A Systematic Study of X-Ray Flares from Low-Mass Young Stellar Objects in the ρ Ophiuchi Star-Forming Region with Chandra

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Abstract

We report on the results of a systematic study of X-ray flares from low-mass young stellar objects, using two deep exposure Chandra observations of the main region of the ρ Ophiuchi star-forming cloud. From 195 X-ray sources, including class I–III sources and some young brown dwarfs, we detected a total of 71 X-ray flares. Most of the flares have the typical profile of solar and stellar flares, fast rise and slow decay, while some bright flares show unusually long rise timescales. We derived the time-averaged temperature (∑kT), luminosity (∑Lx), rise and decay timescales (τr and τd) of the flares, finding that (1) class I–II sources tend to have a high ∑kT, which sometimes exceeds 5 keV, (2) the distribution of ∑Lx during flares is nearly the same for all classes from ∼10^{29.5} to ∼10^{31.5} erg s^{-1}, although there is a marginal hint of a higher ∑Lx distribution for class I than class II–III, and (3) positive and negative log-linear correlations are found between τr and τd, and ∑kT and τr. In order to explain these relations, we used the framework of magnetic reconnection model with heat conduction and chromospheric evaporation to formulate the observational parameters (τr, τd, and ∑kT) as a function of the pre-flare (coronal) electronic density (n_e), the half-length of the reconnected magnetic loop (L), and magnetic field strength (B). The observed correlations are well reproduced if loop lengths are nearly the same for all classes, regardless of the existence of an accretion disk. The estimated loop length is almost comparable to the typical stellar radius of these objects (10^{10}–10^{11} cm),
which indicates that the observed flares are triggered by solar-type loops, rather than larger ones (\(\sim 10^{12}\) cm) connecting the star with its inner accretion disk. The higher \(\langle kT \rangle\) observed for class I sources may be explained by a slightly higher magnetic field strength (\(\approx 500\) G) than for class II–III sources (200–300 G).

**Key words:** ISM: clouds — ISM: individual (\(\rho\) Ophiuchi Cloud) — stars: flare — stars: pre-main-sequence — X-rays: stars

1. Introduction

Low-mass young stellar objects (YSOs) are classified into four evolutionary stages based on the infrared (IR) to sub-millimeter spectral energy distributions (SEDs); the youngest and evolved protostars have class 0 and I SEDs, while classical and weak-lined T Tauri stars (CTTSs and WTTSs) exhibit class II and III SEDs, respectively (Lada 1991; André et al. 1993; André, Montmerle 1994). In the 1980’s, the Einstein satellite discovered X-rays from T Tauri stars (TTSs = CTTSs and WTTSs: Feigelson, DeCampli 1981; Feigelson, Kriss 1981; Montmerle et al. 1983). Koyama et al. (1994) first detected X-rays from the positions of class I sources in the \(\rho\) Ophiuchi dark cloud (WL 6 and WL 15 = Elias 29) with ASCA/GIS. Using ASCA/SIS, which has a better spatial resolution than GIS, Kamata et al. (1997) confirmed the X-ray emission from the class I sources. Independently, Casanova et al. (1995) obtained hints of X-ray detection from class I in the same star-forming area with ROSAT/PSPC. Then, successive observations with ASCA further revealed that many class I protostars are X-ray emitters (Koyama et al. 1996; Ozawa et al. 1999; Tsuboi et al. 2000), thanks to a higher sensitivity for hard X-ray photons (\(> 2\) keV), which are less absorbed, because the extinction cross-section decreases as \(E_X^{-2.5}\) (\(E_X\): X-ray energy). ROSAT observations also detected X-rays from class I (Grosso et al. 1997; Neuhäuser, Preibisch 1997; Grosso 2001). They share the same characteristics of thermal emission with a plasma temperature of 0.5–5 keV and a strong variability with occasional rapid flares, consistent with the scenario of enhanced solar-type activity, attributable to magnetic dynamo processes. Furthermore, a recent observation with the Chandra satellite detected hard X-rays from class 0 source candidates in the Orion Molecular Cloud 3 (Tsuboi et al. 2001), although its characteristics are still poorly understood due to the limited statistics. These pioneering discoveries demonstrate the unique capability of hard X-ray observations to probe YSOs or their close vicinity deeply embedded in dense cores.

Based on the above results, the next step should be a systematic study of X-rays from YSOs and to approach physical conditions of these initial stages of stars, which gives extremely important information concerning star-formation theory. For example, our earlier results of a Chandra observation of the \(\rho\) Ophiuchi cloud suggested that class I protostars tend to show a higher plasma temperature \((kT)\) than TTSs (Imanishi et al. 2001a, hereafter Paper I). Stelzer et al. (2000) also did a systematic study of TTS flares in Taurus–Auriga–Perseus with
ROSAT/PSPC, and found that the flare rate of CTTSs may be somewhat higher than that of WTTSs. To explain the quasi-periodic X-ray flare observed from the class I source YLW 15 in the ρ Ophiuchi dark cloud (Tsuboi et al. 2000), Montmerle et al. (2000) proposed a scenario of star–disk connection by one magnetic loop, where the central forming-star rotates faster than the inner edge of its accretion disk, which triggers periodic X-ray flaring. Shibata and Yokoyama (1999, 2002) further showed that $kT$ is determined by the balance between reconnection heating and conduction cooling, and then derived the relation $kT \propto L^{2/7} B^{6/7}$, where $L$ and $B$ are the half-length of the reconnected magnetic loop and strength of the magnetic field. Hence, larger $L$ and/or $B$ values make a higher temperature plasma. Combining these results, one plausible scenario is that younger sources have a much larger flare loop than evolved sources connecting the central source and the disk, and thus show frequent flares with a higher plasma temperature. Feigelson et al. (2002), on the other hand, reported that X-ray emission has no correlation with the presence or absence of the disk for the Orion Nebula Cluster X-ray sources. It is therefore still controversial whether there is any differences in the observed X-ray properties or emission mechanisms between the different classes.

To address this issue, other important parameters would be the timescales of the flares, which were not considered in the above results. If we assume radiative cooling without successive heating (van den Oord et al. 1988), the decay timescale of flares ($\tau_d$) is equal to the radiative loss timescale, defined as $E_{\text{th}}/R$ ($E_{\text{th}}$ is the total thermal energy and $R$ is emissivity of the plasma). Since $E_{\text{th}}$ is supplied by the magnetic energy ($B^2/8\pi$) and $R$ depends on their plasma electronic density ($R \propto n^2$, $n$: electronic density), $\tau_d$ is tightly correlated with $B$ and $n$. Also, a standard magnetic reconnection model (Petschek 1964) predicted that the rise timescale of flares ($\tau_r$) is proportional to the Alfvén time ($\tau_A$), defined as $L/v_A$, where $v_A$ is the Alfvén velocity ($v_A \propto B$); hence, a larger $L$ and/or a smaller $B$ yield a longer $\tau_r$. In fact, some stellar flares display unusually long rising phases (e.g., UX Ari: Güdel et al. 1999 and ROXs31: Imanishi et al. 2002). To examine any correlations between these observable parameters ($kT$, $\tau_r$, and $\tau_d$) would be fruitful for understanding of physical conditions of YSOs. However, little has been done for systematical approach so far.

In the present work, we made the first systematic study of the flare activity of YSOs, using two deep exposure Chandra observations of the ρ Ophiuchi cloud (hereafter, ρ Oph) at a distance of 145 pc (de Zeeuw et al. 1999). Details of the observations are shown in section 2. We then performed timing and spectral analyses for all detected sources, and examine any correlations between the derived parameters (section 3). From the observed quantities, we estimate the physical parameters and discuss the differences of the derived parameters between each class (section 4).
2. Chandra Observations of the \( \rho \) Ophiuchi Cloud

The Chandra X-ray Observatory (Weisskopf et al. 2002) observed the central region of \( \rho \) Oph twice with a deep exposure of the ACIS-I array, consisting of four abutted X-ray CCDs. The first observation (here and after, obs.-BF) covered the south-east 17\'4 \times 17\'4 area, including cores B, C, E, and F, while the second observation (obs.-A) covered the north-west area centered on core A (Loren et al. 1990). Although some of the ACIS-S chips were simultaneously in operation, we do not use these data because large off-axis angles cause a degeneration of the sensitivity and position determination. From the Chandra X-ray Center (CXC) archive, we retrieved level-2 data, in which the data degradation caused by the increase of charge transfer inefficiency (CTI) in orbit was corrected. The X-ray events were selected with ASCA grades 0, 2, 3, 4, and 6. The afterglow events were also removed. After processing, each observation yielded \( \approx 100 \) ks of live time (table 1). Earlier results of obs.-BF were found in Paper I.

3. Analyses and Results

3.1. X-ray Sources and NIR Counterparts

Figure 1 gives an ACIS image of \( \rho \) Oph. The red and blue colors represent photons in the soft (0.5–2.0 keV) and hard (2.0–9.0 keV) X-ray bands, respectively. First, we discuss the source detection analysis using the wavdetect command (Freeman et al. 2002) in the CIAO package for 2048\times2048 pixel images with the pixel size of \( \sim 0\''5 \). We then consider the search for near-infrared (NIR) counterparts for all detected X-ray sources. The basic procedures of the analysis were the same in Paper I, except for the following points:

1. The significance criterion of wavdetect is relaxed from \( 10^{-7} \) (Paper I) to \( 10^{-6} \).
2. We apply the wavdetect analysis for both the soft and hard X-ray bands as well as for the total (0.5–9.0 keV) X-ray band.
3. For reference of NIR sources, we use the Point Source Catalog in the 2MASS Second Incremental Data Release\(^1\), not that in Barsony et al. (1997), because the former has a better position accuracy (\( \sigma \sim 0\''1 \)) than, and comparable sensitivity (\( K_s < 14.3 \) mag) to the latter (Barsony et al. 1997, \( \sigma \sim 1\''2 \) and \( K < 14.5 \) mag).

We then detected 195 X-ray sources, nine of which were found in both the two observations. Thirteen and nine sources were exclusively found in only the soft and hard bands, respectively (hereafter, the “soft-band sources” and “hard-band sources”). Table 2 (columns 1–4) gives the name, background-subtracted ACIS-I counts, and the coordinates (after the offset correction) for each source. The soft-band and hard-band sources are indicated by the prefixes “S” and “H”. The X-ray photons were extracted from a circle of 1\''2–23\''3 radius, depending on the point spread function (PSF) radius for 1.49 keV photons, which is a function of the

\(^1\) See (http://www.ipac.caltech.edu/2mass/releases/second/doc/).
angular distance from the optical axis of the telescope (psfsize20010416.fits in the CIAO 2.2.1 package). Typically, in the source radius, ≈95% of the X-ray photons are included. In order to obtain a high signal-to-noise ratio for some faint sources, we used a circle of a half radius of the PSF. Background counts were extracted from circles of 38 arcmin$^2$ and 57 arcmin$^2$ areas from the respective source-free regions in the ACIS-I fields of obs.-A and obs.-BF.

In order to check for possible false sources with the wavdetect procedure (Feigelson et al. 2002), we estimated the confidence level ($CL$) of the X-ray counts using Poisson statistics (Imanishi et al. 2001b). Then, 14 sources were found to have a $CL$ value smaller than 99.9%. Although A-48 and A-H2 have significantly high $CL$, these may also be possible false sources because of the larger source size than the PSF radius (A-48) and of the severe contamination from A-2 (A-H2). We hence note that 16 sources were marginal detections, and label them with (m) in column 2 of table 2.

About 60% of the X-ray sources had 2MASS NIR counterparts. Using these pairs, we determined and shifted the absolute positions of the Chandra sources so that the mean values of the Chandra-2MASS offset in the direction of right ascension and declination would become zero. The offset correction of obs.-BF (hence the position of the X-ray sources) was slightly different from those reported in Paper I because of the difference of the reference NIR catalogue. For the remaining sources, we further searched for counterparts using other NIR catalogues, and then identified an X-ray source, BF-90, to be a counterpart of GY 322 (Greene, Young 1992). Finally, we concluded that 110 out of 195 X-ray sources have NIR counterparts. The offset between the X-ray and NIR sources is shown at column 2 in table 3. We also searched for radio (cm) and X-ray counterparts in published catalogues (columns 3–7 in table 3).

Column 9 in table 3 gives the IR classification based on the spectral indices from the NIR to mid-IR band (ISOCAM survey at 6.7 and 14.3 μm; Bontemps et al. 2001). Imanishi et al. (2001a) used the terminology class I$_c$ (class I candidate) for sources previously classified as class I (or flat spectrum source). In this paper, however, we regard all class I$_c$s as class II, following Bontemps et al. (2001). Furthermore, we define some additional classes (class III$_c$, BD, BD$_c$, F, unclassified NIR sources, and unidentified sources). The definition of these classes is given in Bontemps et al. (2001), Imanishi et al. (2001b), and a footnote of table 3 of this paper. We then list 8 class Is, 58 class IIs, 17 class IIIs, 9 class III$_c$s (class III candidates), 2 BDs (brown dwarfs), 3 BD$_c$s (BD candidates), 1 F (foreground star), and 12 unclassified NIR sources. Hereafter, we use the terminology “class III+III$_c$” by combining the class III and class III$_c$ for brevity.

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2 This file was constructed by using the SAOsac raytrace code (Jerius et al. 1995, see also http://asc.harvard.edu/chart/).
3.2. Timing Analysis

We made two X-ray light curves in the 0.5–9.0 keV region for all of the Chandra sources (background was not subtracted), with respective time bins of 2000 s and 4000 s. The source regions were basically the same as those used in an estimation of the source counts (subsection 3.1). For the brightest two sources (A-2 and BF-64), however, we used an annulus of 2''5–12''5 and 2''5–7''5 radius in order to avoid photon pileup (Davis 2001). The light curves show many flare-like events. We defined a “flare time bin” by the following criterion:

\[
\frac{N - N_0}{\Delta N} \geq 2, \tag{1}
\]

where \(N\), \(\Delta N\), and \(N_0\) are the X-ray counts, the statistical 1-\(\sigma\) error for the relevant time bin, and average counts in a 20000 s interval including the relevant time bin, respectively. If the above criterion was satisfied in both of the two light curves (2000 s and 4000 s time bin), we defined the event to be a “flare”. We then picked up 71 flares (table 4). Figure 2 shows all of the light curves of the detected flares. We note that the flare list in Paper I is slightly different from that in this paper, due solely to the different definition of a flare. This slight difference, however, has no significant effect on the following analyses and discussions.

Most flares had the typical profile of those from low-mass main-sequence stars or YSOs; fast-rise and slow-decay, while some sources show unusual flares having slow rise timescale; e.g., BF-64 = YLW 16A (figure 2). We fit the rise and decay phases of the flare by a simple (exponential + constant) model using the QDP command in the LHEASOFT 5.0\(^3\), and derived the respective e-folding times and quiescent level (\(\tau_r\), \(\tau_d\), and \(Q\); table 4) with their 90% errors, where the flare peak time (\(t_p\)) was fixed to be the maximum time bin, except for the second flare of BF-64. Evidently, this simple model cannot reproduce the unusually giant flare from BF-64, even if we relax \(t_p\) to be free. However, we do not intend to make a model of the flare light curve and only have interest in the typical timescales in this paper; hence, we do not discuss this discrepancy in further detail.

3.3. Spectral Analysis

X-ray spectra were made for all of the Chandra sources. For flaring sources, we made time-averaged spectra in the quiescent and flare phases separately. The flare phase was the time from \((t_p - \tau_r)\) to \((t_p + \tau_d)\), and the quiescent phase was that outside of the flare phase. The background regions were the same as used in subsection 3.1. We then fit the spectra by a thin-thermal plasma model (MEKAL: Mewe et al. 1985) with the photoelectric absorption (WABS). The metal abundances were fixed to be 0.3 solar based on previous fitting results (Paper I), unless otherwise noted. If the temperature was not constrained, which is often the case for very faint sources, we fixed the temperature at two representative values of 1 keV (typical of TTSs) and 5 keV (protostars), then estimated the respective absorptions and luminosities. For the

\(^3\) See (http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/).
nine sources detected in both of the observations, we derived the parameters of each spectrum assuming the same absorption. This simple model was generally acceptable. BF-46 (ROXs21) and BF-96 (ROXs31), however, needed multi-temperature spectra with unusual abundances (Imanishi et al. 2002). A-23, A-24 and BF-10, on the other hand, required overabundances (subsubsection 4.8.1 in Paper I; Imanishi 2003). In table 2 (columns 5–9), we summarize the best-fit parameters; time-averaged temperature ($\langle kT \rangle$), emission measure ($\langle EM \rangle$), absorption column ($N_H$), flux, and luminosity ($\langle L_X \rangle$) in 0.5–9.0 keV.

3.4. Luminosity Function

In order to examine the differences along the evolutionary stages, we calculated the X-ray luminosity function for the detected X-ray sources of class I, II, and III+III$_c$ (figure 3), using the ASURV statistical software package (rev.1.2)$^4$ based on the maximum likelihood Kaplan-Meier estimator. The luminosity function of class I seems to be shifted toward higher values than those of class II and III+III$_c$ both in the quiescent and flare phases.

To be more quantitative, we estimated the significance level using two nonparametric two-sample tests in ASURV: the Gehan’s generalized Wilcoxon test (GW) and the logrank test (Feigelson, Nelson 1985). The results are given in table 5, where the blank (...) indicates that the significance level is less than 90%. From table 5, we can see that both the GW and logrank tests for the $\langle L_X \rangle$ difference between class I and the others in the flares show a marginal significance level of $\sim$94%. We should further note that the effect of “undetected” faint flares of class I can not be ignored; if we assume an undetected class I has $\langle L_X \rangle$ smaller than $10^{30}$ erg s$^{-1}$, which is near to the detection threshold of a class I flare, and add this source to the GW and logrank test sample, then the relevant significance level is largely reduced to < 90%. We hence conclude that the higher $\langle L_X \rangle$ of class I than class II+III during flares is marginal.

On the other hand, from table 5, we can see no significant difference between class II and III+III$_c$ source in the flare phase. This is contrary to the results of the Taurus–Auriga–Perseus samples (Stelzer et al. 2000), for which there was a significant difference between the distribution of flare $\langle L_X \rangle$ of class II (CTTS) and class III+III$_c$ (WTTS) sources.

Also, we can see no significant difference of $\langle L_X \rangle$ in the quiescent phase among all classes. This is consistent with the previous estimation for this region with ROSAT derived by Grosso et al. (2000). They tried to estimate the significances rather strictly by considering the upper limit of undetected sources. Our samples give a more severe constraint because the detection threshold is largely reduced to give mean luminosities of $10^{29.5}–10^{29.8}$ erg s$^{-1}$, which are about 10-times lower than that of ROSAT.

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$^4$ See (http://www.astro.psu.edu/statcodes).
3.5. Plasma Temperature and Flare Timescales

In figures 4 and 5, histograms of $\langle kT \rangle$, $\tau_r$, and $\tau_d$ are shown for each class separately, together with the mean values and standard deviations. We exclude the samples whose best-fit parameters and/or those errors were not determined, due to the limited statistics. For sources with multi-temperature plasma (BF-46 and BF-96), we regard $\langle kT \rangle$ of the soft and hard components as the quiescent and flare values, respectively, following the discussion that the former would be steady coronal emission, while the latter is the flare activity (Imanishi et al. 2002).

Most of the $\langle kT \rangle$ values in the quiescent phase are in the range of 0.2–5 keV, while it becomes systematically higher (1–10 keV) in the flare phase, indicating plasma heating during the flare. Although the flare temperature of all classes is distributed around 3–4 keV, some flares of class I and II sources show a higher temperature than 5 keV, while all flares of class III+III$_c$ sources have $\langle kT \rangle$ less than 5 keV. The mean values of $\langle kT \rangle$ during flares for class I and II (4–5 keV) are therefore larger than that of class III+III$_c$ (2.7 keV).

Like the case of $L_X$, we estimated the significance level for the $\langle kT \rangle$ difference among all of the classes with two nonparametric two-sample tests in ASURV. The results are also given in table 5. From table 5, we can see that both the GW and the logrank tests for the difference of $\langle kT \rangle$ during flares between class I+II and class III+III$_c$ sources show high significance level of 94% and 98%. One may be concerned that a systematically large absorption of class I and II sources makes artificial spectral hardening of these classes. We, however, argue that the observed tendency of higher $\langle kT \rangle$ during flares for younger sources is not changed by the extinction differences for the following reasons:

1. If the intrinsic distribution of the flare $\langle kT \rangle$ in class III+III$_c$ is the same as classes I and II, some of the class III+III$_c$ flares should show a higher $\langle kT \rangle$ than 5 keV, but there is no such flare in class III+III$_c$.
2. We re-estimated the mean $\langle kT \rangle$ of class I+II and class III+III$_c$ during the flare for the limited sources of $N_H \leq 5 \times 10^{22}$ cm$^{-2}$ (most of class III+III$_c$ sources have lower $N_H$ than this value). Although the mean $N_H$ is nearly the same (2.5±0.2 and 2.2±0.3 $\times 10^{22}$ cm$^{-2}$ for class I+II and class III+III$_c$), the mean $\langle kT \rangle$ is still higher for class I+II (3.7±0.4 keV) than for class III+III$_c$ (2.4±0.3 keV).

In the quiescent phase, on the other hand, ASURV shows a significance level >95% that the tendency of a higher $\langle kT \rangle$ of class I than the others (table 5). However, we suspect that this may be a bias effect because the quiescent temperatures are systematically low ($\lesssim$ 5 keV), and hence would be significantly affected by the absorption compared with the flare temperatures.

The rise and decay timescales of the flares ($\tau_r$ and $\tau_d$) are distributed around $10^{3.5}$ s and $10^4$ s, respectively. Although the mean value of $\tau_r$ indicates that younger sources have a shorter rise timescale, the difference of $\tau_r$ among these classes is not statistically significant (<90%, table 5). The larger mean values for class III+III$_c$ sources are primarily due to flares
with unusually long timescales of \( \gtrsim 50 \text{ ks} \) (A-2, A-63, and BF-96); such flares are not seen in class I and II sources (\( \approx 30 \text{ ks} \) at the maximum). Since we cannot reject the possibility that these long timescales are simply because of the composition of two (or more) unresolved flares, we further estimate the mean \( \tau_r \) and \( \tau_d \) values of class III+III\(_c\) sources without these flares to be \( 3.1 \pm 0.6 \text{ ks} \) and \( 6.9 \pm 0.8 \text{ ks} \), which is comparable to those of the other classes.

3.6. Correlation between the Flare Parameters

Figure 6 shows the correlations between the derived parameters of flares; \( \tau_r \) vs \( \tau_d \) and \( \langle kT \rangle \) vs \( \tau_r \). In these figures, we exclude those flares for which we could not determine the errors mainly due to limited statistics. Possible positive and negative log-linear correlations can be seen in \( \tau_r \) vs \( \tau_d \) and \( \langle kT \rangle \) vs \( \tau_r \), respectively. We hence checked the significances of these correlations using Cox's proportional hazard model (Isobe et al. 1986) in ASURV. This gives significances of \( \sim 99\% \) (\( \tau_r \) vs \( \tau_d \)) and \( \sim 94\% \) (\( \langle kT \rangle \) vs \( \tau_r \)). We further estimated the best-fit log-linear models with ASURV to be

\[
\left( \frac{\tau_d}{s} \right) = 10^{2.5 \pm 0.4} \left( \frac{\tau_r}{s} \right)^{0.4 \pm 0.1}
\]

(2)

and

\[
\left( \frac{\tau_r}{s} \right) = 10^{3.8 \pm 0.1} \left( \frac{\langle kT \rangle}{\text{keV}} \right)^{-0.4 \pm 0.3}.
\]

(3)

These models are shown by the solid lines in figure 6.

4. Discussion

From the detected 71 X-ray flares of the \( \rho \) Oph X-ray sources, we found that (1) the flares from class I and II sources tend to show a higher plasma temperature, which sometimes exceeds 5 keV, than class III+III\(_c\); (2) the distribution of \( \langle L_X \rangle \) is nearly the same among the classes, although there is the marginal hint of slightly higher \( \langle L_X \rangle \) for class I sources; and (3) the plots of \( \tau_r \) vs \( \tau_d \) show positive and those of \( \langle kT \rangle \) vs \( \tau_r \) show negative log-linear correlations. Using these enormous samples and derived properties, we discuss the overall feature of YSO flares in this section.

4.1. Flare Rate

First, we estimate the flare rate (\( F \)) for each class. Following Stelzer et al. (2000), \( F \) is defined as

\[
F = \frac{(\bar{\tau}_r + \bar{\tau}_d) N_F}{NT_{\text{obs}}} \pm \frac{\sqrt{\sigma^2_{\tau_r} + \sigma^2_{\tau_d}} \sqrt{N_F}}{NT_{\text{obs}}},
\]

(4)

where (\( \bar{\tau}_r \), \( \bar{\tau}_d \)) and (\( \sigma_{\tau_r}, \sigma_{\tau_d} \)) are the mean value and uncertainty of (\( \tau_r \), \( \tau_d \)) derived with ASURV (figure 5), \( N \) and \( N_F \) are the number of sources and detected flares, and \( T_{\text{obs}} \) is the duration of the observations (\( \approx 100 \text{ ks} \)). We then determine \( F \) to be \( 15 \pm 1\% \), \( 8.0 \pm 0.2\% \), and \( 13 \pm 1\% \) for class I, class II, and class III+III\(_c\) sources, respectively. All of the values are much higher
than that derived with ROSAT ($F \sim 1\%$: Stelzer et al. 2000), which may be primarily due to
the extended sensitivity in the hard X-ray band of the Chandra observations, because the flare
activity (flux increase) is clearer in the harder X-ray band.

The surprisingly large value of $F$ for class III+III+c sources is simply due to the effect
of flares with unusually long timescales (A-2, A-63, and BF-96). In fact, if we regard those
unusual flares as being affected by other unknown components (unresolved flares, for example),
and exclude them, $F$ of class III+III+c becomes 5.0±0.1%, which is significantly smaller than
those of class I–II sources. Such a tendency is consistent with the ROSAT results ($F = 1.1±0.4$
% and 0.7±0.2% for class II and III). We hence suggest that younger sources tend to show
frequent flare activity.

4.2. Interpretation of the $\tau_r$ vs $\tau_d$ and $\langle kT \rangle$ vs $\tau_r$ correlations

In order to explain the observed features of the flare parameters, we formulated $\tau_r$, $\tau_d$, and $\langle kT \rangle$ as a function of pre-flare (coronal) electronic density ($n_c$), half-length of the
reconnected magnetic loop ($L$) and strength of magnetic field ($B$), based on the idea of a
standard magnetic reconnection model (Petschek 1964) and the balance between reconnection
heating and conductive cooling (Shibata, Yokoyama 2002). For simplicity, we assumed that $\tau_d$
is equal to the radiative loss timescale ($\tau_{rad}$), although it would be possible that $\tau_d$ is slightly
larger than $\tau_{rad}$ (see appendix 3). We also assumed that the reconnection rate, $M_A$ [ratio of the
reconnection interval and Alfvén timescales; equation (A4)], is 0.01, which is the mean value of
$M_A$ for the solar observations ($0.001–0.1$, table 2 in Isobe et al. 2002). Details of the formulae
are given in appendix 1.

4.2.1. $\tau_r$ vs $\tau_d$

From equation (A9), the reconnection model predicts a positive correlation between $\tau_r$
and $\tau_d$ as $\tau_d = A \tau_r^{1/2}$. The slope of 1/2 shows good agreement with the observed value of
0.4±0.1 [equation (2)], and hence supports our assumption that the decay phase is dominated
by radiative cooling. From equation (A9), we re-estimated log($A$) with a fixed slope of 1/2 to
be 2.06±0.04 (the dashed line in figure 6a). We also calculated log($A$) separately for each class,
and then obtain 2.1±0.1, 2.0±0.1, and 2.0±0.1 for class I, II, and III+III+c, respectively. We
can see no significant difference between the classes; hence, $A$ is assumed to be the same for all
sources. Since $A$ is a function of $n_c$ [equation (A10)], we can determine $n_c$ to be

$$n_c = 10^{10.48±0.09 (M_A/0.01)} \text{ [cm}^{-3}] .$$

Considering the possible range of $M_A$ ($0.001–0.1$), this favors a higher pre-flare density for YSOs
($10^9–10^{12} \text{ cm}^{-3}$) than that for the sun ($\sim 10^9 \text{ cm}^{-3}$). In fact, Kastner et al. (2002) derived the
plasma density of a CTTS (TW Hydrae) using the ratio of Ne_{IX} and O_{VII} triplets, and found
an extremely high density of $\sim 10^{13} \text{ cm}^{-3}$, even in their quiescent phase. Hence, a larger $n_c$
value for YSOs than that for the sun would be a common feature.
4.2.2. \( kT \) vs \( \tau_r \)

The predicted correlations between \( \langle kT \rangle \) and \( \tau_r \) are shown in equations (A11) and (A12). Positive \( (\tau_r \propto \langle kT \rangle^{7/2}) \) and negative \( (\tau_r \propto \langle kT \rangle^{-7/6}) \) correlations are expected for constant \( B \) and \( L \) values, respectively. The dash-dotted and dashed lines in figure 6b show constant \( B \) and \( L \) lines, in which we uniformly assume \( n_c = 10^{10.48} \text{ cm}^{-3} \) [equation (5)]. Our observed negative correlation therefore predicts that flares with a higher temperature are mainly due to a larger magnetic field. However, the observed slope of \(-0.4 \pm 0.3\) is significantly flatter than \(-7/6 \) [equation (A12)], and hence the effect of \( L \) would not be negligible. We estimated the mean \( B \) and \( L \) for each class (table 6) using the mean values of \( \langle kT \rangle \) and \( \tau_r \) (figures 4b and 5a), which are summarized in table 6. Younger sources tend to show larger \( B \) values; the mean values of \( B \) are \( \approx 500, 300, \) and 200 G for class I, II, and III+III\(_c\) sources, respectively. This is consistent with the observed result of a higher plasma temperature for younger sources. Also, the estimated values of \( L (10^{10}–10^{11} \text{ cm}) \) suggest that \( L \) is nearly the same among these classes, comparable to the typical radius of YSOs. These results indicate that the flare loops for all classes are localized at the stellar surface, which is in sharp contrast with the idea of the flares for class I sources triggered by larger flare loops connecting the star and the disk (Montmerle et al. 2000).

It is conceivable that the class III flares with unusually long timescales (A-2, A-63, and BF-96) mainly affect the systematically lower \( B \) for class III sources. Since it is possible that two or more flares make such unusually long timescales, we re-estimated \( B \) and \( L \) using the mean value of \( \tau_r \) without these flares (subsection 3.5). The results are shown by the parentheses in table 6. Again, we confirmed the same results: class III+III\(_c\) sources have a lower \( B \) than, and comparable \( L \) (but slightly lower) to class I and II sources.

4.3. Comparison with the \( kT-EM \) Scaling Law

Shibata and Yokoyama (2002) showed that \( L \) and \( B \) of flares can be estimated from the \( kT-EM \) plot (see appendix 2). This method is completely independent of the flare timescales (\( \tau_t \) and \( \tau_d \)), and hence can be used as a consistency check of our estimation derived in subsection 4.2. The \( \langle kT \rangle - \langle EM \rangle \) relation of the \( \rho \) Oph flares is shown in figure 7. Using ASURV, we determined the mean values of \( \log(\langle EM \rangle) \) to be \( 53.77 \pm 0.20, 53.33 \pm 0.07, \) and \( 53.48 \pm 0.16 \) for class I, II, and III+III\(_c\) sources, respectively. We then calculated the mean values of the magnetic field strength and loop length (\( B_{\text{SY}} \) and \( L_{\text{SY}} \)) by equations (A15) and (A16) using the estimated value of \( n_c = 10^{10.48 \pm 0.09} \text{ cm}^{-3} \) (subsubsection 4.2.1). The results are given in table 6. The values of \( B_{\text{SY}} \) (100–1000 G) are much higher than those derived in Shibata and Yokoyama (2002) and Paper I (50–150 G). This discrepancy is caused by two different assumptions concerning the \( n_c \) value: \( 10^9 \text{ cm}^{-3} \) for Shibata and Yokoyama (2002) and Paper I (typical value of the solar corona), and \( 10^{10.48} \text{ cm}^{-3} \) for this paper. \( B_{\text{SY}} \) and \( L_{\text{SY}} \) show good agreement with those derived in subsubsection 4.2.2 (\( B \) and \( L \) in table 6); higher \( B_{\text{SY}} \) values for younger sources and the same
order of $L_{\text{SY}}$ comparable to the typical stellar radius. Therefore, our estimation of $n_c$, $L$, and $B$ using the $\tau_r-\tau_d$ and $\langle kT \rangle-\tau_r$ relations is cross-checked.

The same conclusion of subsubsection 4.2.2 and this section also indicates the propriety of our assumption of $M_A = 0.01$. If we assume a smaller (or larger) value of $M_A$, $n_c$ [equation (5)] becomes smaller (larger), which causes smaller (larger) estimations of $B_{\text{SY}}$ [equation (A15)], and makes a larger discrepancy between $B$ and $B_{\text{SY}}$ (table 6).

4.4. Evolution of YSO Flares

Combining all of the results discussed in the previous sections, we propose a simple view of the evolution of flare activity on low-mass objects as follows. In their earlier stage (class I), sources have a relatively strong magnetic field ($\approx 500$ G), and show frequent X-ray flares with a higher temperature ($\approx 5$ keV). As stars evolve (class II and IIIIs), the magnetic field gradually decreases (200–300 G) and makes a moderate temperature plasma (2–4 keV) via X-ray flares. During these phases (class I–III), the length of the flare loop does not change significantly ($10^{10}$–$10^{11}$ cm). As approaching to the main-sequence stage, the magnetic field and length of the flare loop become weak (50–150 G for the sun) and short ($10^8$–$10^9$ cm), which causes a lower plasma temperature (0.1–1 keV) and shorter flare timescales (10–100 s), as can be seen in the sun.

Generally, RS CVn systems show smaller flare timescales than YSOs ($\sim 100$ s), while $kT$ is comparable ($\sim 5$ keV). Based on the above idea, this may be due to a larger $B$ value. In fact, Donati et al. (1990) estimated $B$ of RS CVns to be $\approx 1000$ G, which is as large as the maximum value for YSOs (figures 6b and 7).

4.5. Comment on the Giant Flares

Figure 7 indicates that the giant flares ($EM > 10^{55}$ cm$^{-3}$) previously detected with ASCA such as V773 Tau (class III: Tsuboi et al. 1998) and ROXs31 (class III: Imanishi et al. 2002), as well as BF-64 = YLW 16A in this paper (class I; $EM \sim 10^{55}$ cm$^{-3}$), should have either a large $L$ or $B$, if the sustained heating is negligible. Since the flares of ROXs31 and YLW 16A show a relatively large rise timescale ($\sim 10^4$ s), they may have large $L$ values ($10^{11}$–$10^{12}$ cm). Because the rise time of V773 Tau, on the other hand, is among the shortest ($\sim 10^3$ s), the large $L_X$ would be primarily due to the large $B$ value. In fact, a detailed flare decay time analysis for V773 Tau predicted an extremely large $B$ value of $\gtrsim 1000$ G (Favata et al. 2001). We suspect that the binary nature of V773 Tau (Welty 1995) causes such an exceptionally large $B$, which would be the same case as that for the main-sequence RS CVn systems.

5. Summary

We summarize the main results of the flare analysis of two Chandra observations of $\rho$ Oph with $\approx 100$ ks exposure as follows:
1. From 195 X-ray sources detected in the main region of \( \rho \) Oph region, we found 71 X-ray flares. Most of the flares show the typical profile of the solar and stellar flares, while some bright flares have an unusually long rise timescale.

2. Flares from class I and II sources tend to have a high plasma temperature, which sometimes exceeds 5 keV.

3. There is a positive correlation between \( \tau_r \) and \( \tau_d \), which is well explained by the standard magnetic reconnection model. Shorter \( \tau_r \) and \( \tau_d \) are due to the smaller \( L \) and/or larger \( B \) values.

4. We found a negative correlation between \( kT \) and \( \tau_r \), which indicates the same order of the flare loop length regardless of their classes. Larger \( kT \) values for class I and II sources are due to larger \( B \) values.

5. The expected loop length is comparable to the stellar size, indicating that the scenario of the star–disk arcade magnetic loop is unlikely.

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Appendix 1. Magnetic Reconnection Model

In this appendix, we show details for estimating the flare parameters (\( \tau_r \), \( \tau_d \), and \( kT \)), which are used in section 4. These formulations are based on the standard magnetic reconnection model (Petschek 1964), as well as the observed results and analysis of solar flares.

A.1.1. Estimation of the Flare Parameters

- **Plasma temperature (\( \langle kT \rangle \))**

  Shibata and Yokoyama (1999; 2002) showed from MHD simulations that the balance between the heating rate and conduction cooling determines the maximum temperature of reconnection heated plasma (\( T_{\text{max}} \)), and derived a relation for the temperature of the evaporated plasma (\( T \)) filling the reconnected magnetic loop:

\[
T \approx \frac{1}{3} T_{\text{max}} \approx 6.75 \times 10^{7} \left( \frac{n_c}{10^{9} \text{ cm}^{-3}} \right)^{-1/7} \left( \frac{L}{10^{11} \text{ cm}} \right)^{2/7} \left( \frac{B}{100 \text{ G}} \right)^{6/7} \text{ [K]},
\]

where \( n_c \), \( L \), and \( B \) are the pre-flare (coronal) density, semi-length of the loop, and magnetic field strength, respectively. As for the usual stellar flares, we could only determine
the time-averaged temperature ($\langle kT \rangle$) due to the limited statistics. However, van den Oord et al. (1988) showed that the behavior of the flare temperature is exponential, hence we obtain the relation

$$T = \frac{\tau_r + \tau_d}{\int_{0}^{\tau_r} e^{t/\tau_r} dt + \int_{0}^{\tau_d} e^{-t/\tau_d} dt} \cdot \langle T \rangle \approx 1.6 \langle T \rangle.$$  
(A2)

Using equations (A1) and (A2), $\langle kT \rangle$ is determined as

$$\langle kT \rangle \approx 3.64(n_c/10^9 \text{ cm}^{-3})^{-1/7}(L/10^{11} \text{ cm})^{2/7}(B/100 \text{ G})^{6/7} \text{[keV]}.  \tag{A3}$$

- **Rise timescale ($\tau_r$)**
  Based on a standard reconnection model, $\tau_r$ is equal to the interval of magnetic reconnection. Petschek (1964) showed that the reconnection timescale is proportional to the Alfvén time, $\tau_A \equiv L/v_A$, where $v_A$ is the Alfvén velocity. Hence $\tau_r$ is

$$\tau_r = \frac{\tau_A}{M_A} = \frac{\sqrt{4\pi mn_cL}}{M_A B},  \tag{A4}$$

where $m$ is the proton mass ($=1.67 \times 10^{-24}$ g). The correction factor, $M_A$, sometimes referred to as the reconnection rate, was estimated to be 0.01–0.1 (Petschek 1964), while observations for the solar flares show that $M_A$ is in the range of 0.001–0.1 (table 2 in Isobe et al. 2002), regardless of their flare size. $\tau_r$ is therefore

$$\tau_r \approx 1.45 \times 10^4(M_A/0.01)^{-1}(n_c/10^9 \text{ cm}^{-3})^{1/2}(L/10^{11} \text{ cm})(B/100 \text{ G})^{-1} \text{[s]}.  \tag{A5}$$

- **Decay timescale ($\tau_d$)**
  We assume that $\tau_d$ is nearly the same as the radiative cooling timescale ($\tau_{rad}$), i.e,

$$\tau_d \approx \tau_{rad} \approx \frac{3nkT}{n^2\Lambda(T)},  \tag{A6}$$

where $n$ and $\Lambda(T)$ are the maximum plasma density and radiative loss function given by $10^{-24.73} T^{1/4}$ for $T > 20 \text{ MK}$ (Mewe et al. 1985). Furthermore, we assume that magnetic pressure is comparable to the plasma pressure at the flare peak,

$$2nkT = \frac{B^2}{8\pi}.  \tag{A7}$$

Using equations (A1), (A6), and (A7), we obtain $\tau_d$ as

$$\tau_d \approx 7.75 \times 10^4(n_c/10^9 \text{ cm}^{-3})^{-1/4}(L/10^{11} \text{ cm})^{1/2}(B/100 \text{ G})^{-1/2} \text{[s]}.  \tag{A8}$$

*A.1.2. Predicted Correlations between the Flare Parameters*

- **$\tau_r$ vs $\tau_d$**
  Using equations (A5) and (A8), we obtain a relation

$$\left(\frac{\tau_d}{s}\right) = A\left(\frac{\tau_r}{s}\right)^{1/2},  \tag{A9}$$

where
\[ A \approx 640 \left( \frac{n_c}{10^9 \text{ cm}^{-3}} \right)^{-1/2} \left( \frac{M_A}{0.01} \right)^{1/2}. \]  

Hence, a positive correlation is expected between \( \tau_r \) and \( \tau_d \).

- \( \langle kT \rangle \) vs \( \tau_r \)

From equations (A3), (A5) and (5), we obtain

\[ \tau_r \approx 10^{2.20} \left( \frac{n_c}{10^9 \text{ cm}^{-3}} \right) \left( \frac{M_A}{0.01} \right)^{-1} \left( \frac{B}{100 \text{ G}} \right)^{-4} \left( \frac{\langle kT \rangle}{\text{keV}} \right)^{7/2} [s], \]  

(A11)

\[ \tau_r \approx 10^{4.82} \left( \frac{n_c}{10^9 \text{ cm}^{-3}} \right)^{1/3} \left( \frac{M_A}{0.01} \right)^{-1} \left( \frac{L}{10^{11} \text{ cm}} \right)^{4/3} \left( \frac{\langle kT \rangle}{\text{keV}} \right)^{-7/6} [s]. \]  

(A12)

These equations indicate that the positive and negative log-linear correlations of \( \langle kT \rangle \) vs \( \tau_r \) are expected if \( B \) and \( L \) are equal for all sources, respectively.

**Appendix 2. The \( kT-EM \) Scaling Law**

Using equations (A1), (A7), and assuming \( V \approx L^3 \) (\( V \): plasma volume), Shibata and Yokoyama (2002) derived the relation between the flare maximum temperature \( (T) \) and emission measure \([EM]\), equations (5)–(6) in Shibata and Yokoyama (2002)). Similar to equation (A2), the time behavior of \( EM \) is also exponential (van den Oord et al. 1988), hence we assume \( EM \approx 1.6 \langle EM \rangle \). We thus replace equations (5) and (6) in Shibata and Yokoyama (2002) as

\[ \langle EM \rangle \approx 3.7 \times 10^{48} \left( \frac{n_c}{10^9 \text{ cm}^{-3}} \right)^{3/2} \left( \frac{B}{100 \text{ G}} \right)^{-5} \left( \frac{\langle kT \rangle}{\text{keV}} \right)^{17/2} [\text{cm}^{-3}], \]  

(A13)

\[ \langle EM \rangle \approx 7.0 \times 10^{51} \left( \frac{n_c}{10^9 \text{ cm}^{-3}} \right)^{2/3} \left( \frac{L}{10^{11} \text{ cm}} \right)^{5/3} \left( \frac{\langle kT \rangle}{\text{keV}} \right)^{8/3} [\text{cm}^{-3}]. \]  

(A14)

We also derive the following two equations:

\[ B \approx 52 \left( \frac{n_c}{10^9 \text{ cm}^{-3}} \right)^{3/10} \left( \frac{\langle EM \rangle}{10^{50} \text{ cm}^{-3}} \right)^{-1/5} \left( \frac{\langle kT \rangle}{\text{keV}} \right)^{17/10} [\text{G}], \]  

(A15)

\[ L \approx 7.8 \times 10^9 \left( \frac{n_c}{10^9 \text{ cm}^{-3}} \right)^{-2/5} \left( \frac{\langle EM \rangle}{10^{50} \text{ cm}^{-3}} \right)^{3/5} \left( \frac{\langle kT \rangle}{\text{keV}} \right)^{-8/5} [\text{cm}]. \]  

(A16)

**Appendix 3. Possible error for the derived parameters**

In the discussions of the main text (section 4), the assumption of \( \tau_d \) [equation (A6)] includes relatively large uncertainty. Reale et al. (1997) proposed that \( \tau_d \) becomes about a factor of \( \lesssim 10 \) larger than the radiative loss timescale \( (\tau_{rad}) \), if the sustained heating exists during the decay. The dependences of the relevant parameters on \( \tau_d \) are:

\[ n_c \propto \tau_d^{-2}, \]  

(A17)

\[ B \propto n_c^{1/4} \propto \tau_d^{-1/2}, \]  

(A18)

\[ L \propto n_c^{-1/2} \propto \tau_d^{1}. \]  

(A19)

Accordingly, \( n_c \) has large dependence on \( \tau_d \); larger \( n_c \) value than \( \sim 10^{10.5} \text{ cm}^{-3} \) may be conceivable. The dependence of \( L \) is also relatively large. However, this uncertainty makes \( L \) much
smaller, and hence larger flare loops are still less possible.

Another uncertainty is in the $kT-EM$ scaling law. Shibata and Yokoyama (2002) showed that the effect of the filling factor $f (V = fL^3)$ may not be negligible. This gives possible errors for the values in columns 5–6 of table 6. The dependences of the relevant parameters on $f$ are

$$B_{SY} \propto EM^{-1/5} \propto f^{1/5}, \quad (A20)$$

$$L_{SY} \propto EM^{3/5} \propto f^{-3/5}. \quad (A21)$$

Hence, slightly smaller and larger values of $B_{SY}$ and $L_{SY}$ would be conceivable, although the effect is only a factor of $< 5$ (if $f = 0.1$).

References

Andrè, P., Montmerle, T., & Feigelson, E. D. 1987, AJ, 93, 1182
Andrè, P., Ward-Thompson, D., & Barsony, M. 1993, ApJ, 406, 122
Andrè, P., & Montmerle, T. 1994, ApJ, 420, 837
Barsony, M., Burton, M. G., Russell, A. P. G., Carlstrom, J. E., & Garden, R. 1989, ApJ, 346, L93
Barsony, M., Kenyon, S. J., Lada, E. A., & Teuben, P. J. 1997, ApJS, 112, 109
Bontemps, S., et al. 2001, A&A, 372, 173
Bouvier, J., & Appenzeller, I. 1992, A&AS, 92, 481
Casanova, S., Montmerle, T., Feigelson, E. D., & André, P. 1995, ApJ, 439, 752
Comeron, F., Rieke, G. H., Burrows, A., & Rieke, M. J. 1993, ApJ, 416, 185
de Zeeuw, P. T., Hoogerwerf, R., de Bruijne, J. H. J., Brown, A. G. A., & Blauw, A. 1999, AJ, 117, 354
Davis, J. E. 2001, ApJ, 562, 575
Dolidze, M. V., & Arakelyan, M. A. 1959, Astronomicheskii Zhurnal, 36, 444
Donati, J. F., Semel, M., Rees, D. E., Taylor, K., & Robinson, R. D. 1990, A&A, 232, L1
Elias, J. H. 1978, ApJ, 224, 453
Favata, F., Micela, G., & Reale, F. 2001, A&A, 375, 485
Feigelson, E. D., & DeCampli, W. M. 1981, ApJ, 243, L89
Feigelson, E. D., & Kriss, G. A. 1981, ApJ, 248, L35
Feigelson, E. D., & Nelson, P. I. 1985, ApJ, 293, 192
Feigelson, E. D., Broos, P., Gaffney, J. A., III., Garmire, G., Hillenbrand, L. A., Pravdo, S. H.,
Townsley, L., & Tsuboi, Y. 2002, ApJ, 574, 258
Festin, L. 1998, A&A, 336, 883
Freeman, P. E., Kashyap, V., Rosner, R., & Lamb, D. Q. 2002, ApJS, 138, 185
Gómez, M., Whitney, B. A., & Wood, K. 1998, AJ, 115, 2018
Grasdalen, G. L., Strom, K. M., & Strom, S. E. 1973, ApJ, 184, L53
Greene, T. P., & Young, E. T. 1992, ApJ, 395, 516
Grosso, N., Montmerle, T., Feigelson, E. D., André, P., Casanova, S., & Gregorio-Hetem, J. 1997,
Nature, 387, 56
Grosso, N., Montmerle, T., Bontemps, S., André, P., & Feigelson, E. D. 2000, A&A, 359, 113
Grosso, N. 2001, A&A, 370, L22
Güdel, M., Linsky, J. L., Brown, A., & Nagase, F. 1999, ApJ, 511, 405
Hamaguchi, K., & Imanishi, K. submitted to PASJ
Imanishi, K., Koyama, K., & Tsuboi, Y. 2001a, ApJ, 557, 747 (Paper I) [see also erratum Imanishi et al. 2002, ApJ, 579, 920]
Imanishi, K., Tsujimoto, M., & Koyama, K. 2001b, ApJ, 563, 361
Imanishi, K., Tsujimoto, M., & Koyama, K. 2002, ApJ, 572, 300
Imanishi, K., 2003, PhD Thesis, Kyoto University
Isobe, T., Feigelson, E. D., & Nelson, P. I. 1986, ApJ, 306, 490
Isobe, H., Yokoyama, T., Shimojo, M., Morimoto, T., Kozu, H., Eto, S., Narukage, N., & Shibata, K. 2002, ApJ, 566, 528
Jerius, D., Freeman, M., Gaetz, T., Hughes, J. P., & Podgorski, W. 1995, in ASP Conf. Ser. 77, Astronomical Data Analysis Software and Systems IV, ed. R. A. Shaw, H. E. Payne, & J. J. E. Hayes. (ASP: San Francisco), 357
Kamata, Y., Koyama, K., Tsuboi, Y., & Yamauchi, S. 1997, PASJ, 49 461
Kastner, J. H., Huenemoerder, D. P., Schultz, N. S., Canizares, C. R., & Weintraub, D. A. 2002, ApJ, 567, 434
Koyama, K., Maeda, Y., Ozaki, M., Ueno, S., Kamata, Y., Tawara, Y., Skinner, S., & Yamauchi, S. 1994, PASJ, 46, L125
Koyama, K., Hamaguchi, K., Ueno, S., Kobayashi, N., & Feigelson, E. D. 1996, PASJ, 48, L87
Lada, C. J. 1991, in The Physics of Star Formation and Early Stellar Evolution, NATO ASI, ed. C. J. Lada & N. D. Kylafis, Kluwer, 329
Leous, J. A., Feigelson, E. D., Andrè, P., & Montmerle, T. 1991, ApJ, 379, 683
Loren, R. B., Wootten, A., & Wilking, B. A. 1990, ApJ, 365, 269
Mewe, R., Gronenschild, E. H. B. M., & van den Oord, G. H. J. 1985, A&AS, 62, 197
Montmerle, T., Koch-Miramond, L., Falgarone, E., & Grindlay, J. E. 1983, ApJ, 269, 182
Montmerle, T., Grosso, N., Tsuboi, Y., & Koyama, K. 2000, ApJ, 532, 1097
Neuhäuser, R., & Preibisch, T. 1997, A&A, 322, L37
Ozawa, H., Nagase, F., Ueda, Y., Dotani, T., & Ishida, M. 1999, ApJ, 523, L81
Petschek, H. E. 1964, in Proc. of AAS-NASA Symp. on the Physics of Solar Flares, ed. W. W. Hess, (NASA SP-50), 425
Reale, F., Betta, R., Peres, G., Serio, S., & McTiernan, J. 1997, A&A, 325, 782
Shibata, K., & Yokoyama, T. 1999, ApJ, 526, L49
Shibata, K., & Yokoyama, T. 2002, ApJ, 577, 422
Stelzer, B., Neuhäuser, R., & Hambaryan, V. 2000, A&A, 356, 949
Stine, P. C., Feigelson, E. D., Andrè, P., & Montmerle, T. 1988, AJ, 96, 1394
Strom, K. M., Kepner, J., & Strom, S. E. 1995, ApJ, 438, 813
Struve, O., & Rudkjosbing, M. 1949, ApJ, 109, 92
Tsuboi, Y., Koyama, K., Murakami, H., Hayashi, M., Skinner, S., & Ueno, S. 1998, ApJ, 503, 894
Tsuboi, Y., Imanishi, K., Koyama, K., Grosso, N., & Montmerle, T. 2000, ApJ, 532, 1089

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Tsuboi, Y., Koyama, K., Hamaguchi, K., Tatematsu, K., Sekimoto, Y., Bally, J., & Reipurth, B. 2001, ApJ, 554, 734
van den Oord, G. H. J., Mewe, R., & Brinkman, A. C. 1988, A&A, 205, 181
Vrba, F. J., Strom, K. M., Strom, S. E., & Grasdalen, G. L. 1975, ApJ, 197, 77
Weisskopf, M. C., Brinkman, B., Canizares, C., Garmire, G., Murray, S., & van Speybroeck, L. P. 2002, PASP, 114, 1
Welty, A. D. 1995, AJ, 110, 776
Wilking, B. A., & Lada, C. J. 1983, ApJ, 274, 698
Wilking, B. A., Lada, C. J., & Young, E. T. 1989, ApJ, 340, 823
Wilking, B. A., Greene, T. P., & Meyer, M. R. 1999, AJ, 117, 469
Young, E. T., Lada, C. J., & Wilking, B. A. 1986, ApJ, 304, L45
Fig. 1. False-color ACIS image of $\rho$ Oph. Red and blue colors represent photons in the soft (0.5–2.0 keV) and hard (2.0–9.0 keV) bands, respectively.
Fig. 2. Light curves of all detected flares in 0.5–9.0 keV, binned in 2000 s interval. Names and classes for each flare are shown at the upper-left of the panels. The time axis starts at MJD = 51679.9944 (obs.-A) and 51647.7848 (obs.-BF). The solid line is the best-fit (exponential + constant) model. Since the light curve of BF-64 suffers photon pileup during the second flare, we show the two flares separately (the former is extracted from the 7''5 radius and the latter is from 2''5–7''5). That of A-2 is also extracted from the 2''5–12''5 radius circle.
Fig. 2 (Continued)
Fig. 2 (Continued)
Fig. 3. Normalized X-ray luminosity functions of class I (dashed), class II (dash-dotted), and class III (solid) sources in the (a) quiescent and (b) flare phases. The mean value (Mean) and standard deviation (σ) of log\[L_X\] in the unit of erg s\(^{-1}\) for each class are shown in the figures. The parentheses indicate errors of the mean values.
Fig. 4. Histograms of $kT$ in the (a) quiescent and (b) flare phases for each class, with their mean values (Mean) and standard deviation ($\sigma$) in the unit of keV for each class. The parentheses indicate errors of the mean values.

Fig. 5. Same as figure 4, but for the flare rise and decay timescales, with their mean values and standard deviation in the unit of ks for each class.
Fig. 6. Relations between (a) $\tau_r$ vs $\tau_d$ and (b) $kT$ vs $\tau_r$. The circles, triangles, squares, diamonds, and crosses represent flares from class I, class II, class III+III, unclassified NIR sources, and unidentified sources, respectively. The solid lines represent the best-fit log-linear correlations derived with ASURV [equations (2) and (3)]. The dashed line in (a) is the best-fit model of equation (A9), while the dash-dotted and dashed lines in (b) are constant $B$ and $L$ lines derived by equations (A11) and (A12) with the assumption of $n_c = 10^{10.48} \text{ cm}^{-3}$.

Fig. 7. Plot of $\langle kT \rangle$ and $\langle EM \rangle$ in the flare phases. The symbols are the same as in figure 6. The dashed-dotted and dashed lines are constant $B$ and $L$ lines derived by equations (A15) and (A16) with the assumption $n_c = 10^{10.48} \text{ cm}^{-3}$. 

25
| Obs. ID | Sequence ID | Date       | R.A.*   | Decl.*  | Exposure† |
|--------|-------------|------------|---------|---------|-----------|
| BF     | 200060      | 2000 Apr 13–14 | 16ʰ27ᵐ18ˢ1 | −24°34′21″9 | 100.6     |
| A      | 200062      | 2000 May 15–17  | 16ʰ26ᵐ35ˢ3 | −24°23′12″9 | 96.4      |

*The position of the detector aimpoint (the telescope optical axis).
†The live time corrected from deadtime.
Table 2. Chandra X-ray Sources in the ρ Oph Region.

| No. | Count* | R.A.† (J2000) | Decl.† (J2000) | \(\langle kT \rangle \)† (keV) | \(\log(\langle EM \rangle) \)† (cm\(^{-3}\)) | \(N_H \)† (10\(^{22}\) cm\(^{-2}\)) | Flux§ (\(\langle L_X \rangle \))§ (10\(^{22}\) erg s\(^{-1}\)) | Red-\(\chi^2\)∥ | Comment |
|-----|--------|---------------|---------------|----------------|----------------|----------------|----------------|---------|---------|
| A-1# | 13.0(m) | 25 53.22 | 25 37.3 | 1.0(fixed) | 53.6(51.9–56.3) | 45.5(>6.7) | 0.5 | 38.4 | 0.40(2) |
| A-2** | 79359.2 | 26 03.02 | 23 36.1 | 2.9(2.8–3.0) | 54.8(54.8–54.9) | 1.1(1.0–1.1) | 1257.2025 | 1.51(436) | Flare 1 |
| A-3 | 829.9 | 26 07.05 | 27 24.4 | 2.1(1.8–2.7) | 53.1(53.0–53.3) | 3.7(3.2–4.2) | 13.7 | 13.6 | 0.81(76) | Quiescent |
| A-4 | 23.7 | 26 07.36 | 25 31.4 | 19.4(>0.2) | 51.4(51.0–59.7) | 4.6(1.9–44.5) | 0.8 | 0.4 | 0.34(7) | Flare |
| A-5 | 994.2 | 26 07.62 | 27 41.6 | 2.1(1.8–2.4) | 53.1(53.0–53.2) | 2.8(2.5–3.1) | 13.4 | 11.7 | 0.72(114) | Quiescent |
| A-6 | 193.1 | 26 10.34 | 20 54.6 | 2.3(1.4–4.3) | 53.0(52.6–53.4) | 5.8(4.2–8.5) | 8.2 | 9.5 | 0.74(17) |
| A-7 | 83.1 | 26 12.42 | 28 49.0 | 3.3(1.4–10.3) | 52.1(51.8–52.8) | 5.5(3.5–10.2) | 2.0 | 1.6 | 0.57(24) |
| A-8 | 16.2 | 26 13.30 | 28 23.0 | 2.0(>0.2) | 51.4(50.6–56.1) | 3.0(0.8–10.2) | 0.3 | 0.3 | 0.95(2) |
| A-9# | 12.9 | 26 14.34 | 22 25.1 | 1.0(fixed) | 53.0(51.4–54.1) | 26.6(3.4–92.8) | 0.2 | 8.9 | 0.57(2) |
| A-10‡‡ | 10.9 | 26 15.06 | 25 48.1 | ... | ... | ... | ... | ... | ... |
| A-11 | 59.8 | 26 15.71 | 27 49.3 | 3.7(>0.7) | 52.0(51.6–54.2) | 6.6(3.3–25.6) | 1.5 | 1.3 | 0.56(14) |
| A-12 | 180.3 | 26 15.81 | 19 22.2 | 1.2(1.1–1.6) | 52.6(52.3–52.9) | 2.6(2.0–3.0) | 1.8 | 3.1 | 0.73(15) | Quiescent |
| A-13 | 16.2 | 26 16.32 | 18 43.0 | 5.2(>0.5) | 51.4(50.9–55.4) | 5.8(1.6–43.6) | 0.5 | 0.3 | 0.01(1) |
| A-14 | 2068.5 | 26 16.87 | 22 23.0 | 1.7(1.5–1.9) | 53.3(53.2–53.3) | 1.9(1.8–2.1) | 18.6 | 16.3 | 1.14(165) | Quiescent |
| A-15 | 3741.7 | 26 17.06 | 20 21.6 | 1.3(1.2–1.3) | 53.1(53.1–53.1) | 0.5(0.5–0.6) | 19.0 | 10.7 | 1.29(181) | Quiescent |

Legend:
- *Count* refers to the count rate of the X-ray source.
- †R.A. and Decl. refer to the right ascension and declination in J2000 coordinates.
- ‡\(\langle kT \rangle \) is the average temperature of the X-ray emission.
- ⌫\(\langle EM \rangle \) is the average electron temperature.
- ‡\(N_H \) is the column density of hydrogen.
- §Flux is the flux density of the X-ray source.
- ∥Red-\(\chi^2\) is the reduced chi-square value for the fit.
| No.   | Count* | R.A.† | Decl.† | \(\langle kT \rangle \)‡ | \(\log(\langle EM \rangle)\)‡ | \(N_H\)‡ | Flux§ \(\langle L_X \rangle \)§ | Red-\(\chi^2\)∥ | Comment |
|-------|--------|-------|--------|----------------|----------------|-------|----------------|----------------|---------|
| A-16  | 126.2  | 26    | 17.13  | 12 (38.9)     | 0.9 (0.6–1.2) | 52.4 (52.2–52.8) | 1.8 (1.4–2.2) | 1.1 2.5 1.26(16) | Flare 3  |

*Background-subtracted X-ray counts in 0.5–2.0 keV, 2.0–9.0 keV, and 0.5–9.0 keV for soft-band, hard-band, and the other sources, respectively. (m) denotes sources with marginal detections (the confidence level < 99.9%, see subsection 3.1). Although the confidence levels of A-48 and A-H2 are significant enough, we regard them as marginal sources because of the larger source size (A-48) and severe contamination from A-2 (A-H2).

†Right ascension and declination for all sources are 16h and \(-24^\circ\).

‡Parentheses indicate the 90% confidence limits.

§Observed flux \((10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2})\) and absorption-corrected X-ray luminosity \((10^{29} \text{ erg s}^{-1})\) in 0.5–9.0 keV.

∥Reduced-\(\chi^2\) for the spectral fittings. Parentheses indicate the degrees of freedom.

#We determine spectral parameters with fixed temperatures of 1 keV and 5 keV (see text). For sources which only show the parameters for \(kT = 1\) or 5 keV, no good fitting is obtained for the other temperature.

**We assume the same abundances as the “F2” phase in Imanishi et al. (2002). The Quiescent spectrum is not obtained because the decay phases of the two flares occupy all of the light curve.

††The pileup effect is not corrected.

§§Abundances are free parameters (see subsubsection 4.8.1 in Paper I and Imanishi 2003).

∥∥We make the flare spectra with a bit larger timescale in order to obtain as good statistics as possible. Errors of \(\langle EM \rangle\) for A-29 in the quiescent are not determined because of the limited statistics.

###The spectra show possible edge absorption of neutral Ca or warm Ar. The nonthermal model also well reproduces the spectra (Hamaguchi, Imanishi 2002).

##We assume the same temperature because of the limited statistics.

† † †These show non-thermal spectra (Imanishi 2003).

‡ ‡ ‡Imanishi et al. (2002) proposed two temperature model with an unusual abundance pattern.

§§§Foreground star. The distance is 60 pc (Festin 1998).

∥∥∥The best-fit value of \(\langle kT \rangle\) is not determined (larger than 10 keV), hence we assume 10 keV temperature for the estimation of the other parameters.

###\(N_H\) and reduced-\(\chi^2\) are estimated by the simultaneous fittings with the identical sources in obs.-A.
Table 3. Identifications of the X-ray sources.

| No. | Offset* (") | Radio† | X-ray‡ | Other names§ | Class∥ |
|-----|-------------|--------|--------|-------------|--------|
| A-1 | ...         | ...    | ...    | ...         | ...    |
| A-2 | 0.33        | R8, S7 | A11 3  | DoAr21, ROXs8, YLW26, GSS23, Elias14, SKS1-5, ISO10 | III    |
| A-3 | 0.40        | ...    | ...    | ISO13       | II     |
| A-4 | 7.5±(R)     | R9?    | ...    | ...         | ...    |
| A-5 | 0.60        | ...    | A13    | ISO14       | III    |
| A-6 | 0.23        | 16     | ...    | GSS26, CRBR5, SKS1-6, ISO17 | II     |
| A-7 | ...         | ...    | ...    | ...         | ...    |
| A-8 | ...         | ...    | ...    | ...         | ...    |
| A-9 | ...         | ...    | ...    | ...         | ...    |
| A-10| ...         | ...    | ...    | ...         | ...    |
| A-11| ...         | ...    | ...    | ...         | ...    |
| A-12| 0.47        | ...    | ...    | CRBR9, SKS1-7, ISO18 | IIIc   |
| A-13| ...         | ...    | ...    | ...         | ...    |
| A-14| 0.11        | Lp1    | A14    | ROXs11, GSS29, Elias18, CRBR10, SKS1-8, ISO19 | II     |
| A-15| 0.44        | 17     | A15    | DoAr24, ROXs10A, GSS28, Elias19, CRBR11, SKS1-9, ISO20 | II     |
| A-16| 1.08        | ...    | ...    | 2MASS J1626172–241238 | ?      |

*Offset between the Chandra and nearest 2MASS sources. For sources having a radio counterpart only, the offset between the Chandra and radio sources (André et al. 1987; Leous et al. 1991) are shown, which is indicated by (R).
†Radio sources. S, R, and L indicate sources listed in André et al. (1987) (ROC), Stine et al. (1988) (SFAM), and Leous et al. (1991) (LFAM), respectively. Lp denotes possible radio sources in LFAM.
‡X-ray sources detected with ROSAT/PSPC (Casanova et al. 1995), ROSAT/HRI (Grosso et al. 2000), and ASCA (Kamata et al. 1997). “IKT” denotes Chandra sources already listed in Paper I.
§Source names used in the literature. Abbreviations for names are SR (Struve, Rudjjobing 1949), DoAr (Dolidze, Arakelyan 1959), ROXs (Bouvier, Appenzeller 1992), S (Grasdalen et al. 1973), YLW (Young et al. 1986), GY (Greene, Young 1992), WL (Wilking, Lada 1983), VSSG (Vrba et al. 1975), GSS (Grasdalen et al. 1973), Elias (Elias 1978), BBRCG (Barsony et al. 1989), CRBR (Comeron et al. 1993), SKS (Strom et al. 1995), IRS (Wilking et al. 1989), and ISO (Bontemps et al. 2001). For sources having NIR counterpart only in the 2MASS catalog, we alternatively show the 2MASS source names.
∥Source classifications; I: class I, II: class II, III: class III, IIIc: class III candidate (table 5 in Bontemps et al. 2001), BD: brown dwarf, BDc: brown dwarf candidate (Imanishi et al. 2001b), F: foreground star (Festin 1998). Unclassified NIR sources are indicated by “?”, and sources with no NIR counterpart are called “unidentified sources”, labeled no data point (...) in this column. For BD/BDc, we show the available IR classification in Bontemps et al. (2001) in the parentheses.
#Offset from a nearest NIR source in Greene and Young (1992).
**Grosso (2001).
††Tsuboi et al. (2000).
†‡The position of GY5 (Greene, Young 1992) is slightly shifted (~2′′3) from the 2MASS source.
§§A candidate of HH object (Gómez et al. 1998).
∥∥From NIR spectroscopy, Wilking et al. (1999) derived for these M dwarfs masses higher than the hydrogen burning limit.
Table 4. Detected X-ray Flares.

| No. | $t_p$ (ks) | $\tau_t$ (ks) | $\tau_d$ (ks) | $Q$ (count ks$^{-1}$) | Comment |
|-----|-------------|---------------|---------------|----------------------|---------|
| A-49| 58          | 0.9           | 12.2(9.2–16.0) | 0.8(0.5–1.0)         |         |
| BF-26| 18          | 7.3(6.0–9.0)  | 5.5(4.4–6.7)  | 7.0(6.4–7.5)         |         |
| BF-61| 82          | 2.9(2.6–3.2)  | 14.0(12.7–15.6)| 10.7(10.0–11.3)      |         |
| BF-64| 22          | 2.5(2.0–3.2)  | 14.6(13.2–16.1)| 11.4(9.7–13.0)       | Flare 1 |
| †  | 87.3(87.1–87.6)$^\S$ | 5.1$^*$       | 27.7(24.3–31.5)| ...                  | Flare 2 |
| BF-89| 4           | 1.2(0.8–1.6)  | 3.4(2.9–4.1)  | 6.2(5.6–6.7)         | Flare 1 |
| 88  | 4.0(2.4–6.2) | 3.8(2.1–7.5)  | ...           | Flare 2              |
| ... †| 2.3(1.5–3.4) | ...$^+$       | ...           | Flare 3              |
| A-3 | 24          | 6.1(4.3–8.6)  | 3.7(1.8–9.3)  | 7.0(6.4–7.5)         |         |
| A-14| 8           | 4.6(3.3–6.7)  | 12.8(10.6–15.7)| 14.6(13.6–15.6)      |         |
| A-15| 2           | ...$^+$       | 11.7(4.6–28.2)| 28.1(22.4–30.8)      | Flare 1 |
| 60  | 3.4(2.3–5.2) | 4.1(3.0–5.8)  | ...           | Flare 2              |
| 86  | 6.5(3.7–12.1)| 15.1(8.1–48.0)| ...           | Flare 3              |
| A-22| 20          | 4.2(2.8–6.1)  | 10.3(6.3–16.5)| 7.5(6.7–8.2)         |         |
| A-23| 56          | 0.8$^*$       | 4.0(3.3–4.8)  | 2.0(1.7–2.3)         | Flare 1 |
| 74  | 1.9(0.8–3.4) | 3.8(2.1–6.3)  | ...           | Flare 2              |
| A-24| 72          | 2.9(2.7–3.1)  | 12.3(11.3–13.3)| 6.4(5.9–7.0)         |         |
| A-25| 10          | 0.9$^*$       | 1.3$^*$       | 17.0(15.9–18.0)      | Flare 1 |
| 38  | 7.5(4.2–12.3)| 3.0(0.7–10.1) | ...           | Flare 2              |
| 88  | 1.1(0.5–1.7) | 5.6(3.8–9.1)  | ...           | Flare 3              |
| A-34| 36          | 3.0(1.5–5.8)  | 8.1(5.6–11.8) | 2.4(2.0–2.8)         |         |
| A-53| 82          | 2.2(1.2–3.6)  | 5.1(2.8–10.0) | 10.6(10.0–11.3)      |         |
| A-69| 70          | 26.9(11.0–121.3)| 4.7$^*$      | 3.0$^*$              |         |
| A-77| 98          | 3.5(2.2–5.5)  | ...$^+$       | 0.7(0.5–0.8)         |         |
| A-78| 94          | 1.5$^*$       | 3.1$^*$       | 1.0(0.8–1.1)         |         |
| A-79| 42          | 2.8(2.5–3.0)  | 9.0(20.8–16.3)| 2.4(1.7–3.1)         | Flare 1 |
| 62  | 8.1(6.9–9.2) | 17.3(35.9–33.4)| ...           | Flare 2              |
| BF-8 | 66          | 1.0$^*$       | 1.3$^*$       | 0.6(0.3–0.8)         |         |
| BF-17| 32          | 1.4(0.8–2.1)  | 1.7(0.8–2.9)  | 1.0(0.8–1.1)         |         |
| BF-27| 86          | 1.5(0.6–2.5)  | 2.1(1.1–3.4)  | 0.9(0.7–1.1)         |         |
| BF-28| 18          | 0.9(0.2–1.3)  | 2.7(1.9–4.0)  | 1.1(0.9–1.3)         |         |
| BF-31| 54          | 2.5(2.3–2.7)  | 9.1(8.4–10.0) | 1.1(0.8–1.3)         |         |
Table 4. (Continued)

| No.  | \(t_p\) (ks) | \(\tau_r\) (ks) | \(\tau_d\) (ks) | \(Q\) (count ks\(^{-1}\)) | Comment |
|------|--------------|----------------|----------------|-------------------------|---------|
| BF-35 | 61           | 6.0(5.2–6.9)   | 15.8(13.7–18.2)| 2.8(2.3–3.2)            |         |
| BF-42 | 76           | 7.5(3.8–15.1)  | 4.4(1.7–7.6)   | 3.8(3.4–4.2)            |         |
| BF-51 | 5            | 1.0*           | 1.0*           | 0.6(0.4–0.8)\(\parallel\) | Flare 1 |
|       | 61           | 1.5*           | 1.3*           | ...                     | Flare 2 |
| BF-59 | 88           | 3.2(2.7–3.6)   | 7.6(6.2–9.5)   | 2.0(1.7–2.3)            |         |
| BF-63 | 54           | ...\(\dagger\) | ...\(\dagger\) | ...\(\dagger\)          | ...     |
| BF-66 | 98           | 3.0(1.2–5.8)   | 0.5*           | 2.4(2.1–2.7)            |         |
| BF-78 | 4            | 3.7(2.5–5.6)   | 7.9(6.8–9.2)   | 21.8(20.9–22.8)         |         |
| BF-87 | 84           | 3.4(3.1–3.8)   | 6.0(5.4–6.7)   | 1.0(0.8–1.2)            |         |
| BF-88 | 14           | 21.5(10.7–56.0)| 7.0(3.6–15.6)  | 26.0(14.7–32.7)         | Flare 1 |
|       | 46           | 31.1(17.9–52.5)| 22.6(14.7–32.7)| ...                     | Flare 2 |
|       | 84           | 4.2(1.9–20.2)  | 3.0(1.3–9.1)   | ...                     | Flare 3 |
| — Class III — |   |               |               |                         |         |
| A-2\(\dagger\) | ...\(\dagger\) | ...\(\dagger\) | 131*          | ...\(\dagger\)          | Flare 1 |
| A-5   | 70           | 3.7(2.1–5.8)   | 55.6(30.8–117.5)| ...                     | Flare 2 |
| A-20  | 54           | 2.8(1.8–4.1)   | 6.1(4.0–9.5)   | 8.0(7.2–8.7)            | Flare 1 |
| A-41  | 76           | 2.3*           | 7.0(2.6–22.9)  | ...                     | Flare 2 |
| A-63  | 22           | 17.0*          | 8.3(3.4–31.3)  | 27.3*                   | Flare 1 |
| A-81  | 62           | 1.4*           | 2.7(2.7–2.7)   | ...                     | Flare 2 |
| A-41  | 76           | 4.2*           | 9.9(5.6–20.8)  | ...                     | Flare 3 |
| A-41  | 90           | 2.0*           | ...\(\dagger\) | 21.6(20.7–22.4)         |         |
| A-63  | 52           | 2.6(1.3–4.3)   | 66.4*          | 10.3(9.5–11.1)          |         |
| A-81  | 54           | 1.8(1.4–2.2)   | 5.3(4.2–6.7)   | 1.4(1.2–1.7)            |         |
| BF-40 | 76           | 1.8(1.2–2.7)   | 4.9(3.8–6.4)   | 9.7(9.1–10.2)           |         |
| BF-46 | 72           | 3.6(2.8–4.7)   | 10.8(8.1–14.2) | 76.5(74.6–78.3)         |         |
| BF-84 | 72           | 5.5(2.7–12.3)  | 10.2(3.3–24.9) | 1.0(0.7–1.2)            |         |
| BF-96 | 32           | 59.2(41.9–96.7)| 13.8(10.8–17.9)| 27.2(24.8–29.2)         |         |
| — Class IIIc — | | | | |         |
| A-12  | 20           | 0.9*           | 0.9*           | 1.3(1.1–1.5)            |         |
| BF-72 | ...\(\dagger\) | ...\(\dagger\) | 4.1(2.1–6.8)  | 1.2(1.0–1.4)            |         |
| — Unclassified NIR sources — |   |   |   |   |         |
| A-28  | 50           | 8.5(4.3–17.8)  | 23.8(9.1–55.4) | 0.8(0.3–1.1)            |         |
Table 4. (Continued)

| No.   | \( t_p \) | \( \tau_r \) | \( \tau_d \) | \( Q \)    | Comment          |
|-------|----------|-------------|-------------|----------|------------------|
|       | (ks)     | (ks)        | (ks)        | (count ks\(^{-1}\)) |
| A-76  | 72       | 1.9\(^*\)  | 24.0(12.2–129.1) | 1.0(0.8–1.2) |
| BF-55 | 30       | 1.5\(^*\)  | 0.8\(^*\)   | 0.7(0.5–0.9)\| |
| BF-62 | 20       | 3.7(2.6–5.0) | 6.9(4.9–9.9) | 1.2(0.5–1.8) | Flare 1         |
|       | 53       | 5.7(5.0–6.5) | 10.5(9.3–12.0) | ...      | Flare 2         |
| A-29  | 80       | 1.0\(^*\)  | 2.1\(^*\)   | 0.5\(^*\)\| |
| BF-36 | 30       | 4.4(1.7–9.4) | ...\(\|\) | 0.8(0.6–0.9) |
| BF-92 | 20       | 0.5\(^*\)  | 2.6(1.1–4.4) | 1.9\(^*\) |

We can not determine errors because of the limited statistics and/or strong coupling of the other parameters.

\(^*\)Fitting is obtained for light curves in \(2''5–12''5\) (A-2) and \(2''5–7''5\) (BF-64) radius circles in order to avoid the pileup effect.

\(^\|\)No fitting is possible because of the limited statistics and/or the boundary of the observations.

\(\|\)We relax the flare peak time (\( t_p \)) to be free in order to obtain as good results as possible.

\(\|\)This should be the upper limit because the fitting does not include the time bin with zero counts.

Table 5. Results of two-sample tests for the differences of the observed parameters among classes.

| Parameter      | — Sample size\(^*\) — | — Probability for the null hypothesis\(^\|\) — |
|----------------|------------------------|---------------------------------------------|
|                | I     II    III+III\(_c\)  | I vs II+III+III\(_c\)  | I+II vs III+III\(_c\)  | II vs III+III\(_c\)  |
|                | GW logrank | GW logrank | GW logrank | GW logrank | GW logrank |
| \(\log L_X\) (Flare) | 8 36 16 | 0.059 0.063 | ... | ... | ... |
| \(\log L_X\) (Quiescent) | 8 61 26 | ... | ... | ... | ... |
| \(\langle kT \rangle\) (Flare) | 7 35 16 | 0.079 | 0.060 0.017 | ... | 0.047 |
| \(\langle kT \rangle\) (Quiescent) | 7 61 24 | 0.008 0.022 0.046 0.037 | ... | 0.026 |
| \(\tau_r\) | 6 28 8 | ... | ... | ... | ... |
| \(\tau_d\) | 7 28 12 | ... | ... | ... | ... |

\(^*\)The number of data points used for the two-sample tests.

\(^\|\)Probability that the hypothesis of two distributions being the same is true, which is derived with the Gehan’s generalized Wilcoxon test (GW) and the logrank test (Feigelson, Nelson 1985). Blank (...) indicates that the probability is larger than 0.1.
### Table 6. Estimated Mean Values of the Flare Physical Parameters.

| Class | — This work — | — \( kT \) vs \( EM \) — |
|-------|----------------|-----------------------------|
|       | \( \log(n_c) \)\(^{†}\) | \( \log(B) \)\(^{†}\) | \( \log(L) \)\(^{†}\) | \( \log(B_{SY}) \)\(^{§}\) | \( \log(L_{SY}) \)\(^{§}\) |
|       | (cm\(^{-3}\)) | (G) | (cm) | (G) | (cm) |
| I     | 10.48±0.09    | 2.7±0.1 | 10.3±0.1 | 2.6±0.1 | 10.4±0.2 |
| II    | ...           | 2.5±0.1 | 10.4±0.1 | 2.5±0.1 | 10.4±0.1 |
| III+III\(_c\) | ... | 2.3±0.1 | 10.4±0.2 | 2.2±0.1 | 10.7±0.1 |
|       | (2.4±0.1)\(^{∥}\) | (10.0±0.1)\(^{∥}\) | |

Equation\(^*\) (5) (A11) (A12) (A15) (A16)

\(^{†}\)The values are derived by assuming \( M_A = 0.01 \)

\(^{‡}\)We assume the same values of \( n_c \) for all classes (see text).

\(^{§}\)These values are estimated using the derived values of \( n_c (= 10^{10.48} \text{ cm}^{-3}, \text{column 2}) \).

\(^{∥}\)The mean values for class III+III\(_c\) when we exclude the flares with unusually long timescales (A-2, A-63, and BF-96).