X-RAY ENERGY SPECTRA OF THE SUPERSOFT X-RAY SOURCES CAL 87 AND RX J0925.7−4758 OBSERVED WITH ASCA

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ABSTRACT

We report observation results of the supersoft X-ray sources CAL 87 and RX J0925.7−4758 with the X-ray CCD cameras (Solid-State Imaging Spectrometers [SISs]) on board ASCA. Because of the superior energy resolution of the SIS (∆E/E ∼ 10% at 1 keV) relative to previous instruments, we could study detailed X-ray spectral structures of these sources for the first time. We have applied theoretical spectral models to CAL 87 and constrained the white dwarf mass and intrinsic luminosity as 0.8−1.2 M⊙ and 4 × 10^37−1.2 × 10^38 erg s⁻¹, respectively. However, we have found the observed luminosity is an order of magnitude smaller than the theoretical estimate, which indicates that the white dwarf is permanently blocked by the accretion disk, and we are observing a scattering emission by a fully ionized accretion disk corona (ADC) whose column density is ∼ 1.5 × 10^23 cm⁻². Through simulation we have shown that the orbital eclipse can be explained by the ADC model, such that a part of the extended X-ray emission from the ADC is blocked by the companion star filling its Roche lobe. We have found that very high surface gravity and temperature, ∼ 10^10 cm s⁻² and ∼ 100 eV, respectively, as well as a strong absorption edge at ∼ 1.02 keV, are required to explain the X-ray energy spectrum of RX J0925.7−4758. These values are only possible for an extremely heavy white dwarf near the Chandrasekhar limit. Although the supersoft source luminosity should be ∼ 10^38 erg s⁻¹ at the Chandrasekhar limit, the observed luminosity of RX J0925.7−4758 is nearly 2 orders of magnitude smaller, even assuming an extreme distance of ∼ 10 kpc. To explain the luminosity discrepancy, we propose a model in which very thick matter that was previously ejected from the system, as a form of jets, intervenes the line of sight and reduces the luminosity significantly because of Thomson scattering.

Subject headings: accretion, accretion disks — stars: individual (CAL 87, RX J0925.7−4758) — white dwarfs — X-rays: stars

1. INTRODUCTION

Dozens of the supersoft X-ray sources (SSSs), which characteristically are radiating most energies in the softest X-ray energy band (≤ 0.5 keV), have been discovered in the LMC, SMC, M31, and Milky Way by Einstein and ROSAT (for a review, see, e.g., Kahabka & van den Heuvel 1997). It is believed that most SSSs are white dwarf binaries with large mass accretion rates (∼ 1 × 10⁻⁷−5 × 10⁻⁶ M⊙ yr⁻¹), and the energy source is steady nuclear burning on the white dwarf surface (van den Heuvel et al. 1992; Heise, van Teeseling, & Kahabka 1994). Observationally, our knowledge of the X-ray energy spectra of SSSs has been limited by the capability of the conventional X-ray detectors. While the energy bands of the Einstein IPC and ROSAT PSPC (0.1−2 keV) are suitable for the study of SSSs, their energy resolutions (∆E/E ∼ 1 at 0.5 keV) have not allowed one to clearly identify any possible spectral structures, such as emission lines or absorption edges. Having a superior energy resolution (∆E/E ∼ 10% at 0.5 keV), the ASCA Solid-State Spectrometer (SIS; Tanaka, Inoue, & Holt 1994) is potentially a powerful instrument for spectroscopic study of SSSs, although its detectable energy band (0.4−10 keV) is slightly too high to cover the typical SSS spectra.

The two SSSs, CAL 87 and RX J0925.7−4758, are known to have relatively hard energy spectra; therefore, we have chosen these two sources for precise spectral study with the ASCA SIS. While most SSSs have characteristic blackbody temperatures of ≤ 30 eV, those of CAL 87 and RX J0925.7−4758 are ≥ 40 eV (Schmidtke et al. 1993; Motch, Hasinger, & Pietsch 1994). CAL 87 was discovered during the LMC survey observations with the Einstein IPC (Long, Helfand, & Grabelsky 1981). It is an eclipsing binary with a 10.6 hr orbital period, exhibiting orbital eclipses in the optical band and accompanying shallow X-ray dips (Schmidtke et al. 1993; Alcock et al. 1997; Asai et al. 1998). With the assumption that the nondegenerate companion is an F star, Cowley et al. (1990) speculated that the compact...
object is massive and may be a black hole. However, *Hubble Space Telescope* observations revealed two adjacent stars 0\'\,88 and 0\'\,65 from CAL 87 (Deutsch et al. 1996), which have yet to be taken into account when determining the optical properties of CAL 87. Schandl, Meyer-Hofmeister, & Meyer (1997) successfully modeled the observed optical light curve of CAL 87, assuming a 0.75 M\(_\odot\) white dwarf and a 1.5 M\(_\odot\) companion. To account for the shallow X-ray dips, the accretion disc corona (ADC) model was proposed in which the blocking material partially covers the largely extended X-ray-emitting corona (Schmidtke et al. 1993).

RX J0925.7–475 was discovered in the *ROSAT* Galactic Plane survey project (Motch et al. 1994). This unusual, heavily absorbed star exhibits most X-ray emission at energies above ~0.5 keV, while most other SSSs have few X-rays above ~0.5 keV (Motch et al. 1994; Motch 1996). The orbital period is ~3.8 days, and the optical counterpart indicates strong reddening (Motch et al. 1994; Motch 1996; Schmidtke et al. 2000). A transient optical jet, similar to those observed from other superspurer sources, also has been observed (Motch 1998). The reddening, strength of the interstellar absorption lines, and *ROSAT* spectra are all consistent with a large hydrogen column density of N\(_H\) ≥ 10\(^{22}\) cm\(^{-2}\), which suggests that the source is located behind the nearby (d = 425 pc) Vela sheet molecular cloud (Motch et al. 1994). Optical light curve analysis suggests that the mass of the compact object is in the range of 0.5–1.7 M\(_\odot\) and that of the donor star is in the 1–2 M\(_\odot\) range (Schmidtke et al. 2000).

In this paper, we report precise analysis of the X-ray energy spectra of CAL 87 and RX J0925.7–475 observed with *ASCA*. Because of the superior energy resolution of the *ASCA* SIS, we could reveal detailed X-ray spectral features of the two sources. The *ASCA* CAL 87 light curve exhibits shallow orbital eclipses, and its energy spectrum shows deep absorption edges, which are identified as O \(\equiv\) VII and O VIII edges, as already reported by Asai et al. (1998). Preliminary spectral analysis of RX J0925.7–4758 has been reported by Ebisawa et al. (1996), and similar *ASCA* spectral analysis also has been carried out by Shimura (2000). As an extension of these studies, we apply theoretical local thermo-dynamic equilibrium (LTE) and non-LTE white dwarf atmospheric spectral models to CAL 87 and RX J0925.7–4758 and constrain the white dwarf parameters. Also, we carry out a simulation to explain the CAL 87 orbital light curve in the framework of the ADC model, such that a part of the extended ADC X-ray emission is blocked by a companion star and observed as a shallow and wide orbital eclipse.

2. OBSERVATIONS

RX J0925.7–475 was observed with *ASCA* from 13:28 UT on 1994 December 22 to 02:02 UT on December 23. CAL 87 was observed from 06:08 UT on 1996 September 6 to 08:30 UT on September 8. *ASCA* carries two SIS (SIS0 and SIS1) and two Gas Imaging Spectrometer (GIS2 and GIS3) detectors, each combined with an X-ray telescope, and the four sensors point in the same direction (Tanaka et al. 1994). Since RX J0925.7–475 and CAL 87 do not emit significantly in the GIS energy band (0.7–10 keV), we could not detect enough photons with GIS to carry out a spectral analysis. Therefore, we present only the SIS spectral analysis results in this paper. The GIS data of RX J0925.7–475 were used only for a coherent pulsation search, but we obtained null results in the frequency range of \(2 \times 10^{-4}\) to 8 Hz. After appropriate SIS data screening, the total exposure time was 15 ks for RX J0925.7–475 and 70 ks for CAL 87. The SIS 1 CCD Faint mode was used for both observations, and we applied the standard instrumental calibration. On each detector, the X-ray source photons were accumulated within ~4\(^\circ\) of the center of the source. Having made sure that both SIS detectors gave identical results, we combined the data and responses from the two sensors for further analysis to achieve better statistics. The background spectra were made from the region on the same chips where source photons are negligible, normalized by the selected area, and subtracted from the source spectra. Spectral-fitting analysis was carried out with the XSPEC spectral-fitting package (Arnaud 1996). For CAL 87, we used essentially the same data set as in Asai et al. (1998). Average count rates of the sources after background subtraction are 0.015 counts s\(^{-1}\) per SIS for CAL 87 (orbit averaged) and 0.28 counts s\(^{-1}\) per SIS for RX J0925.7–475 from 0.4–2.0 keV.

3. DATA ANALYSIS
3.1. CAL 87

As reported by Asai et al. (1998), *ASCA* data indicate shallow (~60\%) and wide (~30\% of the period) X-ray dips in phase with the optical eclipse of the white dwarf, which confirm the *ROSAT* results (Schmidtke et al. 1993; Kahabka, Pietsch, & Hasinger 1994). In order to study spectral variation, we extracted spectra from the eclipse and out-of-eclipse period in addition to the entire averaged spectrum. We took the ephemeris and orbital period from Alcock et al. (1997): the X-ray eclipse center (orbital phase \(\phi = 0\)) is MID = 50,331.9103, and the period is 0.4426714 day. For the eclipse period, we took the orbital period \(-0.16 < \phi < 0.16\) (see the orbital light curve in Fig. 2 of Asai et al. 1998), outside of which is considered the non-eclipse period.

We take into account both the interstellar absorption in the Milky Way and an intrinsic absorption within the LMC. In the spectral model fitting, following Asai et al. (1998), we fix the former column density at \(8 \times 10^{20}\) cm\(^{-2}\) and allow the latter one to be free. We assume the cosmic abundance for the Milky Way absorption and half the metal abundance for the LMC absorption (Dennefeld 1989; Vassiliadis & Wood 1994). In the tables below, we show only the amount of intrinsic absorption in the LMC thus determined.

3.1.1. Spectral Analysis with Blackbody + Edges

First, to characterize the observed spectrum, we analyze the energy spectrum, applying a simple phenomenological model, and consider how much we can tell about the source with minimum assumptions. We use the average spectrum taken from the entire period.

As we have shown in Asai et al. (1998), the CAL 87 spectral fit requires a deep absorption edge at ~0.85 keV, which may be interpreted as being due to O VII and O VIII edges at 0.74 and 0.87 keV, respectively; these two edges are so close and the source flux is so low, that the *ASCA* SIS cannot resolve them. We fitted the spectrum with these absorption edges with the fixed energies. The optical depth of the O VIII edge is not constrained, so we fixed it to 10.0, which practically allows no photons to escape above the edge energy. In this model, normalization of the continuum (effective emission area), temperature, and amount of absorption are
TABLE 1
CAL 87 BLACKBODY PLUS EDGES MODEL FIT FOR THE AVERAGE SPECTRUM

| Parameter | Unconstrained | Constrained |
|-----------|---------------|-------------|
|           | Temperature Model | Temperature Model |
| $N_H$ \(10^{21} \text{ cm}^{-2}\) | 7.7 ± 4.3 | 3.8 ± 0.5 |
| $T$ (eV) | 53 ± 148 | 75 (fixed) |
| Edge 1: $E_{\text{edge}}$ (keV) | 0.739 (fixed) | 0.739 (fixed) |
| $\tau$ | 0.49 ± 0.37 | 0.73 ± 0.30 |
| Edge 2: $E_{\text{edge}}$ (keV) | 0.871 (fixed) | 0.871 (fixed) |
| $\tau$ | 10.0 (fixed) | 10.0 (fixed) |
| $(R/10^3 \text{ km})^{\frac{1}{3}}$ | 3.2–1000000 | 9.2 ± 3.2 |
| $L_{\text{bol}}$ \(10^{36} \text{ ergs s}^{-1}\) | 15–630000 | 38 ± 10 |
| $\chi^2$/dof | 21.9 (31) | 23.9 (32) |

NOTE.—Absorption edge of the form \([-\tau(E/E_{\text{edge}})^{-3}\]) (for $E > E_{\text{edge}}$) is assumed.
* The distance is assumed to be 55 kpc.

strongly correlated and hardly constrained (Table 1, col. 2).

We may constrain the temperature based on a simple physical consideration, the fact that the $O_{\text{vii}}$ and $O_{\text{viii}}$ edges are observed simultaneously. If we assume the LTE condition, the ionization balance is determined by the temperature, $T$, and the electron density, $N_e$, through the Saha relation. The electron density can be related to the temperature and the pressure by the equation of state $n_e \approx P/kT$. Neglecting the radiation pressure, the gas pressure may be estimated from the hydrostatic equilibrium condition as $P \approx g/\kappa_R$, where $g$ is the surface gravity, which is typically $10^6–10^8 \text{ cm s}^{-2}$ for white dwarfs, and $\kappa_R$ is the Rosseland mean opacity, $\sim 0.4 \text{ cm}^2 \text{ g}^{-1}$. From these relations, for a typical temperature of several tens of eV, the electron densities in the white dwarf atmosphere of an optical depth of roughly unity are considered to be in the range of $10^{18}–10^{19} \text{ cm}^{-3}$. In Figure 1, we show the ion ratios for C, N, O, Ne, and Fe calculated from the Saha relation as functions of the temperature for the two electron densities $n_e = 10^{18}$ and $10^{19} \text{ cm}^{-3}$. It is seen that the condition where the $O_{\text{vii}}$ and $O_{\text{viii}}$ edges are both present (with $O_{\text{viii}}$ being more abundant) requires $T \approx 60–80$ eV.

Therefore, we fix the blackbody temperature at 75 eV. The results are shown in Figure 2 and Table 1 (col. [3]). We found the radius and luminosity with $T = 75$ eV are reasonable for a massive ($\geq 1 M_\odot$) white dwarfs (§ 4.1.1; Fig. 13). Thus, based on a simple model, we see that the energy spectrum of CAL 87 is likely to be explained by atmospheric emission from a massive white dwarf. Our data suggest that the energy spectrum emitted from the white dwarf atmosphere, where the strong absorption edges are produced, is directly seen. Consequently, if the white dwarf is permanently blocked from the line of sight by the outer part of the accretion disk (Schandl et al. 1997) and/or the X-rays are coming from extended ADCs (Schmidtke et al. 1993), the corona has to be optically thin so that the scattering does not smear the absorption edges.

FIG. 1.—Ion fractions of the major heavy elements as a function of the temperature for the two electron densities, $10^{18}$ and $10^{19} \text{ cm}^{-3}$. The LTE condition is assumed. Fractions of the helium-like ions and neon-like ion (for iron) are indicated with the heavy lines.
3.1.2. Theoretical White Dwarf Models

As shown in the previous section, it is likely that the energy spectrum of CAL 87 is explained by emission from a hot white dwarf atmosphere. Therefore, we next apply theoretical white dwarf spectral models to constrain the white dwarf parameters.

We adopt the same LTE model used by Heise et al. (1994) and van Teeseling, Heise, & Kahabka (1996) to fit the SSS energy spectra and the non-LTE model used by Hartmann & Heise (1997). In both models, plane-parallel geometry and hydrostatic equilibrium are assumed, and energy spectra have been calculated for given surface gravities, \( g \), and effective temperatures, \( T_{\text{eff}} \). In the non-LTE model, the photoionization effect is additionally taken into account to calculate the ionization balance. In the LTE model, all the ions of H, He, C, N, O, Mg, Si, P, Ar, Ca, Fe, and Ni are taken into account, and all the edges are included. In the non-LTE model, only major ions and atomic levels of H, He, C, N, O, and Ne are included (see Hartmann & Heise 1997 for details).

Complex line opacities and line blanketing are not taken into account in both models. The significance of the line opacities, as well as the non-LTE effects in the emerging spectra, have been studied by several authors such as Rauch (1997), Hartmann et al. (1999), and Barman et al. (2000). The non-LTE model not including the line opacities (the same model used in this paper) results in the absorption edges at higher energies compared to the LTE model, and every \( 10^5 \) K from \( 3 \times 10^5 \) to \( 10^6 \) K for the non-LTE model. The models mildly depend on the surface gravity, but the temperature and gravity are hardly determined simultaneously (see § 3.1.3). We adopt a surface gravity of \( 10^9 \) cm s\(^{-2}\), which is appropriate for a massive white dwarf with a mass \( \gtrsim 1 M_\odot \); the validity of this assumption is checked a posteriori (§ 4.1.1). The models also weakly depend on the elemental abundances. For CAL 87, the LMC abundance in which metallicity is one-quarter to one-half of the cosmic abundance is used, either taken from Vassiliadis & Wood (1994; LTE model) or Dennefeld (1989; non-LTE model). Effects of changing the surface gravity and abundances are discussed in §§ 3.1.3 and 3.2.2.

In Table 2 and Figure 3, we show the results of the LTE model fit with \( g = 10^9 \) cm s\(^{-2}\). The best-fit temperature, normalization (effective emission area), and hydrogen column density have been determined for the average, eclipse, and out-of-eclipse spectra. To fit the eclipse and out-of-eclipse spectra, the temperature and either the column density or normalization are fixed to the best-fit values determined from the average spectrum, since these parameters are not constrained simultaneously. The confidence contour map of the hydrogen column density and the effective emission area is shown in Figure 5.

The model gives acceptable fits. The temperature is tightly constrained, as expected from the condition that both O\( \text{VII} \) and O\( \text{VIII} \) are present (§ 3.1.1). In addition to the O\( \text{VII} \) and O\( \text{VIII} \) edges, the best-fit model shows N\( \text{VII} \) and
C vi edges (see Fig. 3). Although the temperature is constrained, the normalization and the hydrogen column density are strongly correlated (Fig. 5), and the effective emission area is uncertain by about a factor of 2. This is because the energy band of the ASCA SIS is above $\sim 0.5$ keV, where model spectra are not very sensitive to slight changes in the column densities. Contemporary instruments having both better energy resolution and sensitivity below $\sim 0.5$ keV, such as the grating spectrometers on Chandra or XMM-Newton, will be able to constrain the column density and normalization simultaneously. In § 4.1.1 we will compare the observed luminosity and radius with those predicted by theoretical calculations and discuss the white dwarf parameters. The spectral change during the eclipse is explained as being either due to an increase of the hydrogen column density by $\sim 5 \times 10^{20}$ cm$^{-2}$ or a decrease of the emission area by $\sim 20\%$ (see § 4.1.2; also see Asai et al. 1998).

Results of the non-LTE model ($g = 10^9$ cm s$^{-2}$) fit, which is equally successful, are shown in Figure 4 and Table 3. A contour map of the hydrogen column density and the effective emission area is shown in Figure 5 with that for the LTE model. Compared to the LTE model, the best-fit temperature is significantly lower; this is considered as being because of photoionization effects. The importance of photoionization may be roughly estimated using the ionization parameter $\xi \equiv L/nr^2$, where $L$, $n$, and $r$ are luminosity, density, and radius, respectively. On the nuclear-burning white dwarf with a surface gravity of $10^9$ cm s$^{-2}$ and an effective temperature of $\sim 60$ eV, $\xi$ is estimated to be 1–10. This is large enough to ionize C, N, O, and Ne to the helium-like or hydrogenic stages (see, e.g., Kallman & McCray 1982). Therefore, the effects of photoionization are significant, and the same ionization degree as with the LTE model is achieved at a lower temperature in the non-LTE model (Hartmann & Heise 1997). Compared to the LTE model, the hydrogen column density is smaller and the best-fit surface area is twice as large in the non-LTE model because of the significantly smaller temperature (Fig. 5).

3.1.3. Effects of Surface Gravity and Elemental Abundances

The maximum effective temperature expected on the white dwarf surface is constrained by the Eddington luminosity and may be expressed as $T_{\text{eff}}^{\text{max}} \sim 0.5g^{1/4}$ eV, where $g$

![Table 2](image)

| PARAMETER | AVERAGE | CONstrained Column Density | Constrained Normalization | CONstrained Column Density | CONstrained Normalization |
|-----------|---------|---------------------------|--------------------------|---------------------------|--------------------------|
| $N_H$ ($10^{21}$ cm$^{-2}$) | $2.0 \pm 0.7$ | Fixed | $2.5 \pm 0.2$ | Fixed | $1.95 \pm 0.09$ |
| $T_{\text{eff}}$ (eV) | $75 \pm 1$ | Fixed | Fixed | Fixed | Fixed |
| $(R/10^3$ km)$^a$ | $1.6 \pm 0.9$ | $1.34 \pm 0.11$ | Fixed | $1.67 \pm 0.08$ | Fixed |
| $L_{\text{bol}}$ ($10^{36}$ ergs s$^{-1}$)$^p$ | $6.6 \pm 0.3$ | $5.5 \pm 0.5$ | Fixed | $6.8 \pm 0.3$ | Fixed |
| $\chi^2$/dof | $39.0 / 32$ | $34.7 / 34$ | $33.3 / 34$ | $29.4 / 34$ | $29.0 / 34$ |

$^a$ The distance is assumed to be 55 kpc.
is the surface gravity, which is in the range of $\sim 10^7$–$10^{10}$ cm$^{-2}$ (Fig. 13) and almost uniquely determined as a function of mass using a standard mass-radius relation (§ 4.1.1). Correspondingly, $T_{\text{eff(max)}}$ will be in the range of $\sim 30$–$90$ eV, depending on the white dwarf mass.

To see the effect of changing the surface gravity and elemental abundances, we calculate theoretical spectral models for different surface gravities with the cosmic abundance (more metal-rich than the LMC abundance) and fit the observed spectra. First, we find that the models with $g = 10^8$ cm$^{-2}$ cannot account for the CAL 87 energy spectra, since the possible temperatures are too low to produce the observed high-energy photons. Results of the fitting with $g = 10^9$ and $10^{10}$ cm$^{-2}$ are summarized in Table 4.

The following points are noticeable from the model fitting results: (1) Models with different surface gravities can equally fit the data (unless surface gravity is too low to

| PARAMETER | ECLIPSE | OUT OF ECLIPSE |
|-----------|---------|---------------|
|           | AVERAGE |               |               |
| $N_H$ (10$^{21}$ cm$^{-2}$) | 2.0 $\pm$ 0.6 | Fixed | 2.4 $\pm$ 0.2 |
| $T_{\text{eff}}$ (eV) | 58 $\pm$ 1 | Fixed | Fixed |
| $(R/10^3 \text{ km})^{2a}$ | 4.5 $\pm$ 2.4 | 3.7 $\pm$ 0.3 | Fixed |
| $L_{\text{bol}}$ (10$^{36}$ ergs s$^{-1}$) | 6.6 $\pm$ 2.0 | 5.4 $\pm$ 0.5 | Fixed |
| $\chi^2$/dof | 23.1/32 | 34.6/34 | 33.9/34 |

* The distance is assumed to be 55 kpc.

| PARAMETER | LTE MODEL | NON-LTE MODEL |
|-----------|-----------|---------------|
| $N_H$ (10$^{21}$ cm$^{-2}$) | $2.2 \pm 0.9$ | $2.2 \pm 0.7$ |
| $T_{\text{eff}}$ (eV) | $75 \pm 2$ | $65 \pm 1$ |
| $(R/10^3 \text{ km})^{2a}$ | $2.1 \pm 1.2$ | $3.3 \pm 1.8$ |
| $L_{\text{bol}}$ (10$^{36}$ ergs s$^{-1}$) | $8.6 \pm 4.4$ | $7.7 \pm 2.5$ |
| $\chi^2$/dof | 41.4/32 | 25.2/32 |

* The distance is assumed to be 55 kpc.
3.2. RX J0925.7—4758

3.2.1. Spectral Analysis with Simple Models

First, we show the result of a blackbody plus interstellar absorption model fit (col. [2] in Table 5 and Fig. 6). Although this model does not fit the data at all (reduced $\chi^2 = 8$), the following spectral characteristics are clearly recognized: (1) The spectrum is heavily absorbed ($N_H \approx 10^{22} \text{ cm}^{-2}$). (2) A deep edge feature such as the O Viii edge in CAL 87 is not observed. (3) The energy spectrum is much harder than that of CAL 87 and extends to $\sim 1.5 \text{ keV}$. A thin thermal plasma model (Raymond & Smith 1977) gives $T = 50 \text{ eV}$, $N_H = 1.98 \times 10^{22} \text{ cm}^{-2}$, and a reduced $\chi^2$ of 16. The high absorption and the significant excess above $\sim 1.5 \text{ keV}$ are model-independent. A power law plus absorption model does not give a meaningful result, ending up with a photon index higher than 10.

We next try a blackbody model with absorption edges. We find that three absorption edges are needed to fit the energy spectrum (Table 5, col. [3]). In addition, if we allow oxygen abundance in the interstellar medium to be free, the
### TABLE 5

RX J0925.7—4758 Blackbody (Plus Edges) Model Fit

| Parameter                              | Without Absorption Edges | With Absorption Edges | Free Oxygen Abundance | Free Neon Abundance |
|----------------------------------------|--------------------------|-----------------------|-----------------------|---------------------|
|                                        | (1)                      | (2)                   | (3)                   | (4)                 |
| $N_H$ ($10^{22}$ cm$^{-2}$)            | 2.0                      | 1.14                  | 1.06 ± 0.13           | 1.09 ± 0.11         |
| $T$ (eV)                               | 45                       | 88                    | 92 ± 10               | 88 ± 10             |
| Edge 1:                                |                          |                       |                       |                     |
| $E_{edge}$ (keV)                       | ...                      | 0.86                  | 0.90 ± 0.02           | ...                |
|                                       |                          | 1.17                  | 0.81 ± 0.3            | ...                |
| Edge 2:                                |                          |                       |                       |                     |
| $E_{edge}$ (keV)                       | ...                      | 1.01                  | 1.02 ± 0.02           | 1.01 ± 0.01         |
| $E_{edge}$ (keV)                       | ...                      | 2.35                  | 1.64 ± 0.3            | 1.74 ± 0.3          |
| Edge 3:                                |                          |                       |                       |                     |
| $E_{edge}$ (keV)                       | ...                      | 1.31                  | 1.36 ± 0.07           | 1.36 ± 0.09         |
| $E_{edge}$ (keV)                       | ...                      | 1.18                  | 0.83 ± 0.4            | 0.68 ± 0.6          |
| Oxygen abundance*                     | 1 (fixed)                | 1 (fixed)             | 0.61 ± 0.1            | 0.65 ± 0.1          |
| Neon abundance*                        | 1 (fixed)                | 1 (fixed)             | 1 (fixed)             | 2.3 ± 0.5           |
| $R^2$ (km$^2$)                         | $3.34 \times 10^{10}$   | $22.9 \times 10^4$   | $5.2 \pm 1.9 \times 10^4$ | $9.60 \pm 3.6 \times 10^4$ |
| $L_{bol}$ (ergs s$^{-1}$)             | $1.8 \times 10^{36}$    | $1.8 \times 10^{36}$ | $4.8 \pm 1.7 \times 10^{36}$ | $7.5 \pm 1.7 \times 10^{35}$ |
| $\chi^2$ / dof                         | 605 (75)                 | 102.8 (69)            | 49.2 (68)             | 50.8 (69)           |

**Note.**—Absorption edge of the form $-\exp[-\tau(E/E_{edge})^{-3}]$ for $E > E_{edge}$ is assumed.

* Abundances for the interstellar absorption, relative to the cosmic abundances $[O]/[H] = 7.39 \times 10^{-4}$ and $[Ne]/[H] = 1.38 \times 10^{-4}$ by Anders & Ebihara (1982). The same definition for the following tables.

b The distance is assumed to be 1 kpc.

The hydrogen column densities ($\sim 1 \times 10^{22} - 2 \times 10^{22}$ cm$^{-2}$) are consistent with those estimated from optical/IR and ROSAT observations (Motch et al. 1994). The large column density suggests that the source is beyond the Vela sheet molecular cloud at 425 pc (Motch et al. 1994).

#### 3.2.2. Theoretical White Dwarf Models

Next, we try LTE and non-LTE white dwarf spectral models (cosmic abundance of the white dwarf atmosphere is assumed). The oxygen and neon abundances in the interstellar absorption are allowed to be free, which will be rea-

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**Fig. 7.**—Blackbody plus edge model fit for RX J0925.7—4758. Three edges are included at 0.89, 1.01, and 1.36 keV. The oxygen abundance in the interstellar absorption is reduced more than the cosmic abundance (see text). *Left:* Observed spectrum and best-fit model convolved with the detector response. The fitting residual is also shown. *Right:* Best-fit model before and after the interstellar absorption.
sonable from the consideration in the previous section. Results are shown in Table 6 and Figures 8–11.

Figures 8 and 9 show examples of the fits with the LTE and non-LTE model, respectively, with a surface gravity of $10^9$ cm s$^{-2}$. These model spectra have a very strong O VIII edge at 0.89 keV (LTE model) or an Ne IX edge at 1.20 keV (non-LTE model), but neither of them is actually observed. In fact, there are significant amounts of hard photons above these edge energies, and the observed spectrum indicates the Ne X edge at 1.36 keV, instead of the Ne IX edge in the non-LTE model. A more sophisticated non-LTE model including metal line opacities shows a weaker Ne IX edge but a more conspicuous O VIII edge (Hartmann et al. 1999), being rather similar to the LTE model. Hence, the problem

![Figure 8](image1.png)

**Fig. 8.**—LTE model fit for RX J0925.7−4758 with the surface gravity of $10^9$ cm s$^{-2}$. The oxygen and neon abundances in the interstellar absorption are made free parameters (see text). **Left:** Observed spectrum and best-fit model convolved with the detector response. The fitting residual is also shown. **Right:** Best-fit model before and after the interstellar absorption.

![Figure 9](image2.png)

**Fig. 9.**—Non-LTE model fit for RX J0925.7−4758 with the surface gravity $10^9$ cm s$^{-2}$ and the cosmic abundance. The oxygen and neon abundances in the interstellar absorption are made free parameters (see text). **Left:** Observed spectrum and best-fit model convolved with the detector response. The fitting residual is also shown. **Right:** Best-fit model before and after the interstellar absorption.
TABLE 6

| PARAMETER                  | log \( g = 9 \) without Edge | log \( g = 10 \) without Edge | log \( g = 10 \) with Edge | log \( g = 9 \) without Edge | log \( g = 10 \) without Edge | log \( g = 10 \) with Edge |
|---------------------------|-------------------------------|-------------------------------|---------------------------|-------------------------------|-------------------------------|---------------------------|
| \( N_H \) (10\(^{21}\) cm\(^{-2}\)) | 21.1                         | 16.5                         | 7.1 ± 0.6                 | 8.7                         | 8.5                         | 6.9 ± 0.2                 |
| Oxygen abundance         | 0.92                         | 0.90                         | 0.56 ± 0.14               | 0.65                         | 0.62                         | 0.61 ± 0.15               |
| Neon abundance           | 0.33                         | 0.0                           | 0.56 ± 0.06               | 2.2                          | 0.26                         | 4.0 ± 0.3                 |
| Edge:                    |                              |                              |                           |                              |                              |                           |
| \( E_{\text{edge}} \) (keV) | ...                         | ...                         | 1.02 ± 0.01               | ...                         | ...                         | 1.01 ± 0.01               |
| \( T_{\text{eff}} \) (eV) | 70                          | 86                          | 117 ± 4                   | 74                          | 92                          | 103³                     |
| \( R^2 \) (km\(^2\))     | \( 2.6 \times 10^8 \)        | \( 3.3 \times 10^6 \)        | \( 1.26 \pm 0.24 \times 10^8 \) | \( 2.7 \times 10^4 \)        | \( 7.7 \times 10^3 \)        | \( 2.6 \times 10^5 \)        |
| \( L_{\text{bol}} \) (ergs s\(^{-1}\)) | \( 8 \times 10^{38} \)        | \( 2.3 \times 10^{37} \)        | \( 3.1 \times 10^{34} \)        | \( 1 \times 10^{35} \)        | \( 7 \times 10^{24} \)        | \( 3.8 \times 10^{24} \)        |
| \( \chi^2 \) (dof)       | 288 (73)                     | 288 (73)                     | 79.2 (71)                 | 393 (73)                     | 343 (73)                     | 51.7 (73)                 |

\( ^a \) 103 eV (1.2 \times 10^8 \) K is the highest available temperature in the model.

\( ^b \) The distance is assumed to be 1 kpc.

that there are many more high-energy photons than predicted by our LTE or non-LTE model is unlikely to be solved by further minor improvements to the models.

At the surface gravity of 10\(^9\) cm s\(^{-2}\), the maximum effective temperature will be \( \sim 90 \) eV (§ 3.1.3). On the other hand, the effective temperature has to be as high as \( \sim 100 \) eV so that Ne \( \alpha \) becomes more dominant than Ne \( \alpha \) (Fig. 1). Therefore, expecting a higher temperature and ionization state, we next try models with the surface gravity of 10\(^10\) cm s\(^{-2}\), which would be considered the upper limit for white dwarfs (Fig. 13). The temperature grids are every 10\(^5\) K from \( 8 \times 10^5 \) to 1.9 \times 10^6 for the LTE model and every 10\(^4\) K from \( 8 \times 10^5 \) to 1.2 \times 10^6 K for the non-LTE model. Although models do exhibit an Ne \( \alpha \) edge, the fit does not improve significantly (Table 6), unless an additional edge is placed at \( \sim 1.02 \) keV. In Figures 10 and 11 and Table 6, we show results of the successful LTE and non-LTE model fits with the surface gravity of 10\(^10\) cm s\(^{-2}\) and an absorption edge at \( \sim 1.02 \) keV.

If the CNO cycle is dominant on the white dwarf surface, it will change the relative abundances of these elements, such that C and O abundances are suppressed relative to that of N. With this in mind, we have calculated several LTE and non-LTE models with nonstandard element abundances. However, we could not fit the RX J0925.7–4758 spectrum successfully, unless assuming the \( \sim 1.02 \) keV edge. For example, we have tried an LTE model with \( [N/C] = 200 \) and \( [N/O] = 50 \). The O \( \alpha \) and O \( \alpha \) edges become weak, which, in this sense, fits the data, but the N \( \alpha \) (0.55 keV) and N \( \alpha \) (0.67 keV) edges, which are not observed, are very conspicuous in the model. We have also tried models in which all the heavy element abundances are

![Graph](image_url)

**Fig. 10.**—LTE model fit for RX J0925.7–4758 with the surface gravity 10\(^10\) cm s\(^{-2}\) and an absorption edge at 1.02 keV. The oxygen and neon abundances in the interstellar absorption are made free parameters (see text). **Left:** Observed spectrum and best-fit model convolved with the detector response. The fitting residual is also shown. **Right:** Best-fit model before and after the interstellar absorption.
lowered by an order of magnitude. We have found that reducing the abundance helps to account for the hard tail above the Ne IX edge, which is in agreement with Shimura (2000). However, the 1.02 keV edge feature still remains in the residual.

We have also tried a two-component model, expecting that the hard photons above the O VIII and Ne IX edges might be explained by an additional hard component. Hartmann et al. (1999) fitted the RX J0925.7—4758 spectrum observed with the Low-Energy Concentrators...
ASCA Spectrometer (LECS) on board BeppoSAX with a non-LTE model for the soft component and a thin thermal model for the hard component. We have tried an LTE model with model for the soft component and a thin thermal model for the corresponding maximum effective temperature on the 10$^{18}$ EBISAWA ET AL. Vol. 550

We have applied theoretical LTE and non-LTE models in the framework of the ADC model, namely, a part of the white dwarf surface is also determined solely by mass (§ 3.1.3). These are shown in the top and middle panels of Figure 13, respectively.

From model fitting assuming the surface gravity is \( g = 10^9 \) cm s$^{-2}$, we have obtained effective temperatures. The model spectral shape is hardly dependent on the surface gravity, and the best-fit effective temperature varies with the gravity as \( kT_{\text{eff}} \propto \log g \) (§ 3.1.3). This relation is shown for the LTE and non-LTE fitting results in the middle panel of Figure 13 by two solid lines. The total bolometric luminosity is calculated as \( 4\pi R^2 \alpha T_{\text{eff}}^4 \), using the observed effective temperature and the white dwarf radius derived from the mass-radius relationship, which is also indicated in the top panel by two solid lines for LTE and non-LTE models. Note that the intrinsic luminosities thus calculated are much larger than the apparent observed luminosity derived from the observed flux assuming uniform emission, which suggests most of the emission is blocked (see below).

Steady nuclear burning of the hydrogen accreted onto white dwarfs, observed as supersoft X-ray sources, takes place only in a limited range of the mass accretion rate, \( 1 \times 10^{-7} - 5 \times 10^{-7} M_\odot \text{ yr}^{-1} \) (van den Heuvel et al. 1992). The allowable luminosity range with the steady nuclear burning calculated by van den Heuvel et al. (1992) is shown as shaded area in the top panel of Figure 13. In this panel, the portion of the two lines marked LTE and non-LTE lying on the allowable theoretical luminosity range should give the realistic luminosity and mass ranges. They are \( 1.0 - 1.2 M_\odot \) and \( 6 \times 10^{37} - 1.2 \times 10^{38} \text{ ergs s}^{-1} \) for the LTE model and \( 0.8 - 1.0 M_\odot \) and \( 4 \times 10^{37} - 7 \times 10^{37} \text{ ergs s}^{-1} \) for the non-LTE model. Considering current uncertainties of theoretical spectral models, we conclude that the total bolometric luminosity and mass of CAL 87 are in the range of \( 4 \times 10^{37} - 1.2 \times 10^{38} \text{ ergs s}^{-1} \) and \( 0.8 - 1.2 M_\odot \), respectively.

In the top panel of Figure 13, we also show the range of the bolometric luminosity calculated from the observed flux assuming uniform emission. We can see that the observed luminosity, \( 4 \times 10^{38} \) to \( 1 \times 10^{37} \text{ ergs s}^{-1} \), is about an order of magnitude smaller than the expected luminosity, indicating that only \( \sim 10\% \) of the total emitted X-rays reaches us. This is consistent with, and strengthens, the idea of Schmidtke et al. (1993) and Schandl et al. (1997) that the white dwarf in CAL 87 is permanently blocked from the line of sight by an outer part of the accretion disk and we are observing scattered emission by the ADC. The scattering optical depth of the corona is estimated as \( \sim 0.1 \), which is small enough not to smear the observed deep edge feature (§ 3.1.1).

The hydrogen column density of the ADC will be \( \sim 1.5 \times 10^{23} \) cm$^{-2}$, and its size is estimated as \( \sim 5 \times 10^{10} \) cm (see next section). Correspondingly, the ionization parameter, \( \xi = L/(4\pi R^2 n_e) \approx L/(N_H n_e) \), will be \( 5000 - 16000 \). This will be large enough to completely photoionize heavy elements besides iron, so that absorption edges are fully eliminated below \( \sim 8 \) keV (see, e.g., Kallman & McCray 1982). Hence, the ADC should be observed only as a scatterer, not an absorber, which is consistent with the present observation (see also discussion in Asai et al. 1998).

4.1.2. Orbital Eclipses

Based on the white dwarf parameters obtained in the previous section, we will try to explain the orbital eclipse in the framework of the ADC model, namely, a part of the

| Parameter | Value |
|-----------|-------|
| log g (cgs) | 10 |
| \( N_H (10^{19} \text{ cm}^{-2}) \) | 12.7 |
| Oxygen abundance | 0.67 |
| Neon abundance | 0.68 |
| \( T_{\text{eff}} (\text{eV}) \) | 94 |
| \( R^2 (\text{km})^2 \) | \( 7 \times 10^4 \) |
| \( T (\text{eV}) \) | 103 |
| \( N_x \) | \( 1.5 \times 10^{51} \) |
| \( \chi^2 (\text{dof}) \) | 144 (71) |

* The distance is assumed to be 1 kpc.
* Plasma temperature.
* The plasma emission measure \( n_e n_H V \) (cm$^{-3}$) at 1 kpc, where \( n_e, n_H \), and \( V \) are electron density, hydrogen density, and volume, respectively.

We have applied theoretical LTE and non-LTE models to the CAL 87 energy spectra observed with ASCA and obtained an effective temperature and emission area. Based on the spectral-fitting results, we can constrain white dwarf parameters in CAL 87.

The mass and radius of white dwarfs are related by the theoretical white dwarf mass-radius relation; thus radius and surface gravity are almost uniquely determined as a function of mass. In the bottom panel of Figure 13, we show white dwarf radius and surface gravity as a function of mass, in which we used an approximated formula of the mass-radius relation from Pringle & Webbink (1975). Although the mass-radius relationship is known to be dependent on internal atomic compositions (see, e.g., Panei, Althaus, & Benvenuto 2000), this uncertainty hardly affects our results, since most uncertainties in our discussion originate in the systematic difference of the LTE and non-LTE models and statistical errors from the spectral fitting.

The Eddington luminosity is a function of mass; hence, the corresponding maximum effective temperature on the
extended emission from the ADC is blocked by the companion star, resulting in a shallow and extended X-ray eclipse, as observed (Schmidtke et al. 1993; Schandl et al. 1997). We will carry out a Monte Carlo simulation searching for the orbital parameters and ADC configuration to reproduce the observed X-ray orbital light curve.

In our model, the parameters that affect the orbital light curve are as follows: the white dwarf mass ($M_{\text{WD}}$), companion mass ($M_C$), the size of the ADC, and the orbital inclination angle ($i$). In the previous section we estimated $M_{\text{WD}}$ as $0.8-1.2 \ M_\odot$. In the simulation, we assume $M_{\text{WD}} = 1 \ M_\odot$. The companion mass, $M_C$, is expected to be in the range of $1.4-2.2 \ M_\odot$ from the binary evolution requirements (van den Heuvel et al. 1992); we assume $M_C = 1.5 \ M_\odot$. The orbital period is 10.6 hr (Alcock et al. 1997 and references therein), and the binary separation is determined from Kepler’s law as $a = 2.3 \times 10^{11} \text{ cm}$. The Roche lobe radius is calculated using the formula from Pringle (1985), and we consider that the companion is filling its Roche lobe. The Roche radius for the companion and white dwarf will be $0.41$ and $0.34$ times the binary separation, respectively. The accretion disk radius is assumed to be $0.8$ times the white dwarf Roche lobe radius, following Schandl et al. (1997). The ADC is assumed to be a sphere whose radius is smaller
than the accretion disk radius. The white dwarf is permanently blocked from the line of sight by the outer flared parts of the disk, or the "spray" region (Schandl et al. 1997). This is approximated by assuming that the disk is a slab having a constant thickness 0.2 times the disk radius. Also, the disk is assumed not to be tilted from the orbital plane.

We have carried out Monte Carlo simulations for many different combinations of these parameter values and found that the orbital light curve is most strongly dependent on the orbital inclination, and second, on the ADC size. In particular, we have found that the depth of the eclipse is very sensitive to the inclination, since in our model a tiny portion of the ADC has to be seen just behind the companion (see the diagram at \( \phi = 1 \) in Fig. 14). Dependence on other parameters is relatively minor. In any case, it is impossible to constrain orbital parameters from our simulation, since there are too many combinations that can reproduce the observed X-ray light curve, which is rather noisy.

As a typical example of successful orbital simulation, we show the result with the ADC size of \( 4.8 \times 10^{10} \) cm (0.75 times the accretion disk radius) and \( i = 73^\circ \) (Fig. 14).

Schandl et al. (1997) carried out an orbital simulation and successfully explained the observed optical light curve with \( i = 77^\circ \). We have reached \( i = 73^\circ \), having searched for the best inclination angle around \( i = 77^\circ \) to fit the observed X-ray light curve.

Several remarks should be made here concerning our simulation: If we compare them closely, the observed eclipse is slightly wider than the simulation (Fig. 14). We assumed that the ADC has constant emissivity and did not take into account the rim darkening, inclusion of which should further narrow the simulated eclipse. Our choice of the ADC size (0.75 times the disk radius) is rather arbitrary, but if the ADC size becomes smaller than half of the disk radius, the eclipse will be still narrower, and very fine tuning of the inclination will be required so that the eclipse takes place. Hence, our model favors a large ADC size. Also, there expects to be additional mechanisms to widen the eclipse, which we have not taken into account. For example, we assumed that the companion is a perfect sphere with definite boundaries, but in reality the companion filling the Roche lobe should be elongated toward the white dwarf.
which can block the ADC more effectively and make the eclipse wider. In addition, the companion may have an extended atmosphere and/or winds to attenuate X-rays by scattering, which also will work to widen the eclipse (Asai et al. 1998). Future high throughput observations will allow more precise X-ray eclipse analysis to constrain the binary parameters tightly.

4.2. RX J0925.7$-$4758

We have found that the RX J0925.7$-$4758 spectrum has high-energy photons above the O VIII or Ne IX edge energies and exhibits the Ne X edge at 1.36 keV. Such a hot atmosphere, as high as $T_{\text{eff}} \sim 100$ eV (Table 6), requires an extremely high surface gravity, $g \approx 10^{10}$ cm s$^{-2}$, which may be achieved only close to the Chandrasekhar limit, $\sim 1.4 M_{\odot}$ (Fig. 13; see also Hoshi 1998; Shimura 2000). The presence of such an extremely massive white dwarf is also consistent with optical observations of the binary motion (Schmidtke et al. 2000).

We have found that the model fits always require an additional absorption edge at $\sim 1.02$ keV. This edge feature does not disappear by introducing a second high-energy spectral component (Fig. 12), which was proposed by Hartmann et al. (1999) to explain the BeppoSAX RX J0925.7$-$4758 spectrum.

Near the Chandrasekhar limit, the X-ray luminosity expected from the steady nuclear burning will be as high as $1 \times 10^{38} - 2 \times 10^{38}$ erg s$^{-1}$ (Fig. 13). On the other hand, the luminosity we obtained from the LTE or non-LTE model fitting ($g \approx 10^{10}$ cm s$^{-2}$, including the 1.02 keV edge) is $3 \times 10^{34} - 4 \times 10^{34}$ ergs s$^{-1}$ at 1 kpc. Even if we put the source at $\sim 10$ kpc, the discrepancy between the expected and observed luminosities is still almost 2 orders or magnitude. We have found that the observed luminosity of CAL 87 is just 10% of the expected total luminosity ($\S$ 4.1.1), which we consider because the white dwarf is always hidden by the accretion disk. Blocking by the accretion disk will be unlikely for RX J0925.7$-$4758 though, since neither X-ray or optical eclipses have been detected and the orbital inclination is considered to be much smaller (Motch 1998; Schmidtke et al. 2000).

To solve the luminosity discrepancy, we propose a model in which the white dwarf in RX J0925.7$-$4758 is behind a nonuniform, almost fully ionized Thomson thick cloud, so that heavy electron scattering causes the significant luminosity reduction. Since the cloud is not spherical, photons scattered out of the line of sight will never be observed again. The 1.02 keV absorption edge and the strong low energy absorption may be explained simultaneously, if the ionization state of the cloud in the line of sight is not uniform, so that less ionized part of the cloud is responsible for these absorptions. A transient optical jet has been observed from RX J0925.7$-$4758 (Motch 1998). Therefore, we consider it likely that matter previously emitted as the jet from the binary system lies in the line of sight to scatter the X-rays from the white dwarf.

We consider the observed luminosity, $\sim 3 \times 10^{34}(d/1 \text{ kpc})^2$, to be $e^{-\text{scat}}$ times the actual luminosity, $\sim 10^{38}$ ergs s$^{-1}$, where $\text{scat}$ is the scattering optical depth of the intervening matter. Hence, the column density of the intervening matter may be written as

$$N_H \sim [12 - 7 \log (d/1 \text{ kpc})] \times 10^{24} \text{ cm}^{-2}. \quad (1)$$

On the other hand, the time average of the mass ejection rate due to the jet is

$$\langle dM/dt \rangle = 4\pi v n \delta (\delta/4\pi) w m_H,$$  

where $v$ is the jet velocity, $n$ the number density, $w$ the time fraction when the jet takes place, $\delta$ the solid angle, and $m_H$ the mass per hydrogen atom. The column density can be also written as

$$N_H = \int_R^\infty n w d\rho = \langle dM/dt \rangle / R v \delta m_H,$$  

where $R$ is the white dwarf radius. From these relationships, we get

$$\langle dM/dt \rangle \sim 3 \times 10^{17} \left( \frac{R}{3000 \text{ km}} \right) \left( \frac{v}{5000 \text{ km s}^{-1}} \right) \left( \frac{\delta}{1} \right) \times [12 - 7 \log (d/1 \text{ kpc})] \text{ g s}^{-1}, \quad (4)$$

where plausible values of $v$ and $\delta$ are taken from Motch (1998).

The only constraint we may impose is that the mass ejection rate does not exceed the plausible mass accretion rates for the supersoft sources, $\sim 10^{39}$ g s$^{-1}$ (see, e.g., van den Heuvel et al. 1992). From equation (4), we see that this condition is satisfied as long as $d \gtrsim 1$ pc; hence, we may not constrain the distance to the source. For assumed distances of 1, 3, and 10 kpc, the column densities of the intervening matter necessary to reduce the luminosity will be $\sim 1 \times 10^{23}$, $\sim 9 \times 10^{24}$, and $\sim 5 \times 10^{25}$ cm$^{-2}$, respectively, and the mass ejection rates are $\sim 4 \times 10^{18}$, $\sim 3 \times 10^{18}$, and $\sim 2 \times 10^{18}$ g s$^{-1}$, respectively.

The ionization parameter of the matter may be written as

$$\xi = \frac{L}{n r^2} = L_{\text{w}} \frac{1200}{N_H R} \left( \frac{L/10^{38} \text{ ergs s}^{-1}}{(w/0.04)} \right) \left( \frac{N_H/10^{25} \text{ cm}^{-2}}{R/3000 \text{ km}} \right), \quad (5)$$

where we took the jet frequency $w \sim 0.04$, since the jet was observed in one of 23 nights (Motch 1998). The plasma is almost fully ionized, meaning that it is transparent for low-energy absorption but works just as a scatterer to reduce the observed luminosity. The jet frequency may not be uniform, and there may be a period when $w$ is small and particularly dense material is ejected. In that case, the radial region corresponding that dense matter will have locally a lower ionization state. The 1.02 keV edge may originate in moderately ionized heavy elements such as Ne or Fe in such a low-ionized region.

5. CONCLUSIONS

We have observed the supersoft sources CAL 87 and RX J0925.7$-$4758 with the ASCA SIS and carried out precise spectral analysis. Thanks to the superior energy resolution of SIS ($\Delta E/E \sim 10\%$ at 1 keV) compared to previous instruments, we could study the detailed X-ray spectral structure of these sources for the first time. Important results are summarized as follows:

1. We have applied theoretical spectral models to CAL 87 and constrained the white dwarf mass and intrinsic luminosity as $0.8$--1.2 $M_{\odot}$ and $4 \times 10^{37}$--$1.2 \times 10^{38}$ ergs s$^{-1}$, respectively. We have found the observed luminosity is an
order of magnitude smaller than the intrinsic luminosity, which indicates that the white dwarf is permanently blocked by the accretion disk and not directly seen. This strongly suggests that we are observing a scattering emission by a fully ionized ADC whose column density is $D_{1.5} 10^{23}$ cm$^{-2}$.

2. Through simulation we have shown that the orbital eclipse can be explained by the ADC model, such that a part of the extended X-ray emission from the ADC, whose size is expected to be $\sim 75\%$ of the accretion disk radius, is blocked by the companion star filling its Roche lobe. The orbital inclination angle is $\sim 73^\circ$ to explain the observed eclipse profile.

3. In order to explain the RX J0925.7–4758 spectrum, very high surface gravity and temperature, $D_{10} 10^{10}$ cm s$^{-2}$ and $D_{100} 100$ eV, respectively, are required. These values are only possible for an extremely heavy white dwarf near the Chandrasekhar limit. Therefore, RX J0925.7–4758 may be an immediate progenitor of Type Ia supernovae, which has been long sought (see, e.g., Livio et al. 1996). We have found that the energy spectrum has a $\sim 1.02$ keV edge, which may be a composite of mildly ionized L or K edges of heavy elements.

4. Although supersoft sources should have a luminosity of $\sim 10^{38}$ ergs s$^{-1}$ at the Chandrasekhar limit, the observed luminosity from RX J0925.7–4758 is smaller by more than 2 orders of magnitude. To explain the luminosity discrepancy, we propose a model in which very thick matter (as much as $D_{10} 10^{25}$ cm$^{-2}$) that was previously ejected from the system as jets intervenes the line of sight and reduces the luminosity significantly because of Thomson scattering. We have shown that the matter is almost fully ionized and that it is transparent for soft X-ray photons. Some radial portion of the ejected matter, where the ionization state is locally low and heavy elements are not fully ionized, may be origin of the significant low-energy absorption and the $\sim 1.02$ keV edge.

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