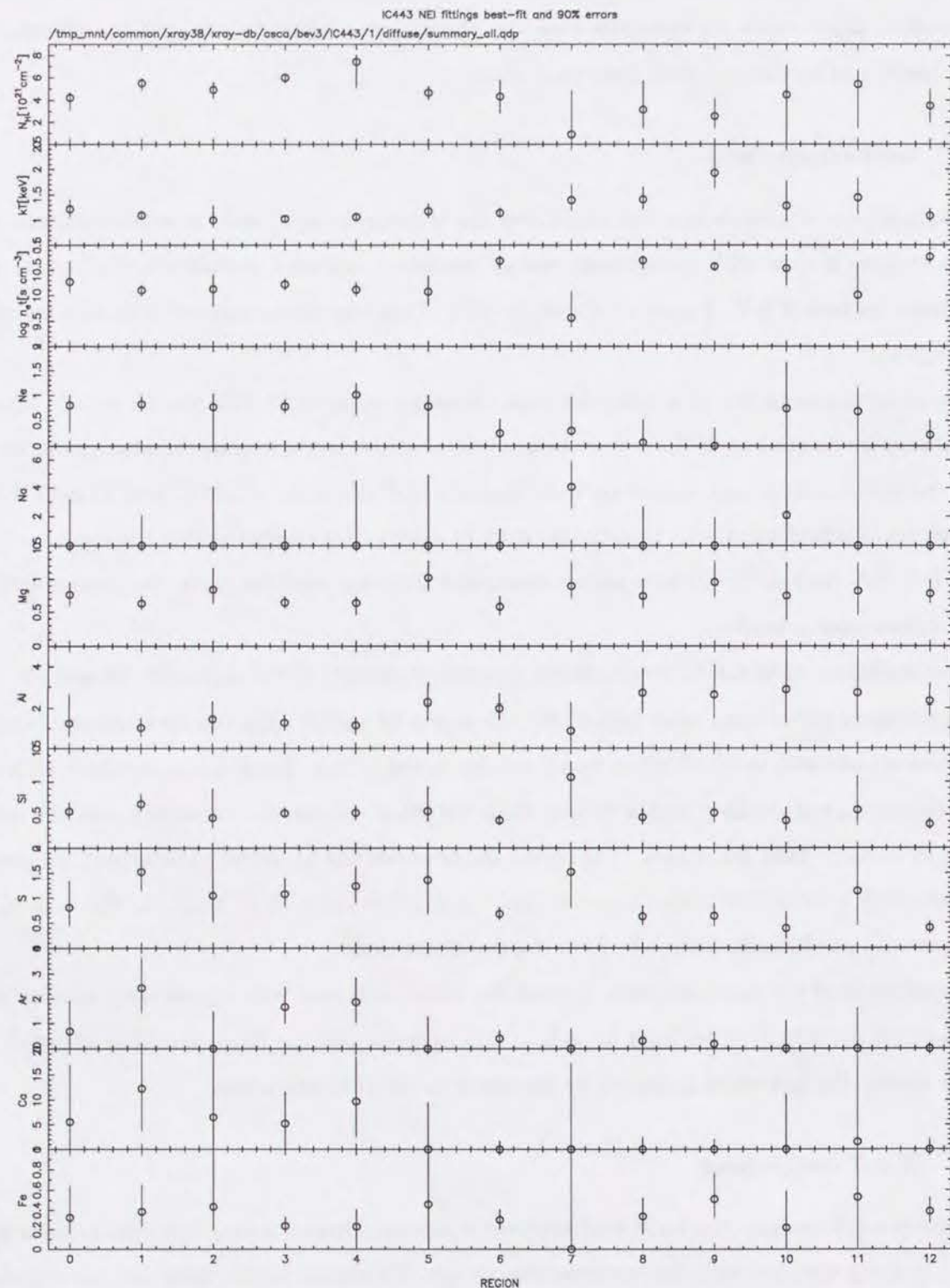


Figure 9.3: The best-fit parameters with 90% errors of the IC 443 soft-component fittings.

2×10^{-4} photons $s^{-1}keV^{-1}cm^{-2}$ (figure 2 of Wang et al. 1992). This suggests that a further extended emission outside the present ASCA FOV may present. Possibly the hard-bar at the southern edge of the PV FOV may be extending to the south, where radio emission is certainly extending.

Due to poor statistics, we could not make clear whether the emission is thermal or not. If the emission is thermal, the high temperature plasma would be due to molecular clouds, because the hard components coincide with them. Since the molecular clouds would have higher density $n_{H_2} \geq 10^5 cm^{-3}$ (Dickman et al. 1992) than the usual interstellar density $n_H \sim 1 cm^{-3}$, the energy transfer from atoms to electrons in the molecular clouds should progress more rapidly than that outside the clouds. Since the transfer speed scales as $n_e^{2/5}$ (equation (2.32)), it is possible that the electron temperature near the molecular cloud is a few times larger than outside, which we exactly found.

As for the non-thermal emission, same candidates as discussed for SN 1006 are conceivable. In addition, we will discuss the relation between the hard component and the GeV gamma-ray emission found with EGRET on Compton Gamma-Ray Observatory (Thompson et al. 1995, Esposito et al. 1996). The semi-circular shape overlaps the EGRET point-source error contour, of which 95% confidence level has about 20 arcmin diameter (figure 9.4) and covers the hard-bar. In the center of the contour, we found no significant hard spot. However, it is possible that the gamma-rays come from the diffuse source because the PSF of EGRET is larger than the spatial extent of IC 443 and the position and the contour were determined under the assumption that the gamma-rays come from a point source (Esposito et al. 1996).

The spectral slopes of the hard-spot and the hard-bar agree with each other within their 90% confidence level error, and also agree with the EGRET point source. It implies that the two different-band spectra are closely related. As the emission mechanism, we can consider that the X-rays are emitted by the synchrotron radiation, and the gamma-ray are by the inverse-Compton mechanism from the same electrons. In this case, we can estimate the magnetic field strength of the synchrotron region using the relative strength of the both region.

Since IC 443 has strong infrared (IR) emission, the inverse-Compton photon flux should be larger than the case that the source photon is only 3 K microwave background. Since we do not know the IR photon density at the inverse-Compton region, we can only estimate the lower-limit of the magnetic field at the scattering region as follows.

For a power-law distribution of relativistic electrons of which the number density with energies between γ and $\gamma + d\gamma$ is expressed in the form

$$N(\gamma)d\gamma = C\gamma^{-p}d\gamma, \quad (9.5)$$

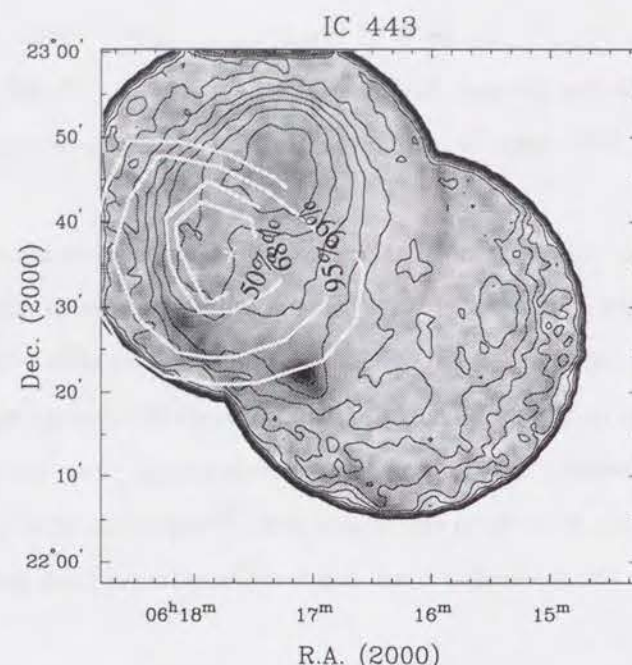


Figure 9.4: The ASCA soft and hard components (the black contour and the grayscale, respectively) and the EGRET point-source confidence contour (white).

where C is the constant, the inverse-Compton spectrum from the black-body radiation becomes

$$I(E) = \frac{C 8\pi^2 r_e^2}{h^3 c^2} (kT)^{\frac{p+5}{2}} F(p) E^{-\frac{p+1}{2}} [\text{photon s}^{-1} \text{erg}^{-1}] \quad (9.6)$$

$$F(p) = A(p) \Gamma\left(\frac{p+5}{2}\right) \zeta\left(\frac{p+5}{2}\right)$$

$$A(p) = 2^{p+3} \frac{p^2 + 4p + 11}{(p+3)^2 (p+5)(p+1)},$$

where r_e is the classical electron radius (Rybicki and Lightman 1979).

Substituting the EGRET observational value (Esposito et al. 1996), we can set the upper-limit to the number of the inverse-Compton electrons C as

$$\frac{C}{D^2} \leq 1.1 \times 10^{17} [\text{cm}^{-2}], \quad (9.7)$$

where D is the distance toward the IC 443. With this condition, we can set the lower-limit of the synchrotron magnetic field strength B to be

$$B \geq 1.0 [\mu\text{G}] \quad (9.8)$$

using equation (2.52). This value is consistent with the mean magnetic field strength on the Galactic plane. Since the hard X-ray region is thought to be inside or near the molecular cloud, the magnetic field could be larger than the average of interstellar space. Therefore, it is reasonable to assume that the X-rays and gamma-rays are emitted from the same electrons with the synchrotron emission and the inverse-Compton mechanism, respectively.

Chapter 10

Conclusion

In the present work, we observed two shell-like supernova remnants, SN 1006 and IC 443, with Ginga and ASCA, and found that each has two qualitatively different emissions, the diffuse soft NEI plasma emission and the edge-confined hard component.

We made clear that the hard component of SN 1006, which has been known as the dominant X-rays and has been discussed for the origin, is not thermal emission, but non-thermal. The spatial distribution of the hard component is completely different from that of the soft, but similar to the radio. The X-ray spectrum can also be smoothly connected to the radio slope. Therefore, both the hard X-ray and radio emissions are originated from the same process, most probably synchrotron radiation of high energy electrons accelerated at the shock front. The highest energy of the source electrons is suggested as large as ~ 100 TeV. We infer that protons are also accelerated up to the same energy, and suggest that the shell-like SNRs are, even if not all, major cosmic X-ray sources.

The X-ray spectrum of the hard components in IC 443 can be described either by a power-law or thermal bremsstrahlung. From radio results together with the GeV gamma with GRO, we propose that likely scenario is that the X-rays are synchrotron emission from high energy electrons up to ~ 100 TeV, although a thermal plasma emission of higher electron temperature than the soft component due to the higher density is also possible. To judge the origin, we need further observations. Since the present hard component is weaker than that detected by Ginga, the component should have more extensive distribution than the ASCA FOV.

The soft component of SN 1006 showed large abundance of heavy elements. This suggests that SN 1006 is still in the free expansion or early adiabatic phase, in which X-rays come mainly from the heavy-elements rich ejecta. Further precise study with improved spatial resolution should be done to separate the thermal emission from the strong non-thermal emission.

For IC 443 soft component, we first carried out the systematic analysis with better energy

resolution than before. We found no significant variation of the absorption column across the whole remnant on the contrary to the previous observations. The abundances are roughly solar with no variation over the whole SNR region, hence the soft X-rays from most region of the remnant are likely from the interstellar gas rather than the ejecta. We therefore infer that IC443 is in a typical phase of adiabatic expansion.

The detection of the hard (and probably synchrotron) emission from both free-expansion and adiabatic phase SNRs suggests that the cosmic rays up to ~ 100 TeV are accelerated in various stage of SNRs. To confirm this possibility, further studies on hard X-rays from other shell-like SNRs in various ages are required.

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All the observational data were obtained by the members of the Ginga team or the ASCA team.

The Ginga data analysis was performed on the FACOM M340 computer of The High Energy Physics Laboratory of Kyoto University.

This research has made use of the HEASARC database, SkyView service (NASA/Goddard), the NASA Astrophysics Data System abstract service and the NASA/IPAC extragalactic database (NED).

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