Part 6
Winds and the ISM

Section A
Supernova Remnants

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Recent X-ray Observations of Pulsar Nebulae

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Abstract. Results from the X-ray observations of pulsars with ASCA are presented. The surroundings of pulsars are investigated in detail taking advantage of ASCA's unique capabilities; high spectral resolution and a high throughput over a wide energy range from 0.4 keV to 10 keV. The spectral characteristics of the nebulae of PSR B1509−58 and the Vela pulsar are spectroscopically investigated. A jet-like feature is found from PSR B1509−58. We detected diffuse emission sources in the vicinity of many pulsars. The high probability of finding such diffuse sources for many pulsars suggests that they exist universally for all the active pulsars, and that they are powered by the pulsars. SNR Kes 32 was imaged in X-ray for the first time. Its X-ray properties can be used to examine its association with the nearby pulsar PSR B1610−50.

1. Introduction

The charged particles accelerated in the vicinity of a pulsar flow out into the interstellar space and form a shock. Here, the charged particles are not only thermalized, but also are accelerated again to produce non-thermal particles. The flow also heats the ambient matter. Such a shock region can produce both thermal emission and synchrotron radiation. The local condition, such as the magnetic field and particle density determines which process dominates. The spatial extent of such emission can vary. It may be as small as to be observed as a point source or as large as more than ten light years.

The Crab nebula is the prototypical example of a pulsar nebula. The equatorially dominated pulsar wind collides with the surrounding matter and forms a shock in a ring shape. The accelerated leptonic particles emit synchrotron radiation.

In some cases, the diffuse emission may be seen in a very asymmetric shape with respect to the pulsar. In the X-ray image of the Vela pulsar and PSR B1509−58, a jet-like feature starting from the pulsar is observed. It suggests the presence of a collimated outflow of charged particles from the pulsar. However, the acceleration mechanism and the emission processes for the collimated outflow are poorly understood. In the following section, we investigate the X-ray spectra of the "jets" of the Vela pulsar and PSR B1509−58.

Determination of the energy budget of pulsars is always elusive. The observed pulsating radiation is only a tiny fraction of the rotation energy loss rate

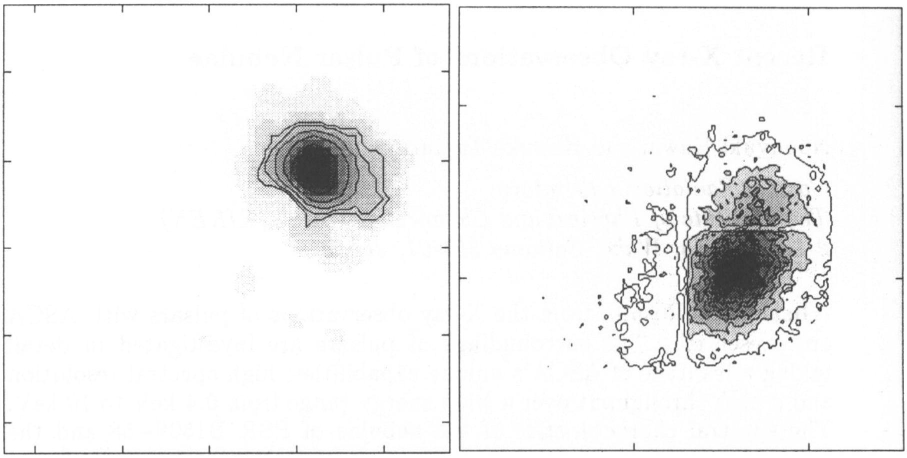

Figure 1. The X-ray image of MSH 15−52 obtained with ASCA SIS. (a) left: Thermal component constructed with Mg Kα line. (b) right: Non-thermal component constructed with the X-rays above 2.2 keV. PSR B1509−58 is located at the brightest region. A jet-like feature is extended to the north from the pulsar in the non-thermal image.

in most cases. Most of the energy is emitted into space in invisible forms such as the pulsar wind. This invisible energy flux may become indirectly observable as the pulsar nebula in particular in the X-ray range. We attempted a search for diffuse X-ray emission in the vicinity of active pulsars. Surprisingly we found diffuse X-ray source in the vicinity of many pulsars we looked at. These results are also presented.

2. Do pulsars have jets?

The Crab nebula is traditionally explained as the synchrotron emission of the leptonic particles that are accelerated at the ring-shaped shock front formed by the pulsar wind in the equatorial region. A ROSAT HRI image suggests the presence of collimated jets in the polar directions (Hester et al. 1995). Evidence for a one-sided outflow from the Vela pulsar has been also discovered (Harnden et al. 1985, Markwart & Ögelman 1995). These arguments for the pulsar jet have been based on rather subjective interpretation of the X-ray images, and theoretical supports have not been given yet. To understand the "pulsar jet", it is necessary to look for more examples. If a suspected feature is found, it should be investigated spectroscopically to clarify the emission process and the nature of the "jet". From this point of view, we analyzed the ASCA data of two pulsars.

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2.1. PSR B1509–58 in the SNR MSH 15–52

PSR B1509–58 is a young pulsar with a characteristic age of 1700 yr and a period of 150 ms. It was found by the Einstein observatory in the SNR MSH 15–52 (Seward & Harnden 1982). In the X-ray image, it consists of two nebulae in the north and the south. The north nebula is coincident with a H II region RCW 89, and the pulsar is located at the center of the south nebula (Seward et al. 1983)

The ASCA Solid-state Imaging Spectrometer (SIS) observations (Tamura et al. 1996) revealed that the south nebula containing the pulsar exhibits a non-thermal spectrum while the north nebula emits strong emission lines characteristics of thin-thermal emission. Taking advantage of ASCA's wide energy band and high spectral resolution (Tanaka et al. 1994), we constructed two X-ray images corresponding to different emission processes. Fig.1(a) is the image constructed only from the photons in the Mg K α line representing the thermal emission. On the other hand, we know from the spectral analysis that very little thermal component is contained in the energy band above 2.2 keV. Fig.1(b) is constructed from the photons above 2.2 keV, and represents the non-thermal emission.

Comparison of the two images reveals that the nature of the two nebulae is completely different. The thermal component is only present in the north nebula, while the non-thermal component is brightest around the pulsar. Most remarkable is the morphology of the non-thermal nebula in the south. It has a narrow jet-like feature extending to the north, and its pointed end coincides just at the center of the north thermal nebula. This feature can be interpreted as a collimated jet emanating from the pulsar and colliding with the dense interstellar matter located in the north nebula. Then the north nebula is heated by the jet and emits thermal X rays. The upper limit for the thermal energy contained in the north nebula is comparable to the rotation energy of a neutron star spinning at 29 ms period. Therefore, the energy budget is consistent if the source of the energy injected in the north nebula is the rotation energy of the fast new-born pulsar. With the higher spatial resolution of ROSAT, a much smaller cross-like shape is also visible around the pulsar, suggesting the presence of jets in this pulsar (Greiveldinger et al. 1995, Trussoni et al. 1996).

2.2. Vela pulsar

The X-ray structure extending toward the south from the Vela pulsar was detected by the Einstein satellite (Harnden et al. 1985), and was clearly imaged by ROSAT (Markwardt & Ögelman 1995). Markwardt & Ögelman (1995) presumed that the "jet" is thermal without firm spectral data. The implied momentum carried by the hot gas moving in the jet is enormous, more than two orders of magnitude larger than the momentum which can be carried by the relativistic charged particles accelerated by the pulsar. Alternatively if it is synchrotron emission, the density and the momentum of the source leptonic particles causes no problem. Therefore, it is quite important to clarify the X-ray spectral nature of the "jet" or nebula of pulsars. We therefore studied the X-ray data of the Vela pulsar taken in the performance verification phase of ASCA.

The X-ray image of the Vela pulsar taken with ASCA GIS is shown in Fig. 2. Although it is difficult to resolve the compact nebula with a size of 1′ from the

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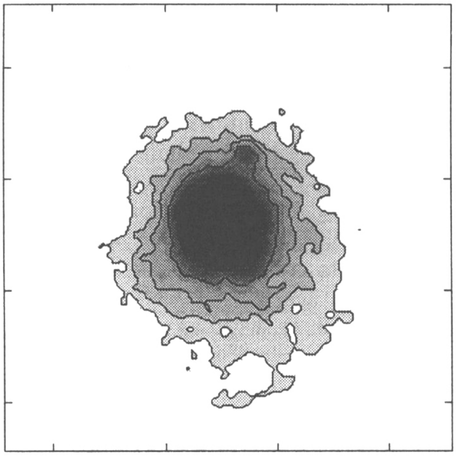

Figure 2. X-ray image of Vela pulsar and the surrounding synchrotron nebula obtained with the ASCA GIS. The dim X-ray source extended toward south corresponds to the base of the "jet".

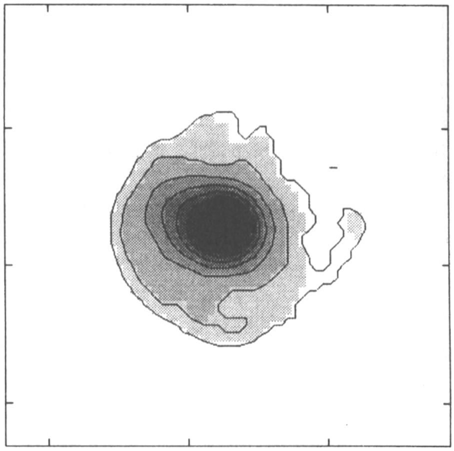

Figure 3. X-ray image of PSR B1951+32 in the SNR CTB 80 with the surrounding synchrotron nebula obtained with the ASCA GIS. A broad dim emission extends toward east.

point source with the spatial resolution of ASCA, a much larger diffuse emission is clearly seen to extend toward south. It can be considered as the base of the "jet" detected by Einstein and ROSAT. Since the point-spread function (PSF) of ASCA is extended and complicated (Serlemitsos et al. 1995), the photons from the jet cannot be separated from those from the compact source simply based on their spatial position in the image. We, therefore, evaluated the spectrum of the jet component as the excess component of the southern semicircle over the northern semicircle, where the whole circle was centered on the pulsar with 19′ radius. The central region within 8′ from the pulsar was not used because that region is dominated by the central compact source. The residual spectra did not have strong emission lines, and in fact we found that a power-law model fits the data better than a thermal model.

3. Are pulsar nebulae universal ?

If most of the rotation energy loss of a pulsar dissipates into interstellar space in invisible forms such as a pulsar wind which conveys magnetic field as well, a synchrotron nebula is expected to be found around an active pulsar as a result of the secondary energy dissipation process. Contrary to such expectation, such synchrotron nebulae have not been found for many pulsars. The X-ray imaging above 2 keV by ASCA, however, advances the understanding of the surroundings

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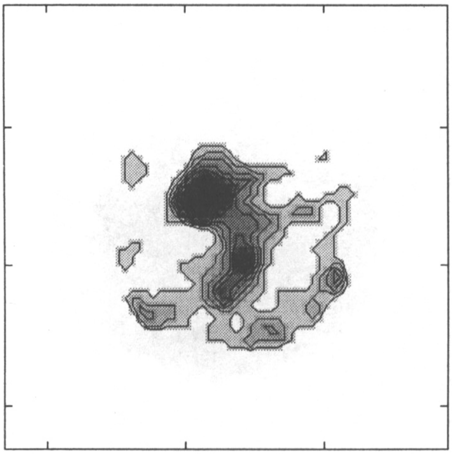

Figure 4. PSR B0656+14 (bright point source in the north) and the diffuse X-ray emission extending from the south-west of the pulsar toward the south.

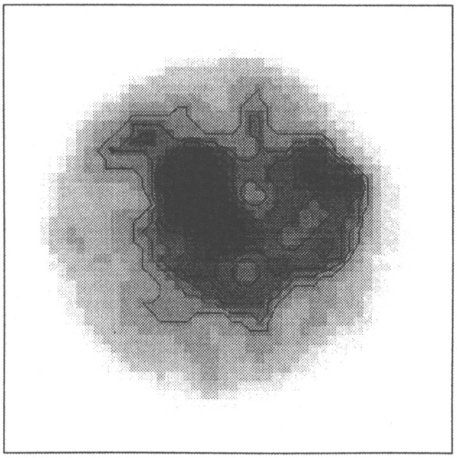

Figure 5. Geminga (brightest point source in the middle) and the diffuse X-ray emission extending in a fan shape toward the west.

of pulsars. In particular, Gas Imaging Spectrometer (GIS) on ASCA with its fairly large field of view (50′ diameter), good high energy response and low background (Ohashi et al. 1996), is suitable for search of extended hard (i.e. non-thermal or hot) X-ray emission. In this section, I summarize some of the results we obtained with the ASCA GIS.[1]

In addition to Crab, Vela, and MSH 15−52, another well-known object of this category is the SNR CTB 80 containing PSR B1951+32. The ASCA GIS image of CTB 80 is shown in Fig. 3. A broad fan-shaped diffuse emission (also seen by ROSAT: Safi-Harb et al. 1995) is extended toward south-east from the pulsar.

If we search for more examples of diffuse X-ray emission powered by pulsars, the physical association of the diffuse component with the pulsar should be examined. It is not always easy, but X-ray spectroscopy can be helpful in some cases.

The GIS image of PSR B0656+14 is shown in Fig. 4. An X-ray source is extended from the pulsar in a shape like the trunk of an elephant. Although the narrow structure close to the pulsar is dim and difficult to examine, the bright knot at the end can be studied spectroscopically. We found that this bright region at the end has much harder spectrum than the pulsar, and likely

[1]The size of the frame of the GIS images in this paper (Fig. 2 – 8) is ∼50′ containing the entire field of view of the ASCA GIS.

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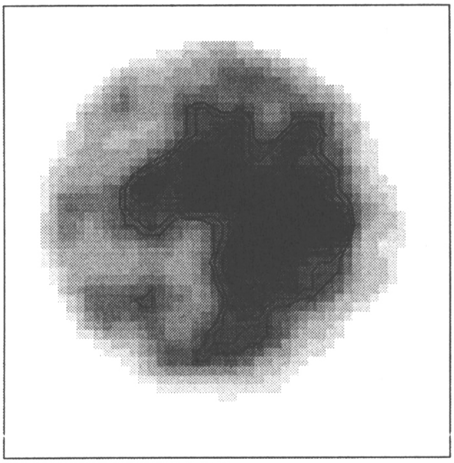

Figure 6. PSR B1929+10 and the diffuse X-ray emission extending toward the west.

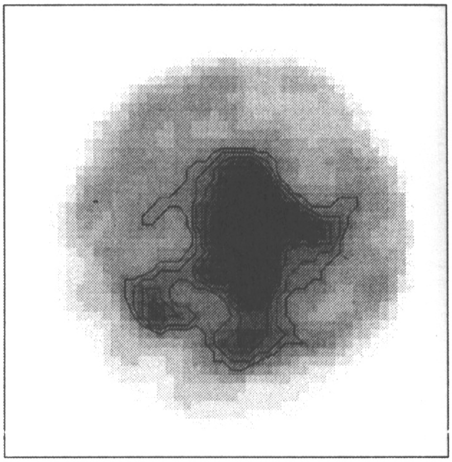

Figure 7. PSR B1046−58 seen as an extended X-ray source.

to be absorbed. Probably not all the extended structure is associated with PSR B0656+14.

Geminga can be found only as a point source in the ROSAT image. In the ASCA image, however, a filamentary structure across the pulsar and a large extended (but dim) emission are seen west of the pulsar (Fig. 5). The large emission region is probably extended beyond the field of view of ASCA.

The diffuse emission in the vicinity of PSR B1929+10 had been found with the ROSAT observations (Yancopoulos et al. 1994), and was interpreted as a "ghost nebula" of the pulsar. In the ASCA image above 2.2 keV (Fig. 6), the diffuse emission is actually brighter than the pulsar, suggesting a harder, possibly non-thermal spectrum.

PSR B1046−58 is relatively unknown, but has a strong "spin-down flux", and non-pulsating GeV gamma-ray emission is detected by EGRET (Thompson, this volume). With ASCA, dim, but extended emission across the pulsar is seen (Fig. 7).

As shown above, more and more examples of extended X-ray emission are found in the vicinity of pulsars. weIn fact, among the pulsars with ASCA data which we looked at, in more than half of them, we saw some form of diffuse emission. In some cases we did not find any only because there were strong contaminations from nearby known X-ray sources such as an accreting binary or an AGN. These findings lead us to speculate that the pulsar-powered nebula is universally present in every pulsars. The actual physical association needs to be examined carefully for each individual cases while more pulsars need to be investigated for the global statistical analyses, such as the correlation with the pulsar properties and the environmental conditions and the energy budget. It must be also noted that the spatial distribution of the emission is often asymmetric

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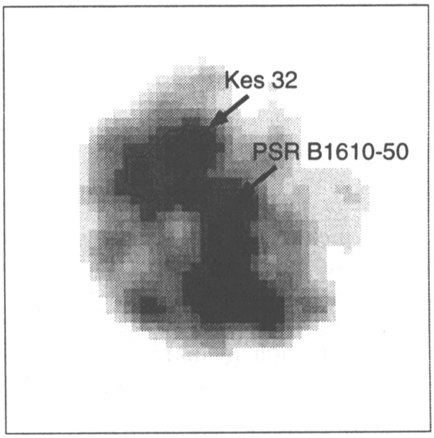

Figure 8. The X-ray image of PSR B1610−50 and Kes 32 obtained with the ASCA GIS. A diffuse emission component is extended from the pulsar to the south.

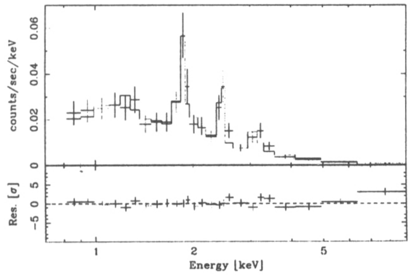

Figure 9. The X-ray spectrum of Kes 32 obtained with the ASCA SIS (crosses) shown with the best-fit NEI thermal model (histogram) and the residual (bottom panel). Strong emission lines of Si, S, and Ar are seen.

and some are pointed ("jet-like"). It suggests presence of collimated outflow of charged particles from the pulsars.

4. Kes 32 and PSR B1610−50

Fig. 8 shows the X-ray (> 2 keV) image of PSR B1610−50 obtained by ASCA GIS. The brightest region in the figure is a SNR named Kes 32, or G332.4+0.1 (Roger et al. 1985). PSR B1610−50 is actually a dim source to the south-west of Kes 32. A diffuse component can be seen to extend toward the south of the pulsar for a several arcmin, which is another example of a pulsar nebula discussed in the previous section.

Kes 32 had been known in the radio image as a shell with a "plume". Observation was attempted with the Einstein observatory, but no detection was made. It was also in the field of view of ROSAT PSPC observation of RCW 103, but the X-ray shell of Kes 32 was not seen. This is understandable because Kes 32 is located in the galactic plane at a great distance (probably > 5 kpc), the interstellar photoelectric absorption and the diffuse X-ray emission of the galactic ridge have effectively hid it in the soft X-ray band. The association of Kes 32 with PSR B1610−50 had been proposed (Caraveo 1993), and now it can be checked with X rays. With a preliminary analysis, at least the X-ray absorption seems to be consistent for both of them. However, the age of the SNR needs a careful study. Fortunately, a small fraction of Kes 32 was in the field

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of view of SIS, and observed with a superior energy resolution. Strong emission lines characteristics of thermal emission were found with a relatively hard continuum (Fig. 9). It can be explained best by a non-equilibrium ionization (NEI) model with rather high temperature (> 4 keV) and small relaxation parameter, implying a young age of the SNR.

5. Conclusions

The pulsar-powered nebula is a good probe to measure the otherwise invisible energy flux dissipating from the pulsar into the surrounding space. The diffuse X-ray emission expected for the pulsar nebulae can be studied by X-ray spectroscopy and imaging above 2 keV. We examined the X-ray image of pulsars obtained with ASCA, and found diffuse X-ray emission in many cases. They are often asymmetric or pointed, suggestive of outflows from the pulsars. In some cases it is likely to be a SNR which may or may not be associated with the pulsar. The nature of the diffuse X-ray emission around pulsars must be studied more in detail and for more targets to investigate their distance, age, and energetics.

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