

CHANDRA X-RAY OBSERVATIONS OF YOUNG CLUSTERS. III. NGC 2264 AND THE ORION FLANKING FIELDS

L. M. REBULL AND J. R. STAUFFER

Spitzer Science Center, California Institute of Technology, MS 220-6, 1200 East California Boulevard,
Pasadena, CA 91125; luisa.rebull@jpl.nasa.gov

S. V. RAMIREZ

IPAC, California Institute of Technology, MS 100-22, 1200 East California Boulevard, Pasadena, CA 91125

E. FLACCOMIO, S. SCIORTINO, AND G. MICELA

INAF—Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, 90134 Palermo, Italy

AND

S. E. STROM AND S. C. WOLFF

National Optical Astronomy Observatory, 950 North Cherry Avenue, Tucson, AZ 85726

Received 2005 November 14; accepted 2006 March 1

ABSTRACT

Chandra observations of solar-like pre-main-sequence (PMS) stars in the Orion flanking fields (FFs; age ~ 1 Myr) and NGC 2264 (~ 3 Myr) are compared with the results of the *Chandra* Orion Ultradeep Project survey of similar objects in the Orion Nebula cluster (ONC; ~ 0.5 Myr). The correlations between $\log L_X$ and mass found for PMS stars on convective tracks in these clusters are consistent with the relationships found for the ONC, indicating little change in the *median* values of either $\log L_X$ or $\log L_X/L_{\text{bol}}$ during the first ~ 3 –5 Myr of evolution down convective tracks. The fraction of stars with extreme values of L_X , more than 10 times higher than the average for a given L_{bol} , or with $\log L_X/L_{\text{bol}}$ greater than the canonical saturation value of -2.9 , is, however, larger by a factor of 2 in the younger ONC when compared with the Orion FFs and NGC 2264. PMS stars in NGC 2264 on radiative tracks have L_X/L_{bol} values that are systematically lower by a factor of ~ 10 than those found for stars of similar mass on convective tracks. The dramatic decrease in flux from convective to radiative phases of PMS evolution is likely related to major structural changes that influence the efficiency of magnetic field generation and thus the level of magnetic activity. As in the ONC, we find that stars with measured periods have, on average, higher X-ray luminosities. However, there is a wide range in L_X and L_X/L_{bol} for both periodic and nonperiodic stars of similar mass. Among stars with measured periods, the level of X-ray emission does not correlate with the rotation rate. For this data set, we find no statistically significant correlation between X-ray flux and (1) the presence or absence of circumstellar accretion disks or (2) disk accretion rates as assessed from ultraviolet excesses.

Key words: open clusters and associations: individual (NGC 2264, Orion) — X-rays: stars

1. INTRODUCTION

Low-mass stars of all stages of evolution—from protostars to the main sequence—emit X-rays (see, e.g., Feigelson & Montmerle 1999). The relationships between the levels of X-ray emission and stellar properties for pre-main-sequence (PMS) stars are, however, very different from the well-established correlations between rotation, Rossby number, and X-ray emission seen in young main-sequence stars (e.g., Stauffer et al. 1994; Micela et al. 1996; Pizzolato et al. 2003). Several factors may contribute to these differences. Low-mass PMS stars are fully convective during their early evolution, and differences in stellar structure (convective in the PMS phase vs. radiative core and convective envelope on the zero-age main sequence [ZAMS]) are likely to produce different levels of magnetic field–related activity. Many PMS stars are still surrounded by accretion disks, which may influence X-ray emission in at least three ways. Additional X-ray emission above coronal levels may be produced in accretion shocks or wind/jet shocks (e.g., Kastner et al. 2002, 2005; Güdel et al. 2005). Depending on the system orientation and the size of disk (and extent of flaring), disks or neutral winds may absorb X-ray photons, decreasing the detected flux, particularly at short wavelengths (e.g., Kastner et al. 2005; Walter & Kuhf 1981).

The rotation speed of PMS stars could, in principle, also affect X-ray emission. If so, then the X-ray properties of stars surrounded by accretion disks may differ systematically from their counterparts that lack disks, owing to the effects of “disk locking” on rotation (e.g., Shu et al. 1987, 2000; Königl 1991, 1989). Finally, there might also be other less direct interactions between accretion, the young stellar object, its outer convective zone, the magnetic field structures, and the X-ray-emitting plasma, as discussed in Preibisch et al. (2005).

The recent *Chandra* Orion Ultradeep Project (COUP; Getman et al. 2005) has investigated the detailed relationships among stellar parameters and X-ray flux among solar-like PMS stars in the Orion Nebula cluster (ONC; Preibisch et al. 2005), which has an age of ~ 0.5 Myr. We consider here the relationships among rotation, X-rays, and disks for several hundred stars in the Orion flanking fields (FFs; ~ 1 Myr) and NGC 2264 (~ 3 Myr). We focus our analysis on objects of masses ~ 0.3 – $2.5 M_{\odot}$.

The stars in these regions are, on average, slightly older than those in the ONC and are therefore, in combination with the COUP data, well suited for searching for changes during the early evolution of PMS stars. Importantly, for stars of ~ 1 – $2 M_{\odot}$ the current sample includes stars spanning the range of ages in which substantial structural changes take place as stars evolve from a

fully convective phase to a phase in which they develop radiative cores and convective envelopes. Since the origin of the X-rays in the Sun is believed to be linked to dynamo-driven activity, we might expect that the mechanism of magnetic field and consequent coronal X-ray generation changes as stars make the transition from a fully convective state to one in which a radiative core is surrounded by a thin convective envelope. Consequently, we might also expect to see a change in the X-ray properties.

The basic presentation of the data for the Orion FFs and NGC 2264 appears in other papers (Ramirez et al. 2004a, 2004b; Flaccomio et al. 2005, 2006); we discuss here the implications of these data. After a brief summary of the observations (§ 2), we consider in some detail the completeness and selection effects of the sample of stars to be discussed here. Then we compare the relationships of $\log L_X$ and $\log L_X/L_{\text{bol}}$ (§ 3) with mass and age for stars on convective tracks in all three clusters and find that the relationships are entirely consistent, thereby indicating that there is little or no evolution in X-ray properties during the first ~ 5 Myr of evolution down convective tracks. We find clear evidence for a decrease in $\log L_X/L_{\text{bol}}$ when stars make the transition from convective to radiative tracks (§ 4). We also discuss the sample with rotation information (§ 5) and find that the subset of stars with measured periods has, on average, significantly higher values of $\log L_X/L_{\text{bol}}$, as was found previously for the ONC (Preibish et al. 2005). Also in accordance with previous studies, we find no clear trend of X-ray emission with rotation among the sample having spot-modulated periods. Finally, in § 6 we examine the relation between disks, mass accretion rate (inferred from ultraviolet excess emission), and X-ray luminosity; we find no clear trends.

2. OBSERVATIONS, DATA, AND SAMPLE SELECTION

2.1. *Observations*

In this paper we discuss stars detected in four *Chandra* ACIS fields: two in NGC 2264 and two in the outer Orion Nebula region, the so-called Orion flanking fields (see Rebull et al. [2000] and Rebull [2001] for more discussion of these fields).

The *Chandra* data for the Orion FFs were first presented in Ramirez et al. (2004b). The two fields here correspond to portions of fields 2 and 4 from Rebull et al. (2000); they are centered on $05^{\text{h}}35^{\text{m}}19^{\text{s}}$, $-04^{\circ}48'15''$ and $05^{\text{h}}35^{\text{m}}06^{\text{s}}$, $-05^{\circ}40'48''$. Standard CIAO procedures were used to reduce the data. With about 48 ks exposure time per field, 417 sources were detected in total over both fields. The distance modulus we assumed for Orion is 8.36 (470 pc).

The *Chandra* data for the northern field in NGC 2264 were first presented in Ramirez et al. (2004a), in which 263 sources were detected in 48.1 ks. The ACIS-I array was centered at $06^{\text{h}}40^{\text{m}}48^{\text{s}}$, $+09^{\circ}51'00''$. These data were also independently analyzed by Sung et al. (2004) in an effort to identify X-ray-emitting weak-line T Tauri stars (WTTs). The ACIS data for the southern field in NGC 2264 is discussed in Flaccomio et al. (2005, 2006). The ACIS-I array was centered at $06^{\text{h}}40^{\text{m}}58.1^{\text{s}}$, $+09^{\circ}34'00''.4$, and 420 sources were detected in 96 ks. Standard CIAO procedures were used to reduce the data. The distance modulus we assumed for NGC 2264 is 9.40 (760 pc).

Following the approach discussed in Ramirez et al. (2004a, 2004b) and Flaccomio et al. (2006), we determined upper limits for all stars with optical data in these fields.

ACIS data have also been recently published for the ONC core region by Feigelson et al. (2003) and as part of COUP (Getman et al. 2005; Preibisch et al. 2005). Those much deeper (~ 20 times deeper) observations of an extremely rich and slightly younger

region (Ramirez et al. 2004b) provide a data set of great statistical weight with which we can compare our results.

2.2. *Ancillary Data and Counterparts*

In order to interpret these X-ray data in the context of young stars, we assembled extensive catalogs of multiwavelength photometric and spectroscopic data for each cluster, as discussed in greater detail in Ramirez et al. (2004a, 2004b). These catalogs combined are hereafter referred to as the ancillary data catalog (ADC). For NGC 2264, the bulk of the data in the ADC come from Rebull et al. (2002b), as well as Park et al. (2000) and the Two Micron All Sky Survey (2MASS). The ADC also contains preliminary proper motions from B. Jones; see Rebull et al. (2002b). We have added to the ADC recently published data from Lamm et al. (2004), Sung et al. (2004), and Dahm & Simon (2005). For the Orion FFs, the ADC was assembled from ~ 30 published articles ranging from the U magnitudes in Rebull et al. (2000) to the JHK photometry from 2MASS; see Ramirez et al. (2004b). The ADC has also been updated with more recently published photometric data from Sicilia-Aguilar et al. (2005), as well as with 126 additional $v \sin i$ measurements and upper limits currently in preparation for publication (L. M. Rebull et al. 2006, in preparation).

For each of the clusters we matched each X-ray detection from Ramirez et al. (2004a, 2004b) to optical and/or NIR counterparts from the ADC based on comparison of the right ascension and declination of the individual objects combined with manual inspection of the NIR field around each X-ray source.

Following the same approach as in, e.g., Rebull et al. (2000), using the stars' positions in the dereddened $I/V - I$ color-magnitude diagram (CMD), we calculated L_{bol} following the precepts summarized by Hillenbrand (1997). Similarly, we assigned masses to the stars according to the two different sets of PMS stellar models: (1) those of D'Antona & Mazzitelli (1994, 1998, hereafter collectively DAM), with conversion from the theoretical to the observational plane (including calculation of L_{bol}) using transformations found in Hillenbrand (1997); and (2) those of Siess et al. (2000, hereafter SDF00), the $Z = 0.02$ model with no overshooting, using conversions from Kenyon & Hartmann (1995). The DAM models are what we have used in previous papers (e.g., Rebull et al. 2000), but the SDF00 models were used by COUP (Preibisch et al. 2005); masses from both models are discussed here to facilitate comparison with these and other papers. If stars fell outside the grid provided by the models, no masses or ages were assigned; such stars were excluded from this analysis. Additional discussion regarding uncertainties in masses and ages appears in Rebull (2001); we repeat here that the largest uncertainties are in the models themselves, and the ages and masses used here are perhaps best thought of as proxies for relative placements in the observational CMD.

In Ramirez et al. (2004b) we have found that the X-ray-selected sample in the Orion FFs (~ 1 Myr) is on average slightly older than that for the ONC (~ 0.5 Myr) but not as old as that for NGC 2264 (~ 3 Myr). Repeating this analysis but now including the second NGC 2264 field, it is still the case that the median age of the FF sample is older than the ONC, and NGC 2264 is older still. The range of ages found within each of these clusters is on the order of ~ 3 Myr and is comparable in all three clusters, with the largest fraction of older stars being found in NGC 2264; see Figure 1. The ages listed here (0.5, 1, and 3 Myr) are obtained from comparing distributions of ages derived using DAM models for the “best possible sample” (see § 2.3) for these clusters. If we use SDF00 models for the same subset of stars, we find ages that are on average older by ~ 1 Myr, but the relative age

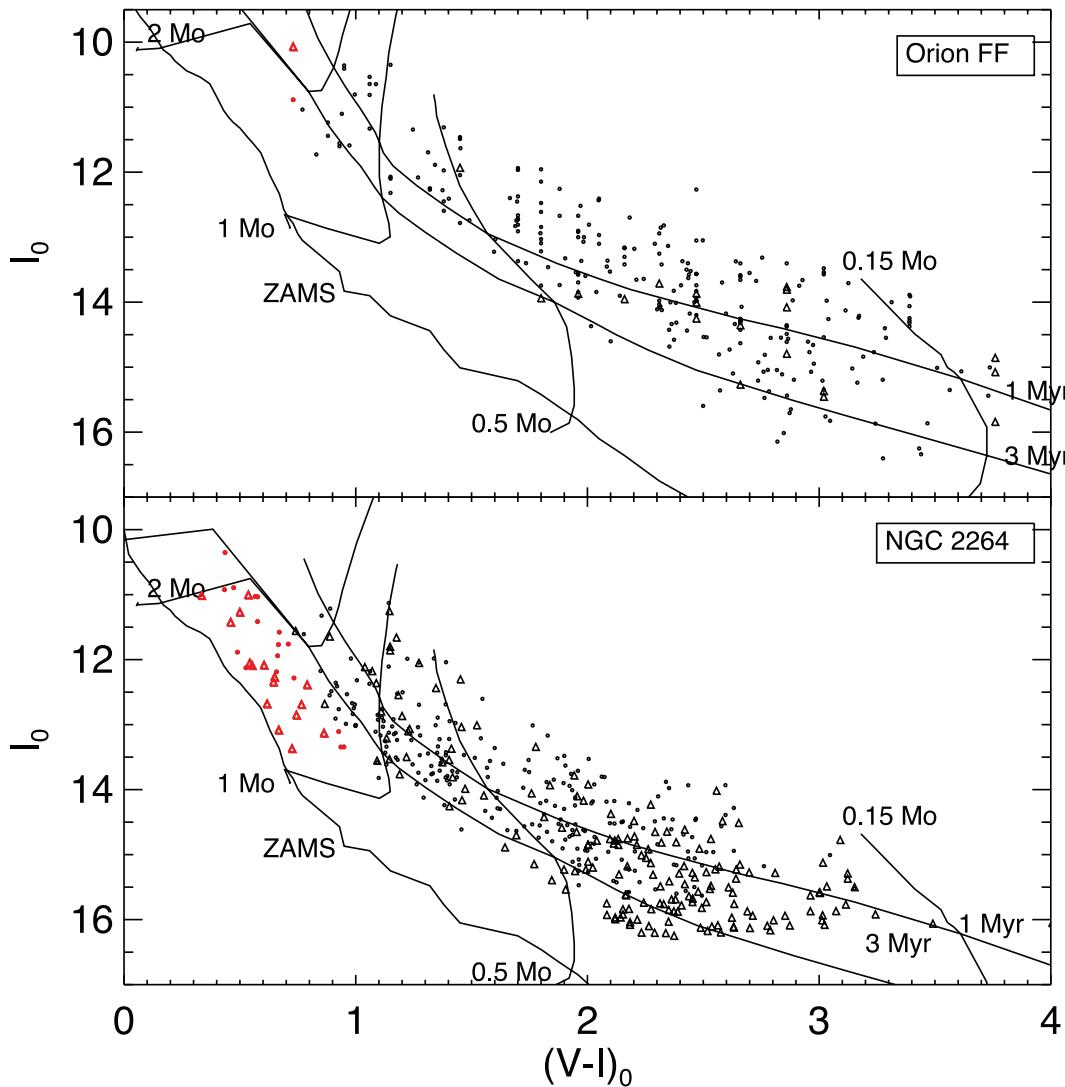


FIG. 1.—CMD for the final best sample to be considered (see text). Circles indicate L_X detections, and triangles indicate L_X upper limits. Isochrone lines overplotted are, from top to bottom, isochrones for 1 Myr, 3 Myr, and the ZAMS; the first panel is from D'Antona & Mazzitelli 98, and the second panel (next page) is from SDF00. Lines of constant mass are, from left to right, 2, 1, 0.5, and 0.15 M_\odot . The apparent quantization arises from correcting the $V - I$ colors to those expected from the spectral type. The range of ages found in these clusters is ~ 3 Myr, but the largest fraction of older stars is found in NGC 2264. The red symbols denote those stars that are no longer on convective tracks; see the discussion in § 4.

placement of the clusters is similar at 1.5, 2, and 4 Myr. The relative placement of the clusters is also consistent with the relative numbers of radiative and convective stars (see below); the fewest radiative stars are found in the ONC, and the most are found in NGC 2264.

2.3. Catalog Statistics and Sample to be Considered Here

In order to interpret our X-ray data, we have to include data from the ADC. However, we cannot simply take all of the ADC data merged with the X-ray data and proceed. Not all stars have a complete set of data in the ADC, and there is a wide range of ADC survey depths among our sample clusters. In this section we describe what kinds of data we require for a given star to appear in subsequent analysis in this paper. In the end, we settle on a sample that we hereafter refer to as the “best possible sample” (as defined below and summarized in Table 1). Within this best possible sample, there are stars that are on radiative tracks according to either the DAM or SDF00 models and stars that are on convective tracks according to those models. These samples are referred to as the best possible radiative and best possible

convective samples. In the figures that follow, in which both the radiative and convective stars appear, the radiative stars are colored red; otherwise, the plots contain just the convective stars. The following discussion is summarized in Table 1, in which the numbers of detections and/or upper limits are tabulated for each of a variety of criteria.

While there are 416 X-ray sources detected in the Orion FFs and 683 sources detected in NGC 2264 (line A in Table 1), only 84% (348) of the FF sources and 75% (509) of the NGC 2264 sources have optical and/or NIR counterparts in the ADC (line B in Table 1). For determining, among other things, masses and ages, we require V and I magnitudes so that we can place all the stars in the same CMD and at least derive self-consistent values. There are 278 (67%) of the FF X-ray detections and 465 (68%) of the NGC 2264 X-ray detections that meet those criteria (line D in Table 1). Furthermore, of those, 94% (261 in the FFs and 438 in NGC 2264) are likely cluster members based on position in the sky and position in the CMD (line E in Table 1)—these objects appear in a clear “locus” above the ZAMS (see Rebull et al. [2000, 2002b] for full CMDs and additional discussion).

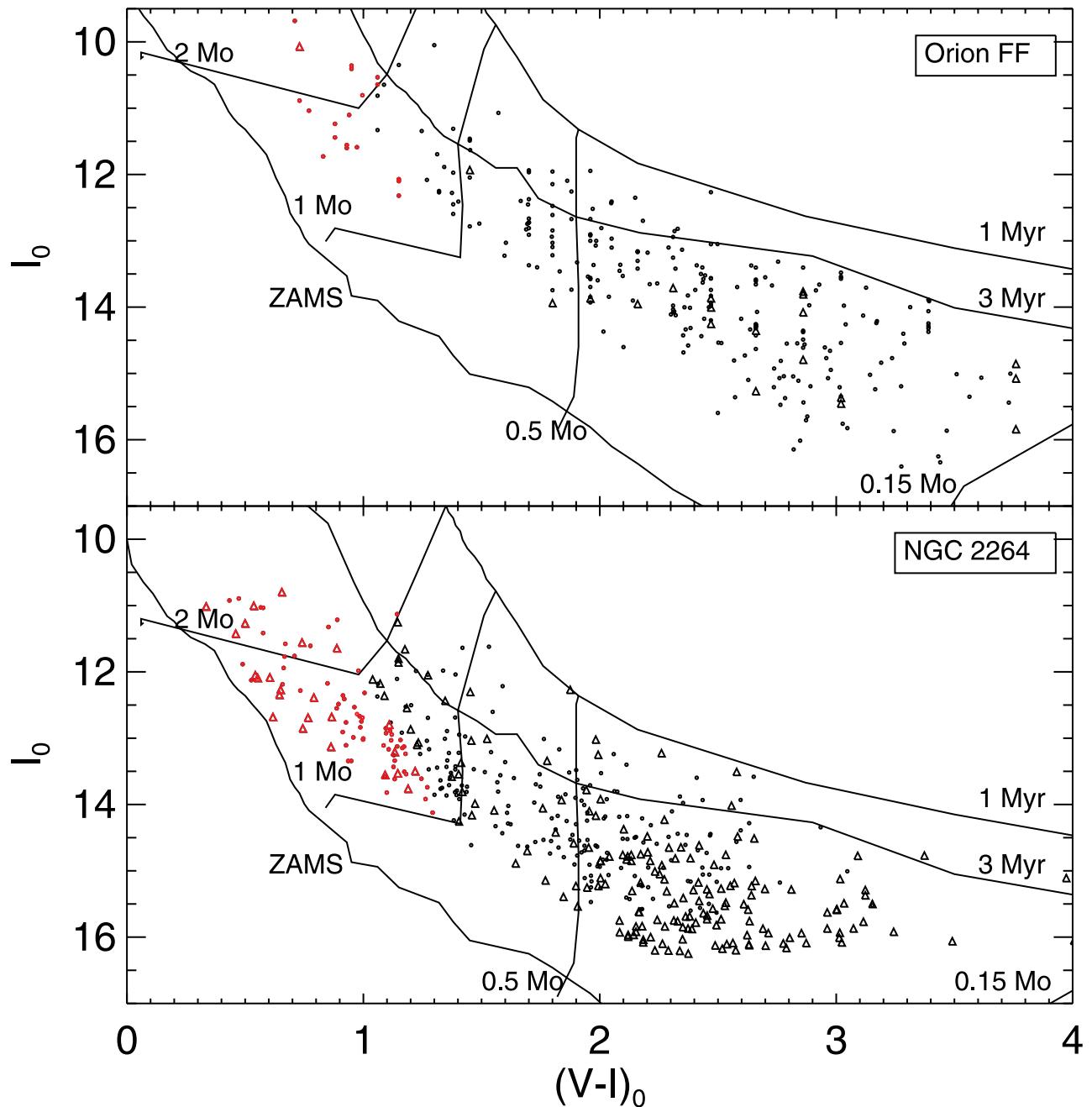


FIG. 1.—Continued

Of the entire set of X-ray detections, only 115 (27%) Orion FF sources and 294 (52%) NGC 2264 sources can be identified with counterparts that have known spectral types in the ADC (line C in Table 1). Because of the original motivations behind the studies amassing most of these spectral types, the set of stars with known types is strongly biased toward the stars with known rotational periods. As we see below, stars with measured periods are brighter in X-rays, which therefore affects the set of stars with both X-ray detections and known spectral types.

As a result of this bias, we chose *not* to limit our analysis here solely to the stars with known spectral types. In order to minimize the chances of field star contamination we have, however, restricted our discussion to objects (261 detections in the FFs and 438 detections in NGC 2264) that are likely members based on position in the sky and in the CMD (line E in Table 1).

Upper limits can be important for determining trends in complex data sets such as this. We obtained upper limits in L_X for stars with optical detections in the ADC. For the FFs, this adds 84 upper limits to the 261 detections to be considered (for just the stars that are likely to be members, i.e., the ones in the CMD locus, an increase of $\sim 30\%$). The optical surveys of NGC 2264 incorporated into the ADC are very deep and are not well matched to the relatively shallow *Chandra* survey. If the entire optical sample from the ADC were included (line F in Table 1), the number of X-ray upper limits would dwarf the detections (and moreover would likely be dominated by nonmembers). We have therefore limited our analysis to likely member stars (line G in Table 1; those both on the molecular cloud and in the CMD locus) with $I < 16$, which is well matched both to the L_X detections and to the optical surveys incorporated into the ADC for both

TABLE 1
SUMMARY OF SELECTION CRITERIA USED TO ASSEMBLE THE “BEST POSSIBLE SAMPLE”

CRITERIA	ORION FFs		NGC 2264	
	Detections	Limits	Detections	Limits
A: X-ray detections.....	416	...	683	...
B: Line A + optical/NIR counterpart.....	348 (84% of A)	...	509 (75% of A)	...
C: Line B + spectral type.....	115 (27% of A)	...	294 (52% of A)	...
D: Line B + V, I detection.....	278 (67% of A)	...	465 (68% of A)	...
E: Line D + inferred cluster membership.....	261 (94% of D)	...	438 (94% of D)	...
F: Upper limits for optical/NIR object in catalog.....	...	147	...	1388
G: Upper limit for optical/NIR likely member.....	...	84	...	479
H: Lines E and G + $I < 16$ (NGC 2264 only).....	349	168
I: Best possible sample; line D (FFs), line H (NGC 2264) + DAM $M < 2.5 M_{\odot}$ + age exists.....	250	80	317	139
J: Line D (FFs), line H (NGC 2264) + SDF00 $M < 2.5 M_{\odot}$ + age exists.....	258	80	327	146
K: Line I, radiative tracks only, DAM models.....	1	1	17	16
L: Line J, radiative tracks only, SDF00 models.....	18	1	64	24
M: Line I, convective tracks only, DAM models.....	249	79	300	123
N: Line J, convective tracks only, SDF00 models.....	240	79	263	122
O: Line M + periods.....	110	15	181	38
P: Line M + $v \sin i$	64	5	30	3

clusters. In order to make a fair comparison with the set of detections, we further limit even the L_X detections to those stars with $I < 16$. This adds 168 upper limits to the now-reduced 349 detections to be considered in NGC 2264 (line H in Table 1). These restrictions should also reduce the contamination of our sample by nonmembers. The percentage of nonmembers is probably higher among stars with no detections (because members are more likely to be bright in X-rays) and at the faint end (because the mass function means there are simply more low-mass stars in the field). This cut in I of course has implications for the mass and age range to be considered here; see Figure 1. This cut eliminates stars with $M \lesssim 0.3 M_{\odot}$ and $t > 5$ Myr, using DAM models.

To summarize the discussion to this point (line H in Table 1), then, there are 261 X-ray detections with optical counterparts from the ADC that are likely stellar members of the Orion FFs, with 84 additional upper limits. There are 349 X-ray detections with optical counterparts from the ADC with $I < 16$ that are likely stellar members of NGC 2264, with 168 additional upper limits.

Because we will be comparing the X-ray properties of stars on radiative tracks with the stars on convective tracks, we have further limited the discussion to just stars that fall within the range of L and T_{eff} spanned by published stellar models (the “model grid”) and those with $M < 2.5 M_{\odot}$. This leaves 250 detections and 80 upper limits in the FFs and 317 detections with 139 upper limits in NGC 2264 (lines I and J in Table 1).

The sample considered here uses the best available information for each star; e.g., if there is a spectral type in the ADC, the star is dereddened by values specific to each star, and if there is no type available, the star is dereddened by the most likely reddening in the direction of the cluster (see Rebull et al. [2000, 2002b] for more discussion on reddening toward these clusters). A CMD for this sample appears in Figure 1. Note that there are no stars included in this sample that fall outside the model grid. Note also that despite using two different models, DAM and SDF00, the number of stars in the best possible sample using DAM models is very similar to the best possible sample using SDF00 models.

For each of the evolutionary models (DAM and SDF00) depicted in Figure 1, the red symbols indicate the stars between ~ 1 and $\sim 2.5 M_{\odot}$ that are on radiative tracks (lines K and L in Table 1). There are very few of these radiative stars available in

the FFs, with only 1 X-ray detection (and 1 upper limit) using DAM models and 18 X-ray detections (and 1 upper limit) using SDF00 models. But in NGC 2264, using the DAM models, there are 17 X-ray detections and 16 upper limits; using the SDF00 models, there are 62 X-ray detections and 24 upper limits. *The red points here are the “best possible radiative sample.”*

Essentially all of the discussion that follows is restricted to stars on convective tracks with masses $\leq 2 M_{\odot}$, e.g., the black points in Figure 1. *The black points here are the “best possible convective sample.”* For the best possible convective sample, using DAM models, this leaves 249 detections and 79 upper limits in Orion, so 24% of the best possible convective sample is upper limits; in NGC 2264 there are 300 detections and 123 upper limits, so 29% of the best possible convective sample in this cluster is upper limits. Similar numbers are obtained for SDF00 models; see Table 1. In most discussions that follow, we consider only the convective sample. Where the radiative stars are included in subsequent discussion and plots, we note this explicitly. In the figures that follow, where both the radiative and convective stars appear the radiative stars are colored red.

Of this final, best possible sample of convective stars, we also want to know how many stars have measured periods and $v \sin i$ values (lines O and P in Table 1). There are 110 stars in the Orion FFs with measured periods that are also detected in X-rays and 15 stars with measured periods but upper limits in X-rays; there are 64 stars with measured $v \sin i$ and X-ray detections and 5 with upper limits in X-rays. In NGC 2264 there are 181 stars with measured periods and X-ray fluxes and 38 more with upper limits in L_X . There are only 30 stars with measured $v \sin i$ and X-ray detections and 3 more stars with upper limits in L_X .

3. L_X VERSUS L_{bol}

All recent investigations, including the COUP study (e.g., Preibisch et al. 2005), have found a clear positive correlation between $\log L_X$ and $\log L_{\text{bol}}$ but with a very large intrinsic (as opposed to instrumental) scatter (Feigelson et al. 2003).

Figure 2 shows the results for the ONC from the COUP sample, the Orion FFs, and NGC 2264. The best possible radiative sample for NGC 2264 and the Orion FFs is shown in red, and the best possible convective sample is shown in black (essentially all of the COUP stars are convective). Also shown is the best-fit

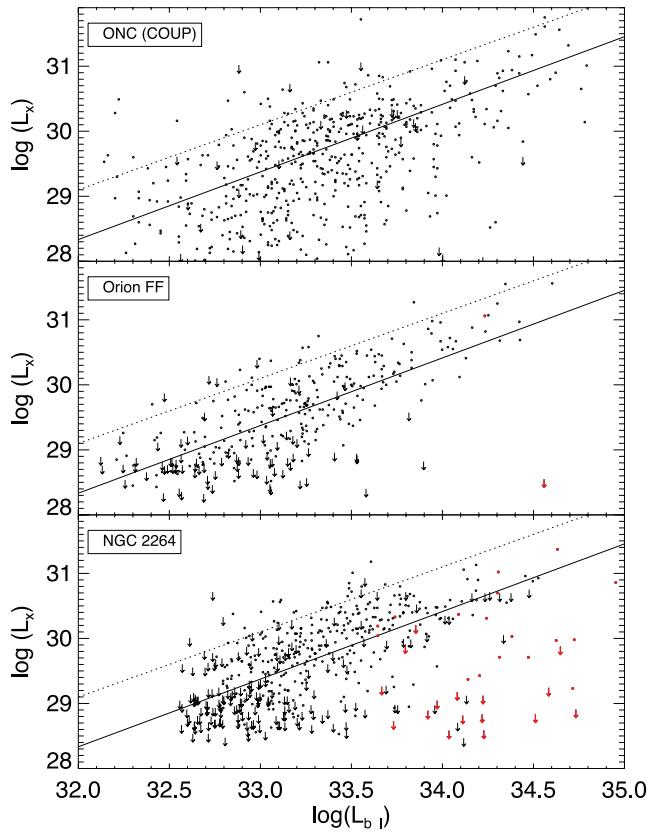


FIG. 2.—Plot of $\log L_X$ vs. $\log L_{\text{bol}}$ for the stars (see § 2.3) in the ONC from the COUP sample (top), the Orion FFs (middle), and NGC 2264 (bottom). Only detections from COUP are shown, whereas upper limits are shown for the other two panels. The upper limits occur at all values of L_X because the PSF varies significantly across the field of view, so a star appearing at the edge of the field will have a much higher upper limit than a star near the center of the field. The boundaries for this plot were optimized for the FFs and NGC 2264 data; 24 detections and 14 limits from the COUP data appear outside of this region, all but four detections (and one limit) of which appear below $\log L_X = 28$. The solid line is the best-fit value to the ONC COUP data analyzed by Preibisch et al. (2005). The dotted line is the canonical “saturation” value of $\log L_X/L_{\text{bol}} \sim -2.9$. In the lower two panels we see a suggestion of a bifurcation in the distribution beginning at about half the luminosity of the Sun and extending to higher luminosities. In NGC 2264, 50% of the stars on the lower branch are on radiative tracks (red) and therefore may have X-ray properties that are different from stars on convective tracks. A discussion of the comparison with the ONC is provided in the text.

straight line obtained by Preibisch et al. (2005) for the ONC COUP data, which has a sensitivity limit of about $\log L_X = 27.0$. This should be compared with a sensitivity limit of about $\log L_X \sim 28.5$ for our observations. The line derived for the ONC is a reasonable fit to the data for stars on convective tracks for both of our regions. We note, however, that many of our points near $\log L_{\text{bol}} \sim 33.5$ lie above the mean line for the ONC, and there is a cloud of points with low values of $\log L_X$ that lie below the line near $\log L_{\text{bol}} \sim 32.8$, suggesting that perhaps a linear fit may not be appropriate. However, both of these features are also seen in the ONC plots and may thus reflect some inadequacy in the ability of a straight line to fit the data for both data sets. Figure 3 depicts the same data as Figure 2, but in box plot form. These box plots have been used in other papers (e.g., Flaccomio et al. 2003c) as a mechanism for interpreting scatter plots. We emphasize that the boxes in Figure 3 have been corrected using the Kaplan-Meier estimator for censored data to take into account the upper limits present in the data. The central line in each box denotes the (corrected) median; the ends of each

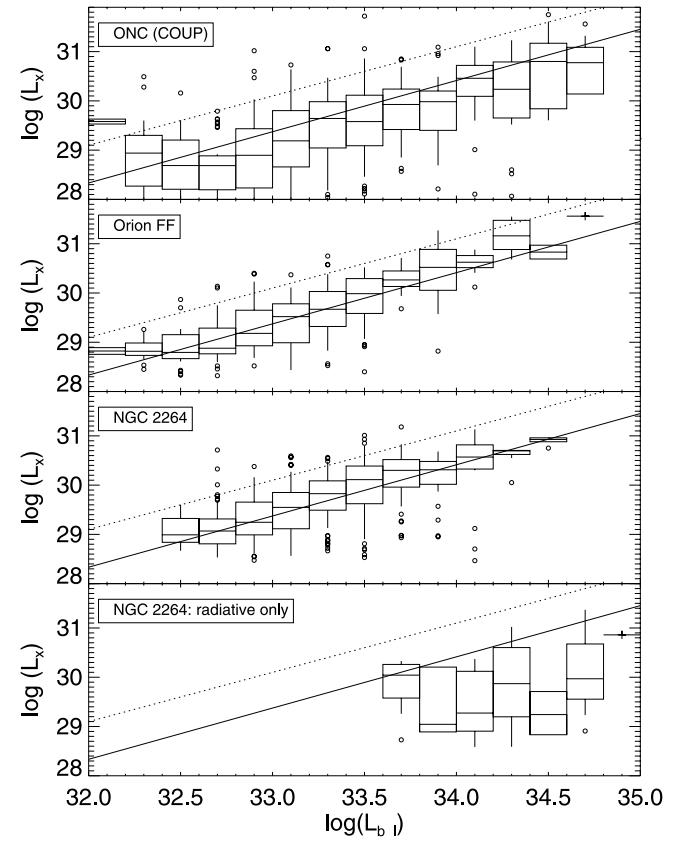


FIG. 3.—Plot of $\log L_X$ vs. $\log L_{\text{bol}}$ for the stars from Fig. 2, but represented in box plot form. The top three panels are convective stars; the bottom panel displays the radiative stars in NGC 2264 (there are not enough radiative stars in the other clusters to merit a separate plot). It is readily apparent here that the X-ray properties of the radiative stars are different from those of the convective stars.

box are the first and third quartile of the (corrected) distribution; the lines extend to the most extreme values that are not more than 1.5 times the interquartile range; and the circles are those points outside 1.5 times the interquartile range. If downward-pointing triangles appear in the boxes (as they do below in Fig. 9), then the true (corrected) lower limit of the box is located at some unknown location below the line indicated. The top three panels in Figure 3 contain only convective stars; the bottom panel contains only the radiative stars in NGC 2264 (there are not enough radiative stars in Orion to merit a separate plot). Examination of Figure 3 reveals that the X-ray properties of the radiative stars are significantly different from those of the convective stars.

Preibisch & Feigelson (2005) used the Orion data to search for changes in X-ray emission with age. They assumed that the stars in Orion ranged in age from 0.1 to 10 Myr (Palla & Stahler 1999). Because contraction down the Hayashi tracks slows with increasing age, at ages of ~ 3 Myr typical uncertainties in derived luminosities and effective temperatures lead to age uncertainties of ~ 2 –3 Myr (1σ errors; Hartmann 2001). Based on the ONC data alone, Preibisch & Feigelson concluded that the mean L_X decayed slowly with age ($L_X \propto \tau^{-1/3}$) during the first 10 Myr for stars with masses in the range 0.5 – $1.2 M_{\odot}$. However, in order to match the X-ray properties of ZAMS stars in young clusters the decay of L_X must be accelerated at ages $t > 10$ Myr. For stars with masses in the range 0.1 – $0.4 M_{\odot}$ they found only a modest decrease in $\log L_X$ during the first 100 Myr and a possible slight increase in $\log L_X/L_{\text{bol}}$ over that same time period. Flaccomio et al. (2003c) also investigate trends of X-ray emission with time,

comparing median levels of X-ray emission in several star-forming regions. They found constant $\log L_X$ and an increase in $\log L_X/L_{\text{bol}}$ with time through $\sim 3\text{--}4$ Myr and a subsequent leveling off at saturation level ($\log L_X/L_{\text{bol}} \sim -3$).

Our own data are for clusters that contain stars that are on average older than the stars in the ONC. We see two differences with respect to the ONC data. First, the upper envelope in $\log L_X$ for ONC data lies about 1.5 dex or a factor of 30 above the best-fit straight line. For the Orion FFs and NGC 2264, the upper envelope is only about a factor of 10 (1 dex) above the best-fit straight line. As Figure 2 also shows, very few of the Orion FF and NGC 2264 stars lie above the nominal “saturation” limit of $\log L_X/L_{\text{bol}} = -2.9$, while a large number of ONC stars lie above this limit (Preibisch et al. 2005). Quantitatively, 14% of the detected ONC stars have $\log L_X/L_{\text{bol}} \geq -2.9$, and 4.6% have $\log L_X/L_{\text{bol}} \geq -2.5$. For the Orion FFs the fractions are 5% and 0.4%, respectively, and for NGC 2264 the fractions are 7% and 0.9%, respectively. In other words, there is a significantly larger number of stars with high L_X and high L_X/L_{bol} in the younger ONC. There are three possible explanations for this effect. First, it could be entirely an age effect, in that the most *extreme* levels of activity may decay during early PMS evolution. Second, it could be the intrinsic variability of the stars themselves in L_X . Third, it could be the intrinsic variability of the stars themselves in the optical photometry that goes into the L_{bol} estimate. In either of these latter cases, the variability could be more extreme in the younger stars, allowing for more outliers. With regards to the variability in L_X , Favata et al. (2005), in studying the brightest $\sim 1\%$ of the COUP flares, find some objects that flare 1–2 orders of magnitude and that the characteristic times for these flares range from 10 to 400 ks. In the specific case of the COUP sample, however, as Preibisch & Feigelson (2005) point out, the influence of individual flares on the total L_X reported for any one star is reduced by the long time baseline of their observations. Thus, outliers solely due to flares in the COUP data set are less likely than in the other (much shorter) observations. Variability in the optical data that go into the calculation of L_{bol} may account for some fraction of the outliers; optical variability can exceed a magnitude. Rebull et al. (2002a) discussed the sources of these errors in detail for stars with spectral types over limited mass ranges and in regions of less reddening. For the COUP sample in particular, even though reddening is a concern, spectral types are known for every object, and so it is unlikely that this can account for all (or even most) of the outliers. More data on time variability will be required to determine why there are more outliers with high L_X in the ONC.

The lower envelope of the X-ray-detected stars in all three regions for both L_X and L_X/L_{bol} , however, is comparable for stars with L_{bol} similar to that of the Sun, and so the decay in the *mean* and *lower bounds* of the X-ray luminosities with time during the first 5 Myr of PMS evolution indeed appears to be small, as Preibisch & Feigelson (2005) reported for the ONC alone. Unfortunately, because of the shallow depth of our current survey, we cannot compare the lower bounds of the detections of stars with $M < 1 M_{\odot}$ in these three regions. Since more than half the stars in our sample were detected, we can compare the *median* $\log L_X$ and $\log L_X/L_{\text{bol}}$ for the best possible convective sample in all three clusters. The median $\log L_X$ for the ONC (further restricted to $M > 0.16 M_{\odot}$ to account for the difference in survey depths), the Orion FFs, and NGC 2264 are 29.55, 29.71, and 29.90, respectively; the median values of $\log L_X/L_{\text{bol}}$ (in the same order) are -3.71 , -3.50 , and -3.44 . (There are some upper limits in this sample, so as a simple worst-case test we recomputed the medians, adopting the upper limits for all stars as detections, and

it does not change these median values very much.) These results are consistent with that obtained by COUP for the ONC. While it is true that the most luminous objects have disappeared by the age of NGC 2264, there is not much change in the median values. We certainly do not see a significant decrease during the first 5 Myr, in agreement with the Preibisch & Feigelson (2005) work on the ONC alone.

4. X-RAY PROPERTIES AND STELLAR STRUCTURE: THE TRANSITION FROM CONVECTIVE TO RADIATIVE TRACKS

In this section we compare the X-ray properties of low-mass stars still located on fully convective tracks with those of higher mass stars, some of which appear to lie on convective tracks, while others of slightly greater age have developed radiative cores and are proceeding toward the main sequence along radiative tracks. In Figure 1 the stars on radiative tracks are indicated.

In Figures 4 and 5 we plot $\log L_X$ and $\log L_X/L_{\text{bol}}$ versus mass, retaining the red for radiative and black for convective convention. Among the detections, the stars on radiative tracks have lower values than their similar mass counterparts located on convective tracks; moreover, there is a higher fraction of upper limits among the radiative stars than among the convective stars. Examining solely stars with detections in NGC 2264, the median $\log L_X/L_{\text{bol}}$ for all convective stars between 1 and $2.5 M_{\odot}$ is -3.51 ; the median $\log L_X/L_{\text{bol}}$ for radiative stars (over the same mass range) is -4.01 . However, many of the values for radiative stars are upper limits; adopting the upper limits for all stars as detections at the level of their upper limits, the median $\log L_X/L_{\text{bol}}$ for the convective stars changes subtly to -3.54 , while the median for the radiative stars changes to -4.48 . By assigning the upper limits to be “detections,” we of course obtain a conservative limit on the median $\log L_X/L_{\text{bol}}$; even so, the medians for the convective and radiative samples differ by a factor of 10. Evidently, the transition from a fully convective state to a radiative-core and convective envelope configuration results in a dramatic decrease in coronal activity as diagnosed by X-rays; Gagne et al. (1995) also report differences in the X-ray properties between the convective and radiative stars in Orion based on *ROSAT* observations (see also Strom [1994] and Flaccomio et al. [2003a]).

We have examined the COUP data to search for a similar trend among the ONC sample. Unfortunately, because the region is younger, too few stars have evolved to their radiative phases to enable a convincing test.

Preibisch et al. (2005) reported a weak but significant correlation between $\log L_X/L_{\text{bol}}$ and mass. Spearman’s correlation coefficient does not find any significant correlations in our data for the Orion FFs and NGC 2264. However, we note that our survey covers a much smaller mass range than COUP. Restricting the comparison with COUP data to the same mass range reveals no clear trends in either sample. Because our data are dominated at low masses by upper limits, we are also unable to search for mass-dependent differences in $\log L_X/L_{\text{bol}}$ as reported by Flaccomio et al. (2003a, 2003c), who find similar $\log L_X$ versus mass relationships to that reported by Preibisch et al. (2005).

The conclusion that X-ray luminosity is related to the interior structure of PMS stars is of course valid if and only if stars assigned to radiative tracks are placed correctly in the H-R diagram, if these stars are predominantly members of the Orion FFs and the ONC, and if the X-ray flux is not dominated by a faint companion that is not visible in the optical. We now examine each of these requirements for NGC 2264, which has the largest number of massive stars in apparent postconvective evolution.

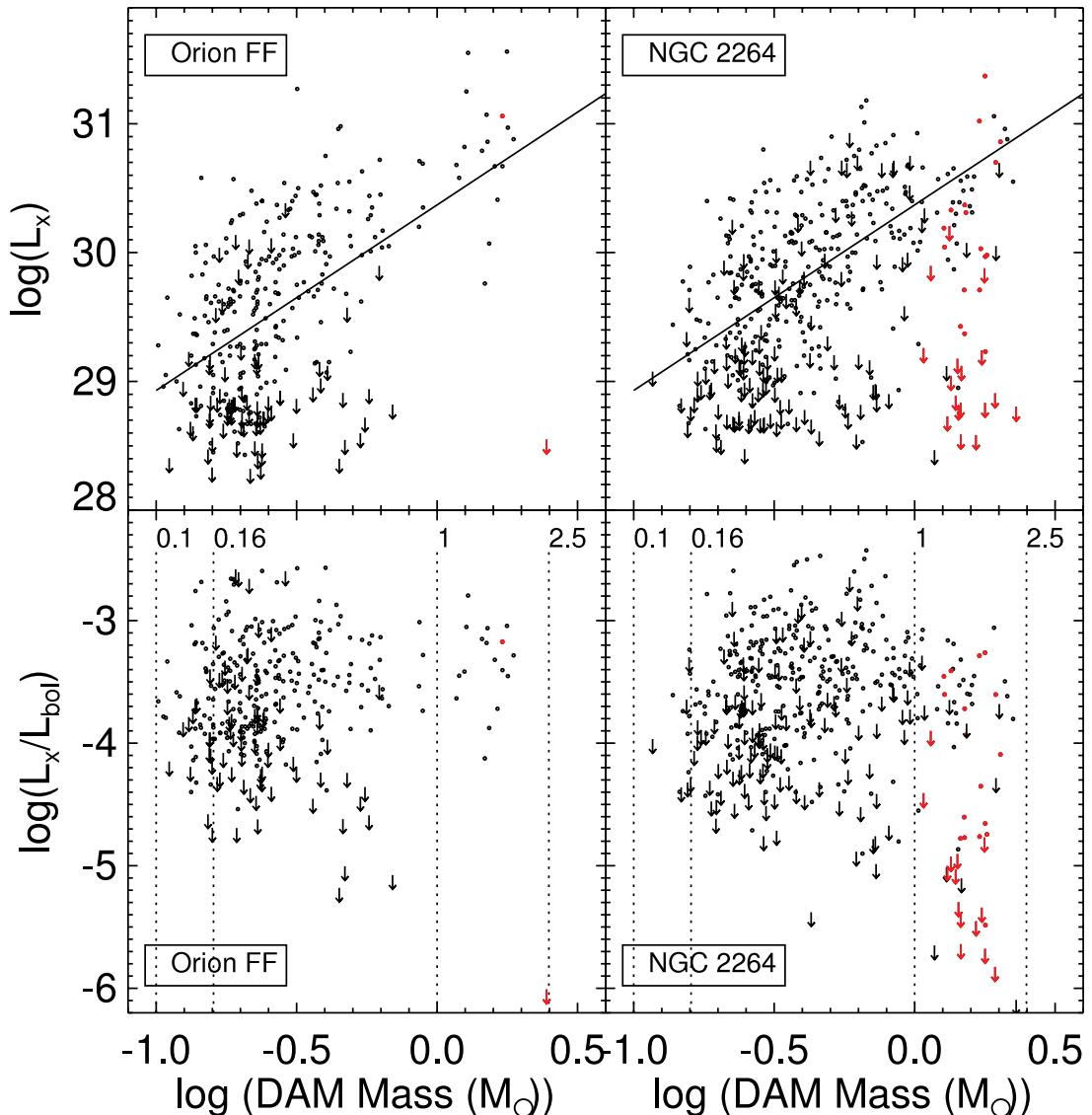


FIG. 4.—Plot of $\log L_X$ (top) and $\log L_X/L_{\text{bol}}$ (bottom) vs. $\log M/M_\odot$ from DAM for the Orion FFs (left) and NGC 2264 (right) for the best samples available for each cluster (see § 2.3). The solid line is the relationship between L_X and SDF00 masses found for the ONC by Preibisch et al. (2005). Note again the apparent bifurcation at about $0.5 M_\odot$. Red symbols are those stars still on radiative tracks; see Fig. 1. Dotted lines indicate 0.1, 0.16, 1, and $2.5 M_\odot$, from left to right.

How accurately have we located these stars in the H-R diagram? These stars are among the brightest in the cluster, and for 94% of the radiative stars (both detections and upper limits) we have spectral types; they range in type from A0 to K4. Because we have types, we are able to deredden each star individually with a correction appropriate to that specific star. Therefore, the placement of these stars in the dereddened CMD would appear to be as secure as possible for young (often variable) stars. These stars appear in the correct vertical position to be taken as cluster members; they do not appear significantly above or below the ZAMS for a cluster at the distance of NGC 2264. We therefore believe that most of these stars are members based on their position in the H-R diagram.

Because these stars are among the brighter stars in the cluster, we have preliminary proper motions (see Rebull et al. 2002b) for 54% of the stars on radiative tracks; 33% of the red points (detections and upper limits) in Figure 1 (DAM models) are likely members, 22% are likely nonmembers, and the rest have no proper-motion membership information available. Of the avail-

able sample, at least 60% of the stars are thus members based on proper motions.

Another indicator of likely membership is the presence of a circumstellar disk. Seventy percent of the best possible radiative sample has positive circumstellar and/or accretion disk indicators, suggesting at least 70% of the sample are indeed members.

Are unresolved binaries important? They may play a role, particularly in the case of X-rays, where low-mass companions can outshine their primaries. However, what we have shown is that the fluxes of the stars on radiative tracks are systematically *lower* than those of stars with similar masses on convective tracks. If optically fainter companions do contribute some of the flux, then the discrepancy must be even larger.

In summary, then, we believe that most (>70%) members of the best possible radiative sample are indeed cluster members. We therefore conclude that there is a significant decrease in X-ray luminosity as stars of similar mass evolve from convective tracks, where $\log L_X/L_{\text{bol}}$ values lie close to the “saturation limit,” to radiative tracks, where L_X/L_{bol} values are ~ 10 times

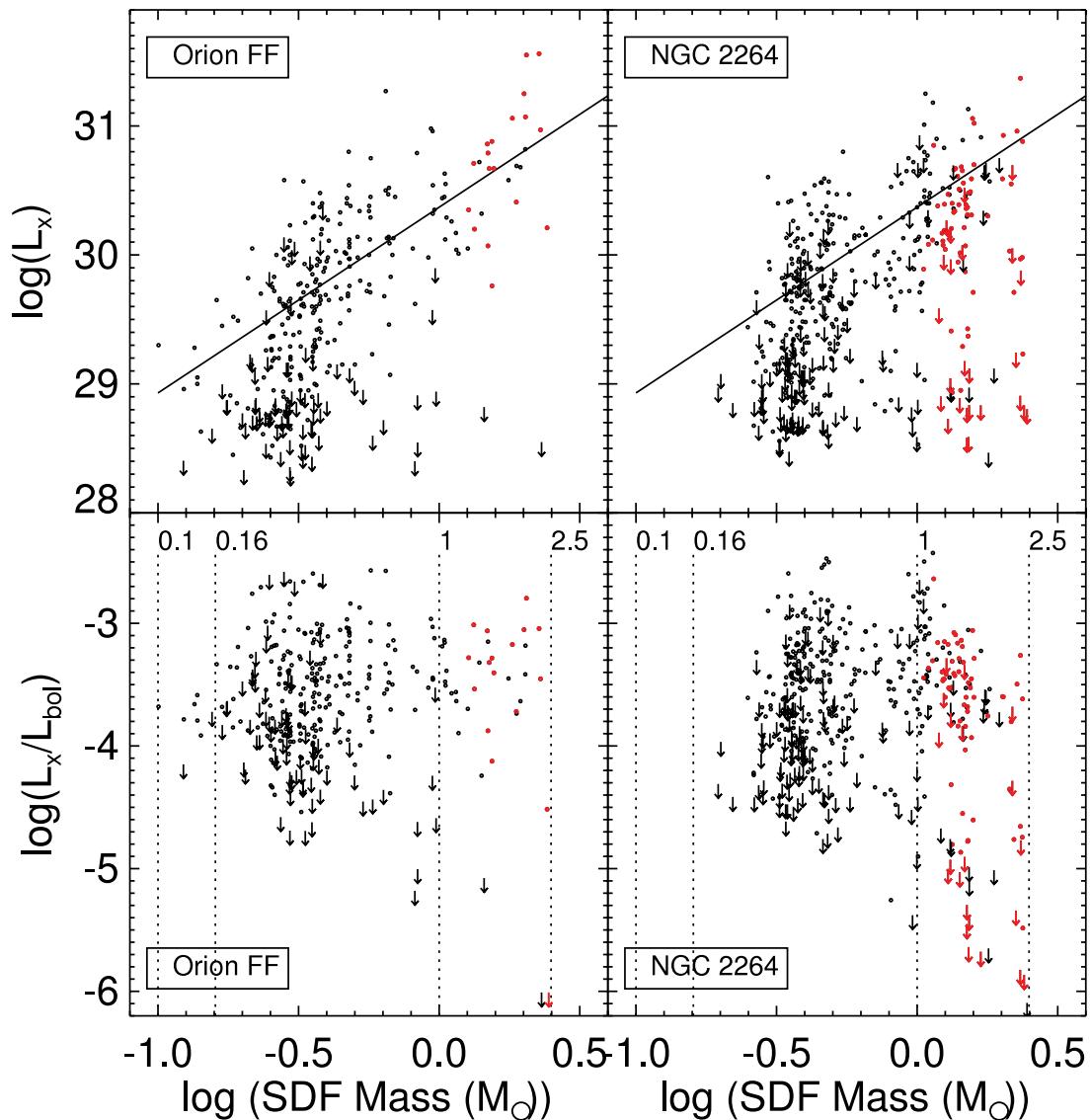


FIG. 5.—Plot of $\log L_X$ (top) and $\log L_X/L_{\text{bol}}$ (bottom) vs. $\log M/M_\odot$ from SDF00 for the Orion FFs (left) and NGC 2264 (right) for the best samples available for each cluster (see § 2.3). The solid line is the relationship between L_X and SDF00 masses found for the ONC by Preibisch et al. (2005). Note again the apparent bifurcation at about $0.5 M_\odot$. Red symbols are those stars still on radiative tracks; see Fig. 1. Dotted lines indicate $0.1, 0.16, 1$, and $2.5 M_\odot$, from left to right.

smaller. In support of this result we note two additional observations: (1) the apparent “bifurcation” in L_X/L_{bol} disappears for masses lower than about $0.5 M_\odot$, which is approximately the mass below which stars remain fully convective from the stellar birth line to the ZAMS; and (2) the levels of L_X and L_X/L_{bol} for stars on radiative tracks are roughly in agreement with the values found in this mass range in the NEXXUS survey of nearby field stars (Schmitt & Liefke 2004).

5. X-RAY EMISSION AND ROTATION

Flaccomio et al. (2003a) first found evidence that stars in the ONC for which rotation periods are known have higher X-ray luminosities than stars that show no clear evidence of spot-modulated rotation; Stassun et al. (2004) confirm this result.

The same trend is seen among fully convective stars ($M < 0.5 M_\odot$) in both the Orion FFs and NGC 2264. Figure 6 shows that the stars with derived periods in these two associations are clearly brighter in $\log L_X/L_{\text{bol}}$, and, conversely, stars that are bright in $\log L_X/L_{\text{bol}}$ are more likely to have a measurable period. For the best possible convective sample (Fig. 6), the best-fit

slopes to the bottom panels in Figure 6 are 0.34 ± 0.05 (for the FFs) and 0.26 ± 0.05 (for NGC 2264). These values do not change significantly when considering other possible subsamples of the data. Median values of $\log L_X/L_{\text{bol}}$ for the best possible convective sample for the ONC, the FFs, and NGC 2264, for the sample with periods, are $-3.57, -3.35$, and -3.37 , respectively. For the best possible convective sample without periods (in the same order), the medians are $-3.81, -3.65$, and -3.53 , respectively. It is clear that the samples with measured period P are brighter in X-rays (and again there are no trends with age).

In searching for correlations between the X-ray emission and rotation rates of PMS stars, another concern is whether the sample of stars with known periods represents the full range of rotation rates for PMS stars. It might be, for example, that periodic stars are biased toward PMS stars dominated by either long or short rotation periods, or by stars viewed more nearly equator-on than pole-on. The study of periods and $v \sin i$ in the ONC by Rhode et al. (2001) concluded that there was no difference in the distribution of rotation rates for samples of stars with periods and

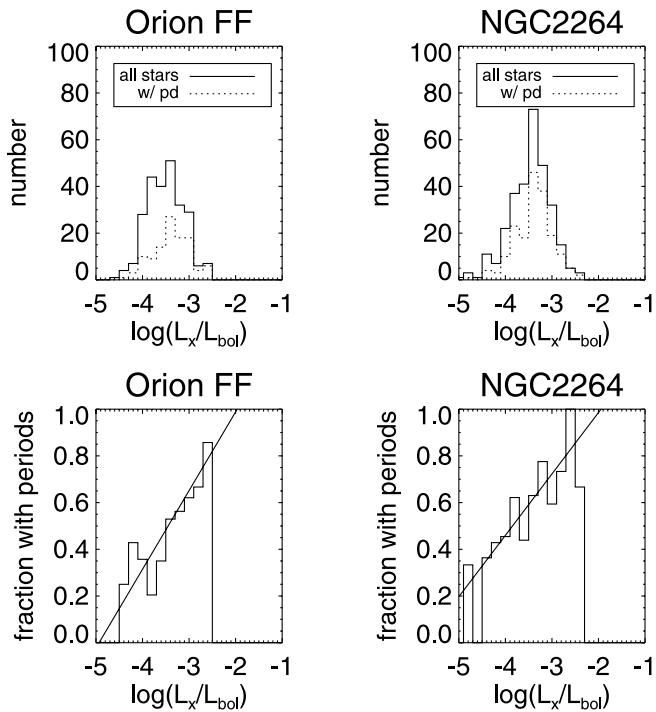


FIG. 6.—Plot of $\log L_X/L_{\text{bol}}$ distribution for the best samples available for each cluster (see § 2.3, including only convective stars) for stars with and without measured periods. Stars with measured periods are X-ray bright, and stars that are X-ray bright are more likely to have measured periods. The diagonal line is a fit to the ratio. The slopes are 0.34 ± 0.05 (Orion FFs) and 0.26 ± 0.05 (NGC 2264).

samples of stars with $v \sin i$. A similar test is performed for the current data set in Figure 7. For the purpose of this graph, rotational velocities have been derived from P and an estimate of the radius (see, e.g., Rebull et al. [2002b] for more on this calculation); the $v \sin i$ values have been converted to velocity by multiplying the observed rates by $4/\pi$ to allow for inclination effects (Chandrasekhar & Muench 1950; Gaige 1993). The Orion FFs appear to exhibit a relative paucity of objects with low $v \sin i$. However, this reflects the resolution limit of the data rather than a real physical effect. Taking this into account, we conclude from these data that there is no apparent bias in the period-selected sample. However, our data set is too sparse to distinguish whether the $v \sin i$ distribution for the low L_X/L_{bol} stars that lack periods differs from the ensemble distribution.

Why are we more likely to be able to determine periods from photometric monitoring programs for stars with large values of $\log L_X/L_{\text{bol}}$? In order to obtain an optical photometric period, we require a clear view of the stellar photosphere in which there are large, stable, relatively isolated spots or spot groups rotating into and out of view, causing periodic modulations. Stassun et al. (2004) have suggested that perhaps more active stars have larger and/or more organized magnetic spot coverage and that periodic variations are more easily measured in such circumstances. If so, then stars with more organized spots also have higher levels of coronal activity, leading to higher X-ray luminosity.

Since the earliest days of X-ray astronomy, investigators have sought a relation between rotation rate (periods or $v \sin i$) and X-ray luminosity for PMS stars. Because the X-ray flux is thought to originate in coronal activity, which is driven by convection and rotation, and because faster-rotating main-sequence stars are brighter in X-rays (e.g., Stauffer et al. 1994; Micela et al. 1996; Pizzolato et al. 2003), it was perhaps reasonable to expect to find

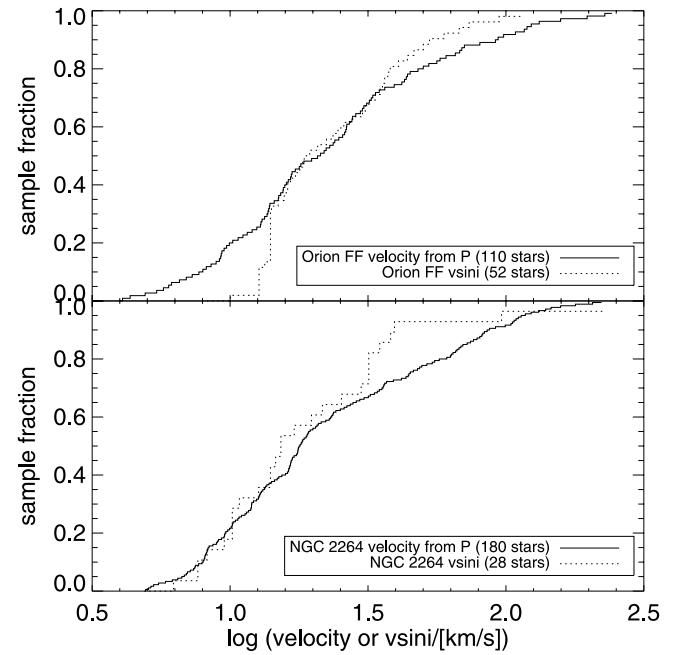


FIG. 7.—Cumulative distributions of measured $v \sin i$ (multiplied by $4/\pi$ to account for projection effects; dotted line) and calculated velocity (solid line) for the FFs (top) and NGC 2264 (bottom). Aside from where the spectral resolution cuts off the $v \sin i$ measurements, the distributions are indistinguishable.

a similar relation in younger stars, but the evidence remains mixed. Table 2 contains a listing of the conclusions on this topic from the literature to date. Most recently, COUP (Preibisch et al. 2005) found a weak but statistically significant correlation between P and $\log L_X/L_{\text{bol}}$.

Figure 8 plots $\log L_X$ and $\log L_X/L_{\text{bol}}$ against $\log P$ for our sample, and Figure 9 shows the same data but in box plot form. There is no significant trend in these plots, nor in similar plots of X-ray emission against linear P , $v \sin i$, or $1/P$. Upper limits are found at all periods and rotation rates. The current data do not support as strong a correlation between period and fractional X-ray luminosity as the one reported for the ONC by Preibisch et al. (2005). We also do not find the same correlations as can be found in main-sequence stars.

6. DISK AND ACCRETION EFFECTS

Two processes associated with disk accretion can, in principle, affect the observed X-ray properties of solar-type PMS stars: (1) local heating of the stellar photosphere at the “footprints” of magnetospheric funnel flows, where highly supersonic ($v > 200 \text{ km s}^{-1}$) gas lands on the stellar surface (e.g., Kastner et al. 2002; Schmitt et al. 2005), producing shocks, local heating, and, as a result, soft X-rays; and (2) absorption of keV coronal X-ray emission by gas associated with accretion-driven outflows (Walter & Kuhi 1981). The first of these processes would qualitatively produce an *increase* in X-ray emission above coronal activity levels as disk accretion rates increase. Quantitative estimates of the magnitude of the expected increase are not available, owing primarily to the complexity of the detailed radiative transfer studies needed to estimate the X-ray flux emerging from accretion spots. The second process would produce a *decrease* of X-ray emission with increasing accretion rate, since the column density, and hence the X-ray optical depth of outflowing material, is expected to increase with increasing accretion rate. For isotropic outflows, significant 5 keV absorption is expected to

TABLE 2
SUMMARY OF RECENT STUDIES OF LARGE SURVEYS OF STAR-FORMING REGIONS CONSIDERING EFFECTS OF DISKS, ACCRETION, DEGREE OF EMBEDDEDNESS, OR PERIOD ON L_X

Work	Instrument	Cluster	Range of L_X/L_{bol}^a	Disk Indicator	Conclusion on Disks ^b	Conclusion on Rotation
Bouvier (1990).....	<i>Einstein</i>	Taurus-Auriga	$\log L_X = 27-32$	$H\alpha > 10 \text{ \AA}$	No difference	Anticorrelation
Feigelson et al. (1993).....	<i>ROSAT</i> PSPC	Cha I	-2 to -5	$\text{EW}(H\alpha) > 10 \text{ \AA}$	$L_X(C) < L_X(W)$ but no difference within selection effect	No correlation
Gagne & Caillault (1994).....	<i>Einstein</i>	ONC	-2 to -7 (-2 to -4.5)	$H - K, H\alpha$	No difference	No correlation
Damiani & Micela (1995).....	<i>Einstein</i>	Taurus-Auriga	-3 to -5	IRAS-25	WTTS fainter	Weak anticorrelation with scatter
Gagne et al. (1995).....	<i>ROSAT</i> HRI	ONC	-2 to -7 (-2 to -5)	$\Delta(H - K) > 0.1$	$L_X, L_X/L_{\text{bol}}(C) < L_X, L_X/L_{\text{bol}}(W)$	No correlation
Casanova et al. (1995).....	<i>ROSAT</i> PSPC	ρ Oph	-2 to -5	Class 0-3	$L_X(\text{embedded}) \sim L_X(\text{less embedded})$, no difference	N/A
Neuhauser et al. (1995).....	<i>ROSAT</i> All-Sky Survey	Taurus-Auriga	-4 to -7	$\text{EW}(H\alpha) > 5-15 \text{ \AA}$	$L_X(C) < L_X(W), L_X(C)$ harder than W	Correlation
Lawson et al. (1996).....	<i>ROSAT</i> PSPC	Cha I	-2 to -5	$H\alpha$	No difference	N/A
Preibisch (1997).....	<i>ROSAT</i> PSPC	Several	$\log L_X = 27-32$	N/A	N/A	Anticorrelation
Alcalá et al. (2000).....	<i>ROSAT</i> All-Sky Survey	Orion	$\log L_X \sim 31$	N/A	N/A	No correlation for K stars
Wichmann et al. (2000).....	<i>ROSAT</i> All-Sky Survey	Taurus-Auriga	-2.5 to -5	N/A	N/A	Correlation
Flaccomio et al. (2000).....	<i>ROSAT</i> HRI	NGC 2264	-2 to -5 (-2 to -4)	$H\alpha$	No difference, but C more variable	N/A
Grosso et al. (2000).....	<i>ROSAT</i> HRI	ρ Oph	-2 to -4	<i>Infrared Space Observatory</i> data HBC listing W/C		N/A
Stelzer et al. (2000).....	<i>ROSAT</i> PSPC	Taurus-Auriga			$L_X(C) < L_X(W)$ but stronger flares and C more variable	Anticorrelation
Imanishi et al. (2001).....	<i>Chandra</i> ACIS	ρ Oph		Class 0-3	$L_X/L_{\text{bol}}(\text{Class I}) < L_X/L_{\text{bol}}(\text{Class II and III})$	N/A
Stelzer & Neuhauser (2001).....	<i>ROSAT</i> PSPC	Taurus-Auriga	-3 to -6	$\text{EW}(H\alpha) > 10 \text{ \AA}$	$L_X(C) < L_X(W)$	Correlation
Preibisch & Zinnecker (2002).....	<i>Chandra</i> ACIS	IC 348	-2 to -6 (-2 to -4.5)	$\text{EW}(H\alpha) \geq 10 \text{ \AA}, \Delta(K - L) > 0.17$	$L_X(C) < L_X(W)$, but likely to be selection effect [goes away for $\Delta(K - L)$]	N/A
Feigelson et al. (2002, 2003).....	<i>Chandra</i> ACIS	ONC	-2.5 to -6	$\Delta(I - K) > 0.3$	No difference	Weak correlation
Getman et al. (2002).....	<i>Chandra</i> ACIS	NGC 1333		JHK	No difference	N/A
Tsujimoto et al. (2002).....	<i>Chandra</i> ACIS	OMC-2, OMC-3		Class 0-3	kT of C higher than W, but possible selection effect	N/A
Flaccomio et al. (2003b).....	<i>ROSAT</i> HRI	NGC 2264, Cha I	-2 to -7.8 (-2 to -5)	$\Delta(I - K) > 0.8$	$L_X, L_X/L_{\text{bol}}(C) < L_X, L_X/L_{\text{bol}}(W)$	N/A
Flaccomio et al. (2003a).....	<i>Chandra</i> HRC	ONC	-2 to -7.8 (-2 to -5)	$\text{EW}(\text{Ca II}) > 1 \text{ \AA}$	$L_X, L_X/L_{\text{bol}}(C) < L_X, L_X/L_{\text{bol}}(W)$	No correlation; stars with measured P have high L_X
Stassun et al. (2004).....	<i>Chandra</i> ACIS	ONC	-2 to -6	$\text{EW}(\text{Ca II}) > 1 \text{ \AA}$	$L_X, L_X/L_{\text{bol}}(C) < L_X, L_X/L_{\text{bol}}(W)$	$\log L_X/L_{\text{bol}}$, correlation with P , but not $v \sin i$; stars with measured P have high L_X
Feigelson & Lawson (2004).....	<i>Chandra</i> ACIS	Cha I	$L_X = 28-31$	Various	$L_X(C) < L_X(W)$ (slightly)	N/A
Preibisch (2004).....	<i>XMM-Newton</i> EPIC	Serpens	Approximately -3	Literature	Class I more variable than classes II and III	N/A
Ozawa et al. (2005).....	<i>XMM-Newton</i> EPIC	ρ Oph	-2 to -5	Literature	Class I has higher T and absorption than classes II and III	N/A
Preibisch et al. (2005).....	<i>Chandra</i> ACIS	ONC (COUP)	-1 to -6	$\Delta(I - K), \Delta(K - L), \text{EW}(\text{Ca II})$	Accretors less active	Weak correlation

^a Values in parentheses are for the low-mass stars in the sample.

^b "C" = CTTS; "W" = WTTS.

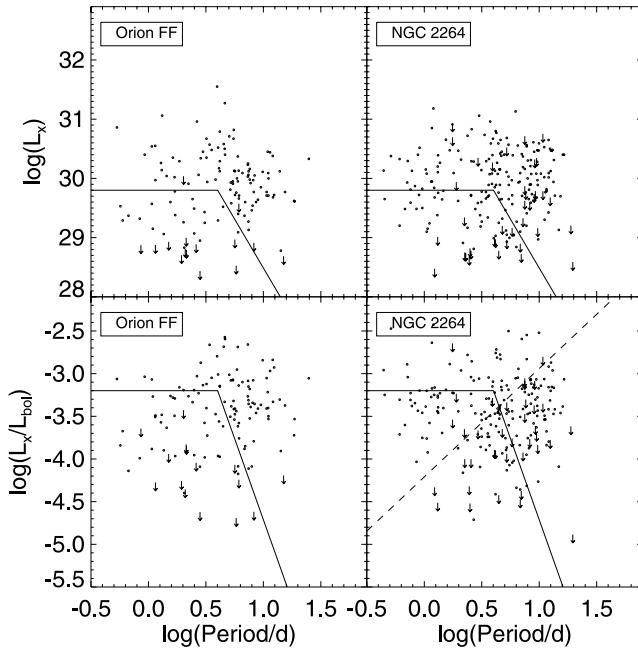


FIG. 8.—Plot of $\log L_X$ and $\log L_X/L_{\text{bol}}$ vs. \log period for the best samples available for each cluster (see § 2.3). There is no correlation here, but keep in mind that stars with measured periods are X-ray bright (see previous figure). The dashed line represents the relationship between L_X/L_{bol} found by Preibisch et al. (2005) for the ONC, and the solid line represents the approximate relationship found for main-sequence stars. We do not see a similar correlation (either the ONC or the main-sequence one) for either the Orion FFs or NGC 2264.

occur for mass outflow rates of $10^{-8} M_{\odot} \text{ yr}^{-1}$ or mass accretion rates of $\sim 10^{-7} M_{\odot} \text{ yr}^{-1}$.

There has been a great deal of work attempting to uncover relationships between circumstellar disks, disk accretion, and X-ray emission (either $\log L_X$ or $\log L_X/L_{\text{bol}}$). Table 2 collects the conclusions from large surveys of X-ray emission for accreting and nonaccreting PMS stars. Kastner et al. (2002) and Schmitt et al. (2005) find evidence of enhanced X-ray emission associated with transient increases in disk accretion rate, thus suggesting that at least some X-ray emission may be associated with accretion as opposed to coronal activity. In ensemble, there is no evidence of *excess* X-ray emission for accreting PMS stars. Rather, the trend, if any, is for an anticorrelation between the presence of an accretion disk and total X-ray luminosity.

Walter & Kuhu (1981) were the first to report an inverse correlation between soft X-ray flux and H α emission for classical T Tauri stars (CTTSs). Working under the assumption that the observed equivalent width of H α serves as a surrogate for mass outflow rate, they argued that the apparent decrease of X-ray emission with increasing H α equivalent width reflected the effects of X-ray absorption by outflowing gas. More recently, Flaccomio et al. (2003a) find a similar result: a larger fraction of stars with active accretion signatures, there measured by Ca II emission, have fainter L_X values than nonaccretors when stars of similar masses are compared. Stassun et al. (2004) also report a similar result for a sample of young solar-like PMS stars, particularly for those stars with $M < 0.5 M_{\odot}$. Preibisch et al. (2005) find significantly lower X-ray emission for accreting as opposed to nonaccreting PMS stars (as selected on the basis of Ca II triplet emission equivalent width) for the restricted mass range $0.3 - 0.5 M_{\odot}$. They also find that the nonaccretors show a better defined correlation between L_X and L_{bol} than the accretors, that the median value of L_X/L_{bol} is nearly a factor of 3 lower for ac-

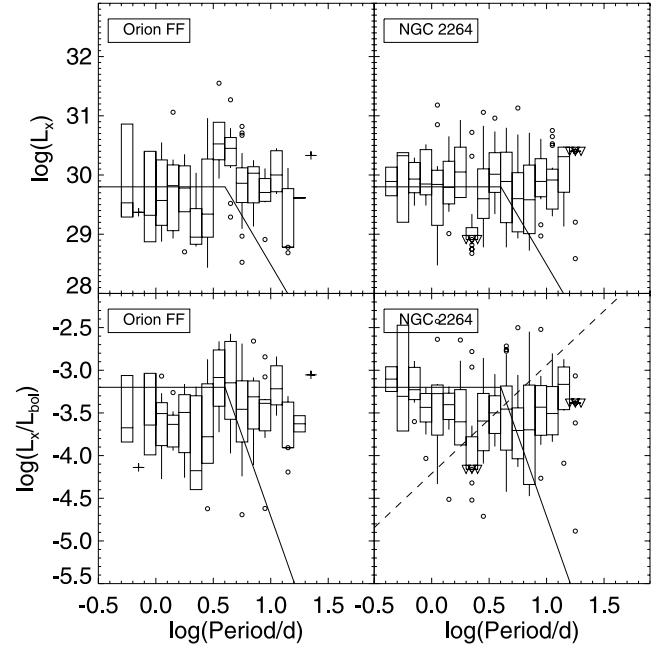


FIG. 9.—Data from Fig. 8, but in box plot form. We do not see a correlation similar to that from the ONC (dashed line) or from the main sequence (solid line) for either cluster.

cretors, and that there is a weak anticorrelation of the fractional X-ray luminosity with accretion rate. In looking for correlations of X-ray emission with the presence/absence of accretion disks for which there is no direct evidence of accretion, Preibisch et al. (2005) find, somewhat surprisingly, that there are significant differences in L_X/L_{bol} for stars with and without NIR $I - K$ excesses but no differences for stars with and without $K - L$ excesses; $K - L$ is usually considered to be a more reliable disk indicator.

In our particular case, we have three different disk and/or accretion indicators ($I - K$, $H - K$, and $U - V$ excesses) for both clusters and a fourth indicator (H α equivalent widths) for NGC 2264. We note that the H α measurements were only obtained for stars with classification spectra in NGC 2264. Most of these spectra were obtained as part of the studies by Rebull et al. (2002b) and Makidon et al. (2004), where the goal was to classify stars with known periods. Therefore, the sample of stars with H α is likely to be biased toward stars that are brighter in X-rays (see Fig. 6).

The numbers of stars available from the best possible sample are summarized in Table 3. While $I - K$ and $H - K$ excesses indicate the presence of either passive or actively accreting circumstellar disks, $U - V$ excesses and H α arise from active accretion; $U - V$ excesses have already been translated directly to mass accretion rates for many of our targets (Rebull et al. 2000, 2002b).

Based on previously published results, we might expect that any correlations between total and fractional X-ray luminosity and stellar properties are likely to be weak (and, in fact, they are). We show plots for two of our available diagnostics of disks and/or accretion in Figures 10 and 11. Note that, for the NIR disk indicators, redder colors suggest disks, whereas for $U - V$, bluer colors suggest accretion. The placement of the disk cutoffs is discussed in Rebull et al. (2000, 2002b), along with a comparison of the disk indicators for the same stars.

There is a very large amount of scatter in these two figures, as there are in the plots for $H - K$ and H α , which are not shown, although the scatter is somewhat smaller in the plots with

TABLE 3
SUMMARY OF NUMBERS OF STARS AVAILABLE WITH AND WITHOUT DISKS

DISK INDICATOR	ORION FFs		NGC 2264	
	Nondisk Detections ^a	Disk Detections ^a	Nondisk Detections ^a	Disk Detections ^a
$I - K$ excess	129 (38)	109 (37)	226 (42)	63 (21)
$H - K$ excess	171 (56)	64 (15)	236 (56)	52 (15)
$U - V$ excess	28 (4)	25 (3)	87 (14)	151 (48)
$H\alpha$ equivalent width	77 (8)	46 (12)

^a Values in parentheses are the number of stars that have upper limits in each category.

$\log L_X/L_{\text{bol}}$ than in the plots with $\log L_X$. For this reason, we have chosen to show only the box plot representations of these data.

No statistically significant or consistent trends are seen in Figures 10 and 11 (or in similar plots with the other available disk indicators). In stars *without* evidence for disks, we find examples of stars in which L_X is high and $\log L_X/L_{\text{bol}}$ is close to -3 , but comparably large values are not seen in stars *with* disks or active accretion. The upper bound on both the total and fractional X-ray luminosity appears to decrease with increasing $I - K$ excess for NGC 2264 (but not the FFs) and with increasing $U - V$ excess for the FFs (but not NGC 2264). The X-ray fluxes do not appear to depend on $H - K$ excess for either cluster or on $H\alpha$ for NGC 2264. These confusing, inconsistent results suggest that if there is any trend, it is subtle, and, despite the numbers of points we have (see Table 3), we require many more data points to securely detect it.

Figure 12 looks for correlations explicitly with $\log \dot{M}$ derived from the $U - V$ excess as in Rebull et al. (2000, 2002b). The data in the Orion FFs are too sparse to reach any conclusion. For NGC 2264, however, there may be evidence of a trend: the upper envelope of L_X/L_{bol} is near 10^{-3} for stars with accretion rates $< 10^{-8} \dot{M} \text{ yr}^{-1}$ but progressively decreases by nearly a factor of

10 for stars with higher accretion rates—a result in concordance with previously reported anticorrelations between X-ray luminosity and accretion for solar-like PMS stars.

It is perhaps surprising that there are no clear correlations of X-ray emission with either the presence or absence of accretion disks or the magnitude of accretion rate apparent from our data, particularly given the plausibility of proposed X-ray production and absorption processes. Perhaps the intrinsic range in X-ray emission properties is so large that trends are difficult to discern, even with samples as large as several hundred stars. Alternatively, it may be that multiple mechanisms are at work simultaneously, and sorting among them may require a somewhat finer characterization of X-ray properties than L_X —the single property thus far used in searching for accretion-related correlations.

We anticipate that the COUP data, in combination with the Orion Treasury program (Robberto 2005) and the *Spitzer* data in Orion (S. T. Megeath et al. 2006, in preparation), will provide considerably more insight into the physical processes accompanying disk accretion. In particular, the Treasury program will provide robust estimates of ultraviolet excess emission for a large sample, which in combination with extant optical spectroscopic studies yielding R and T_{eff} estimates should provide accretion rate estimates for a large (perhaps 1000 stars) sample of accreting

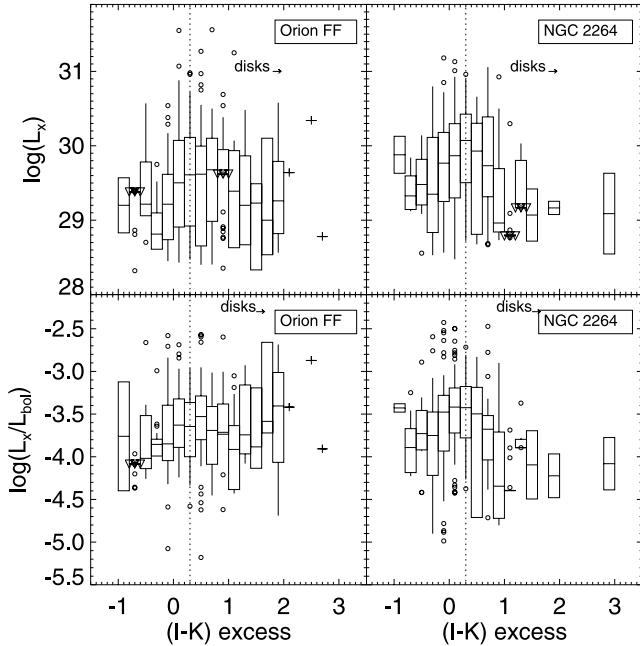


FIG. 10.—Plot of $\log L_X$ and $\log L_X/L_{\text{bol}}$ vs. $I - K$ excess disk candidates for the best samples available for each cluster (see § 2.3). Disk candidates are redder than 0.3 mag (right of dotted line; see text).

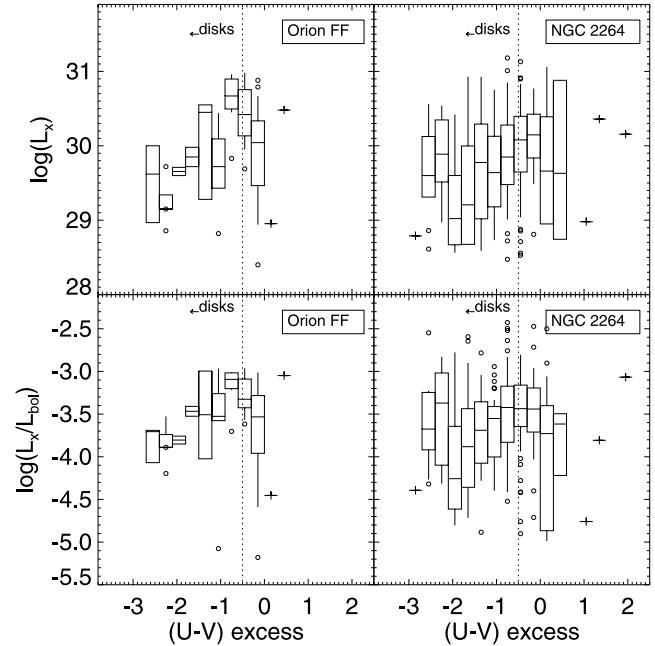


FIG. 11.—Plot of $\log L_X$ and $\log L_X/L_{\text{bol}}$ vs. $U - V$ excess disk candidates for the best samples available for each cluster (see § 2.3). Disk candidates are bluer than -0.5 mag (left of dotted line; see text).

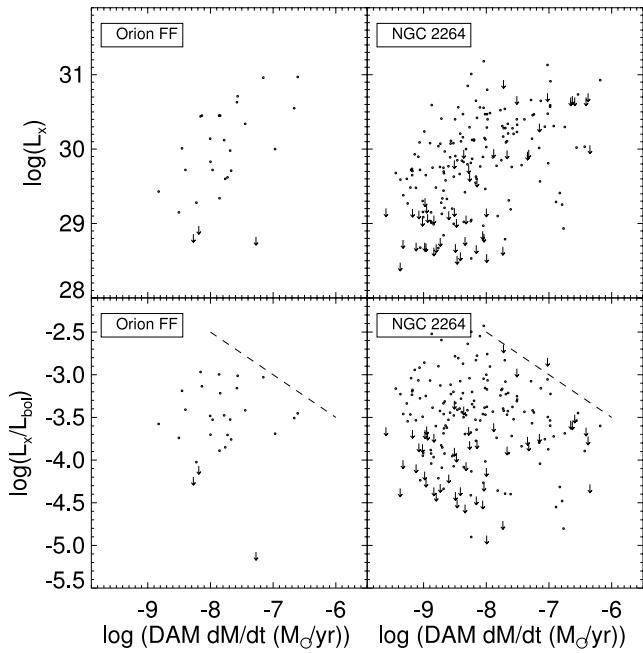


FIG. 12.—Plot of $\log L_X$ and $\log L_X/L_{\text{bol}}$ vs. \dot{M} (derived using DAM masses) for the best samples available for each cluster (see § 2.3). There is a trend in L_X , which is a rediscovery of the mass-dependent effects of L_X found in Fig. 4 and of \dot{M} found in Rebull et al. (2000). There is no trend in L_X/L_{bol} , but the dashed lines trace a trend with the highest \dot{M} values.

PMS stars. The deep COUP exposures of the ONC (20 times the length of the *Chandra* observations reported here) should provide well-characterized X-ray spectral energy distributions from 0.5 to 5 keV—sine qua non for sorting the relative contributions of soft X-ray emission that may arise from accretion, harder coronal X-ray emission, and the effects of absorption arising in mass outflows.

7. CONCLUSIONS

We have studied the X-ray properties of stars in the Orion FFs and NGC 2264. With ages of ~ 1 and ~ 3 Myr, respectively, both regions contain stars that are older than most stars in the ONC. Rotation periods are available for a relatively large fraction of the PMS population in these regions. Furthermore, NGC 2264 contains a significant number of stars that have made the transition to radiative tracks. These samples thus enable study of evolution- and rotation-driven changes in X-ray properties over the age range 1–5 Myr.

The data for the Orion FFs and NGC 2264, when combined with the much more extensive data from the COUP survey of the ONC, establish a number of clear patterns in the behavior of X-ray emission in PMS stars. In all three regions, $\log L_X$ for stars on convective tracks correlates positively with both $\log L_{\text{bol}}$ and stellar mass, not surprisingly, since $\log L_{\text{bol}}$ is strongly correlated with mass. As Preibisch et al. (2005) point out, a strong correlation between X-ray emission and stellar properties argues that the X-ray emission probably originates primarily in compact (coronal?) structures associated with the star. We confirm as well that the level of X-ray emission is directly related to stellar structure in that the level of emission drops on average by ~ 10 when PMS stars with masses in the range ~ 1 – $2 M_{\odot}$ make the

transition from fully convective to radiative tracks, where stars of about solar mass have radiative cores and convective envelopes.

The fractional X-ray luminosity, $\log L_X/L_{\text{bol}}$, is not strongly correlated with mass for stars on convective tracks; the scatter in the relationships of both $\log L_X$ and $\log L_X/L_{\text{bol}}$ with mass is large. The physical reasons for this large scatter remain unclear. Age is apparently not a large contributor; while there is evidence that the ONC has nearly twice as many stars with extremely high X-ray emission ($\log L_X/L_{\text{bol}} \geq -2.9$) as the Orion FFs and NGC 2264, we see little change in *median* values of either $\log L_X$ or $\log L_X/L_{\text{bol}}$ during the first ~ 5 Myr of evolution down convective tracks. In sharp contrast to main-sequence stars, we find no correlation between $\log L_X$ and $\log L_X/L_{\text{bol}}$ with P or $v \sin i$ for stars on convective tracks, although more $v \sin i$ data are needed in NGC 2264. Preibisch et al. (2005) have argued that X-ray variability at typical levels is likely to be too small to account for the scatter in L_X/L_{bol} .

In both the Orion FFs and NGC 2264 we find, in agreement with earlier studies of the ONC, that stars with larger values of $\log L_X/L_{\text{bol}}$ are more likely to exhibit spot-modulated periods. Approximately three-fourths of the stars with $\log L_X/L_{\text{bol}} > -3$ are periodic, while only about one-third of the stars with $\log L_X/L_{\text{bol}} < -4$ have periods, and this difference does not appear to be the result of any biases in the samples. It may well be that, as Stassun et al. (2004) have suggested, more active stars have larger and/or more organized magnetic spot coverage and that periodic variations are more easily measured in such circumstances.

We have searched for a correlation between $\log L_X$ and $\log L_X/L_{\text{bol}}$ and (1) NIR excess, which is a circumstellar disk indicator; (2) UV excess and $H\alpha$, both of which are indicators of accretion; and (3) the mass accretion rate, as inferred from the UV excess. There is substantial scatter in all of these relationships, and no clear trends emerge. Discovery of the relationship, if any exists, between accretion and X-ray emission awaits the combination of COUP results, which provide measures of X-ray luminosity and X-ray spectral energy distributions, with the corresponding results from the ongoing *Hubble Space Telescope* Orion Treasury program, which promises to provide accurate estimates of accretion rates for large samples of PMS stars, and the *Spitzer* data in Orion, which will provide more accurate mid-IR disk indicators.

We would like to thank J. Najita for extensive discussions regarding the power of X-ray observations to test competing wind models. E. F., G. M., and S. S. acknowledge support from INAF and MIUR-PRIN grants. This research has made use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center, funded by the National Aeronautics and Space Administration and the National Science Foundation. These data were served by the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The research described in this paper was partially carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Alcalá, J. M., Covino, E., Torres, G., Sterzik, M. F., Pfeiffer, M. J., & Neuhauser, R. 2000, *A&A*, 353, 186

Bouvier, J. 1990, *AJ*, 99, 946

Casanova, S., Montmerle, T., Feigelson, E. D., & Andre, P. 1995, *ApJ*, 439, 752

Chandrasekhar, S., & Muench, G. 1950, *ApJ*, 111, 142

Dahm, S., & Simon, T. 2005, *AJ*, 129, 829

Damiani, F., & Micela, G. 1995, *ApJ*, 446, 341

D'Antona, F., & Mazzitelli, I. 1994, *ApJS*, 90, 467

—. 1998, Pre-Main-Sequence Tracks and Isochrones (Rome: Oss. Astron. Roma), <http://www.mporzio.astro.it/~dantona/prems.html>

Favata, F., Flaccomio, E., Reale, F., Micela, G., Sciortino, S., Shang, H., Stassun, K. G., & Feigelson, E. D. 2005, *ApJS*, 160, 469

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

Feigelson, E. D., Casanova, S., Montmerle, T., & Guibert, J. 1993, *ApJ*, 416, 623

Feigelson, E. D., Gaffney, J. A., III, Garmire, G., Hillenbrand, L. A., & Townsley, L. 2003, *ApJ*, 584, 911

Feigelson, E. D., & Lawson, W. A. 2004, *ApJ*, 614, 267

Feigelson, E., & Montmerle, T. 1999, *ARA&A*, 37, 363

Flaccomio, E., Damiani, F., Micela, G., Sciortino, S., Harnden, F. R., Jr., Murray, S. S., & Wolk, S. J. 2003a, *ApJ*, 582, 398

Flaccomio, E., Micela, G., & Sciortino, S. 2003b, *A&A*, 397, 611

—. 2003c, *A&A*, 402, 277

Flaccomio, E., Micela, G., Sciortino, S., Damiani, F., Favata, F., Harnden, F. R., Jr., & Schachter, J. 2000, *A&A*, 355, 651

Flaccomio, E., Micela, G., Sciortino, S., Harnden, F. R., & Hartmann, L. 2005, *Mem. Soc. Astron. Italiana*, 76, 279

Flaccomio, E., et al. 2006, *A&A*, in press

Gagne, M., & Caillault, J.-P. 1994, *ApJ*, 437, 361

Gagne, M., Caillault, J.-P., & Stauffer, J. 1995, *ApJ*, 445, 280

Gaige, Y. 1993, *A&A*, 269, 267

Getman, K. V., Feigelson, E. D., Grosso, N., McCaughrean, M. J., Micela, G., Broos, P., Garmire, G., & Townsley, L. 2005, *ApJS*, 160, 353

Getman, K. V., Feigelson, E. D., Townsley, L., Bally, J., Lada, C. J., & Reipurth, B. 2002, *ApJ*, 575, 354

Grosso, N., Montmerle, T., Bontemps, S., André, P., & Feigelson, E. D. 2000, *A&A*, 359, 113

Güdel, M., Skinner, S. L., Briggs, K. R., Audard, M., Arzner, K., & Telleschi, A. 2005, *ApJ*, 626, L53

Hartmann, L. 2001, *AJ*, 121, 1030

Hillenbrand, L. 1997, *AJ*, 113, 1733

Imanishi, K., Koyama, K., & Tsuboi, Y. 2001, *ApJ*, 557, 747

Kastner, J. H., Franz, G., Grosso, N., Bally, J., McCaughrean, M. J., Getman, K., Feigelson, E. D., & Schulz, N. S. 2005, *ApJS*, 160, 511

Kastner, J. H., Huenemoerder, D. P., Schulz, N. S., Canizares, C. R., & Weintraub, D. A. 2002, *ApJ*, 567, 434

Kenyon, S., & Hartmann, L. 1995, *ApJS*, 101, 117

Königl, A. 1989, *ApJ*, 342, 208

—. 1991, *ApJ*, 370, L39

Lamm, M. H., Bailer-Jones, C. A. L., Mundt, R., Herbst, W., & Scholz, A. 2004, *A&A*, 417, 557

Lawson, W. A., Feigelson, E. D., & Huenemoerder, D. P. 1996, *MNRAS*, 280, 1071

Makidon, R. B., Rebull, L. M., Strom, S. E., Adams, M. T., & Patten, B. M. 2004, *AJ*, 127, 2228

Micela, G., Sciortino, S., Kashyap, V., Harnden, F. R., Jr., & Rosner, R. 1996, *ApJS*, 102, 75

Neuhäuser, R., Sterzik, M. F., Schmitt, J. H. M. M., Wichmann, R., & Krautter, J. 1995, *A&A*, 297, 391

Ozawa, H., Grossi, N., & Montmerle, T. 2005, *A&A*, 429, 963

Palla, F., & Stahler, S. W. 1999, *ApJ*, 525, 772

Park, B.-G., Sung, H., Bessell, M. S., & Kang, Y. H. 2000, *AJ*, 120, 894

Pizzolato, N., Maggio, A., Micela, G., Sciortino, S., & Ventura, P. 2003, *A&A*, 397, 147

Preibisch, T. 1997, *A&A*, 320, 525

—. 2004, *A&A*, 428, 569

Preibisch, T., & Feigelson, E. 2005, *ApJS*, 160, 390

Preibisch, T., & Zinnecker, H. 2002, *AJ*, 123, 1613

Preibisch, T., et al. 2005, *ApJS*, 160, 401

Ramirez, S., et al. 2004a, *AJ*, 127, 2659

—. 2004b, *AJ*, 128, 787

Rebull, L. 2001, *AJ*, 121, 1676

Rebull, L., Hillenbrand, L. A., Strom, S. E., Duncan, D. K., Patten, B. M., Pavlovsky, C. M., Makidon, R. B., & Adams, M. T. 2000, *AJ*, 119, 3026

Rebull, L., Wolff, S., Strom, S., & Makidon, R. B. 2002a, *AJ*, 124, 546

Rebull, L., et al. 2002b, *AJ*, 123, 1528

Rhode, K. L., Herbst, W., & Mathieu, R. D. 2001, *AJ*, 122, 3258

Robberto, M. 2005, in Star Formation in the Era of Three Great Observatories (Cambridge: SAO), 44

Schmitt, J., & Liefke, C. 2004, *A&A*, 417, 651

Schmitt, J. H. M. M., Robrade, J., Ness, J.-U., Favata, F., & Stelzer, B. 2005, *A&A*, 432, L35

Shu, F. H., Adams, F. C., & Lizano, S. 1987, *ARA&A*, 25, 23

Shu, F., Najita, J., Shang, H., & Li, Z.-Y. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 789

Sicilia-Aguilar, A., et al. 2005, *AJ*, 129, 363

Siess, L., Dufour, E., & Forestini, M. 2000, *A&A*, 358, 593 (SDF00)

Stassun, K. G., Ardila, D. R., Barsony, M., Basri, G., & Mathieu, R. D. 2004, *AJ*, 127, 3537

Stauffer, J. R., Caillault, J.-P., Gagne, M., Prosser, C. F., & Hartmann, L. W. 1994, *ApJS*, 91, 625

Stelzer, B., & Neuhauser, R. 2001, *A&A*, 377, 538

Stelzer, B., Neuhauser, R., & Hambaryan, V. 2000, *A&A*, 356, 949

Strom, S. E. 1994, in ASP Conf. Ser. 64, Cool Stars, Stellar Systems, and the Sun, ed. J.-P. Caillault (San Francisco: ASP), 211

Sung, H., Bessell, M., & Chun, M.-Y. 2004, *AJ*, 128, 1684

Tsujimoto, M., Koyama, K., Tsuboi, Y., Goto, M., & Kobayashi, N. 2002, *ApJ*, 566, 974

Walter, F., & Kuhi, L. 1981, *ApJ*, 250, 254

Wichmann, R., et al. 2000, *A&A*, 359, 181