Röntgenstrahlung from Herbig Ae/Be stars

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Abstract. Herbig Ae/Be stars are young, pre-main-sequence stars of intermediate mass ($2-8\,M_\odot$). They are the more massive analogs to T Tauri stars, but unlike T Tauri stars they are not believed to be convective, convection being a pre-requisite for sustaining magnetic activity, necessary for coronal heating and thus X-ray emission.

We present ROSAT observations of 30 Ae/Be stars, about half of which were detected as X-ray sources with rather high X-ray luminosities up to 10^{32} erg/sec. The X-ray spectra and hardness ratios indicate plasma temperatures of 10^7 K, typical for coronal emission.

The high detection rate of X-ray emission from Ae/Be stars is surprising, if the above reasoning is correct. We discuss several possibilities for the origin of the X-ray emission: Shock interaction of the Ae/Be star stellar wind with remnant circumstellar matter, coronal emission caused by a shear dynamo, and unresolved T Tauri companions.

1. Introduction

Herbig Ae/Be stars (HAEBEs) are stars of spectral type between B0 and early F that show emission lines in their spectra (especially Hα), lie in obscured regions and illuminate reflection nebulae (Herbig 1960). In the HR diagram they lie above the main sequence and thus they are interpreted to be intermediate mass ($2-8\,M_\odot$) pre-main-sequence stars with typical ages between 10^5 and 10^7 years. The HAEBEs are the more massive analogs to the T Tauri stars. It must be emphasised that all HAEBEs are young, but not all young stars of spectral type A or B are HAEBEs (see Herbig 1994).

HAEBEs are generally fast rotators ($v \sin i \approx 100-200$ km/sec), often have fast winds ($v \approx 100-1000$ km/sec; $\dot{M} \approx 10^{-8}-10^{-5}\,M_\odot$/yr), and for most of them there is evidence for circumstellar matter, e.g. from infrared excesses or 1.3mm dust continuum emission.

Since the HAEBEs are intermediate mass objects, they should not show strong X-ray emission: While in late type (F to M) stars a hot corona is the source of the X-ray emission, in early type (O to B1) stars the X-ray emission seems to originate from shock heated regions in the radiation driven winds (see Pallavicini 1989; Schmitt, these Proceedings). The class of later B to early F stars investigated here does possess neither a strong radiation driven wind nor a corona (no dynamo available).

Indeed, main-sequence B and A stars do not seem to be X-ray emitters: In EINSTEIN observations of more than 1000 B5–B9 stars (Grillo et al. 1992) only $\approx 3\%$ were found to be X-ray sources. In the ROSAT All Sky Survey only $\approx 10\%$ of the optically bright A/B stars were detected (Schmitt et al. 1993; Berghöfer & Schmitt 1994 and priv. comm.).

Even young A and B stars (not HAEBEs!) do not seem to be X-ray emitters: In a ROSAT study of 27 B6 – A5 stars in the Orion nebula region only $\approx 20\%$ were detected as X-ray sources (Caillault et al. 1994).

2. ROSAT observations

Up to now we have studied 30 HAEBEs in pointed ROSAT observations. Some of the data were taken from the ROSAT data archive. We could detect 14 of the 30 objects as X-ray sources, so the detection frequency is much higher than for main-sequence A and B stars. The detection frequency of the Be stars is not significantly different from that of the Ae stars.

The X-ray luminosities of the HAEBEs (see Fig. 1) range up to 10^{32} erg/sec and show no obvious dependence on the spectral type. We could find no statistically significant correlation between L_X and L_{bol} (see Fig. 2). The ratio L_X/L_{bol} lies between 10^{-7} (typical for O stars) and 10^{-4} (typical for T Tauri stars). No relation between the rotational velocity and the X-ray luminosity can be found.

X-ray spectral information can be derived only for very few objects, since most HAEBEs were detected with less than 100 source counts. Even for the objects with the highest number of source counts the signal-to-noise ratio of the X-ray spectra is rather low, so that only very simple isothermal plasma models can be used to fit the spectra. The plasma temperatures found in these fits were around or above 10^7 K, quite typical for active coronal sources.

3. Possible explanations for the X-ray properties of the HAEBEs

Since the origin of the X-ray emission of the HAEBEs is not yet known, we will discuss several possible explanations.

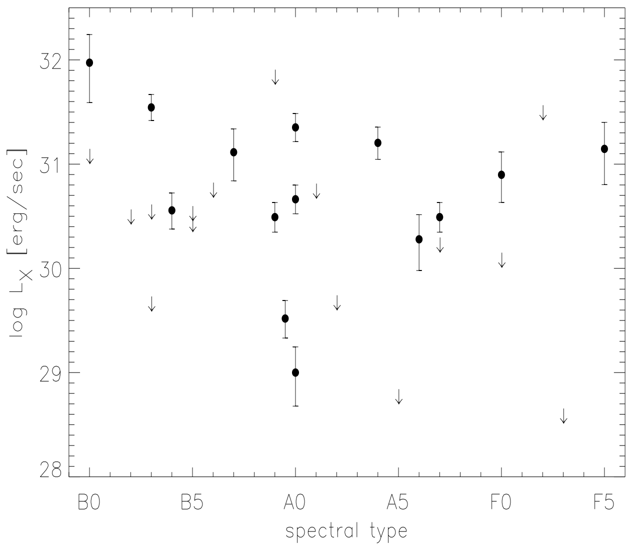

Fig. 1. X-ray luminosity versus spectral type. The arrows denote upper limits.

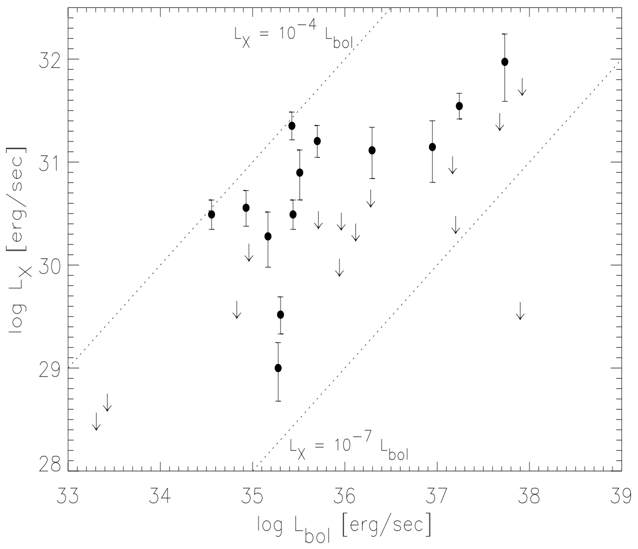

Fig. 2. X-ray luminosity versus bolometric luminosity. The ratios L_X/L_{bol} typical for O stars and for T Tauri stars are shown as the dotted lines.

3.1. Shocks caused by the stellar wind

The first mechanism we have investigated is based on the rather strong stellar winds of the HAEBEs. Since nearly all HAEBEs show evidence for circumstellar matter, the wind may collide with this material. In this case strong shocks are to be expected in the collision zones and in these shocks material could be heated to X-ray emitting temperatures. A similar mechanism was recently proposed by Zhekov et al. (1994); in hydrodynamical model calculations they could show that colliding winds in close binary systems can produce quite high X-ray luminosities.

However, a closer investigation reveals serious difficulties with the wind shock explanation. The first difficulty occurs when comparing the observed X-ray luminosities to the mechanical power of the wind, estimated from the simple formula

$$P_{\rm wind} \approx \frac{1}{2}\,\dot{M}\,v_{\rm wind}^2$$

It turns out that a very high efficiency in transforming wind power into X-ray luminosity of up to more than 1% would be required to explain the observed X-ray luminosities (see Fig. 3). This seems unrealistically high, since

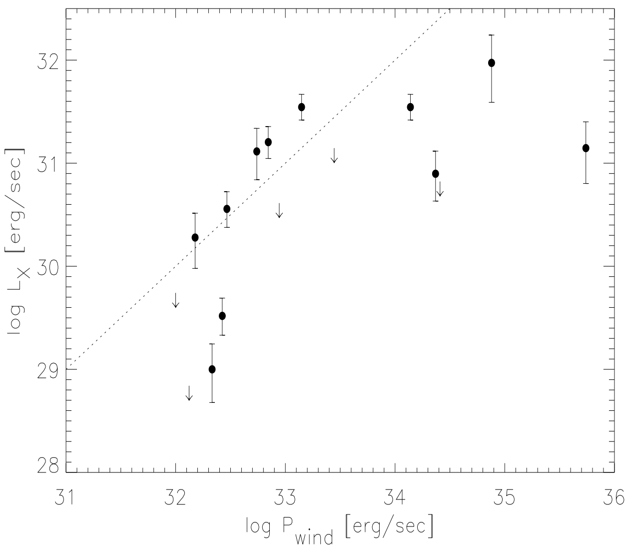

Fig. 3. X-ray luminosity and kinetic wind power for the HAEBEs. The dotted line shows the relation $L_X/P_{\rm wind} = 10^{-2}$.

one has to take into account that most X-ray photons originating in the shock will be absorbed within the shocked wind material. In the models of Zhekov et al. (1994) the efficiency is much smaller, $L_X/P_{\rm wind} \ll 10^{-3}$ for most models. Thus the observed winds can hardly explain the high X-ray luminosities.

The second problem with this model concerns the plasma temperature. One can estimate the shock temperatures T_s from the wind velocities v with the simple formula

$$T_s = 1.44 \times 10^5\,{\rm K}\,\left(\frac{v}{100\,{\rm km/sec}}\right)^2$$

(Krolik & Raymond 1985). From the observed wind velocities in the range 100 – 400 km/sec one would expect $T_s \approx 10^6$ K. This is in contrast to the plasma temperatures $T_X \gtrsim 10^7$ K found from the X-ray spectra.

We conclude that the wind shock model seems not to be able to explain the observed X-ray properties of the HAEBEs.

3.2. Coronal emission due to a shear dynamo

Very recently, Tout & Pringle (1995) proposed a model that explains the X-ray emission of HAEBEs as coronal emission. They assume that the HAEBEs have a strong rotational shear (that is, roughly speaking, the difference in angular velocity between the stellar interior and surface). In their model this shear causes dynamo action that generates magnetic fields at the stellar surface and ultimately leads to coronal X-ray emission. Since the shear energy is limited and diminished by heating the corona, the model predicts a strong time dependence of the X-ray luminosity. L_{X} should be rather constant for about one million years and should decline rapidly thereafter.

We can test this prediction by placing the HAEBEs in the HR diagram, in which we also have plotted evolutionary tracks (Fig. 4). Indeed, our data are in good agreement with this prediction. The youngest objects show the highest X-ray luminosities, while the older objects close to the main sequence are much weaker X-ray sources.

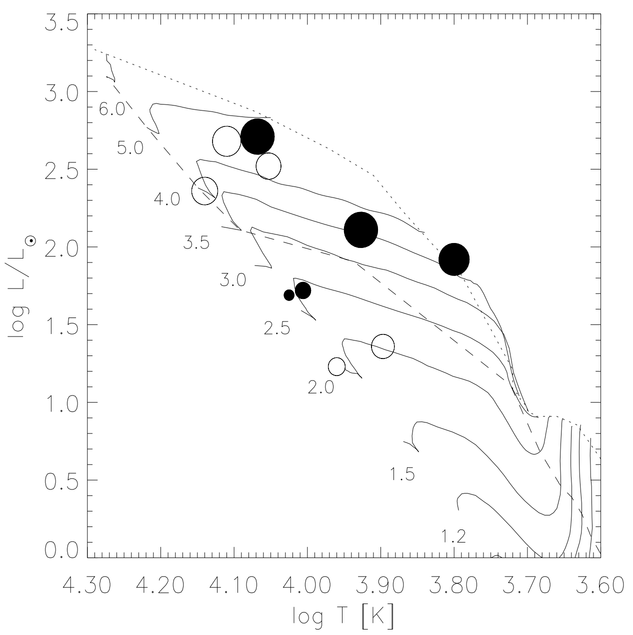

Fig. 4. Position of the HAEBEs in the HR diagram; known binaries and objects with uncertain bolometric luminosity or spectral type have been excluded. The filled circles denote the X-ray detected objects, the empty circles the non-detections. The size of the symbols indicates the X-ray luminosity resp. the corresponding upper limit. The evolutionary tracks from Palla & Stahler (1993) are shown as solid lines. Each track is labeled by the corresponding mass, in solar units. The dashed line shows the 10^6 years isochrone, the dotted line the stellar birthline.

3.3. Late type companions

The last explanation we will discuss here is that the X-ray emission does not originate from the HAEBEs themselves, but from companions of spectral type later than $\approx$ F5 that are known to show coronal X-ray emission. Since the HAEBEs are very young objects and the companions should be coeval, they should be T Tauri stars.

It is very difficult to estimate the fraction of HAEBEs that can be expected to have late type companions. Estimates based on the binary frequency of main sequence A and B stars range from $\approx 20\%$ (Caillault et al. 1994) up to $\approx 50\%$ (Abt 1983). As far as HAEBEs are concerned, we only know that their binary frequency seems to be rather high (Leinert et al. 1994). From this we conclude that the X-ray detection frequency of nearly 50% probably may be explained by late type companions.

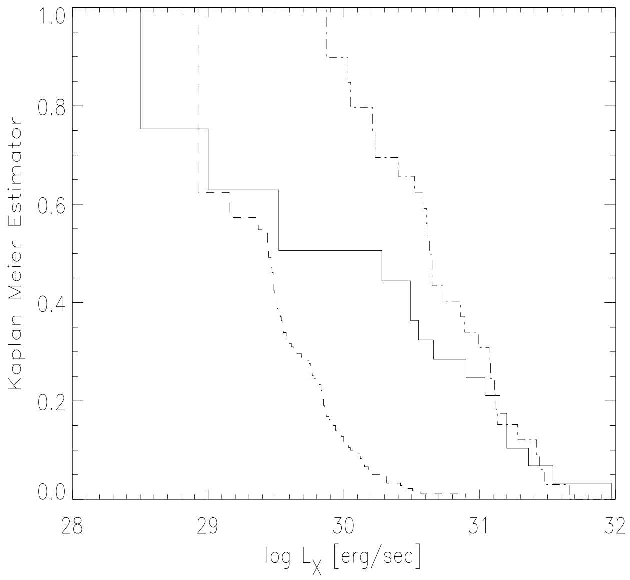

Fig. 5. Kaplan-Meier estimator of the cumulative X-ray luminosity function of the HAEBEs (solid line) compared to that of the T Tauri stars in the Taurus-Auriga molecular cloud (dashed line; data from Neuhäuser et al. 1995). The dashed-dotted line shows the X-ray luminosity function of the G type T Tauri stars in the Orion nebula region (data from Gagné et al. 1995).

However, in the framework of this model it is quite difficult to understand the rather high X-ray luminosities of the HAEBEs. In Fig. 5 we compare the cumulative X-ray luminosity function of the HAEBEs to that of the T Tauri stars in the Taurus-Auriga molecular cloud. The later should be typical for T Tauri stars. One can see that companions like typical T Tauri stars are too faint in X-rays to explain the X-ray luminosity function of the HAEBEs.

The late type companion model only works, if we assume the companions to be as X-ray luminous as the G type T Tauri stars in the Orion nebula region. These stars are considerably stronger X-ray emitters than a sample of all T Tauri star that is dominated by K and M stars. We have investigated this possibility further by calculating a simulated X-ray luminosity function for the HAEBEs under the assumption that all X-ray detected HAEBEs have companions like the Orion G type T Tauri stars while the not detected HAEBEs show no X-ray emission. Indeed, the simulated X-ray luminosity function reproduces the observed X-ray luminosity function of the HAEBEs quite well.

4. Conclusions

We have observed 30 Herbig Ae/Be stars with ROSAT and could detect nearly half of them to be X-ray emitters. Several possible explanations for the origin of the X-rays were investigated and our conclusions can be summarized as follows:

The assumption of a wind related origin of the X-ray emission can hardly explain the high X-ray luminosities of the HAEBEs and cannot explain the quite high plasma temperatures ($\approx 10^7$ K) that are observed.

The model of coronal emission due to a shear dynamo is in good agreement with our data and even predicts the correct age dependence of the X-ray luminosity. However, the theoretical foundations of this model seem not to be fully developed.

The assumption of late type companions as the source of the X-ray emission can probably reproduce the X-ray detection frequency of the HAEBEs. However, most of the HAEBEs must have very X-ray luminous companions like the G type T Tauri stars in Orion, since the typical population of T Tauri stars is too faint in X-rays to explain the observed X-ray luminosity function of the HAEBEs.

In our opinion, T Tauri star companions are the origin of the X-rays for some, perhaps even for the majority of the HAEBEs. However, some HAEBEs are apparently single (even in Speckle observations, e.g. AB Aur) and nevertheless show X-ray emission. We are planning to test this conjection through high spatial resolution infrared observations. At least for the apparently single objects another emission mechanism is probably needed, and here the shear dynamo model may be a good explanation.

We are continuing our study with additional ROSAT observations and also will include further data from the ROSAT data archive. Hopefully, a larger sample will help us getting further insights.

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