Detection of hard X-rays from a Class I protostar
in the HH24-26 region in the Orion Molecular Cloud

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ABSTRACT

We observed the HH24-26 region in the L1630 Orion molecular cloud complex with the X-ray observatory ASCA in the 0.5–10 keV band. X-ray emission was detected from the T Tauri star SSV61 and from the region where the Class I protostars SSV63E and SSV63W are located (hereafter SSV63E+W). The spectra of both SSV63E+W and SSV61 are well explained by an optically thin thermal plasma model. The spectrum of the T Tauri star SSV61 has a low temperature of $kT = 0.9 (0.7–1.2)$ keV and a moderate absorption of $N_H = 1.3 (0.9–1.7) \times 10^{22}$ cm$^{-2}$, while that of the protostar SSV63E+W has a high temperature of $kT = 5.0 (3.3–7.9)$ keV and a heavy absorption of $N_H = 1.5 (1.2–1.8) \times 10^{23}$ cm$^{-2}$. The X-ray light curve of SSV63E+W showed a flare during the observation. The peak flux reached about 9 times that of the quiescent flux. The temperature and the absorption column density do not change conspicuously during the flare. The 0.5–10 keV luminosity of SSV63E+W was about $1 \times 10^{32}$ erg s$^{-1}$ in the quiescent state. The present detection of hard X-rays from SSV63E+W is remarkable, because this is the first X-ray detection of a protostar in Orion.

Subject headings: stars: flare—stars: formation—stars: individual (SSV61, SSV63E+W)—stars: pre-main sequence—X-rays: stars
1. Introduction

Young stellar objects (YSOs) are divided into 4 classes by the spectral-energy distribution at infrared to millimeter wave lengths (André & Montmerle 1994): Class 0 and Class I protostars, Class II sources (classical T Tauri stars, CTTS) and Class III sources (weak-line T Tauri stars, WTTS). The Class 0 protostars have massive envelopes which collapse towards the central region. Their age is estimated to be $\sim 10^4$ yr. The class I protostars have circumstellar disks and dilute dust envelopes. Their age is estimated to be $\sim 10^5$ yr. The Einstein and ROSAT observatories detected soft X-ray emission from both CTTS and WTTS, whose luminosities range from $10^{28}$ erg s$^{-1}$ to $10^{30}$ erg s$^{-1}$ (Montmerle et al. 1993, Neuhäuser 1997). Recently, ROSAT and ASCA discovered X-ray emission from Class I protostars (Casanova et al. 1995, Koyama et al. 1996, Grosso et al. 1997, Kamata et al. 1997). Since X-ray emission has been detected from only a dozen protostars (Carkner et al. 1998), it is important to increase the sample size of X-ray emitting protostars to investigate the origin of their X-ray emission.

The HH24-26 region is located in the L1630 Orion molecular cloud complex at a distance of about 460 pc (Chini et al. 1993). This region is an active star-forming region containing several YSOs, Class 0 sources (HH24MMS, HH25MMS), Class I sources (SSV63, SSV59) and a Class II source (SSV61) (Bontemps et al. 1995). SSV63 and SSV61 were detected in the 2.2 $\mu$m mapping survey (Strom et al. 1976) and later SSV63 was resolved into four near-infrared sources, SSV63E, SSV63W, SSV63NE-1, and SSV63NE-2 (Moneti & Reipurth 1995). Both SSV63E and SSV63W show flat or rising spectra in the near- and mid-infrared band (Zealy et al. 1992), and hence belong to Class I. SSV63NE-1 and SSV63NE-2 are unclassified diffuse sources, and may be reflection nebulae (Moneti & Reipurth 1995). A complex of Herbig-Haro jets (HH24) was detected around SSV63 by optical observations and some of the jets are probably associated with SSV63 itself (Jones...
et al. 1987, Mundt et al. 1991). In this paper, we report the first detection of X-ray emission from the infrared protostar SSV63.

2. Observations

We observed the HH24-26 region with the ASCA observatory (Tanaka et al. 1994) for a net exposure time of about 30 ks on 1998 October 2. The center coordinates of the pointing position were R.A.(J2000)= 5^h 46^m 27.6^s and Decl.(J2000)= −0° 7′ 58.7″. ASCA has four identical X-ray telescopes (XRT), which achieve large effective area at energies up to 10 keV (Serlemitsos et al. 1995). Two Solid state Imaging Spectrometers (SIS0, SIS1) and two Gas Imaging Spectrometers (GIS2, GIS3) are located at each focus of an XRT. Each SIS has four CCD chips, which have an 11′ × 11′ field of view each. These instruments cover the energy range from 0.4 keV to 10 keV (Burke et al. 1991) with an energy resolution of ∼160 eV (FWHM) at 6 keV and ∼100 eV (FWHM) at 1.5 keV at the time of the present observation. The GIS has a field of view of 40′ diameter and covers the energy range from 0.7 keV to 10 keV with an energy resolution of 0.5 keV (FWHM) at 5.9 keV (Ohashi et al. 1996). In this observation, the SIS was operated in the 2-CCD mode, while the GIS was in the normal pulse-height mode with nominal bit assignments.

3. Results

3.1. X-ray image of HH24-26 region

Figure 1 shows the SIS soft band (0.7−2.0 keV) and hard band (2.0−8.0 keV) images of the HH24-26 region averaged over the whole observation. In the figure, the SIS0 and SIS1 images are superimposed and smoothed by a gaussian function with σ of 0.2′. The symbols with numbers from 1 to 8 in Figure 1 correspond to the sources cited in the caption.
Clearly, we detected two X-ray sources. The southern source is conspicuous only in the soft band (0.7−2.0 keV) image, whereas the northern source is predominant in the hard band (2.0−8.0 keV) image. Both detections are consistent with point sources within the angular resolution of the XRT (half power diameter about 3′). In order to derive accurate positions and count rates of the detected sources, we performed 2-dimensional fitting to the SIS image using the point spread function of the XRT (Ueda 1996). The positions determined with ASCA are (5h46m7.0s, −0°10′7″) and (5h46m7.3s, −0°12′4″), with 1σ error of 14″. Based on the positional coincidence, the southern source is identified with the T Tauri star SSV61. The northern source is identified with the protostars SSV63E/SSV63W, but the ASCA image resolution does not allow us to resolve X-ray emission of the two (hereafter we designate the emission as from SSV63E+W). The count rates in the 0.7−7.0 keV band of SSV61 and SSV63E+W are 1.4 (1.3−1.6) ×10\(^{-2}\) counts s\(^{-1}\) (the errors in parentheses indicate a 90% confidence region) and 8.2 (7.0−9.4) ×10\(^{-3}\) counts s\(^{-1}\), respectively. We were not able to detect any evidence of X-ray emission from the Class I protostar SSV59 or the Class 0 protostars, HH24MMS and HH25MMS. We derived upper limits (2σ) of count rates of these protostars, 2 ×10\(^{-4}\) counts s\(^{-1}\), 8 ×10\(^{-4}\) counts s\(^{-1}\), and 5 ×10\(^{-4}\) counts s\(^{-1}\), respectively for SSV59, HH24MMS, and HH25MMS.

3.2. Light curve

Figure 2 shows background-subtracted light curves in the hard (3.0−8.0 keV) and the soft (0.7−2 keV) X-ray bands. In the figure, all the data from the four sensors (SIS0, SIS1, GIS2, GIS3) are combined to obtain the best statistics. The data were taken from regions of 6′ radius for the GIS and 4′ radius for the SIS, centered at the position of SSV63E+W. The circle shown in Figure 1 indicates the region where the SIS light curve was derived. We extracted the background which is constructed from the whole FOV of each sensor where
point sources were excluded, correcting for the positional dependence of the background intensity (Ueda 1996). Although the region contains both SSV61 and SSV63E+W, the hard band light curve should correspond to that of SSV63E+W and the soft band light curve to that of SSV61, as expected from the image analysis in section 3.1. We discarded the data in the 2.0–3.0 keV band from the hard band light curve because X-rays both from SSV63E+W and SSV61 contribute comparably in the 2.0–3.0 keV band, as shown in Figure 3 of section 3.3.

As can be seen from the top panel of Figure 2, SSV63E+W showed flare-like time variability. On the other hand, the soft band light curve (bottom panel of Figure 2) showed little intensity variability, suggesting that the T Tauri star SSV61 was relatively stable during the ASCA observation. The flare from SSV63E+W is characterized by a slow rise followed by an exponential decay. We fitted the light curve with a model consisting of a linear rise and an exponential decay to a constant level of the form,

\[
F(t) = \begin{cases} 
\frac{N}{\tau_r}(t - t_p + \tau_r) + C, & (t < t_p), \\
N \exp\left\{\frac{-(t-t_p)}{\tau_d}\right\} + C, & (t \geq t_p).
\end{cases}
\]  

This model has five free parameters, flare peak time \( t_p \), rise time \( \tau_r \), a constant level \( C \), the normalization of the exponential function \( N \), and e-folding decay time \( \tau_d \). The solid curve in Figure 2 shows the best-fit model. From the fit, we derived a peak flux \((N + C)\) of 0.18 (0.16–0.19) cts s\(^{-1}\), \( C = 0.02 \) (0.016–0.026) cts s\(^{-1}\), \( \tau_r = 1.7 \) (1.2–2.2) \( \times 10^4 \) s, and \( \tau_d = 1.2 \) (0.9–1.5) \( \times 10^4 \) s.

### 3.3. Energy spectrum

The upper and lower panels in Figure 3 show background-subtracted spectra taken from the interval A (hereafter termed the “flare state”) and the interval B (the “quiescent state”) indicated in Figure 2, respectively. Since the separation between SSV63E+W
and SSV61 (~2') is not large enough compared with the PSF of the XRT of ASCA, it is difficult to obtain spectra from SSV63E+W and SSV61 without contamination from the other even if we extract the spectra in a small region around each source. Hence, we accumulated photons in the same region as used in section 3.2 to obtain better statistics. The background spectrum is also extracted from the same region as used in section 3.2. Since the region includes both the positions of SSV63E+W and SSV61, the spectra will contain contributions from both the sources. Both of the spectra in Figure 3 show a double peak feature, suggesting the existence of two (hard and soft) components. Combined with the results from the image analysis in section 3.1, we assume that the soft and the hard components correspond to SSV61 and SSV63E+W, respectively. In fact, the soft component does not show a significant change between the two states, while the hard component is enhanced during the flare state. This confirms that the hard component in the spectrum really corresponds to the emission from the Class I protostar SSV63E+W.

In the hard component during the flare state, an emission line feature is clearly seen at 6.6 (6.5-6.7) keV, which is consistent with the Kα line from He-like iron ions. This suggests that the hard component during the flare state originates from an optically thin thermal plasma. On the other hand, the origin of the soft component from SSV61 is also considered to be thin thermal coronal emission, which is typical for T Tauri stars (Montmerle et al. 1993, Neuhäußer 1997). Accordingly, we fit the combined GIS and SIS spectra with a model consisting of two thermal components with different absorption column densities, in which the high and low temperature components represent the contribution from SSV63E+W and from SSV61, respectively. This model of two thermal components was also adopted for the quiescent spectrum, utilizing the thin thermal spectral model calculated by Raymond and Smith (1977; hereafter the “RS model”). Since the statistics of the spectrum are not good enough to determine the abundance of the soft component, we fixed this at 0.5 solar for SSV61 because the metal abundances of late-type stars are roughly 0.5 solar
For the hard component, we used an Auxiliary Response Function (ARF) constructed for a point source located in the center of the region selected (i.e., SSV63E+W), while for the soft component, we used an ARF constructed for a point source located at the position of SSV61.

Using this “two-component” RS model, we obtained acceptable fits for both of the flare-state and quiescent state spectra. The temperature and the absorption column density did not change significantly between the flare state and the quiescent state for either the hard or soft components. Hence, to make the tightest constraints on these parameters, we extracted spectra averaged over the whole observation, and fit them with the same model. We again obtained acceptable fits with parameters listed in Table 1. We derived plasma temperatures $kT = 0.9 \,(0.7-1.2)$ and $5.0 \,(3.3-7.9)$ keV, time-averaged emission measures of $5.3 \,(3.2-9.0) \times 10^{54}$ cm$^{-3}$ and $14 \,(9.5-25) \times 10^{54}$ cm$^{-3}$, and absorption column densities $N_H =1.3 \,(0.9-1.7) \times 10^{22}$ cm$^{-2}$ and $1.5 \,(1.2-1.8) \times 10^{23}$ cm$^{-2}$, respectively for the low and high temperature components. We obtained an abundance of 0.45 ($0.28-0.69$) solar for the high temperature component, SSV63E+W. Finally, to determine the spectral parameters of SSV63E+W separately during the flare state and the quiescent state, we repeated the fit by fixing the parameters of the soft component at the best-fit values obtained from the whole observation. The results are also listed in Table 1.

4. Discussion

Since X-ray emission from Class 0 protostars has not been detected yet, it is interesting whether Class 0 protostars in the HH24-26 region, HH24MMS and HH25MMS, emit X-rays or not. The present ASCA observation, however, failed to detect X-ray emission from either HH24MMS or HH25MMS. We estimate upper limits of X-ray luminosity as $9 \times 10^{30}$ erg s$^{-1}$ for HH24MMS, $7 \times 10^{30}$ erg s$^{-1}$ for HH25MMS, and $4 \times 10^{30}$ erg s$^{-1}$ for the Class I
protostar SSV59, assuming a RS model with $kT = 5$ keV, $N_H = 1 \times 10^{23}$ cm$^{-2}$, and a metal abundance of 0.5 solar. We note that these estimates depend on the spectral parameters assumed.

The most remarkable result here is the first detection of X-ray emission from a Class I protostar SSV63E+W in Orion. The significant features of the X-ray emission are: (1) a large X-ray luminosity of about $1 \times 10^{32}$ erg s$^{-1}$ in the 0.5–10 keV band and a high temperature of $kT = 5.2$ ( $> 2.3$) keV during the quiescent state, (2) an X-ray flare with total energy release of $5 \times 10^{36}$ erg with an elevated temperature of $kT \sim 6$ keV, and (3) a large absorption column density of $N_H = 1.1 (1.0–1.3) \times 10^{23}$ cm$^{-2}$.

SSV63E+W has a high temperature plasma even during the quiescent state, which is comparable to that during the flare state. Such a high temperature is not observed in TTSs during the quiescent state. A cluster of Class I protostars in the R CrA molecular cloud also showed a high temperature of $kT \sim 7$ keV during the quiescent state (Koyama et al. 1996). Thus, some of the Class I sources have high temperature plasmas of $\sim 6$ keV.

In order to know the mechanism of the quiescent X-ray emission, we compare the $L_X/L_{bol}$ ratio of SSV63E+W with those of T Tauri stars. The bolometric luminosity of SSV63E is estimated to be 22.4 $L_\odot$ (Berrilli et al. 1989, Zealey et al. 1992). Although that of SSV63W is highly uncertain, assuming the X-ray emission of SSV63E+W comes from only SSV63E, we obtained $L_X/L_{bol}$ ratio of $1.2 \times 10^{-3}$ in the quiescent state. Since the typical $L_X/L_{bol}$ ratio of T Tauri stars is $5 \times 10^{-4}$ and the maximum is $3 \times 10^{-3}$ (Preibisch et al. 1998), our value of the $L_X/L_{bol}$ ratio of SSV63E+W is comparable to that of T Tauri stars. Thus the X-ray emission mechanism from protostars during the quiescent state has to produce higher temperature plasmas of $\sim 6$ keV, but not larger $L_X/L_{bol}$ ratios than those of T Tauri stars. The enhanced disk-magnetosphere interaction (Shu et al. 1997) may provide such high temperature plasmas in protostars.
The hard ($kT \sim 6$ keV) X-ray flare of SSV63E+W can probably be explained by strong magnetic activity, by analogy with the X-ray flares of TTSs. Such a hard X-ray flare was also observed from a protostar in the R Cr A molecular clouds (Koyama et al. 1996). Hayashi et al. (1996) suggested a model for hard X-ray flares in protostars, based on a closed magnetic loop connecting the central star and disk. This model can explain the high temperature of X-ray emitting protostars during the flare state. From the decay time analysis (van den Oord & Mewe 1989, Montmerle 1990) of the observed flare, we estimated the electron density $n_e \sim 1 \times 10^{11}$ cm$^{-3}$, the volume of the emission region $V \approx E.M./n_e^2 \sim 2 \times 10^{33}$ cm$^3$, the typical length of the region $d = V^{\frac{1}{3}} \sim 1 \times 10^{11}$ cm, and the magnetic field strength $B \sim 200$ gauss for the flare region in SSV63E+W. These parameters constrain the model of X-ray flare of the protostar.

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Fig. 1.— The SIS images of the HH24-26 region in the soft band (0.7–2.0 keV, left panel) and in the hard band (2.0–8.0 keV, right panel). The symbol with number 1 corresponds to HH24MMS (Class0), 2 HH25MMS (Class0), 3 SSV59 (Class I), 4 SSV63W (Class I), 5 SSV63E (Class I), 6 SSV61 (Class II), 7 SSV63NE-1 (reflection nebulae), 8 SSV63NE-2 (reflection nebulae), respectively (Cohen & Schwartz 1983, Bontemps et al. 1995, Zealey et al. 1992., Moneti & Reipurth 1995). The circle with 4’ radius indicates the region where X-ray photons were extracted to produce light curves and spectra (see section 3.2 and 3.3).

Fig. 2.— X-ray light curves in the HH24-26 region. Upper panel: the light curve in the 3.0–8.0 keV band, predominantly corresponds to the protostar SSV63E+W. Lower panel: the light curve in the 0.7–2.0 keV band, predominantly to the T Tauri star SSV61. The solid line in the upper panel indicates the best-fit model (see section 3.2). The intervals A and B indicate the flare state and the quiescent state, used for extraction of spectra in section 3.3.

Fig. 3.— GIS (open squares) and SIS (filled circles) energy spectra obtained from the HH24-26 region during the flare state (upper) and during the quiescent state (lower). The dotted lines indicate the best-fit models of the soft and the hard components, and the solid line indicates the total. The soft component corresponds to the emission from the T Tauri star SSV61 and the hard component to that of the protostar SSV63E+W.
Table 1. Best fit spectral parameters\textsuperscript{a} and X-ray luminosity for SSV61 and SSV63E+W

<table>
<thead>
<tr>
<th></th>
<th>SSV63E+W</th>
<th>SSV63E+W(flare)\textsuperscript{d}</th>
<th>SSV63E+W(quiescent)\textsuperscript{d}</th>
<th>SSV61</th>
</tr>
</thead>
<tbody>
<tr>
<td>$kT$ (keV)</td>
<td>5.0 (3.3–7.9)</td>
<td>6.3 (3.9–11.6)</td>
<td>5.2 (&gt;2.3)</td>
<td>0.9 (0.7–1.2)</td>
</tr>
<tr>
<td>$N_H$ ($10^{22}$ cm\textsuperscript{-2})</td>
<td>15 (12–18)</td>
<td>14 (12–17)</td>
<td>14 (8.7–23)</td>
<td>1.3 (0.9–1.7)</td>
</tr>
<tr>
<td>abundance</td>
<td>0.45 (0.28–0.69)</td>
<td>0.55 (0.33–0.96)</td>
<td>0.34 (0.0–2.2)</td>
<td>0.5 (fixed)</td>
</tr>
<tr>
<td>$E.M.$\textsuperscript{b} ($10^{54}$ cm\textsuperscript{-3})</td>
<td>14 (9.5–25)</td>
<td>21 (14–35)</td>
<td>7.4 (3.5–2.7)</td>
<td>5.3 (3.2–9.0)</td>
</tr>
<tr>
<td>$L_x$\textsuperscript{c} ($10^{31}$ erg s\textsuperscript{-1})</td>
<td>22</td>
<td>35</td>
<td>11</td>
<td>6.2</td>
</tr>
<tr>
<td>$\chi^2$/d.o.f.</td>
<td>68.5/69</td>
<td>54.7/56</td>
<td>39.7/37</td>
<td>68.5/69</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Single-parameter 90\% confidence regions are shown in parentheses.

\textsuperscript{b}The emission measures were calculated from the best-fit GIS parameters. Those from SIS parameters are consistent within statistical errors.

\textsuperscript{c}Intrinsic X-ray luminosities in the 0.5–10 keV band corrected for absorption, and assuming a source distance of 460 pc.

\textsuperscript{d}The parameters in the flare state and the quiescent state were obtained by fixing the parameters of the soft components to the best-fit values.