THE ASTROPHYSICAL JOURNAL, 436:807–817, 1994 December 1

EINSTEIN X-RAY OBSERVATIONS OF HERBIG Ae/Be STARS

F. DAMIANI, G. MICELA, AND S. SCIORTINO
Istituto e Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, 90134 Palermo, Italy

AND

F. R. HARNDEN, JR.
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
Received 1994 February 22; accepted 1994 June 6

ABSTRACT

We have investigated the X-ray emission from Herbig Ae/Be stars, using the full set of *Einstein* IPC observations. Of a total of 31 observed Herbig stars, 11 are confidently identified with X-ray sources, with four additional dubious identifications.

We have used maximum likelihood luminosity functions to study the distribution of X-ray luminosity, and we find that Be stars are significantly brighter in X-rays than Ae stars and that their X-ray luminosity is independent of projected rotational velocity $v \sin i$. The X-ray emission is instead correlated with stellar bolometric luminosity and with effective temperature, and also with the kinetic luminosity of the stellar wind.

These results seem to exclude a solar-like origin for the X-ray emission, a possibility suggested by the most recent models of Herbig stars' structure, and suggest an analogy with the X-ray emission of O (and early B) stars. We also observe correlations between X-ray luminosity and the emission at 2.2 μm (*K* band) and 25 μm, which strengthen the case for X-ray emission of Herbig stars originating in their circumstellar envelopes.

Subject headings: stars: emission-line, Be — stars: pre–main-sequence — X-rays: stars

1. INTRODUCTION

Herbig Ae/Be stars are more massive ($M \sim 2$–$10\ M_{\odot}$) counterparts of T Tauri stars, associated with reflection nebulosity and obscured regions. Since their original definition by Herbig (1960), the number of known stars of this class has increased continuously with the studies by Strom et al. (1972) and Finkenzeller & Mundt (1984), among others, which have confirmed the pre–main-sequence nature of these stars. They share with the lower mass T Tauri stars peculiarities such as infrared excess emission, conspicuous (optical and UV) line emission, and irregular photometric variability.

All these peculiarities have a circumstellar, rather than an intrinsic stellar, origin in both Herbig and T Tauri stars. According to classical models (Iben 1965), manifestations of purely stellar activity were not expected to be similar in Herbig and T Tauri stars because of the essential differences in these stars' internal structure. These models indicated that A and B stars were completely radiative, while deep convective zones were present within late-type stars. However, more recent models of protostellar and pre–main-sequence evolution of Herbig stars (Palla & Stahler 1990, 1991, 1993) have suggested that during the pre–main-sequence phase a transient deuterium-burning shell develops, inducing a period of subphotospheric convection, at least in the cooler (Ae) stars.

Since the presence of a convective zone is supposed to be a necessary ingredient for the operation of a stellar (α-ω) dynamo, some magnetic activity might also be expected to be observable in Herbig Ae/Be stars, and observational evidence of magnetic fields on these stars, although indirect, has been found in some cases. In *IUE* UV spectra of the Herbig Ae stars AB Aur, Praderie et al. (1986) found periodical variations in the extent of the Mg II λ2800 line wings and interpreted them as due to alternating fast and slow streams in a wind, forced by the magnetic field to corotate with the star up to some distance. Other indications of a chromospheric-like activity exist for Ae/Be stars, as summarized by Catala (1989).

In late-type stars, in addition to chromospheric emission, coronal X-ray emission (Vaiana et al. 1981) can be an indicator of magnetic activity. In these stars, the X-ray emission level has been shown to correlate with magnetic dynamo parameters such as stellar rotation rate (Pallavicini et al. 1981; Maggio et al. 1987; Bouvier 1990; Damiani & Micela 1994).

In order to ascertain whether X-ray emission is present in Herbig stars, as in their low-mass T Tauri counterparts, and to determine whether such emission can be taken as a (further) indication of magnetic activity in these stars, giving additional support to theoretical models, we have undertaken a search for X-ray sources, detected with the *Einstein* IPC (Giacconi et al. 1979) and positionally coincident with Herbig stars. To date, only three Herbig Ae/Be stars have been reported as X-ray emitters on the basis of *Einstein* data, namely TY CrA (Walter & Kuhi 1981), V380 Ori (Pravdo & Marshall 1981; Sanders, Cassinelli, & Anderson 1982), and HD 200775 (Grillo et al. 1992a), but their detailed X-ray properties have not been systematically investigated. Very recently, preliminary reports on new X-ray observations of Herbig stars, performed with the *ROSAT* PSPC, have been presented by Zinnecker & Preibisch (1994) and by Damiani, Sciortino, & Micela (1994b), regarding samples of 14 and three stars, respectively. Although the *ROSAT* PSPC has higher sensitivity and better spatial and spectral resolution than the *Einstein* IPC, the present study may serve as a basis for these forthcoming, more detailed investigations. Also, the information provided by the *Einstein* data will allow the study of the long-term X-ray variability of these stars and of their X-ray emission between 2 and 3.5 keV (due to the different *Einstein* and *ROSAT* bandpasses).

Our paper is structured as follows: § 2 is a description of the data selection and X-ray source identification, and § 3 deals with X-ray data analysis; in § 4 we present the resulting distributions of X-ray luminosity for Herbig Ae/Be stars and explore correlations between X-ray emission and other stellar parameters, and in § 5 we discuss the results we obtained.

2. SAMPLE SELECTION

2.1. *The Optical Sample*

Our initial optical sample consisted of all Herbig Ae/Be stars listed by Finkenzeller & Mundt (1984), together with all stars listed in the Herbig & Bell (1988) catalog of pre–main-sequence (PMS) stars with spectral type earlier than F5. This choice, although not strictly conforming to the original definition of the Herbig Ae/Be class (Herbig 1960), may allow us to investigate possible dependences of X-ray emission on spectral type over a somewhat larger sample of stars. In support of this choice, we note that some of the stars listed by Finkenzeller & Mundt (1984) and Hillenbrand et al. (1992) as (likely) members of the Herbig Ae/Be class have an F spectral type.

We have excluded from our sample the star Z CMa, although it is listed by Finkenzeller & Mundt (1984), since more recent studies (Hartmann et al. 1989) have shown that it should be, more appropriately, considered a FU Ori object rather than a Herbig Ae/Be star.

In a search of the stellar database of *Einstein* X-ray observations (Sciortino et al. 1988; Harnden et al. 1990) for X-ray sources associated with Herbig Ae/Be stars, we cross-checked the positions of stars in our optical sample with those of all IPC X-ray sources, retaining an X-ray source as a possible identification whenever it fell within 2$'$.5 of an optical position. Optical coordinates were taken primarily from the Herbig & Bell (1988) catalog. For the few stars in our optical sample not listed in this catalog, we have precessed the coordinates given by Finkenzeller & Mundt (1984) and have checked them using the SIMBAD database; among these stars, only two (HD 53367 and LkHα 119) fell within IPC fields of view. With this preliminary criterion we identified 15 stars with X-ray detections, while for 16 other stars that fell within IPC fields of view we obtained only upper limits.

However, not all 15 stars satisfying this identification criterion were actually reliably associated with an X-ray source. For some of them, another PMS (usually late-type) star was also a possible counterpart for the given X-ray source, so we had to examine carefully each individual case. As a result, we have discarded four stars as unlikely optical–X-ray identifications (see below for the criteria used). Since positional uncertainty up to $\sim 1'$ may exist both in X-ray source positions (because of low signal-to-noise ratio [S/N]) and in the optical position (because of circumstellar diffuse emission; Herbig & Bell 1988), some of the stars we have discarded could actually be true X-ray sources. Until more accurate optical and X-ray positions become available, however, we conservatively regard these stars as undetected in X-rays; this raises the number of undetected stars to 20, leaving only 11 stars with a sufficiently reliable (to our judgement) X-ray identification.

2.2. *Retained Identifications*

A detailed description of our adopted criteria for accepting a given optical identification is given below. A similar description is given in the next subsection for the discarded identifications.

1. *BF Ori.*—This star is about 1$'$.0 from the corresponding X-ray source. There is no other obvious optical counterpart.

2. *LkHα 220.*—This star is offset 0$'$.4 from the X-ray position. No other PMS star lies within 3$'$ of the X-ray position.

3. *V380 Ori.*—This star is closely coincident with a strong (10.2 σ) X-ray source (with an offset of 0$'$.1–0$'$.4) detected in three distinct IPC observations. Although Proust, Ochsenbein, & Pettersen (1981) reported the existence of a companion, Herbig & Bell (1988) remark that this may be simply a structure in the surrounding nebula. We therefore retain V380 Ori as the X-ray emitter. Furthermore, its X-ray luminosity is too high to arise from a T Tauri companion (Damiani et al. 1991, 1994a).

4. *LkHα 234.*—This star is 1$'$.1 from the X-ray position, lying within 1$'$ of the IPC image center. With the same X-ray source is associated another Herbig star (+65° 1637, with an offset of 0$'$.9), as well as a T Tauri star (HBC 731, with an offset of 1$'$.7). Both Herbig stars are closer to the X-ray position than the T Tauri star, and because of the small off-axis angle of the source we consider the two former stars as associated with the X-ray source. Zinnecker & Preibisch (1994) have recently reported on the lack of X-ray detection of LkHα 234 with the *ROSAT* PSPC, with an upper limit on L_x much smaller than the value we derive here. However, since we cannot resolve the two stars (LkHα 234 and +65° 1637) with the IPC nor can we rule out X-ray variability between the two epochs of observation, we retain LkHα 234 as a possible X-ray identification.

5. *+65° 1637.*—See note on LkHα 234. This star can be confidently associated with the X-ray source.

6. *HD 200775.*—This star is closely coincident with the position of a fairly strong (8.5 σ) X-ray source (with an offset of 0$'$.3). The T Tauri star FU Cep is 1$'$.1 distant from the same X-ray source. However, and *Einstein* HRI observation of the same field shows that the positional coincidence of HD 200775 with the X-ray source is within about 3$''$, confirming the identification of the X-ray source with this star rather than with FU Cep.

7. *HD 259431.*—This star is offset 0$'$.3 from the X-ray position. The T Tauri star LkHα 217 lies 2$'$.3 from the same X-ray source, and on the basis of this larger offset is a less likely optical counterpart than HD 258 431.

8. *TY CrA.*—This star coincides closely with an X-ray source, with a 0$'$.2 offset. Since TY CrA is a known eclipsing binary (Kardopolov, Sahanionok, & Philipjev 1981), we will discuss in § 4.1 the likelihood that its X-ray emission is due to the companion.

9. *VY Mon.*—This star is one of the six PMS counterparts of an X-ray source and is offset from it by 1$'$.2. The other five stars (LkHα 274, VY Mon/G4, VY Mon/G2, V481 Mon, and VY Mon/G5) all lie within 1$'$.1 of the X-ray source and are all equally likely counterparts.

10. *VY Mon/G2.*—See note on VY Mon.

11. *LkHα 215.*—This star is 1$'$.5 from the X-ray position. Other counterparts are LkHα 213 (with an offset of 1$'$.4) and LkHα 214 (with an offset of 0$'$.7). Given the large off-axis angle of the X-ray source (27$'$) all three stars are equally likely identifications.

2.3. *Discarded Identifications*

1. *T Ori.*—This star and the T Tauri star AN Ori are both identified with the same X-ray source, but their offsets from the X-ray position are 1$'$.7 and 0$'$.5, respectively, at an off-axis angle of 26$'$. In another observation, where these stars lie 8$'$ off-axis and the positional accuracy of the IPC is better, the discrepancy between the positions of T Ori and of the X-ray source is even larger; therefore, the T Tauri star AN Ori is to be regarded as the most likely counterpart to the X-ray source.

2. *LkHα 25 (V590 Mon, W90).*—This is one of the many counterparts of an X-ray source in Monoceros, from which its offset is 1$'$.5. The star LR Mon is closer to the X-ray position, with an offset of 0$'$.9 (at an off-axis angle of 4$'$).

3. *CU Cha* (*HD 97048*).—This star is offset 2'.3 from an X-ray source. A more likely counterpart is LkHα 332−17, offset by only 0'.3 (at an off-axis angle of 9').

4. *MR Ori*.—This star is near the Orion Trapezium region, 1'.5 from a strong X-ray source (0'.2 off-axis). Many other stars are closer to the X-ray source position and are more probable counterparts.

3. X-RAY ANALYSIS

There were two automatic source detection algorithms for IPC data in the Rev 1 processing (Harnden et al. 1984), the so-called *Local* and *Map* methods, differing in the evaluation of the background at a given position in an image. Source detection was done separately in the "soft" (0.16–0.8 keV), "hard" (0.8–3.5 keV), and "broad" (0.16–3.5 keV) IPC spectral bands. We have adopted in each case the count rates given by the Map method, which is more sensitive in the case of weak X-ray sources, applied to the broad band. Whenever this method did not detect the source, we have made use of count rates given by the Local method (in the broad band if possible, or alternatively in the hard band).

In those few cases in which a star has been detected in many IPC images, we have retained the count rates of the corresponding X-ray sources only if these were unobscured by the detector window support structure. In two cases (V380 Ori and HD 200775) where a choice among different X-ray count rates still remained, we adopted the one with the highest S/N, after having explored whether the individual rates obtained gave any indication of variability. While HD 200775 was constant within errors, X-ray variability seemed to be present in the case of V380 Ori (a star with a good optical–X-ray identification). Two X-ray detections gave count rates differing by a factor of 2 (at the 3 σ confidence level). We have adopted the lower count rate, since this detection has higher S/N (another detection of this star, although partially affected by the detector support structure, gave a similarly low count rate).

The derived count rates were then divided by the number of (a priori) equally likely counterparts. Five stars of our sample (out of 11 likely detections) belong to groups unresolved by the IPC, and the determination of their X-ray fluxes is therefore affected by this choice.

Count rates have been transformed to intrinsic source fluxes using suitable conversion factors (Harris et al. 1993), which depend on source spectrum and on line-of-sight absorption of X-rays (parameterized by the hydrogen column density $N_{\rm H}$). A rough idea of intrinsic source spectrum and intervening absorption can be gained directly from the limited spectral resolution of the IPC, provided that a sufficient number of X-ray counts (more than ~70) have been recorded, as was the case for three Herbig stars (V380 Ori, TY CrA, and HD 200775). Fits to the IPC spectra (using the IRAF/PROS spectral package) showed that in all three cases a Raymond model provided a reasonable fit to the observed spectrum, as summarized in Table 1.

TABLE 1

SUMMARY OF X-RAY SPECTRAL FIT RESULTS

Star	χ^2	d.o.f.	T (keV)	$\log N_H$ (cm^{-2})	$\log N_H(A_V)$ (cm^{-2})
V380 Ori	7.2	6	$1.08^{+0.62}_{-0.23}$	$21.87^{+0.18}_{-0.27}$	21.58
TY CrA	13.7	7	$1.04^{+?}_{-0.29}$	$21.74^{+0.36}_{-0.74}$	21.35
HD 200775	5.2	7	$0.80^{+0.30}_{-0.40}$	$21.68^{+0.32}_{-1.28}$	21.65

The source temperatures appear similar to those inferred in the case of T Tauri stars (Walter & Kuhi 1981; Damiani et al. 1994a). To derive the conversion factor of count rate to flux, we assumed $kT = 1$ keV for all stars of our sample, while our choice of a value of $N_{\rm H}$ for each star is problematic. If one assumes an average interstellar gas-to-dust mass ratio along the lines of sight toward the Herbig stars, the $N_{\rm H}$ values derived from the optical extinction A_V ($N_{\rm H} = 2.22 \times 10^{21} A_V$ cm^{-2}; Gorenstein 1975) would be more than a factor of 2 *lower* than those we have derived for V380 Ori and TY CrA from direct fitting procedure (see Table 1), although this discrepancy remains within the typical uncertainties on $N_{\rm H}$ determination. We are unable to ascertain on the basis of the IPC data alone, whether this apparently systematic effect is real. For stars without published A_V values, we assumed for $N_{\rm H}$ the median value of the other stars.

Most of the absorption toward these stars probably arises in the immediate stellar neighborhood, where prevailing conditions are expected to differ substantially from those in the average interstellar medium (higher ionizing radiation flux, or some unspecified stellar-wind heating mechanism); hence relations derived on the basis of average interstellar conditions may not be appropriate. However, since no better estimates of $N_{\rm H}$ are presently available for most stars in our sample, we elected to infer $N_{\rm H}$ from the optical extinction, with the caveat that this introduces an uncertainty, on the order of a factor of 2 in $N_{\rm H}$ and no more than 30% in the derived X-ray flux.

X-ray luminosities L_x were inferred from the derived fluxes, corrected for absorption, using the distances given by Hillenbrand et al. (1992). For stars of our sample not considered by those authors, we have assumed the same distance as for other stars associated with the same clouds (associated clouds for each star are reported by Herbig & Bell 1988).

We also computed upper limits on X-ray luminosities of undetected stars, with limiting count rates taken as equal to those of the neighboring X-ray source for the stars listed as "discarded identifications" in § 2.3. For other stars, a limiting count rate was calculated using the prescription of Harris et al. (1993), choosing a significance level of 3.5 σ. Limiting count rates were converted to upper limits on L_x following the same method as used for detections.

The X-ray luminosities together with other relevant X-ray data are listed in Table. 2. In the identification flag ("Id. Flag") column we give an estimate of the reliability of the optical–X-ray identification, on the basis of the arguments presented in §§ 2.2 and 2.3. Relatively certain identifications are labeled with "H," while tentative identifications requiring confirmation are labeled with "L." Note that we have classified as good identifications both stars of the pair LkHα 234/+65°1637, since at least one of the two Herbig stars (and not another late-type star) is the likely X-ray source.

4. RESULTS

4.1. *The X-Ray Luminosity Distribution of Herbig Ae/Be Stars*

Given the large fraction of sample stars not detected in X-rays, we choose to study the X-ray luminosity distribution of our sample using the Kaplan-Meier estimator (Avni et al. 1980; Feigelson & Nelson 1985; Schmitt 1985), an approach justified by the fact that the detection and upper limit threshold distributions are indistinguishable. Detection fractions were 9/20 for Be stars, 1/8 for Ae stars, and 1/3 for F0–F5 stars. Since we detected less than half of our Herbig stars (11 of 31),

TABLE 2

X-RAY DATA FOR HERBIG Ae/Be STARS

HBC	Name	IPC Seq.	Offset (′)	Offaxis (′)	Count rate (cts/sec)	S/N	Nr. of Counterp.	Id. Flag	log L_x (ergs/s)
164	V380 Ori	7241	0.1	2.6	0.019	10.25	1	H	31.38
169	BF Ori	7241	1.0	15.7	0.006	4.18	1	H	30.56
287	TY CrA	4512	0.2	7.9	0.040	7.58	1	H	30.42
309	LkHα 234	5038	1.1	0.8	0.009	3.73	2	H	31.66
202	VY Mon	5034	1.2	29.1	0.009[a]	2.51	6	L	30.66
522	VY Mon/G2	5034	1.1	29.1	0.009[a]	2.51	6	L	30.66
528	LkHα 215	7237	1.5	27.1	0.006	3.80	3	L	30.95
529	HD 259431	7237	0.3	18.8	0.003	3.19	1	H	31.04
551	LkHα 220	10726	0.4	5.3	0.005	3.57	1	H	31.59
726	HD 200775	10066	0.3	0.2	0.031	8.51	1	H	31.92
730	+65° 1637	5038	0.9	0.8	0.009	3.73	2	H	31.46
154	T Ori	7248	...	25.0	<0.021	...	...	...	<31.42
219	LHα 25	5089	...	6.1	<0.012	...	...	...	<31.47
246	CU Cha	10350	...	7.0	<0.011	...	...	...	<30.41
456	MR Ori	2567	...	1.6	<0.132	...	...	...	<32.22
3	LkHα 198	2244	...	27.2	<0.034	...	...	...	<31.99
78	AB Aur	3810	...	8.1	<0.003	...	...	...	<29.31
192	HD 250550	5033	...	0.3	<0.008	...	...	...	<31.16
201	LkHα 341	7237	...	28.9	<0.006	...	...	...	<31.36
281	LkHα 118	3124	...	27.5	<0.013	...	...	...	...
288	R CrA	4512	...	9.0	<0.011	...	...	...	<30.08
290	T CrA	4512	...	10.0	<0.011	...	...	...	<30.04
310	+46° 3471	5039	...	1.2	<0.016	...	...	...	<31.89
312	LkHα 257	5039	...	18.3	<0.021	...	...	...	<32.00
325	V376 Cas	2244	...	27.0	<0.034	...	...	...	<32.04
451	HD 245185	9060	...	5.9	<0.009	...	...	...	<30.62
493	V350 Ori	4921	...	0.1	<0.009	...	...	...	<31.05
689	+40° 4124	5036	...	0.5	<0.010	...	...	...	<31.97
690	V1686 Cyg	5036	...	0.6	<0.010	...	...	...	<32.14
...	HD 53367	10725	...	7.3	<0.007	...	...	...	<31.84
...	LkHα 119	3124	...	29.1	<0.014	...	...	...	<32.48

[a] X-ray source detected only in the hard band with the Map method.

we failed to sample the median of their L_x distribution, and our maximum likelihood luminosity function is therefore representative only of the high-luminosity end of the true distribution. Moreover, the upper limits on L_x that we derived are generally rather high and therefore do not put stringent constraints on the X-ray luminosity, but merely rule out L_x above 10^{30}–10^{31} ergs s^{-1} for some stars. On the other hand, we positively detected a few Herbig stars with X-ray luminosity as high as $L_x \geq 10^{31}$ ergs s^{-1}.

Since the whole sample of Herbig stars ranges in spectral type from B0 to F2, it may be so heterogeneous a sample of objects that constructing separate X-ray luminosity functions for the Ae and for the Be stars could prove revealing. Such luminosity functions are plotted in Figure 1, where we also report for comparison the X-ray luminosity function of the T Tauri population in the Taurus-Auriga star-forming region (Damiani et al. 1994a). The obvious difference between the luminosity functions of the T Tauri and the Be stars strengthens our identifications of X-ray sources with Herbig stars rather than with other possible T Tauri counterparts (§ 2.2).

Note that for the Herbig Be stars, the percentage of X-ray detections (~45%) is apparently higher than that found (~5%) for the overall sample of B stars (Grillo et al. 1992a), despite the similarity in the distributions of detection thresholds for the two samples. The Herbig Be star X-ray luminosity function compares well with the high-luminosity tail of that of bright B stars (Grillo et al. 1992b). This similarity in X-ray emission levels suggests that the X-ray emission mechanisms might be similar in Herbig Be and in other bright B stars.

The X-ray luminosity function of Herbig Ae stars looks quite different from that of Be stars, with the average L_x being more than an order of magnitude lower. A quantitative (Wilcoxon) test shows these distributions to be different at the 99.1% confidence level, suggesting that the X-ray emission of Ae and Be stars might have different origins. However, a caveat is in order: the very limited sample size, and the even smaller number of detections, requires that this and other conclusions be confirmed by further (more sensitive) observations.

While it appears different from that of Be stars, the X-ray luminosity function of Ae stars is very similar to that of T Tauri stars in Taurus-Auriga (Damiani et al. 1991, 1994a); a Wilcoxon test cannot reject the hypothesis that the two samples are extracted from the same parent population (confidence level only 28%). Therefore, present data are in agreement with the hypothesis that the X-ray emission of Herbig Ae stars might actually originate from (mostly unknown) T Tauri companions, rather than from the Ae stars themselves, a hypothesis put forth by various authors (Schmitt et al. 1985; Caillault & Zoonematkermani 1989; Micela et al. 1990) to explain the (rare) cases of detection of X-ray emission from main-sequence A or late B stars, which lack both a convective structure, necessary to drive a magnetic dynamo (as in late-type stars), and strong winds, whose instabilities may give rise to shocked, X-ray–emitting regions (as in O stars). It should be noted, however, that a few cases exist in which the X-ray emission apparently does arise from the A star itself (Micela et al. 1990 and references therein).

We note that we adopted a spectral type B9 for the star TY

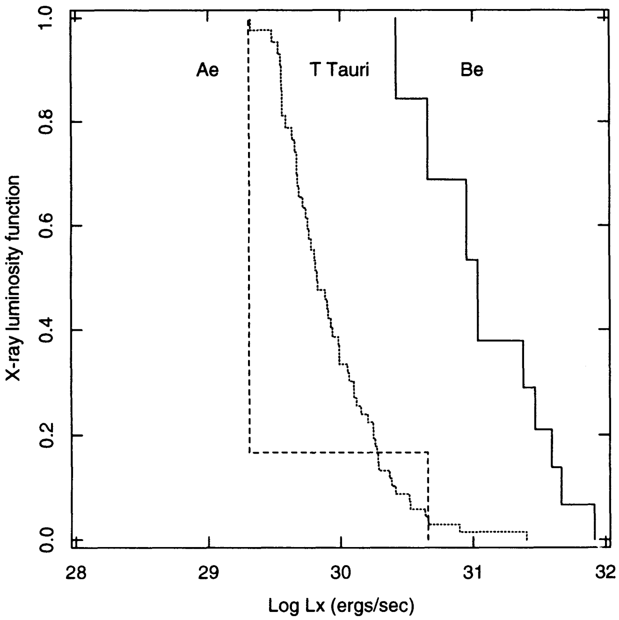

FIG. 1.—Maximum likelihood luminosity distributions for Herbig Be stars (*solid*), Ae stars (*dashed*), and Taurus-Auriga T Tauri stars (*dotted*).

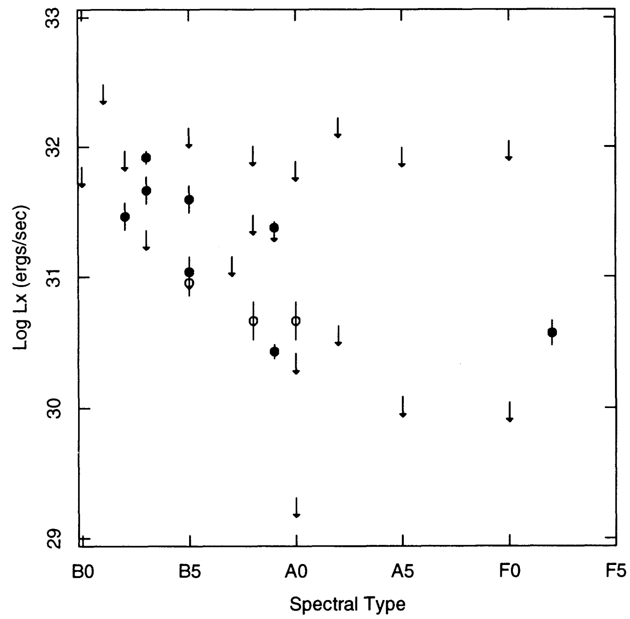

FIG. 2.—X-ray luminosity L_x as a function of spectral type. Filled dots indicate stars with the most reliable X-ray identifications, and empty dots the remaining stars. Arrows are X-ray upper limits. Error bars on L_x reflect only statistical uncertainties.

CrA, as reported by Herbig & Bell (1988; see also Finkenzeller & Mundt 1984; Casey et al. 1993), and not A5 as tabulated by Hillenbrand et al. (1992), although a B9 type implies a value of $R\ (\equiv A_V/E_{B-V}) \sim 6.5$, rather than the usual $R = 3.1$, in order to be compatible with photometric data.[1] Had we assumed an A5 spectral type, TY CrA would turn out to be the brightest Herbig Ae star in X-rays. However, since it is a known eclipsing binary (Kardopolov et al. 1981), we would attribute its X-ray emission to the companion rather than the the Ae star itself. In fact, assuming for the companion a rotation period equal to the binary period (2.888777 days; Kardopolov et al. 1981), the observed L_x agrees with the correlation between X-ray emission and rotation found for low-mass PMS stars (Bouvier 1990; Damiani et al. 1991; Damiani & Micela 1994). Therefore, even assigning an A5 spectral type to TY CrA, there is no need to invoke intrinsic X-ray emission from the Herbig Ae star itself. We also note that the only detected Ae star (VY Mon/G2) has an uncertain identification and could not be responsible for the observed emission.

4.2. *Relationships between X-Ray Emission and Spectral Type, Bolometric Luminosity, and Rotation*

A plot of L_x versus spectral type (taken from Hillenbrand et al. 1992, or Herbig & Bell 1988) is shown in Figure 2. A trend of increasing L_x toward earlier spectral types, for types earlier than about A5, is supported by the low upper limits for four A0–A5 stars. Application of statistical tests, available in the ASURV package (Rev. 1.1, LaValley, Isobe, & Feigelson 1992; see also Isobe, Feigelson, & Nelson 1986), yields the result that L_x and $T_{\rm eff}$ (derived from spectral type using the calibration of Cohen & Kuhi 1979) are correlated (probabilities of no correlation are only $P = 0.0010$ and $P = 0.0013$, according to a Cox proportional hazard test and to a generalized Kendall's τ-test, respectively). Effective temperatures and other data for Herbig stars, taken from the literature are listed in Table 3.

[1] Accordingly, we also adopted bolometric luminosity and $v \sin i$ from Casey et al. (1993).

In order to check to what extent the correlation probabilities found may be affected by errors in the adopted data, we have repeatedly added randomly scattered errors to the original data, each time applying the above tests. As noted by Skinner et al. (1993), typical uncertainties for $T_{\rm eff}$ are about 25% for Herbig stars. Applying the tests to the scattered data 100 times, we obtained a range of values for the probabilities of no correlation, whose 16%, 50%, and 84% quantiles are $P = 0.0004$, 0.0017, and 0.0049 (Cox test) and $P = 0.0011$, 0.0028, and 0.0058 (Kendall's τ-test), respectively. Therefore, the correlation found is not significantly affected by possible errors in the adopted effective temperature.

Since Herbig (Be) stars are not far off the main sequence in the H-R diagram, a dependence on spectral type implies a dependence on stellar bolometric luminosity. Such a dependence might provide a clue about the origin of X-ray emission in Herbig stars that is easier to interpret than the correlation with $T_{\rm eff}$. A scatter plot of L_x versus $L_{\rm bol}$ is shown in Figure 3: as expected, a trend of increasing L_x with $L_{\rm bol}$ is indeed visible. Values of $L_{\rm bol}$ for Herbig stars have been derived by various authors (e.g., Strom et al. 1972; Finkenzeller & Mundt 1984; Berrilli et al. 1992; Hillenbrand et al. 1992) and differ sometimes by more than one order of magnitude for one given star. However, we have preferred to use here the values of Hillenbrand et al. (1992) (rather than some average value), which take appropriately into account the large (up to 90% of total $L_{\rm bol}$) radiative output of these stars at UV wavelengths. The errors for the $L_{\rm bol}$ estimates of Hillenbrand et al. (1992) are typically a factor of 2, in agreement with the average uncertainty estimated by Skinner et al. (1993).

We have previously suggested that any X-ray emission from Herbig Ae stars might be intrinsic to the Ae stars themselves and that therefore one should consider the Ae stars separately from the Be stars when looking for correlations between L_x and $L_{\rm bol}$. If one ignores stars of type Ae and later (Fig. 3, *squares*) in the L_x-$L_{\rm bol}$ plot, the Be sample alone (*circles*) no

TABLE 3

OPTICAL DATA FOR HERBIG Ae/Be STARS

HBC	Name	Sp. Type	Dist. (pc)	$\log L_{bol}$ ($L_\odot$)	EW(Hα) (Å)	FWHM(Hα) (km/s)	A_V	V	$v \sin i$ (km/s)	$\log L_{25\mu}$ (ergs/s)	$\log \dot{M}$ ($M_\odot$/yr)	$\log L_{kin}$ (ergs/s)
164	V380 Ori	B9	460	1.93	58	260	1.7	10.00	...	34.23	-7.94	32.69
169	BF Ori	F2	460	0.49	13	350	0.0	10.32	...	33.37	-8.81	32.08
287	TY CrA	B9	130	1.94	2	...	1.0	8.95	<15	33.94	...	...
309	LkHα 234	B3	1000	3.24	25	140	3.4	11.90	<200	35.94	-7.16	32.94
202	VY Mon	B8	800	...	50	...	...	12.89	...	35.61	...	...
522	VY Mon/G2	A0	800	...	21	...	...	17.90	...	...	...	...
528	LkHα 215	B5	800	2.95	25	380	2.1	10.42	<200	34.67	-7.33	33.63
529	HD 259431	B5	800	3.80	52	200	1.6	8.69	100	35.07	-6.82	33.58
551	LkHα 220	B5	1150	...	35	280	...	12.30	...	34.40	...	...
726	HD 200775	B3	600	4.25	32	280	2.0	7.39	60	35.16	-6.55	34.14
730	+65° 1637	B2	1000	3.38	26	280	1.9	10.15	180	35.21	-7.07	33.62
154	T Ori	B9	460	1.92	16	280	1.7	9.96	100	...	-7.95	32.75
219	LHα 25	B8	800	0.96	47	340	0.6	12.78	...	34.62	-8.52	32.34
246	CU Cha	A0	215	1.84	30	...	1.3	8.45	140	34.23	-8.00	...
456	MR Ori	A2	460	...	...	...	...	10.55	...	...	...	...
3	LkHα 198	A5	600	0.75	85	...	2.5	14.29	...	35.49	-8.65	...
78	AB Aur	A0	140	1.76	27	240	0.4	7.07	140	33.94	-8.04	32.52
192	HD 250550	B7	700	2.38	40	220	0.5	9.48	110	34.65	-7.67	32.81
201	LkHα 341	B3	800	...	42	...	...	13.36	...	33.10	...	...
281	LkHα 118	B5	...	...	20	400	3.3	11.13	...	...	...	...
288	R CrA	A5	130	1.90	...	...	1.9	10.74	...	34.58	-7.96	...
290	T CrA	F0	130	0.78	...	...	1.7	13.37	...	33.77	-8.63	...
310	+46° 3471	A0	900	2.73	20	210	1.7	10.10	150	34.09	-7.46	32.98
312	LkHα 257	B8	900	...	...	...	...	13.17	...	33.77	...	...
325	V376 Cas	F0	600	0.45	37	...	2.9	15.60	...	35.46	-8.83	...
451	HD 245185	A2	400	1.23	12	180	0.1	9.93	80	33.94	-8.36	31.95
493	V350 Ori	B5	460	...	...	...	...	...	...	33.53	...	...
689	+40° 4124	B2	1000	3.85	94	360	3.0	10.52	180	...	-6.79	34.12
690	V1686 Cyg	B5	1000	3.25	...	...	4.8	12.90	...	36.03	-7.15	...
...	HD 53367	B0	1150	5.38	11	270	2.3	7.01	30	35.44	-5.87	34.79
...	LkHα 119	B1	1900	...	14	280	...	...	...	...	...	...

REFERENCES.—Spectral types, distances, bolometric luminosities, and optical extinctions are taken from Hillenbrand et al. 1992, except for TY CrA (Casey et al. 1993), the distance of LkHα 119 (Boesono, Thé, & Tlin A. Djie 1987), and the A_V of LkHα 119 (Finkenzeller & Mundt 1984). Hα EWs are from Finkenzeller & Mundt 1984 and Herbig & Bell 1988; Hα FWHMs are from Finkenzeller & Mundt 1984. V magnitudes are from Herbig & Bell 1988, except for HD 53376 (Hillenbrand et al. 1992). Rotational velocities are from Davis et al. 1983, Finkenzeller 1985, and Casey et al. 1993. Luminosities at 25 μm, mass-loss rates, and wind kinetic luminosities are also derived from literature data, as described in the text.

longer shows correlation. Hence the suggested trend of L_x versus L_{bol} should be interpreted with caution. On the other hand, the (low) upper limits on L_x for Ae stars do give meaningful constraints on the L_x-L_{bol} relation: they imply that any physical mechanism giving rise to X-ray emission in Herbig Be stars is no longer efficient for Ae stars of lower bolometric luminosities (or at least, results in L_x values two orders of magnitude smaller). On this basis, the gross features of the mechanism giving rise to X-ray emission in Herbig stars should include a substantial dependence on the stellar bolometric luminosity, reminiscent of the behavior of O stars. A statistical analysis, applied to the whole Ae/Be sample, yields probabilities of no correlation between L_x and L_{bol} of $P = 0.0039$ (Cox test) and $P = 0.0061$ (Kendall's τ-test), respectively. The correlation between L_x and L_{bol} is therefore not significantly different from that between L_x and T_{eff}. Also in this case, we have applied the same tests 100 times to randomly scattered L_{bol} data, obtaining (for the probabilities of no correlation) distributions whose 16%, 50%, and 84% quantiles are $P = 0.0025$, 0.0044, and 0.0084 (Cox test) and $P = 0.0055$, 0.0104, and 0.0168 (Kendall's τ-test), respectively. Also in this case, uncertainties on L_{bol} do not significantly affect the correlation.

A related possibility is that a bimodal distribution of X-ray activity levels exists for Ae/Be stars, namely, that the mechanism giving rise to X-ray emission in the hotter (or more luminous) stars ceases to operate for stars cooler (less luminous) than some threshold, but is otherwise unrelated to T_{eff} (L_{bol}). Our data are insufficient, however, to discriminate between this possibility and a "true" correlation.

We have also investigated whether this correlation could be a spurious effect of the limited sensitivity of the X-ray observations. Indeed, we have verified that the X-ray detection thresholds for the given IPC observations increase with increasing L_{bol}. However, if L_x were actually independent of L_{bol} (a "flat" dependence), one would see an increasing proportion of nondetections toward high L_{bol} because of the detection threshold distribution, which is just the opposite of what is shown in Figure 3. We conclude that any bias introduced by instrument sensitivity is not strong enough to induce a spurious relation and that a real correlation between X-ray and bolometric luminosity does exist.

A similar correlation between X-ray and bolometric luminosities has been obtained by Feigelson et al. (1993) for the T Tauri population of the Chamaeleon star formation region, as well as by Damiani & Micela (1994) for the weak-lined T Tauri stars in Taurus-Auriga (but not, however, for the whole T Tauri population of this region). Note however that the X-ray emission from T Tauri stars was found to correlate more strongly with the stellar rotation, at least in Taurus-Auriga,

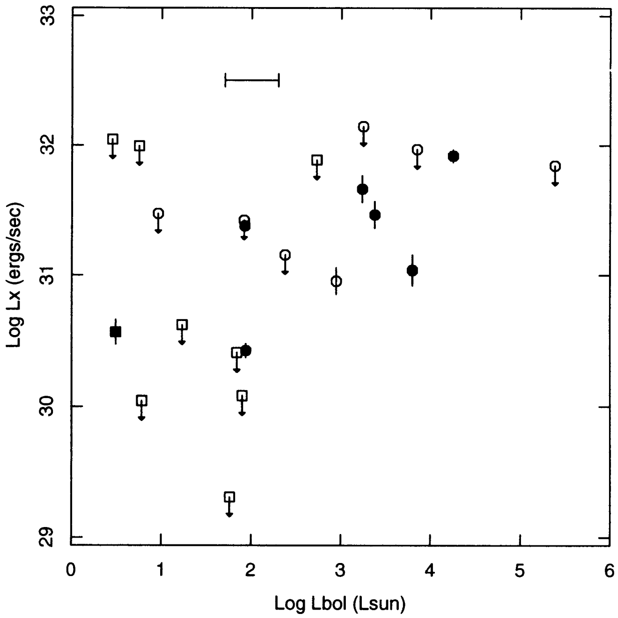

FIG. 3.—X-ray luminosity L_x vs. bolometric luminosity L_{bol}. Squares indicate A0–A5 stars, and circles B0–B9 stars. Filled symbols indicate stars with the most reliable X-ray identifications, and empty symbols the remaining stars. Arrows are X-ray upper limits. The segment in the upper left indicates the average error on L_{bol}.

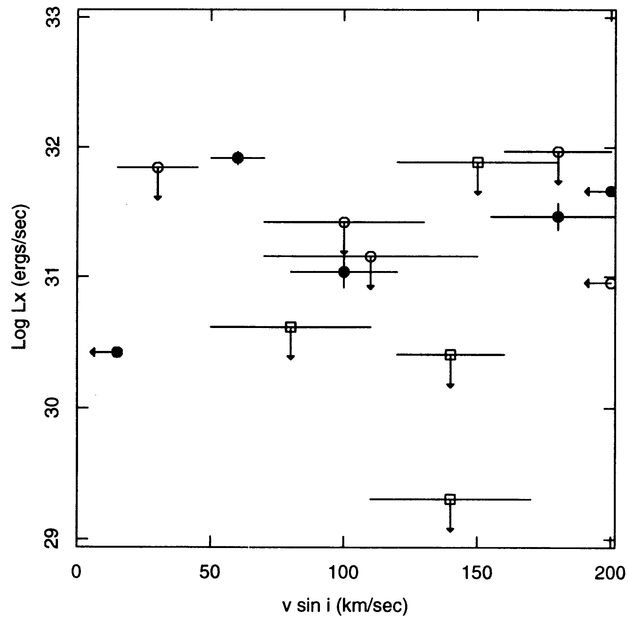

FIG. 4.—X-ray luminosity L_x vs. projected rotational velocity v sin i. Uncertainties on v sin i are taken from Finkenzeller (1985). The symbols have the same meaning as in Fig. 3.

while this seems not to be the case for Herbig stars (see below). For this reason, and also since classical models of stellar structure show that early- and late-type stars have different internal structure, we suggest that this apparently similar trend of X-ray emission correlating with bolometric output is not due to analogous X-ray emission mechanisms in early- and late-type stars.

Although classical models assume early-type stars to be entirely radiative, as mentioned in § 1, recent models of Herbig star structure include the existence of an interior transient deuterium-burning shell which might induce subphotospheric convection at some time during PMS evolution. Such a feature could in turn produce a transient magnetic dynamo, leading to magnetic activity otherwise unexpected in Ae/Be stars. In spite of some evidence of magnetic fields on the surface of Herbig Ae/Be stars, the observed X-ray emission seems not to be due to magnetic dynamo activity, since this is not expected to scale with stellar luminosity. Moreover, if such a subphotospheric convection zone were related to a magnetic origin for the X-ray emission, a *decrease* of X-ray emission would be expected in going from Ae to Be stars, since the convection zone should be much more conspicuous in the late type stars (if present at all in Be stars; Palla & Stahler 1991, 1993), a trend directly opposite to what we have found. This casts further doubt on a substantial role for dynamo generation of the X ray emission from Herbig stars.

As a final test of the plausibility of a magnetic origin for this X-ray emission, we examined the relation between L_x and the projected stellar rotational velocity v sin i; this provided no support for a magnetic dynamo origin for the X-ray emission of Herbig stars. For practically all late-type stars, in which X-ray emission most likely originates from magnetic dynamo activity, X-ray emission is found to be correlated with the stellar rotation (e.g., Pallavicini et al. 1981; Maggio et al. 1987), a result that holds for T Tauri stars as well (Bouvier 1990; Damiani et al. 1991; Damiani & Micela 1994). A scatter plot of L_x versus v sin i for Herbig stars is shown in Figure 4 (v sin i values are taken from Finkenzeller 1985; Davis, Strom, & Strom 1983; or Herbig & Bell 1988). Although projection effects (contained in the sin i factor) might be present and might alter the appearance of this plot, no relation is apparent (taking into account the limited statistics available). In particular, the X-ray–bright star HD 200775 has a relatively small v sin i, while the relatively fast rotator CU Cha has a lower upper limit on its L_x.

4.3. *Relationships of X-Ray Emission with Circumstellar Envelopes and Winds of Herbig Stars*

To gain further insight into the meaning of the apparent L_x-L_{bol} correlation, we studied the correlation properties between X-ray emission and other diagnostics, whose energy sources may be related to stellar bolometric output.

The intensity and profile of the strong emission lines of Herbig stars indicate an origin from extended circumstellar envelopes. Clear signatures of strong winds (e.g., P Cygni profiles) are detected only for 20%–30% of the stars (Finkenzeller & Mundt 1984; Hamann & Persson 1992), but conversely only in a very small number of Herbig stars have profiles suggesting infall has been found (Hamann & Persson 1992). The existence of outflows from some Herbig stars has also been established through radio observations in the CO lines (e.g., Levreault 1988). It therefore appears that outflow motions are much more common than infall, and we will assume in the following that, in general, the emission lines of these stars arise from stellar winds. Note that this is not necessarily ruled out by the lack of P Cygni profiles in the strongest emission lines, since these may be canceled by radiative transfer effects: for example, the star HD 200775 has a strong and symmetric Hα line, while its higher Balmer lines show P Cygni profiles (Strom et al. 1972). It is also unlikely that the (broad and structured) emission-line profiles of Herbig stars may be mainly due to circumstellar turbulent motions.

Also IR excesses are commonly detected in Herbig stars, in both the near-IR photometric bands (*JHKL*) and the *IRAS* bands (12–100 μm), and may constitute a relevant part of the total stellar radiative output in some cases (e.g., Hillenbrand et al. 1992; Lada & Adams 1992; Berrilli et al. 1992). Recent models show that these likely originate from extended dusty envelopes (Hartmann, Kenyon, & Calvet 1993).

We have looked for correlations between X-ray emission of Herbig stars and properties of their envelopes, choosing as representative two distinct bands, namely, the *K* band at 2.2 μm and the *IRAS* 25 μm band. The IR spectra of these stars are broader than single-temperature blackbodies, suggesting emission from material with a range of temperatures. The choice of these two IR bands permits the sampling of different regions of these stars' envelopes: relatively hotter ones, plausibily closer to the star, in the *K* band, and more extended and cooler ones in the *IRAS* 25 μm band. Although the spatial regions where the emission in these bands arises are different, they are physically linked in some way. With the *K*-band photometry from Hillenbrand et al. (1992) and the *IRAS* data from Weaver & Jones (1992), we find that the *K* absolute magnitude and the luminosity in the 25 μm *IRAS* band are loosely correlated, with a scatter of one order of magnitude. We have not attempted to subtract any photospheric contribution from the *K*-band flux.

Figure 5 is a plot of L_x versus the luminosity in the 16–30 μm IR band, derived from the *IRAS* flux at the nominal wavelength of 25 μm (following the prescriptions by Emerson 1988). The probabilities that no correlation exists between L_x and 25 μm luminosity are $P = 0.0071$ (Cox test) and $P = 0.0169$ (Kendall's τ-test). This suggests that either X-ray emission originates in the extended envelopes of Herbig stars or at least that X-ray and IR emission share a common energy source.

A correlation is also present, as shown in Figure 6, between the X-ray luminosity and the *K* absolute magnitude (the probabilities of no correlation being 0.0192 and 0.0214 for Cox and Kendall's τ-test, respectively). Given a correlation between L_x and the 25 μm emission, a correlation with *K* magnitude as well is not guaranteed, since the 25 μm and *K*-band emissions are only loosely correlated. Hence, this correlation between L_x and *K* magnitude does provide a new piece of information. The probability of no correlation between L_x and $L_{25\,\mu m}$ turns out to be close to that between L_x and *K* magnitude.

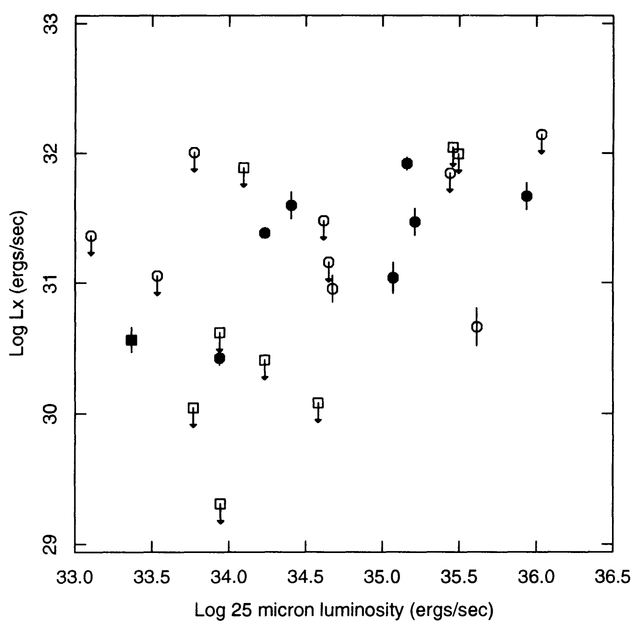

FIG. 5.—X-ray luminosity L_x vs. 25 μm *IRAS* luminosity. Symbols as in Fig. 3.

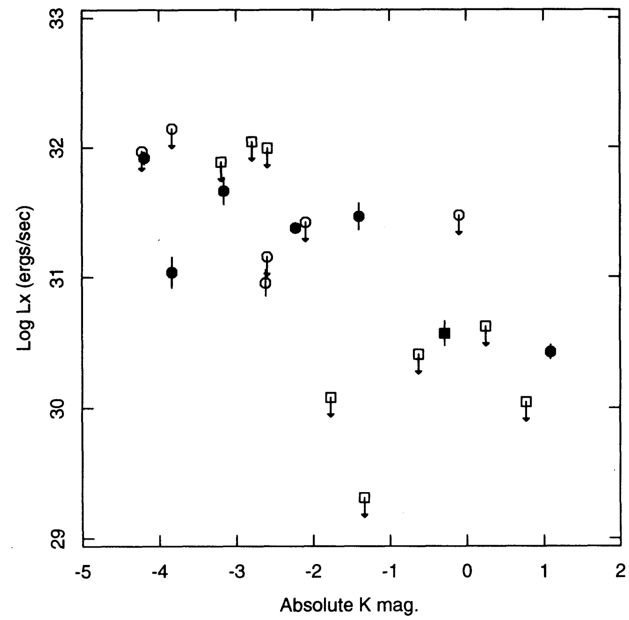

FIG. 6.—X-ray luminosity L_x vs. 25 μm *IRAS* luminosity. Symbols as in Fig. 3.

In view of such suggestions that X-ray emission is correlated with the IR emission arising both from relatively extended regions (25 μm), it is tempting to speculate that the X-ray emission originates in circumstellar regions, where the large stellar radiative output interacts strongly with matter, especially in the case of Be stars. We have summarized above the available evidence for winds and outflows in Herbig stars, and strong winds are also detected in main-sequence early-type stars, such as O and early B stars. For these stars, systematic investigations of their X-ray emission (Chlebowski, Harnden, & Sciortino 1989; Sciortino et al. 1990; Grillo et al. 1992a) have shown that these stars are strong X-ray sources, with X-ray luminosities up to $L_x \sim 10^{34}$ ergs s^{-1}. Sciortino et al. (1990) and Chlebowski & Garmany (1991) have suggested that the X-ray emission of O stars is correlated with the so-called kinetic luminosity of their winds, namely, the mechanical power output $1/2\dot{M}V_\infty^2$; on the other hand, the X-ray emission of O stars is not correlated with the stellar $v \sin i$ (Sciortino et al. 1990). For B stars, Grillo et al. (1992b) find that the X-ray luminosity distributions are different for stars with bolometric luminosities below and above a threshold, corresponding to the onset of intense radiation-driven winds. They therefore suggest that, at least in bright B stars (mostly early B stars), the X-ray emission mechanism should be analogous to those invoked to explain the X-ray emission of O stars.

We have therefore looked for relationships between X-ray emission and wind diagnostics in Herbig stars. We have started from the most readily available diagnostic, the equivalent width (EW) of the Hα emission line. With the values of EW(Hα) taken from Finkenzeller & Mundt (1984) and Herbig & Bell (1988), we have plotted L_x versus EW(Hα) (Fig. 7), finding them

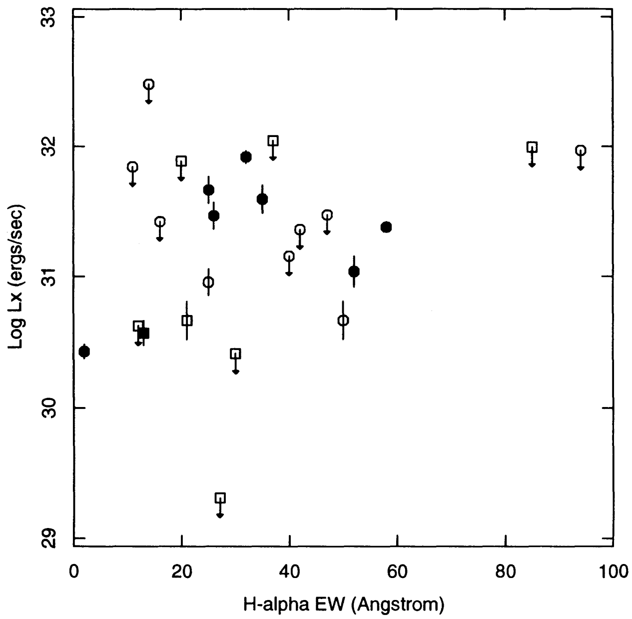

FIG. 7.—X-ray luminosity L_x vs. Hα equivalent width. Symbols as in Fig. 3.

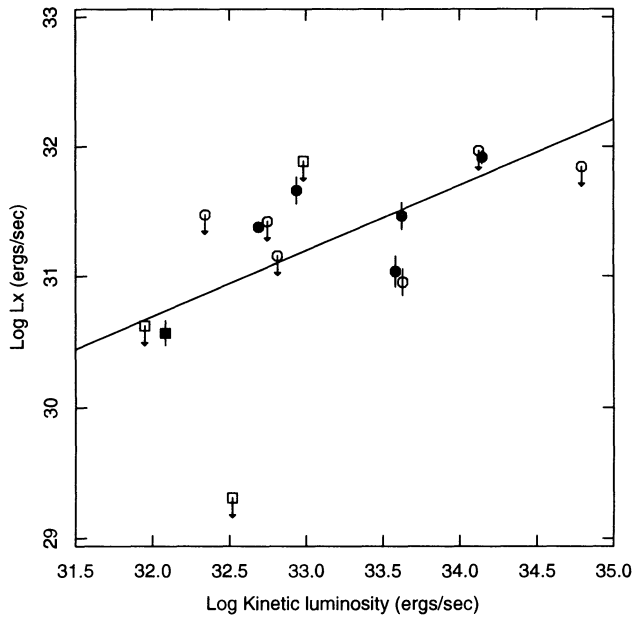

FIG. 8.—X-ray luminosity L_x vs. wind kinetic luminosity $1/2\dot{M}V_\infty^2$, derived as explained in the text. Symbols as in Fig. 3. The straight line is the best-fit relation found by Sciortino et al. (1990) for O stars.

to be uncorrelated. This is confirmed by the statistical tests, which give probabilities of no correlation of $P = 0.2393$ (Cox test) and $P = 0.2675$ (Kendall's τ-test). We have tried also using the Hα FWHM instead of equivalent width, and again this quantity is not correlated with L_x (Hα FWHMs have been taken from Finkenzeller & Mundt 1984). The rationale of such an attempt is that the Hα FWHM is related to a characteristic velocity of the stellar wind. However, this result is not discouraging our attempt to identify in a radiatively driven wind the region where X-rays from Herbig stars originate: also in O stars, it is found (Sciortino et al. 1990) that the X-ray luminosity is not correlated with the wind terminal speed V_∞, notwithstanding the correlation between X-ray and kinetic luminosity.

We have therefore tried to evaluate the wind kinetic luminosity in Herbig stars. Since, as we have mentioned, radiative transfer effects may be nonnegligible in the optical emission lines, the outflowing envelope may be optically thick to line radiation and therefore (partially) invisible. Optical emission lines are therefore not best suited for mass-loss rate estimates (at least in the absence of a detailed model of the line formation). Instead, Skinner et al. (1993) gives an useful relation between the mass-loss rate of Herbig stars, obtained through radio measurements, and stellar bolometric luminosity, namely, $\log \dot{M} = -9.1 + 0.6 \log (L_{\rm bol}/L_\odot)\ M_\odot\ {\rm yr}^{-1}$. We shall adopt this parametrization for the mass-loss rate in deriving wind kinetic luminosities. The wind terminal speed V_∞ might in principle be evaluated from the extent of the wings of emission-line profiles, but again the wide variety of line profiles encountered in Herbig stars makes it difficult to find a well-identified line-profile feature, unambiguously marking the wind terminal speed for every star in the class. Rather, we have preferred to estimate V_∞ by taking it equal to the Hα FWHM (using $\Delta\lambda/\lambda = v/c$), which should approximately scale proportionally to the wind speed.

The scatter plot in Figure 8 shows that L_x and the kinetic luminosity $1/2\dot{M}V_\infty^2$ are indeed correlated, although with some scatter. The Cox and Kendall's tests give as probabilities of no correlation $P = 0.0266$ and $P = 0.0493$, respectively. Our hypothesis that, like in O stars, the X-ray emission of Herbig stars originates from instabilities (shocks) in a radiatively driven wind is not contradicted by these data. The scatter visible in Figure 8 is probably mainly due to our rough evaluation of the kinetic luminosities, and in some cases to the low S/N of the X-ray data. We should note again, as we did about the L_x-$L_{\rm bol}$ correlation, that the correlation between L_x and kinetic luminosity tends to disappear when we consider only the Be stars, but nevertheless the occurrence of strong X-ray emission almost uniquely in stars having strong winds still argues in favor of a wind origin for the observed X-ray emission for Herbig stars.

A wind origin for the X-ray emission is further suggested by the close proximity of the data points in Figure 8 to the best-fit regression line derived by Sciortino et al. (1990) for the case of O stars (also reported in Fig. 8), despite the quite different X-ray emission levels of O stars with respect to Herbig stars. We also note that Grillo et al. (1992b) find that ordinary Be stars follow the same relation, extending it to even smaller X-ray luminosities than those of Herbig stars.

As a final check, we have estimated the wind momentum flux $\dot{M}V_\infty$, using mass-loss rates and wind speed, as before, and have made a scatter plot of L_x versus $\dot{M}V_\infty$. This looks very similar to the previous one involving the kinetic luminosity, giving essentially no new information. It is not possible, on the basis of available data, to establish which one of these two correlations better describes the real situation. We should mention a possible difficulty of the wind-shock model when it is applied to Herbig stars, namely, that wind terminal velocities are here much lower than in OB stars, leading to weaker shocks. In any case, shock speeds of about 300 km s^{-1}, not implausible in Herbig stars, are sufficient to raise the temperature of the shocked material to 10^6 K (see MacFarlane & Cassinelli 1989), making it detectable with the IPC. Although the IPC X-ray spectra are of insufficient quality to give us further insight on this issue, the analysis of new *ROSAT* PSPC data of Herbig stars will allow us to put more stringent constraints on the proposed model.

Our suggestion that the X-ray emission of Herbig stars arises from shocked regions within the stellar wind is not in contradiction with existing models of optical/UV line formation in the wind (Catala 1988, and references therein), since we have checked that in order to produce the observed X-ray emission only a small fraction of the wind volume needs to be hotter than the maximum temperature allowed by these models (about 2–3 $\times$ 10^4 K), and such a small amount of very hot material is unlikely to alter the thermal balance in the wind significantly. Assuming that X-ray emission arises in a single, spherically symmetric shocked region of width dR and radial distance R, we have computed an order-of-magnitude estimate of dR/R for HD 200775, the star of our sample detected with the highest S/N in X-rays. From X-ray spectral fits, we get an emission measure EM ($=n_e^2 V$) of 4.3 $\times$ 10^{54} cm^{-3}, where n_e is the electron density and V is the emitting volume. We write $V = 4\pi R^2 \, dR$ and $n_e \sim \dot{M}/4\pi R^2 v \langle m \rangle$, the latter corresponding to ionized hydrogen gas, appropriate for shocked regions; v is the wind speed at R, and $\langle m \rangle$ is the average particle mass. Using the same parametrization as above, $\dot{M} = 2.8 \times 10^{-7}$ $M_\odot$ yr^{-1}; we get $v = 280$ km s^{-1} from the Hα FWHM, and the stellar radius $R_* = 9.6 \times 10^{11}$ cm from $L_{\rm bol} = 4\pi R_*^2 \sigma T_{\rm eff}^4$. Setting the distance of the shocked region R to be twice R_*, we obtain $dR/R \sim 10^{-3}$. Therefore, hot X-ray–emitting regions occupy only a minor fraction of the envelopes of these stars.

We should remark that the suggested wind-shock picture does not apply to a star such as TY CrA, which lacks emission lines entirely, and accordingly it does not appear in Figure 8. Other evidence exists that this is a peculiar object (a binary star with a nonthermal radio spectrum; Kardopolov et al. 1981; Skinner et al. 1993), and therefore its X-ray emission also may have a different nature than that of other Herbig Ae/Be stars.

5. CONCLUSIONS

Although the sample available for our study of X-ray emission from Herbig Ae/Be stars was rather limited and the sensitivity of *Einstein* IPC observations allowed us only to detect the X-ray–brightest members of the class, some interesting results have nevertheless been obtained from this study.

Herbig Ae stars remained mostly undetected in X-rays. The only case of detection is VY Mon/G2, a member of an X-ray–unresolved group, and its X-ray emission level is well compatible with its originating from the companions. Furthermore, the derived upper limits on L_x are lowest in the case of Ae stars, excluding X-ray luminosities in excess of $10^{30.5}$ ergs s^{-1} in many cases. Therefore, no clear evidence exists from IPC data of any X-ray emission intrinsic to Herbig Ae stars, at least none of any above $L_x \sim 10^{30.5}$ ergs s^{-1}.

On the other hand, Herbig Be stars have in many cases been confidently identified with X-ray sources, and X-ray luminosities $L_x \geq 10^{31}$ ergs s^{-1} seem to be produced by the Be stars themselves; such high luminosities are incompatible with emission from late-type PMS companions. In the case of undetected Be stars, the L_x upper limits we have found are compatible with the high X-ray luminosities of the detected stars.

Herbig Be stars are more frequently detected in X-rays than main-sequence B stars. On the main sequence, Grillo et al. (1992a) find that almost exclusively early B stars are detected in X-rays, while late B stars are more rarely X-ray emitters. We detect three (out of seven observed) B7–B9 Herbig stars, a fraction apparently higher than the main-sequence value, although the small statistics prevents any definitive conclusion. Since we have also found that the X-ray luminosity is correlated with bolometric luminosity, the location of the Herbig stars above the main sequence in the H-R diagram might explain their apparently higher X-ray detection percentages with respect to main-sequence B stars.

The trend of increasing X-ray luminosity with stellar bolometric luminosity (or effective temperature) we observe contradicts some of our initial expectations, namely, that during PMS evolution transient magnetic dynamo activity might give rise to observable X-ray emission. As we pointed out in § 1, there is both theoretical support (Palla & Stahler 1990, 1991, 1993) and some observational evidence for the existence of such magnetic activity, at least for Ae stars. It is worth noting here that exactly those stars for which evidence of magnetic fields has been found (AB Aur [Praderie et al. 1986] and HD 250550 [Catala et al. 1991]) remain undetected in our X-ray study. Thus, magnetic activity, although likely present in these stars, is not able to produce very strong X-ray–emitting coronae; to probe the existence of moderately active magnetic coronae on Herbig (Ae) stars, X-ray observations more sensitive than those available with the IPC are needed.

The X-ray emission of the detected Herbig stars, instead, seems not to have a magnetic origin. It is not correlated with the stellar rotation, as in late-type stars, but rather increases with the total stellar luminosity. Moreover, L_x is correlated with the emission in the near-IR K band and in the 25 μm *IRAS* band, and this may suggest that the X-ray emission region lies at some distance from the stellar surface.

We suggest that the X-ray emission of Herbig Be stars may have an origin analogous to that of the X-ray emission O and early B stars: in these latter, the strong UV line emission from the stellar photospheres is able to radiatively drive a strong wind; however, the wind-driving mechanism is intrinsically unstable, and shocks may easily develop in which the outflowing plasma is locally heated to sufficiently high temperatures to emit X-rays. This is in accordance with the dependence of X-ray luminosity on stellar luminosity (which ultimately drives the wind) and can be checked by investigating the relationships between X-ray emission and the power (or momentum flux) deposited in the wind. The fact that a correlation is indeed found between L_x and the wind kinetic luminosity (and momentum flux) gives additional support to our suggestion of a wind origin for X-ray emission of Herbig stars. It is also noticeable in this respect that the X-ray emission from Herbig stars follows the same relation with the wind kinetic luminosity derived by Sciortino et al. (1990) in the case of O stars. Our data are of insufficient quality, however, to discriminate between this picture and the existence of some other (yet unknown) alternative mechanism directly relating the generation of X-ray emission to stellar bolometric luminosity; in the latter case, the correlations we find between L_x and wind diagnostics would simply be a by-product of the correlation between L_x and $L_{\rm bol}$.

To overcome many of the ambiguities encountered in the X-ray source identification and to detect a larger number of stars in X-rays at lower luminosity levels, new X-ray observations are needed, with higher spatial resolution and sensitivity than those performed with the *Einstein* IPC. Advances in the X-ray study of Herbig stars are expected from new *ROSAT* observations. To this end, we have recently obtained *ROSAT* PSPC data on three Herbig stars (HD 200775, BD +61°154, and VV Ser; see Damiani et al. 1994b for a preliminary report), and we are currently investigating the applicability of the wind-shock picture to the X-ray emission of Herbig stars in the light of the more detailed PSPC X-ray spectra now available. We plan to report on these new observations in a future paper.

We acknowledge support by the Italian Ministero per la Ricerca Scientifica e Tecnologica, CNA-CNR, and Agenzia Spaziale Italiana (F. D., G. M., and S. S.). F. R. H. acknowledges partial support under NASA contract NAS 8-30751. We are grateful to S. Serio, F. Reale, M. Barbera, and F. Grillo for useful comments on this work. This research has made use of the SIMBAD database, operated at Centre, de Données Stellaires, Strasbourg, France. We are also indebted to T. Simon and the referee for their suggestions, which allowed us to improve this paper.

REFERENCES

Avni, Y., Soltan, A., Tananbaum, H., & Zamorani, G. 1980, ApJ, 238, 800
Berrilli, F., Corciulo, G., Ingrosso, G., Lorenzetti, D., Nisini. B., & Strafella, F. 1992, ApJ, 398, 254
Boesono, B., Thé, P. S., & Tjin A. Djie, H. R. E. 1987, Ap&SS, 137, 167
Bouvier, J. 1990, AJ, 99, 946
Caillault, J.-P., Zoonematkermani, S. 1989, ApJ, 338, L57
Casey, B. W., Mathieu, R. D., Suntzeff, N. B., Lee, C.-W. Cardelli, J. A. 1993, AJ, 105, 2276
Catala, C. 1988, A&A, 193, 222
———. 1989, in Low Mass Star Formation and Pre–Main-Sequence Evolution, ed. B. Reipurth (Garching: ESO), 471
Catala, C., Czarny, J., Felenbok, P., Talavera, A., & Thé, P. S. 1991, A&A, 244, 166
Chlebowski, T., & Garmany, C. D. 1991, ApJ, 368, 241
Chlebowski, T., Harnden, F. R., & Sciortino, S. 1989, ApJ, 341, 427
Cohen, M., & Kuhi, L. V. 1979, ApJS, 41, 743
Damiani, F., & Micela, G. 1994, ApJ, submitted
Damiani, F., Micela, G., Sciortino, S., & Harnden, F. R. 1994a, ApJ, submitted
Damiani, F., Micela, G., & Vaiana, G. S. 1991, in Angular Momentum Evolution of Young Stars, ed. S. Catalano & J. R. Stauffer (Dordrecht: Kluwer), 89
Damiani, F., Sciortino, S., & Micela, G. 1994b in The Nature and Evolutionary Status of Herbig Ae/Be Stars, ed. P. S. Thé, M. Perez, & E. P. J. van den Heuvel (ASP Conf. Ser.), in press
Davis, R., Strom, K. M., & Strom, S. E. 1983, AJ, 88, 1644
Emerson, J. P. 1988, in Formation and Evolution of Low-Mass Stars, ed. A. K. Dupree & M. T. V. T. Lago (Dordrecht: Kluwer), 193
Feigelson, E. D., Casanova, S., Montemerle, T., & Guilbert, J. 1993, ApJ, 416, 623
Feigelson, E. D., & Nelson, P. I. 1985, ApJ, 293, 192
Finkenzeller, U. 1985, A&A, 151, 340
Finkenzeller, U., & Mundt, R. 1984, A&AS, 55, 109
Giacconi, R., et al. 1979, ApJ, 230, 540
Gorenstein, P., 1975, ApJ, 198, 95
Grillo, F., Sciortino, S., Micela, G., Vaiana, G. S., & Harnden, F. R. 1992a, ApJS, 81, 795
———. 1992b, Mem. Soc. Astron. Ital., 63, 739
Hamann, F., & Persson, S. E. 1992, ApJS, 82, 285
Harnden, F. R., Jr., Fabricant, D. G., Harris, D. E., & Schwartz, J. 1984, Smithsonian Astrophys. Obs. Spec. Rep., No. 393
Harnden, F. R., Sciortino, S., Micela, G., Maggio, A., Vaiana, G. S., & Schmitt, J. H. H. M. 1990, in Imaging X-ray Astronomy, ed. M. Elvis (Cambridge: Cambridge Univ. Press), 313
Harris, D. E., et al. 1993, NASA Technol. Memo. 108401
Hartmann, L., Kenyon, S. J., & Calvet N. 1993, ApJ, 407, 219
Hartmann, L., Kenyon, S. J., Hewett, S. J., Edwards, S., Strom, K. M., Strom, S. E., & Stauffer, J. R. 1989, ApJ, 338, 1001
Herbig, G. H. 1960, ApJS, 4, 337
Herbig, G. H., & Bell, K. R. 1988, Third Catalog of Emission-Line Stars of the Orion Population, Lick Obs. Bull. No. 1111
Hillenbrand, L. A., Strom, S. E., Vrba, F. J., & Keene, J. 1992, ApJ, 397, 613
Iben, I. 1965, ApJ, 141, 993
Isobe, T., Feigelson, E. D., & Nelson, P. I. 1986, ApJ, 306, 490
Kardopolov, V. I., Sahanionok, V. V., & Philipjev, G. K. 1981, Perem. Zvezdy (Variable Stars), 21, 589
Lada, C. J., & Adams, F. C. 1992, ApJ, 393, 278
LaValley, M., Isobe, T., & Feigelson, E. D. 1992, BAAS, 24, 839
Levreault, R. M. 1988, ApJS, 67, 283
MacFarlane, J. J., & Cassinelli, J. P. 1989, ApJ, 347, 1090
Maggio, A., Sciortino, S., Vaiana, G. S., Majer, P., Bookbinder, J., Golub, L., Harnden, F. R., & Rosner, R. 1987, ApJ, 315, 687
Micela, G., Sciortoni, S., Vaiana, G. S., Harnden, F. R., Rosner, R., & Schmitt, J. H. M. M. 1990, ApJ, 348, 557
Palla, F., & Stahler, S. W. 1990, ApJ, 360 L47
———. 1991, ApJ, 375, 288
———. 1993, ApJ, 418, 414
Pallavincini, R., Golub, L., Rosner, R., Vaiana, G. S., Ayres, T. R., & Linsky, J. L. 1981, ApJ, 248, 297
Praderie, F., Simon, T., Catala, C., & Boesgaard, A. M. 1986, ApJ, 303, 311
Pravdo, S. H., & Marshall, F. E. 1981, ApJ, 248, 591
Proust, D., Ochsenbein, F., & Pettersen, B. R. 1981, A&AS, 44, 179
Sanders, W. T., Cassinelli, J. P., & Anderson, C. M. 1982, BAAS, 14, 629
Schmitt, J. H. M. M. 1985, ApJ, 293, 178
Schmitt, J. H. M. M., Golub, L., Harnden, F. R., Jr., Maxson, C. W., Rosner, R., & Vaiana, G. S. 1985, ApJ, 290, 307
Sciortino, S., Harnden, F. R., Maggio, A., Micela, G., Vaiana, G. S., Schmitt, J. H. H. M., & Rosner, R. 1988, in Astronomy from Large Databases, ed. F. Murtagh & A. Heck (Garching: ESO)
Sciortino, S., Vaiana, G. S., Harnden, F. R., Ramella, M., Morossi, C., Rosner, R., & Schmitt, J. H. H. M. 1990, ApJ, 361, 621
Skinner, S. L., Brown, A., & Stewart, R. T. 1993, ApJS, 87, 217
Strom, S. E., Strom, K. M., Yost, J., Carrasco, L., & Grasdalen, G. 1972, ApJ, 173, 353
Vaiana, G. S., et al. 1981, ApJ, 245, 163
Walter, F. M., & Kuhi, L. V. 1981, ApJ, 250, 254
Weaver, W. B., & Jones, G. 1992, ApJS, 78, 239
Zinnecker, H., & Preibisch, T. 1994, in The Nature and Evolutionary Status of Herbig Ae/Be Stars, ed. P. S. Thé, M. Perex, & E. P. J. van den Heuvel (ASP Conf. Ser.), in press