THE X-RAY ORIGIN OF HERBIG AeBe SYSTEMS: NEW INSIGHTS

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ABSTRACT

We present a statistical study of the X-ray emission toward 22 Herbig AeBe stars (HAEBE) using the Chandra archive. We probe the origin of the X-rays toward Herbig stars: are they intrinsic? This question is addressed by correlations between the physical stellar properties and the X-ray emission. There is a weak correlation between the continuum radio emission at $\lambda = 3.6$ cm and $L_X$, which suggests that the X-ray emission depends upon the source. On the other hand, no correlation was found with the stellar rotational period, but that only excludes solar-like magnetic activity as the origin of the X-rays. Most importantly, the X-ray luminosity of HAEBE has a different distribution from that of T Tauri stars, suggesting that X-ray emission from an unseen late-type star companion can be ruled out with an 80% confidence level. This implies that the HAEBE must have magnetic activity. In addition, we report the observation of five sources for the first time, in three detections.

Key words: methods: statistical – radiation mechanisms: thermal – stars: pre-main sequence – X-rays: stars

1. INTRODUCTION

Herbig AeBe stars (HAEBE) are young intermediate-mass stars, ranging roughly from 2 to 20 $M_\odot$ of spectral types A, B and early F (Herbig 1960). They are considered the more massive counterparts of T Tauri stars (TTS). The study of HAEBE disks has attracted particular interest in investigating their formation and evolution into planetary systems. Unfortunately, their pre-main-sequence (PMS) evolution is more difficult to study with as much detail as TTS, as they are less abundant and evolve faster; the formation and evolution processes are presumably accelerated and more embedded. The existence of circumstellar disks in HAEBE systems was confirmed with interferometric millimeter observations (e.g. Mannings & Sargent 1997), and more recent results have resolved these disks (e.g. Hamidouche et al. 2006). Fuente et al. (2003) have reported the first evidence of a disk around the more massive Herbig Be stars. The detection of these disks is relevant in probing the X-ray origin in HAEBE systems. In fact, numerous authors have already suggested that star–disk magnetic interactions may generate the X-rays (Montmerle et al. 2000).

Although X-ray detection toward HAEBE stars has become quite common (e.g. Hamaguchi et al. 2005; Stelzer et al. 2006), its origin is more difficult to explain than the X-ray detection of lower mass TTS. The later-type TTSs are also routinely observed in the X-ray. The process usually invoked to explain their X-ray origin is solar-type coronal loops in the 1–10 keV band (Feigelson et al. 2007), while in some active protostars, larger magnetic structures can possibly connect the stellar photosphere and the circumstellar accreting disk (Montmerle et al. 2000; Feigelson et al. 2007). Using the Chandra Orion Ultralow Energy Project (COUP; Getman et al. 2005a), and the XMM-Newton Extended Survey of the Taurus Molecular Cloud (XEST; Güdel 2007), several studies have shown that TTS X-rays are mostly due to coronal emission and not to accretion emission, which only has a minor effect in the soft <1 keV regime (e.g. Preibisch 2007; Güdel 2007). Nevertheless, accreting stars were found to have a lower X-ray activity than non-accreting stars. The accreting material cools down the corona hot plasma. Therefore, the cool plasma generates very soft X-rays hardly detectable with Chandra and XMM-Newton (Preibisch 2007).

Numerous surveys of X-ray emission toward HAEBE stars have been done: Stelzer et al. (2006) have reported a fraction of $\sim$76% from a sample of 17 sources using Chandra, including emission from known companions; Hamaguchi et al. (2005) have detected 31% from a sample of 35 sources using ASCA; Zinnecker & Preibisch (1994) have detected 52% from a sample of 21 sources using ROSAT; and Damiani et al. (1994) have detected 35% from a sample of 31 sources using Einstein.

In this paper, we report on a sample of 22 sources using the Chandra archive, 17 sources from Stelzer et al. (2006), and five new sources. With these data, we compare the X-ray emission to the stellar properties in order to look for possible correlations, and hence whether the X-rays are intrinsic to the Herbig stars or not.

2. DATA SAMPLE AND OBSERVATIONS

We have correlated the Chandra archive with the HAEBE stars catalogs of Mora et al. (2001), Natta et al. (2000), Thé et al. (1994), and Hillenbrand et al. (1992). We chose the sources of spectral types earlier than F5. This provides a sample to probe and compare the X-rays of both the coolest Herbig Ae (late B, A, and early F) stars and the Herbig Be (early/mid B) stars (e.g. Natta et al. 2000). Data mining the Chandra’s public archive for observed sources allowed us to make a list of 22 HAEBE observations, whether they were serendipitous observations or not. In fact, there are 13 sources that were not observed as the main target, but were in the field of view during other observations. The list of sources with known stellar parameters is given in Table 1.

Fortuitously, our sample includes HAEBE sources of different spectral types, which will provide a better analysis of the X-ray properties of HAEBE stars. Our sample includes stars of masses ranging between $\sim$2–26 $M_\odot$ of different ages between $10^5$ and $10^7$ years (van den Ancker et al. 1998, 2000).

Table 2 summarizes the Chandra observations. The observations are obtained with the Advanced CCD Imaging Spectrometer (ACIS) detector within Chandra’s band 0.5–10 keV. Although many of our sources were reported in

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Table 1

| Object         | Spectral type | Distance (pc) | Log $L_{X\text{tot}}^{a,b}$ ($\text{ergs s}^{-1}$) | $S_{15,\mu\text{m}}^{c}$ (mJy) | Log $T_{e}^{b}$ (K) | $v_{\text{rad}}^{b}$ (km s$^{-1}$) | $v_{\text{bulk}}^{b}$ (km s$^{-1}$) | R.A. a.b.d | Decl. a.b.d | 
|----------------|---------------|---------------|-----------------------------------------------|-----------------------------|---------------------|---------------------------------|---------------------------------|------------|------------|
| MWC 297       | B1Ve          | 250           | 38.08                                        | <8.78                       | 4.52                | 385                            | 380                             | 18 27 39.6 | -03 49 52  |
| LP Ori        | B2            | 460           | 36.68                                        |                             | 4.29                | 100                            |                                 | 05 35 09.83 | -05 27 53.33 |
| HD 147889     | B2            | 140           | 36.88                                        |                             | 3.43                |                                 |                                 | 16 25 24.31 | -24 27 56.56 |
| V361 Ori      | B4/S          | 460           | 36.18                                        |                             | 4.14                | 50                             |                                 | 05 35 31.43 | -05 25 54.05 |
| Z CMa         | B5            | 1150          | 36.98                                        | 3.1                         | 3.80                | <130                           | 500                             | 07 03 43.16 | -11 33 06.20 |
| Lkhu 25       | B7            | 800           | 36.51                                        | <0.10                       | 4.05                |                                 | 340                             | 06 40 44.56 | +09 48 02.2  |
| BD+30 549     | B8/V          | 390           | 34.68                                        |                             | 4.08                |                                 |                                 | 03 29 19.77 | +31 24 57.04 |
| R CrA         | A5II          | 130           | 35.68                                        | 0.23                        | 4.06                |                                 | 150                             | 19 01 53.65 | -36 57 07.62 |
| V380 Ori      | B8/A1         | 460           | 35.48                                        | <0.09                       | 3.97                | 200                            | 260                             | 05 36 25.43 | -06 42 57.70 |
| HD 97300      | B9V           | 188           | 35.08                                        |                             | 4.03                |                                 |                                 | 11 09 50.01 | -76 36 47.72 |
| HD 100546     | B9V           | 103 $\pm$ 7   | 35.09                                        |                             | 4.04                | 65 $\pm$ 5                      |                                 | 11 33 25.44 | -70 11 41.23 |
| HD 176386     | B9            | 130           | 35.28                                        |                             | 4.03                |                                 |                                 | 01 19 38.93 | -36 53 26.54 |
| HD 141569     | B9.5          | 99 $^{+9}_{-7}$ | 34.93                                        |                             | 4.02                | 258 $\pm$ 17                   |                                 | 15 49 57.74 | -03 55 16.36 |
| AB Aur        | B9/A0V        | 144 $^{+17}_{-17}$ | 35.28                                        | 0.15                        | 3.98                | 140                            | 225                             | 04 55 45.84 | +30 33 04.29 |
| V372 Ori      | B9.5V         | 460           | 35.8                                         |                             | 3.93                | 125                            |                                 | 05 34 46.98 | -05 34 14.60 |
| HD 150193     | A2IV          | 150 $^{+30}_{-30}$ | 35.01                                        | 0.16                        | 4                   | 100                            | 130                             | 16 40 17.92 | -23 53 45.18 |
| HD 163296     | A1            | 122 $^{+13}_{-13}$ | 35.06                                        | 0.42                        | 3.97                | 135 $\pm$ 6                    | 220                             | 17 56 21.28 | -21 57 21.88 |
| MR Ori        | A2V           | 460           | 35.48                                        |                             | 3.93                |                                 |                                 | 05 35 16.99 | -05 21 45.6  |
| TY CrA        | B9            | 130           | 35.38                                        | 1.2                         | 4.07                | 10                             |                                 | 19 01 40.83 | -36 52 33.88 |
| Elias 3-1     | A6            | 160           | 33.46                                        | 0.48                        | 3.91                |                                 | 250                             | 04 18 40.60 | +28 19 16.7  |
| HD 104237     | A4            | 116 $^{+6}_{-5}$ | 35.18                                        |                             | 3.93                | 12 $\pm$ 2                     | 500                             | 12 00 05.08 | -78 11 34.56 |
| AK Sco        | F5IV          | 150 $^{+30}_{-30}$ | 34.46                                        |                             | 3.81                | 18.5 $\pm$ 1                   |                                 | 16 54 44.84 | -36 53 18.57 |

Notes.

a References: Hillenbrand et al. (1992), Thé et al. (1994), Malffait et al. (1998), van den Ancker et al. (1998), Natta et al. (2000), Fuente et al. (2002), and Hamaguchi et al. (2005).

b References: Damiani et al. (1994), Skinner et al. (1993), and Mora et al. (2001).

c Reference: S$_{\text{15,\mu m}}$ are from Skinner et al. (1993), Forbrich et al. (2006), and Natta et al. (2004).

d Reference: this research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

Stelzer et al. (2006), the fact that we have five additional sources leads us to re-analyze all of them in order to be consistent. In addition, our detection criteria are more focused on the removal of companion emission (see HD 150193 in Section 3.1). The Chandra data analysis software CIAO$^2$ version 3.1 and the X-ray spectral fitting package XSPEC version 11.3 (Arnaud 1996) are used for our data reduction and analysis. We obtained the Event 2 level processed data from Chandra archives. We extract the background light curve and use ChIPS to exclude the time periods of high background by removing spikes on the background light curve. These processes give the good time interval. The event files with applied good time interval are then used to detect point sources and further extract spectra of these sources.

The WAVEDETECT was used to detect point sources within a 50 $\times$ 50 pixel area centered on the source IR/optical position. This algorithm uses Mexican Hat wavelet functions to correlate the images and identify source regions with large positive correlation. We generate regions centered at the detected peak emission within a 3$\sigma$ ellipse, including 90% of the point-spread function (PSF) at 1.497 keV. With detected point sources, we use Sherpa to plot the radial profile to look for any possible signatures of extra emission that may be due to companions.

3. RESULTS AND DISCUSSIONS

3.1. X-Ray Detections

Count rates are estimated within a circular or elliptical region, depending on the source geometry, around the optical position of the source after removing the background. The background is estimated in a different region of the image map and normalized by the surface area of the source region. Our criteria for the detection was based on the signal-to-noise ratio (S/N) higher than $\approx$3. The count rate was estimated in the “broad” band...
The X-ray luminosity rate uncertainties, we consider distance uncertainties to estimate is the distance of the source (Table 1). In addition to the count-rates allows an estimation of the flux density for the other flux density values of the eight brightest sources against the derived from this spectral analysis. Extrapolating linearly the $N_{\text{H}}$ emissivities (Kaastra & Mewe2000)( Table 4). The flux density, Table 3 summarizes all the sources and their correspond-
tions of 8 of the detected sources were serendipitous observa-
tions. The number of detected sources is 14, out of 22 sources; for the eight brightest detected sources, the flux density was derived by fitting thermal plasma models based on MEKAL 2 emissivities (Kaastra & Mewe 2000) (Table 4). The flux density, gas column density $N_{\text{H}}$, and the gas temperature $kT$ are then derived from this spectral analysis. Extrapolating linearly the flux density values of the eight brightest sources against the count rates allows an estimation of the flux density for the other six sources, which have lower count rates. $N_{\text{H}}$ from the spectra fitting could be used to correct our flux from the absorption of the gas through the line-of-sight. However, we chose not to correct our flux since these $N_{\text{H}}$ values are not well determined (e.g. V361 Ori, HD 97300, V372 Ori, HD 104237.

Notes. a The underlined sources' observations are reported in this study for the first time (Section 3.1).

The number of detected sources is 14, out of 22 sources; 8 of the detected sources were serendipitous observations of Chandra, 3 of which had not yet been reported. Table 3 summarizes all the sources and their corresponding X-ray luminosity. The upper limits were estimated at a 90% confidence level using the Bayesian method (Kraft et al. 1991). The deduced percentage of HAEBE stars de-
tected $\geq 43\%$ (see Table 3), compared to 64% from Stelzer et al. 2006. Out of the five Herbig Be stars, earlier than B6, three were detected (60%), and of the 17 Herbig Ae stars, 11 were detected (65%).

The X-ray parameters from the spectral analysis (Table 4) are then used to estimate the flux densities for the other sources, which have lower count rates. $N_{\text{H}}$ from the spectra fitting could be used to correct our flux from the absorption of the gas through the line-of-sight. However, we chose not to correct our flux since these $N_{\text{H}}$ values are not well determined (e.g. V361 Ori, HD 97300, V372 Ori, HD 104237.

Notes. a Fitted temperatures using one- or two-temperature MEKAL models, based on the best fit model or $\chi^2$. However, AK Sco shows a very low count rate below our detection criteria; we do not consider it as detected. We have also detected X-ray emission toward HD 150193, but it is offset by $\approx 2.5\arcsec$ from its optical position (see Stelzer et al. 2006). These sources were both considered detected by Stelzer et al. 2006.

In addition, this is the first study where Chandra observations toward the additional five sources (underlined in Table 3) are reported (Figure 1). From these five sources, we detected V361 Ori, AB Aur, and V372 Ori, and did not detect LP Ori and MR Ori. Using ASCA, Hamaguchi et al. (2005) also did not detect LP Ori or MR Ori. In the ROSAT survey, Zinnecker & Preibisch (1994) detected AB Aur with a slightly higher Log $L_X = 29.5$ ergs s$^{-1}$, while it was not detected by Hamaguchi et al. (2005) and Damiani et al. (1994) using Einstein. V372 Ori was detected by Gagne et al. (1995) in a ROSAT survey, Log $L_X = 30.3$ ergs s$^{-1}$. These results are consistent with our detections; however, our $L_X$ are slightly lower since we did not correct for absorption. This is the first detection of V361 Ori.

Table 3

| Object | S/N | Count rate (cts ks$^{-1}$) | PSF | $\log L_X$ (ergs s$^{-1}$) | Intended target | $\log L_X/L_{bol}$ | Detected |
|--------|-----|--------------------------|-----|--------------------------|-----------------|-------------------|-----------|
| MWC 297 | 4.54 | 2.88 ± 0.52 | 0.9 | 29.53 ± 0.18 | Yes | −8.54 | Yes |
| LP Ori | 0.78 | <0.027 | 0.9 | <29.87 | No | −6.8 | No |
| HD 147899 | 1.28 | <0.62 | 0.9 | <28.91 | No | −7.98 | No |
| V361 Ori | 54.64 | 44.59 ± 0.56 | 0.9 | 30.94 ± 0.17 | No | −5.24 | Yes |
| Z CMa | 6.33 | 1.08 ± 0.15 | 0.9 | 30.75 ± 0.17 | Yes | −6.14 | Yes |
| Lkhr 25 | 0.98 | <0.04 | 0.9 | <30.36 | No | −6.15 | No |
| BD+30 349 | 4.92 | 1.05 ± 0.13 | 0.6 | 29.81 ± 0.16 | No | −4.87 | Yes |
| R CrA | 10.73 | 3.04 ± 0.18 | 0.9 | 28.98 ± 0.17 | Yes | −6.69 | Yes |
| V380 Ori | 30.49 | 47.36 ± 1.08 | 0.9 | 30.88 ± 0.17 | No | −4.60 | Yes |
| HD 97300 | 32.76 | 16.03 ± 0.34 | 0.9 | 29.66 ± 0.18 | No | −5.4 | Yes |
| HD 100546 | 5.90 | 13.11 ± 1.96 | 0.9 | 29.13 ± 0.18 | Yes | −6.1 | Yes |
| HD 176386 | 1.14 | <0.05 | 0.9 | <28.84 | No | −6.43 | No |
| HD 141569 | 1.26 | <0.66 | 0.9 | <28.59 | Yes | −6.33 | No |
| AB Aur | 5.28 | 0.59 ± 0.13 | 0.55 | 28.92 ± 0.17 | No | −6.36 | Yes |
| V372 Ori | 17.55 | 6.43 ± 0.28 | 0.9 | 29.97 ± 0.17 | No | −5.83 | Yes |
| HD 150193 | 1.95 | <1.4 | 0.5 | <29.00 | Yes | −6.00 | No |
| HD 163296 | 34.28 | 53.70 ± 1.18 | 0.9 | 29.47 ± 0.19 | Yes | −5.59 | Yes |
| MR Ori | 0.62 | <0.07 | 0.9 | <29.88 | No | <5.59 | No |
| TY CrA | 71.55 | 134.88 ± 1.31 | 0.9 | 30.31 ± 0.18 | No | −5.07 | Yes |
| Elias 3-1 | 39.87 | 89.26 ± 1.40 | 0.9 | 30.36 ± 0.19 | No | −3.10 | No |
| HD 104237 | 20.48 | 154.34 ± 5.67 | 0.9 | 30.03 ± 0.18 | Yes | −5.15 | Yes |
| AK Sco | 1.31 | <0.63 | 0.9 | <28.95 | Yes | <5.50 | No |

Notes.

Table 4

| Object | Model | $T^a$ (keV) | $N_{\text{H}}$ (10$^{22}$ cm$^{-2}$) | $\chi^2$ (dof)$^b$ |
|--------|-------|-------------|-------------------------------|-------------------|
| V361 Ori | 2T | 0.95, 3.08 | 0.13 ± 0.03 | 0.38(273) |
| V380 Ori | 2T | 1.12, 2.31 | 0.15 ± 0.07 | 0.44(121) |
| HD 97300 | 2T | 0.86, 2.91 | 0.31 ± 0.15 | 0.17(310) |
| V372 Ori | 1T | 0.97 | 0.18 ± 0.01 | 1.03(23) |
| HD 163296 | 1T | 0.39 | 0.06 ± 0.05 | 0.19(542) |
| TY CrA | 2T | 0.79, 2.07 | 0.21 ± 0.04 | 0.33(303) |
| Elias 3-1 | 1T | 2.18 | 0.67 ± 0.18 | 0.21(360) |
| HD 104237 | 1T | 0.67 | 0.38 ± 0.07 | 0.13(430) |

Notes.

a Fitted temperatures using one- or two-temperature MEKAL models, based on the best fit model or $\chi^2$.

b Reduced $\chi^2$ level and the number of degrees of freedom are shown in parentheses.

(0.5–8 keV), including both soft and hard X-rays. The sources with low S/N were classified as non-detections.

The underlined sources' observations are reported in this study for the first time (Section 3.1).
Figure 1. Maps of the five new observed Herbig sources with Chandra (Section 3.1). V361 Ori, V372 Ori, and AB Aur are detected and MR Ori and LP Ori are not detected (Table 3). The ellipses mark the PSF and the crosses the optical positions of the sources.
3.2. X-Ray Relations to Stellar Properties

If the X-ray emission is intrinsic to the stellar systems, there may be some correlation between the star and the X-ray emission. We have performed Kendall’s τ-tests, including the upper limits data (non-detections), as implemented in the ASURV package (Isobe et al. 1986). We first compare the stellar bolometric luminosity with the X-ray luminosity $L_X$. We find a mean ratio $\log(L_X/L_{bol}) = -5.62 \pm 1.18$ for the detected sources (Table 3). This ratio is consistent with the recent values found toward HAEBE stars (e.g. Skinner et al. 2004).

Figure 2 (top) shows $L_X$ for detected sources and upper limits for the undetected ones, versus $L_{bol}$. Most points are between the two lines corresponding to the TTS ratio $-3.75$ (Skinner et al. 2004) and main-sequence OB stars’ ratio $-7.0$ (Berghoefer et al. 1997). Using the Kendall’s τ-test, we found a probability of $P = 0.42$ that a correlation is not present. Interestingly, the test for the surface area $4\pi r^2 = L_{bol}/\sigma T_{eff}^4$ and $L_X$ provides a similar result $P = 0.39$ (Figure 2, bottom).

We probe the relations of $L_X$ with the stellar rotation period, $P_{rot} = 2\pi r_*/v_{rot} \sin i$, and the wind velocity $v_{wind}$, for the sources with known values (Table 1). We did not find a correlation between the luminosity ratio $L_X/L_{rot}$ and the stellar rotational period $P_{rot}$, Kendall τ-test probability of no correlation $P = 0.44$ (Figure 3). For comparison, late-type main-sequence stars are known to have a clear correlation between the luminosity ratio and the stellar rotation period (Pallavicini et al. 1981; Preibisch 2007). On the other hand, they did not use their non-detection limits, so we repeated the Kendall τ-test for only our detected sources and still did not find a strong correlation, probability of no correlation $P = 0.65$. Therefore, a solar-like magnetic dynamo mechanism can be excluded as the origin of HAEBE X-ray activity. We used the relation of mass-loss rate and bolometric luminosity for Herbig stars given by Skinner et al. (1993): $\log M = -9.1 + 0.6 \log(L_{bol}/L_{\odot}) \ M_\odot$ year$^{-1}$ to deduce the wind kinetic luminosity $L_{kin} = 1/2 M v_{wind}^2$. Figure 4 shows that $L_{kin}$ is below the dashed line, corresponding to $L_X = L_{kin}$, by about two orders of magnitude. In addition, Figure 5 shows that most points are above the maximum temperature, dashed line, that can be generated if all the kinetic energy is converted into thermal bremsstrah lung energy. Although only three sources have known $v_{wind}$ and do not satisfy this later condition, we can suggest that the wind-shock model does not appear as the origin of the X-ray emission for these sources. HD 104237 has a wind velocity that may generate part of the X-rays. Its corresponding point is below the dashed line (Figure 5). Skinner et al. (2004) have suggested a possible existence in this source of a thin convective zone of $\approx 0.9\%$ stellar radius and a magnetic activity, but it may not be strong enough to produce the detected $L_X$. We can naively suggest that a fraction of the wind kinetic energy can be a complementary process to the stellar coronal magnetic activity to produce the observed X-rays.

Figure 6 displays $L_X$ versus the radio continuum luminosity at $\lambda = 3.6$ cm, $L_{\nu,3.6\,\text{cm}}$. There is a correlation between the two variables. The Kendall τ-test’s probability of no correlation is only $P = 0.025$, which becomes $P = 0.01$ when only the
detected sources in both X-ray and radio are considered in the test. We deduce an almost linear relation between \( L_X \) and the stellar radio emission \( L_X \propto 10^{11–12}L_{3.6\text{ cm}} \) (Hz). Both X-ray and radio emissions can be related to the stellar magnetic activity at different levels, assuming that they come from the same star. Similarly, Güdel (2002) reported in his analysis toward active stars with a hot plasma emitting both thermal X-rays and nonthermal radio radiation. However, we note that our analysis is for Herbig Ae stars only, for which we know \( L_{3.6\text{ cm}} \), and they are known to possibly have a thin convective zone that may generate the X-rays (e.g. Skinner et al. 2004).

4. X-RAY EMISSION FROM COMPANIONS?

The X-ray emission from intermediate-mass HAEBE stars (and AB stars) is a standing puzzle as they are not known to have convective outer layers that generate the magnetic dynamo as in the lower-mass TTS (e.g. Feigelson & Montmerle 1999). The most common explanation of the X-ray origin is from an unresolved lower-mass TTS companion (e.g. Feigelson et al. 2003; Vink et al. 2005). However, Chandra cannot resolve companions closer than \( \lesssim 1'' \) or \( \sim 100–1000 \) AU for our sources. This is larger than the typical binary separations, which can be \( \sim 0.1'' \) (e.g. Baines et al. 2006; Tokovinin et al. 2006).

4.1. Comparison to the Orion Nebula Sources

We combine our detected HAEBE stars data with TTS and HAEBE stars observed in the Orion Nebula Cluster (ONC). The Orion observations used here are from the COUP project. COUP has detected more than 1600 X-ray sources of different spectral types and ages \( \sim 10^{6–7} \) yr, a similar age range to our sources. We select COUP stars that have known spectral types. Since COUP observations are much more sensitive than Chandra observations in our sample, we also truncated the COUP sample at \( L_X > 28.59 \) corresponding to the lowest \( L_X \) of our sample. This prevents a comparison of inhomogeneous observations in terms of sensitivity limit. Making a list with the ONC sources and completing it with our HAEBE stars gives us a unique opportunity to directly compare the X-ray luminosity distribution of different spectral-type stars. To make our statistical comparison consistent, we use their uncorrected luminosity distribution of different spectral-type stars. To make our statistical comparison consistent, we use their uncorrected luminosity with spectral type in both Group I and II. On the other hand, Group III shows a slight dependence of \( L_X \) on spectral type.

The sources were sampled into three groups of stellar objects: (1) Group I earlier than B3, (2) Group II intermediate-mass stars, HAEBE, of spectral type B3–F5, and (3) Group III TTS, spectral type later than F5. We chose to use the spectral type to make different groups instead of the mass since the spectral type is often better known. However, we checked the known masses of Group III sources (or TTS) and found that their masses \( \lesssim 5 M_\odot \) are consistent with TTS.

Figure 7 shows the X-ray luminosity variation with the spectral type. In Group I, the X-ray luminosity is very scattered, \( \sigma_{\log L_X} = 1.26 \), around the mean value \( \log L_X = 30.74 \). Group II sources are less scattered, \( \sigma_{\log L_X} = 0.82 \), and have a slightly lower mean value \( \log L_X = 30.1 \). We also note in Group II that the \( L_X \) range of our sources is similar to the range of intermediate-mass stars from the COUP observations. There is no apparent dependence of \( L_X \) with spectral type in both Group I and II. On the other hand, Group III shows a slight dependence of the luminosity with spectral type. It decreases with the spectral type. The luminosity mean value is \( \log L_X = 29.76 \), smaller than in Group I and slightly smaller than in Group II. Figure 8 shows the \( L_X \) cumulative distribution function of TTS (Group III), Herbig Ae, Herbig Be, and HAEBE (Group II) samples. The \( L_X \) distribution for Group III follows a nearly uniform distribution. Herbig Ae’s curve mostly resembles Group III’s; but Group III’s curve has a more extended tail toward lower...
Table 5

| Test          | Datasetsa | K–S test probabilityb (%) | WRS test probabilityb (%) |
|---------------|-----------|----------------------------|---------------------------|
| 1             | Sub-Group III–sub-Group III | 99.99                      | 95                         |
| 2             | Group I–Group II            | 55                         | 28                         |
| 3             | Group II–Group III          | 20                         | 6                          |
| 4             | Group I–Group III           | 9                          | 2                          |
| 5             | Herbig Ae–Group III         | 88                         | 42                         |

Notes.

a See Section 4.1: Group I (B3), Group II (B3–F5), and Group III (F5–).
b Small values of the probability show that the distributions of the two datasets are significantly different.
c Splitting randomly Group III in half to make two sub-Groups; taking then the tests on these two sub-Groups allows us to check the robustness of our tests.

4.2. Statistical Comparison

To quantify our finding, we use the Kolmogorov–Smirnov (K–S) (e.g. Press et al. 1993) and the Wilcoxon rank-sum (WRS) tests (Lehmann 1975) to test the $L_X$ distributions. To check the robustness of this statistical comparison, we randomly split the largest sample, Group III, into two sub-Groups (test 1 in Table 5). We find that the two sub-Groups derive from the same distribution, with a confidence level higher than 99.99% (K–S) and 95% (WRS). This shows that our strategy is effective.

The results are presented in Table 5. The two tests (K–S and WRS) provide a consistent variation of the probability, WRS probabilities are lower, which may be due to the difference of the median values of $L_X$ in each group.

4.3. DISCUSSION

We can rule out the hypothesis that X-rays detected toward Herbig systems (Group II) are from TTS companions with an 80% confidence level. Furthermore, we cannot reject the hypothesis that Herbig Ae stars and TTS X-rays derive from the same distribution. We find a probability of 12% that Herbig Ae stars’ X-rays have a different parent distribution than TTS, which is much lower than the entire Herbig stars ensemble. This may be due to the fact that the process generating the X-rays in the Herbig Ae stars is similar to the TTSs. In the same way, it was already proposed that late Herbig Ae stars may have an outer convective zone that supports the magnetic activity, similar but quite thinner than TTS’ (e.g. Vink et al. 2003; Skinner et al. 2004). Herbig stars and OB stars (Group I) have a same parent distribution at a 55% confidence level. This may be due to a similar origin of the X-rays, magnetic activity caused by a fossil magnetic field from the parent molecular cloud. This may be the case for at least the more massive Herbig Be stars, which have a relatively different $L_X$ distribution than the Herbig Ae stars (Natta et al. 2000). It is important to note that the uncertainties of the source spectral type will affect the group selection, particularly at the edges around F5 or B2. When placing sources in the group, we compared their masses (e.g. Getman et al. 2005b) before placing them in the respective group. However, this is not a large effect on our statistical tests as the key parameter is the overall distribution of the $L_X$ over the group, not the exact
The luminosity ranges between about 64%. The Herbig Ae stars have a higher rate of detection for the several discussions on physical processes in the X-ray. 

1. Out of 22 HAEBE sources, 14 have been detected in X-rays, about 64%. The Herbig Ae stars have a higher rate of detection compared to the Herbig Be stars. The luminosity ranges between $\log L_X = 30–31\text{ ergs s}^{-1}$. This is higher than TTS but overlaps the TTS $L_X$ range. We report the first detection of V361 Ori and the first detections of AB Aur and V372 Ori with Chandra.

2. Although the wind kinetic energy is strong enough to produce the detected $L_X$, the estimated temperatures are relatively high to be generated by such low velocities. This shows that the wind-shock model does not appear to generate the observed X-rays, but one needs to be careful as this statement is based on only a few sources. More investigation including more sources with known $v_{\text{wind}}$ needs to be done to confirm this. Nevertheless, HD 104237 has a relatively high wind velocity. Its X-ray emission can be partially or fully due to the kinetic $L_{\text{kin}}$.

3. Comparing the X-ray emission to the stellar parameters: (i) a luminosity ratio $\log L_X/L_{\text{bol}} = -5.62 \pm 1.18$ is lower than the typical TTS ratio; (ii) there is no correlation with the rotational period $P_\text{rot}$, which excludes the possibility of a solar-like dynamo effects to produce the X-rays for the Herbig stars for which we know $v \sin i$; and (iii) we deduced a nearly linear correlation between the continuum radio emission at $\lambda = 3.6$ cm and $L_X$ toward Herbig Ae sources, with known $L_{\text{bol}}$. This, suggests that the emission does not depend on a companion.

4. The results of Section 4 show that HAEBE stars’ X-ray emission being from an unresolved TTS companion can be ruled out at an 80% confidence level using the K–S test on the $L_X$ distribution. In addition, the results show that the X-ray emission of HAEBE stars is different than OB stars with only a 45% confidence level.

Overall, we suggest that the X-rays are intrinsic to the HAEBE stars. In that case, they must have stellar magnetic activity. This is likely due to the remnant magnetic field after the collapse (Tassis & Mouschovias 2004; Montmerle et al. 2005). Indeed, Wade et al. (2007) using spectro-polarimeter observations reported the measurement of a magnetic field toward HAEBE stars. The existence of circumstellar disks toward HAEBE systems has been confirmed observationally in the last few years (e.g. Natta et al. 2000). Star–disk magnetic interaction can be an appropriate explanation of the X-ray origin (e.g. Montmerle et al. 2000).

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