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ASCA SOLID STATE IMAGING SPECTROMETER OBSERVATIONS OF O STARS

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ABSTRACT

We report *ASCA* Solid State Imaging Spectrometer (SIS) X-ray observations of the O stars δ Ori and λ Ori. The energy resolution of the SIS allows us to resolve features in the O star X-ray spectra which are not apparent in spectra obtained by X-ray spectrometers with lower energy resolution. SIS spectra from both stars show evidence of line emission, suggesting the thermal nature of the X-ray source. However, the observed line strengths are different for the two stars. The observed stellar X-ray spectra are not well described by isothermal models although absorbed thermal emission models with two or more temperatures can provide an adequate fit to the data. For both stars we present evidence of absorbing columns significantly larger than the known ISM columns, indicative of absorption by a circumstellar medium, presumably the stellar winds. In addition, the λ Ori spectrum shows the presence of emission at energies >3 keV which is not seen in the δ Ori spectrum.

Subject headings: stars: early-type — stars: individual (λ Orionis, δ Orionis) — X-rays: stars

1. INTRODUCTION

Early observations with the imaging instruments on the *Einstein Observatory* (Seward et al. 1979; Harnden et al. 1979) verified that luminous O and B stars are sources of X-ray emission. Although X-ray emission is now well established for all O stars and early B stars (Rosner, Golub, & Vaiana 1985), the origin and location of the X-ray emission is less certain. Initial attempts to explain this emission ranged from deeply embedded coronal models (Cassinelli & Olson 1979; Waldron 1984), which predicted a large wind absorption at the O K-shell edge (~0.6 keV), to distributed shock models (Lucy & White 1980). The major discriminator between these models relies on determining the amount of wind X-ray attenuation which in turn places constraints on the location of the X-ray source (see Cassinelli et al. 1981). The large absorption predicted by the coronal model was not supported by the *Einstein Observatory* Solid State Spectrometer (SSS) data (Cassinelli & Swank 1983). The strong instabilities associated with radiatively driven winds (Owocki & Rybicki 1984) suggest that a distribution of hot shocked gas throughout the wind should develop and, in principle, could produce the observed X-rays (Owocki, Castor, & Rybicki 1988). However, spectra produced by distributed shock models have also had problems matching the observed X-ray spectra (Casinelli & Swank 1983).

Thus, after nearly 15 years of study, we still do not have a clear understanding of the mechanisms responsible for the characteristics seen in OB star X-ray spectra. This is in part due to the limited bandpass and energy resolution of X-ray detectors like the IPC and PSPC which have observed the largest number of OB stars in X-rays (Chlebowski, Harden, & Sciortino 1989; Grillo et al. 1992). Generally the X-ray spectra obtained by the IPC and PSPC can be fitted with single-temperature coronal emission models without absorption, although exceptions to this generalization do exist (Cassinelli et al. 1981; Waldron 1984; MacFarlane et al. 1993). Hillier et al. (1993) analyzed a well-exposed PSPC spectrum of ζ Pup and showed that the spectrum required the presence of absorption by the circumstellar wind material. X-ray spectra of a limited number of OB stars have been obtained by detectors with higher energy resolution, and these data have generally indicated significant complications to the simple picture. Cassinelli & Swank (1983) published moderate resolution ($E/\Delta E \sim 6$) observations of three OB stars (δ Ori, ϵ Ori, and ζ Ori) obtained by the SSS, while Corcoran et al. (1993) published a moderate-resolution ($E/\Delta E \sim 11$) spectrum of ζ Pup obtained by the Broad-Band X-ray Telescope (BBXRT). These observations show that the X-ray spectra from OB stars are far richer than could be discerned in the IPC and PSPC data. In particular, Cassinelli & Swank reported the detection of line emission in ζ Ori, while Corcoran et al. noted line emission in ζ Pup and found the first detection of a wind absorption K-shell edge due to ionized oxygen. However, the presence of ice on the SSS (which caused uncertainties in measuring spectral features near 0.5 keV), the high background of the SSS (which caused uncertainties in determining the high-energy emission above 2 keV), and the limited observing time available to BBXRT meant that important issues (e.g., the ubiquity of circumstellar absorption, the nature of the spectrum above 2 keV, etc.) could not be addressed with these data sets.

The *ASCA* Solid State Imaging Spectrometers (SIS) have the highest energy resolution ($E/\Delta E \sim 17$) and widest bandpass (0.4–10 keV) of any X-ray spectrometer yet flown and are ideal for addressing the outstanding questions concerning the X-ray emission from OB stars. In this letter we report our initial investigation of the X-ray spectra of two

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TABLE 1

SUMMARY OF *ASCA* OBSERVATIONS

Parameter	δ Ori	λ Ori
Observation start (MJD)	49426.09212	49423.16398
Observation end (MJD)	49426.62515	49423.71525
Exposure time (s)	17764	21168
Net counting rate, SIS0 (counts s^{-1})	0.29	0.12

nearby O stars, δ Ori and λ Ori, obtained with the SIS0 detector. More detailed analyses of these observations, including the SIS1 and GIS data, along with a more extensive modeling effort, will be presented in a later paper.

2. OBSERVATIONS AND DATA REDUCTION

Table 1 lists the exposure times and counting rates for each observation. δ Ori is a spectroscopic and eclipsing binary (O9.5 II + B0 III) with a 5.7 day period. The *ASCA* observation of δ Ori started at phase 0.75 and ended at phase 1.10, where phases are calculated from the ephemeris given in Koch & Hrivnak (1981). During this time we detected no strong evidence of significant variability. While variable X-ray emission from δ Ori has been reported (Snow, Cash, & Grady 1981), this variability is not known to be phase locked (Haberl & White 1993). λ Ori (O8 III((f))) has a B0.5 V companion 4" away, which is unresolved by *ASCA*. Since X-ray luminosity scales as bolometric luminosity (Sciortino et al. 1990), the X-ray luminosity of the B stars is expected to be about 10% of the luminosity of the O stars. However, because low-luminosity early B stars are generally very soft X-ray sources (peaking below 0.3 keV; Cassinelli et al. 1994) and because of the fact that the low-energy cutoff for the SIS is >0.3 keV, the B stars should contribute much less than 10% of the observed counts in the *ASCA* bandpass.

For each star, data from the SIS0 detector were obtained and cleaned of hot and flickering pixels. The data were further selected based on appropriate values of object elevation and magnetic rigidity. An image was extracted from the cleaned photon events, and the sources of interest were identified. In each image the target stars were the brightest sources in the field, although at least one fainter source was apparent in the λ Ori field. A spectrum was extracted from all photons lying within a 4' radius circle centered on the source (excluding any serendipitous sources). Background spectra were created by extracting all photons within the source region from a cleaned "blank sky" observation provided by the *ASCA* Guest Observer Facility. The net spectra were then binned before analysis so as to have more than 10 counts in each bin.

3. DISCUSSION

Figure 1 shows the net SIS0 source spectra for δ Ori and λ Ori. The shape of the continua are different, with λ Ori showing significantly more emission at $E > 3$ keV than δ Ori. Resolved line emission at 1.3 keV (due primarily to Mg XI) and at 1.86 keV (due primarily to K-shell emission from Si XIII) is clearly seen in the δ Ori spectrum, with evidence for K-shell emission from S XV at 2.46 keV. Line emission in the λ Ori spectrum is less obvious. In order to look for the presence of lines, we tried to fit the λ Ori spectrum in the interval 1.2–2.8 keV with a smooth power-law continuum and Gaussian lines near 2.5, 1.9, and 1.3 keV. We applied an F-test to determine the significance of the emission lines. For a pure power-law continuum, the best fit in this energy range is $\chi^2 = 53.3$ with 57 degrees of freedom. A fit with a power-law plus Gaussian line near 2.5 keV yielded $\chi^2 = 45.5$ with 55 degrees of freedom. We then fitted the restricted spectrum with a power-law continuum plus a Gaussian line near 2.5 and an additional Gaussian line near either 1.9 or 1.3 keV. These fits resulted in values of $\chi^2 = 45.5$ with 54 degrees of freedom. We conclude that there is a significant line feature near 2.5 keV in the λ Ori spectrum, but no significant line features near 1.9 or 1.3 keV. From our best fit, the energy of the line near 2.5 keV is determined to be 2.42 ± 0.06 keV which is consistent with energy of the S XV K-shell line.

We tried to model these spectra with simple combinations of absorbed coronal plasma emission models. For comparison purposes, Figure 1 shows the best fit to the observed data for a single-temperature Mewe-Kaastra plasma model (Mewe, Gronenschild, & van den Oord 1985; Kaastra 1992) with absorbing columns fixed at the known ISM values ($N_H = 1.5 \times 10^{20}$ for δ Ori and $N_H = 7 \times 10^{20}$ for λ Ori; Shull & Van Steenberg 1985). One of the important results of the present

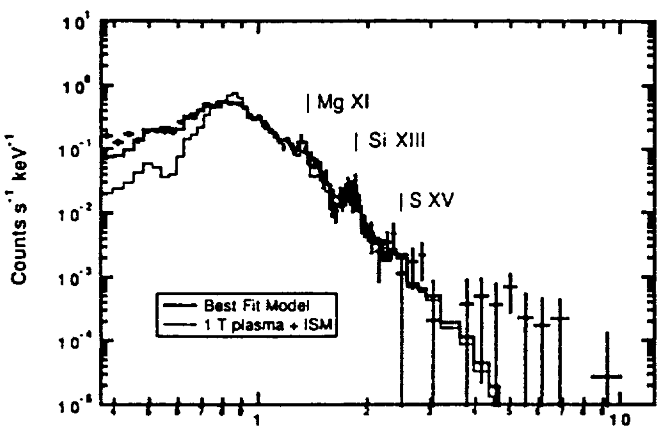

FIG. 1a

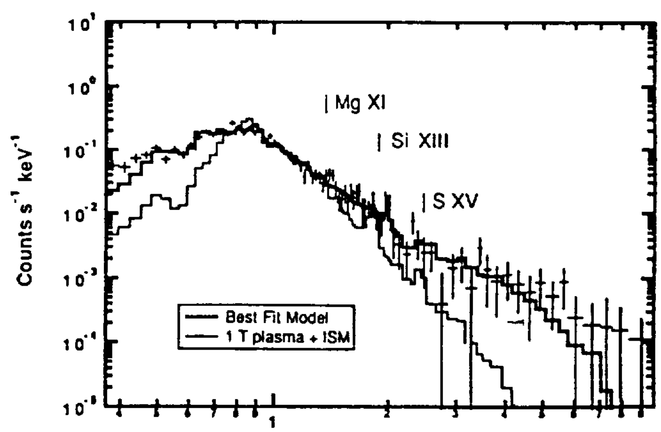

FIG. 1b

FIG. 1.—The observed SIS0 spectrum of δ Ori along with the best-fit solar abundance model in which absorption is due to the ISM alone (*thin line*) and the best fit two-temperature, "warm" absorption model described in text. (*b*) The observed SIS0 spectrum of λ Ori along with the best-fit solar abundance model in which absorption is due to the ISM alone (*thin line*) and the best fit two-temperature, "warm" absorption model described in text.

TABLE 2

BEST-FIT PARAMETERS FOR ASSUMED MODEL SPECTRA

Parameter	δ Ori	λ Ori
ISM N_H (10^{21} cm^{-2}) (fixed)	0.15	0.70
log T_{hot} (K)	6.84 ± 0.12[a]	7.42 ± 0.30
log EM_{hot} (cm^{-3})	54.73 ± 0.14	54.24 ± 0.23
Wind N_H, hot component (10^{21} cm^{-2})	<0.1	<1.0
log T_{cool} (K)	6.46 ± 0.08	6.53 ± 0.07
log EM_{cool} (cm^{-3})	55.20 ± 0.17	55.09 ± 0.12
Wind N_H, cool component (10^{21} cm^{-2})	3.90 ± 0.50	2.83 ± 0.20
log L_X (ergs s^{-1})	32.63	32.37
χ^2_ν	1.29[b]	1.27[b]

[a] Errors and upper limits are 90% confidence for one parameter of interest.
[b] Fit to spectrum above 0.5 keV.

work is that emission from a single-temperature plasma plus ISM absorption alone *cannot* fit the observed spectra for either δ Ori or λ Ori. In each case, a plasma which is hot enough to produce the emission at $E > 1$ keV produces too much emission near 0.8 keV and does not produce enough X-ray emission at lower energies.

Because of the inadequacy of the single-temperature models, we tried more complicated models. We were unable to fit the spectra with two-temperature emission models absorbed by the ISM column alone. Since the X-ray source is most likely buried inside the massive stellar wind, we next considered adding additional absorption. We could not fit the observed spectra with either a single- or two-temperature emission model using additional absorption from an un-ionized ("cool") medium. We therefore tried to model the spectrum using absorption from an ionized ("warm") absorbing medium (Waldron 1984), as representative of the photoionized stellar wind material. We found that we could achieve a satisfactory fit to the δ Ori and λ Ori spectra above 0.5 keV for a two-temperature plasma model with warm absorption plus an overlying ISM column, letting the amount of absorption to the cooler emission component be independent of the amount to the hotter component. The parameters for our best-fit models are given in Table 2 for each star. The luminosities listed in Table 2 have been corrected for ISM + circumstellar absorption and are in the range 0.4–4.0 keV, using distances of 500 pc for both stars. The absorbing columns we derive are significantly larger than the ISM values. Taking the derived column densities at face value, simple modeling (see, e.g., Corcoran et al. 1993) of the wind absorption means that most of the X-rays originate from a region <2 stellar radii above the photosphere (consistent with the results obtained for ζ Pup by MacFarlane et al. 1993). However, in order to achieve a formally acceptable fit to both the δ Ori and λ Ori spectra, we needed to reduce the abundance of Fe to one-fifth the solar value and allow the Mg abundance to depart from the solar value as well. Changing the model abundances in this way does not necessarily indicate the presence of noncosmic abundances in either δ Ori or λ Ori; the abundances derived could be artifacts of uncertainties in the plasma models (for, e.g., radiation transfer effects) or instrumental calibration (or any combination). We point out that analysis of the photospheric spectrum of δ Ori fixed the abundance of He (and presumably other metals as well) at the solar value (Voels et al. 1989).

Although our best fit required emission from plasma at two temperatures, we could not rule out the presence of additional temperature components. Note that the distribution of temperatures in δ Ori is significantly different from that in λ Ori; λ Ori exhibits significantly hotter emission than δ Ori. The reason for this difference is not known. Since λ Ori does lie in a fairly crowded field, some of this emission could be due to the presence of an unresolved X-ray source such as a late-type or pre–main-sequence star (which generally show high-temperature emission). We note that an image of λ Ori obtained by the *ROSAT* PSPC (observation sequence number 200200) indicates the presence of two X-ray sources separated from λ Ori by about 1′ and 2′. Since these sources could not be resolved in the SIS, it is possible that one or both make some contribution to the observed X-ray emission for λ Ori.

Chen & White (1991) have suggested that inverse Comptonization of the photospheric UV field by a population of fast particles accelerated by a distribution of shocks should produce a nonthermal tail at high energies which could be observable in the SIS spectra. We see no unambiguous evidence for such a nonthermal tail, although addition of a nonthermal component can slightly improve the reduced χ^2 for both δ Ori and λ Ori (from roughly $\chi^2 = 1.3$ to 1.1 for both stars).

Haberl & White (1993) fitted the PSPC spectrum of δ Ori with 2 components as well, although their derived temperatures were 0.1 and 0.2 keV. However, simultaneous fits to the *ASCA* SIS0 and PSPC spectra of δ Ori require at least three components, with temperatures near 0.1, 0.3, and 0.6 keV. The latter two components contribute in the *ASCA* bandpass, while the 0.1 keV component makes little contribution. Similarly, the PSPC spectrum is dominated by the 0.1 and 0.3 keV components, with little contribution from the 0.6 keV component.

The SIS0 spectra of δ Ori and λ Ori clearly illustrate the richness of OB star X-ray spectra when this emission is measured with sufficient energy resolution. The observed spectral details suggest that a complexity of physical processes may be responsible for the observed X-ray emission. Though it is not yet possible to fully discern the nature of these processes, further studies of X-ray spectra from OB stars with ASCA will provide necessary and heretofore unobtainable information on the composition, location, and dynamics of the hot plasma.

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15. Supplementary Notes

The results of this study have been published in "The Astrophysical Journal" (see enclosure).

16. Abstract

We obtained an ASCA SIS observation of the 08 III ((f)) star, Lambda Ori. The main scientific objectives were to search for evidence of X-ray line emission and stellar wind X-ray absorption.

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