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# Iron and dust in the supernova remnant IC 443

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We observed the supernova remnant IC 443 with the IRSF 1.4-m telescope, using the narrow-band filters tuned for the [Fe II] 1.257, 1.644 $\mu$m, Pa$\beta$, and $H_2$ 1–0 S(1) lines. Comparing these results with the intensities of thermal emission from the warm dust associated with IC 443, derived by *AKARI* and *Spitzer* images, we find that the [Fe II] emission is enhanced relative to the dust emission in the central region of IC 443. The Pa$\beta$ emission is also detected in the regions where the [Fe II] emission is bright. In contrast, the $H_2$ emission is limb-brightened in the southern ridge. We also derived the highly-ionized Fe line intensity map from the data obtained by *Suzaku*. From these results, we have investigated the origin of the [Fe II] emission, which is difficult to be explained simply by considering the lifetime of 0.1-$\mu$m silicate dust grains against sputtering destruction and the time for Fe to reach an ionization equilibrium in the hot plasma of IC 443.

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## 1. Introduction

The interstellar medium (ISM), composed of gas and dust, is heated and destroyed by shocks in supernova remnants (SNRs). In addition, SNRs release metal-rich ejecta and possibly provide dust to the ISM. Through these processes, SNRs contribute to the evolution of the ISM and give us a place to investigate such physical processes.

IC 443 is one of the SNRs which strongly interact with the surrounding ISM, and its age is estimated to be ~30,000 yr [1]. The presence of a pulsar wind nebula and metal-rich X-ray plasma suggests that the SNR is of a core-collapse origin [2]. The northeastern region of IC 443 is limb-brightened in the *J* and *H* bands. These bands are most likely to be dominated by the [Fe II] line emissions, which are thought to originate from dust destruction [3]. In contrast, the southern ridge is bright in the $K_s$ band. The $H_2$ lines, which are excited by shocks, are most likely to be dominant in this band, which means that slow shocks propagate in the dense medium. As described above, IC 443 shows different types of interaction between shocks and the ISM, and thus, is an excellent laboratory to investigate such physical processes.

## 2. Observations and Results

We observed IC 443 with the near-infrared (IR) camera SIRIUS (Simultaneous Infrared Imager for Unbiased Survey) on the IRSF (Infrared Survey Facility) 1.4-m telescope, located at the South African Astronomical Observatory, using the narrow-band filters tuned for the [Fe II] 1.257, 1.644 $\mu$m, Pa$\beta$ 1.282 $\mu$m, and $H_2$ 1–0 S(1) 2.121 $\mu$m lines. The far- and mid-IR images of IC 443 are derived by *AKARI* (65, 90, 140, 160 $\mu$m) and *Spitzer* (24 $\mu$m), respectively. We also used the X-ray spectra obtained by the *Suzaku*/XIS (X-ray Imaging Spectrometer) which covers the energy range of 0.5–12 keV.

Figure 1 (left) shows the pseudo color map of near-IR line emissions with the contours of the intensity of the warm dust emission associated with IC 443, derived by fitting the spectral energy distributions created from the far- and mid-IR images [4]. As can be seen in the figure, we detect the [Fe II] 1.257 $\mu$m emission all over the observed region. The Pa$\beta$ emission shows a spatial distribution similar to the [Fe II] emission, and the dust emission shows the shell structure. The $H_2$ emission is detected from the southern ridge.

To obtain the intrinsic line intensities, we performed extinction correction using the line ratio of the [Fe II] 1.257 and 1.644 $\mu$m. Since they are due to the electronic transitions from the same upper level, the intrinsic line ratio must be fixed at a value of 1.36 [5]. Comparing the observed line ratio with the theoretical one, we estimated the foreground extinction. Figure 1 (top right) shows the correlation plot between the intensities of the extinction-corrected [Fe II] 1.257 $\mu$m emission and the warm dust emission. The figure shows that the [Fe II] emission in regions B and C is enhanced relative to the dust emission as compared with regions A and D. The bottom right panel of Fig. 1 shows the correlation plot between the intensities of the extinction-corrected [Fe II] 1.257 $\mu$m and Pa$\beta$ emissions. As can be seen in the figure, both line emissions correlate fairly well with each other in all the four regions.

We also derived the spatial distribution of the highly-ionized Fe line intensity by fitting the XIS spectra with the model composed of bremsstrahlung and 6.7-keV Fe-K line emission. Figure

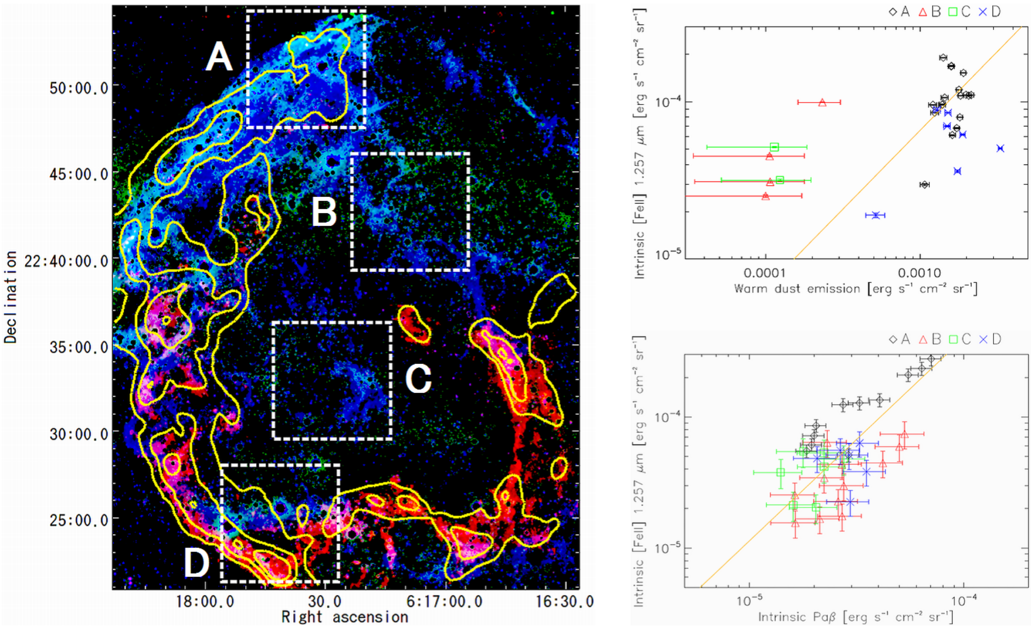


**Figure 1:** Left: Pseudo color image (red: $H_2$ 1–0 S(1), green: Pa$\beta$, blue: [Fe II] 1.257 $\mu$m) of IC 443, with the contours of the intensity of the warm dust emission. Right: correlation plots of the intensities of the extinction-corrected [Fe II] 1.257 $\mu$m emission with the warm dust emission (top), and with the Pa$\beta$ emission (bottom). Regions A to D are defined in the left panel, and the lines fitted to the data points of region A in the top panel, and all the regions in the bottom panel are overlaid in each panel. The data points are spatially sampled every 90$'$, which corresponds to 200 pixels of the camera array.

2 (left) shows one of the fitting results and Fig. 2 (right) shows the resultant line intensity map, with the contours of the smoothed [Fe II] 1.257 $\mu$m line intensity. From the figure, we can see that the highly-ionized (He-like) Fe is distributed in the northwestern region of IC 443.

## 3. Discussion

The origin of gas-phase Fe in SNRs is thought to be dust destruction because more than 99% of Fe is depleted to dust in the ISM. As seen in Fig. 1, the intensities of the [Fe II] emission and the warm dust emission in regions A and D seem to correlate with each other, supporting that the [Fe II] emission is related to the dust destruction. In regions B and C, however, the [Fe II] emission is notably strong relative to the dust emission as compared with regions A and D. This result is difficult to be explained, considering the lifetime of dust and the timescale for Fe to reach an ionization equilibrium in the hot plasma of IC 443: the former is estimated to be $\sim 1 \times 10^5$ yr by assuming 0.1-$\mu$m silicate dust grains, while the latter is estimated to be $\sim 2 \times 10^4$ yr [4]. Hence Fe should be highly ionized, and thus, the [Fe II] emission should be faint or absent in the regions where dust is completely destroyed. However the [Fe II] emission is bright in regions B and C where the dust is completely destroyed, and it does not seem to be consistent with the above time scales.

If $Fe^+$ in regions B and C is of ejecta origin, the abundance of $Fe^+$ relative to H in these regions must be larger relative to the other regions. However Fig. 1 shows that the line ratio of the

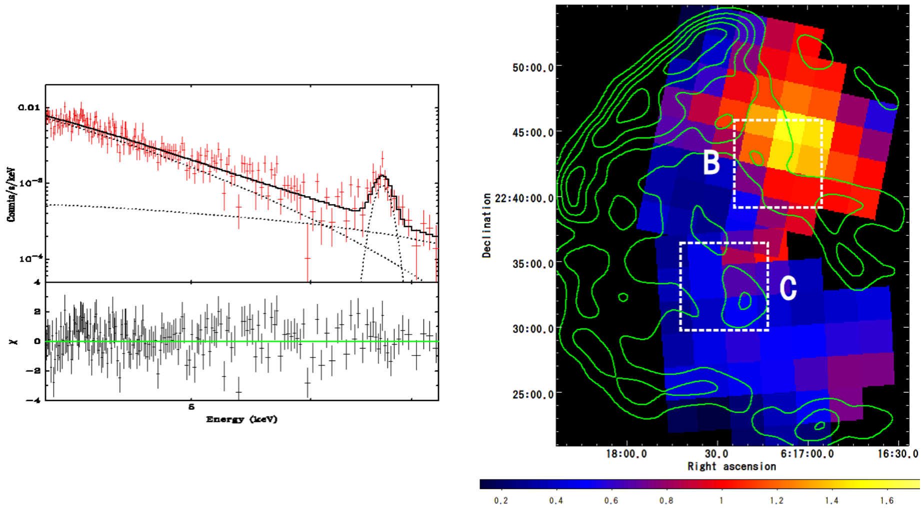


**Figure 2:** Left: an example of XIS spectral fitting results in the energy range of 4.0–7.3 keV. The top panel shows the spectrum with the best-fit model (bremsstrahlung and 6.7-keV Fe line emission plus CXB power-law component). The error bar is $1\sigma$. The bottom panel shows the residual from the best-fit model. Right: the 6.7-keV Fe line intensity map derived by the XIS spectral fitting, with the contours of the [Fe II] 1.257 $\mu$m line intensity smoothed by the gaussian of $\sigma$ =100 pixels, which corresponds to 45$'$. The color levels are given in units of photons $s^{-1}$ $cm^{-2}$ $sr^{-1}$.

[Fe II] 1.257 $\mu$m to Pa$\beta$ is almost the same over regions A to D, indicating that $Fe^+$ in regions B and C is of interstellar origin rather than of ejecta origin, which is also applicable to regions A and D. On the other hand, the highly-ionized Fe is distributed near region B and extended toward region C, suggesting that Fe in regions B and C is really interacting with the hot plasma for a significant fraction of Fe to be highly ionized. The lack of dust in regions B and C indicates relatively long interaction time scales, and yet the fact that $Fe^+$ still remains in such regions implies that gas-phase Fe was released from dust to the ISM at very late stages of dust sputtering destruction. One possibility is that most of the Fe atoms are contained in the deepest cores of dust grains, and another is that there is a population of Fe-rich dust which is relatively tough against sputtering.

## References


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