Astron. Astrophys. 322, 193–196 (1997)

ASTRONOMY AND ASTROPHYSICS

A new correlation for Be/X-ray binaries: the orbital period-Hα equivalent width diagram

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Received 17 June 1996 / Accepted 3 December 1996

Abstract. A correlation between the orbital period and the strength of the Hα line in Be/X-ray binaries has been found. Those systems with shorter orbital periods show less emission in Hα than those with longer orbital periods. The neutron star appears to act as a barrier which prevents the formation of a extended disk in systems with short orbital period.

Key words: stars: Be – stars: neutron – X-rays: stars – binaries: close

1. Introduction

The class of Be/X-ray binaries consists of about 30 systems and is the largest of the groups of massive X-ray binaries. The optical star is an Oe/Be star, i.e. a rapidly rotating star near the main sequence (luminosity class III-V) whose spectrum shows hydrogen and other lines in emission. These are believed to originate from a equatorially distributed envelope. According to these luminosities and spectral types the primary stars have masses in the range 8 - 20 $M_{\odot}$. The companion is a neutron star, which produces the observed X-ray emission when material from the primary is accreted on to its surface. A notable characteristic of these sources is that their X-ray emission is highly variable and most of them are transient. This means that they appear as strong X-ray sources from time to time (the so called Type II outbursts, Stella et al. 1986) and are not detected for extended periods. The X-ray emission during active periods occurs as flares, usually with a sharp rise and gradual fall. The X-ray luminosity can be as high as the Eddington luminosity for neutron stars. In some systems, recurrent outbursts at regular intervals (with the recurrence period coinciding with the binary orbital period) have been observed. These are known as Type I outbursts.

2. The P_{orb}–EW(Hα) diagram

Fig. 1 shows a plot of the maximum equivalent width of the Hα line versus the orbital period for 11 Be/X-ray binaries. The equivalent widths of the Hα line plotted in the diagram are the highest values found for each star either in the literature or from our observations. For all stars but one these values were measured when the sources were in outburst. The only exception is 4U 1258-61, for which no Hα measurements contemporaneous to an X-ray outburst have been found. The two systems represented by filled squares are GRO J1008-57 and A 1118-616. Their orbital period is not known but it has been estimated by interpolating in the P_{spin}–P_{orb} diagram (Corbet 1986). Table 1 summarizes the properties of the systems used in this study. The last column indicates from where the Hα equivalent width was obtained. Note that we have not included X Per in our list in despite of having known pulse period and values of the Hα equivalent width. This is because this source does not show transient behaviour. X Per is the prototype of a class of Be/x-ray binaries which are persistent sources with low X-ray luminosities (10^{33}-10^{35} erg s^{-1}) which are believed to be powered by the stellar wind from the optical primary.

As it can be seen there exists a correlation between these two physical magnitudes. Apart from GRO J1008-57 and A 1118-61, a linear correlation analysis gives a linear correlation coefficient of 0.95 and a probability that the points are not correlated of less than 10^{-3}. Since the equivalent width of the Hα line represents the projected size of the circumstellar envelope (Dachs et al. 1986a), this diagram implies that the neutron star plays a fundamental role in the evolution of disks in Be/X-ray binaries.

As a further support of this picture there is the fact that isolated Be stars, that is, Be stars without a compact companion, have, on the average, stronger Hα emision. Fig. 2 compares the number of isolated Be stars and Be star taking part in massive X-ray binaries with Hα equivalent widths larger than –20 and –30 Å. The isolated Be stars were taken from the whole sample of O9–B2 Be stars in the Bright Star Catalogue (Hoffleit & Jascheck 1982), which according to Jaschek & Jaschek (1983) amounts to 52 Be stars. The values of the Hα equivalent width were obtained from the following references: Andrillat & Fehrenbach (1982), Andrillat (1983), Dachs et al. (1977), Dachs et al. (1986b), Dachs et al. (1989), Dachs et al. (1992), Fontaine et al. (1982), Hanuschik (1986), Hanuschik et al. (1988), Men-

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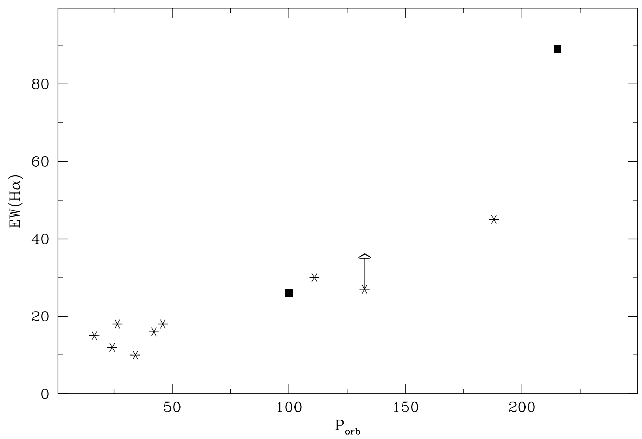

Fig. 1. Maximum Hα emission as a function of the orbital period. The two systems marked with solid squares have had their binary orbital period deduced from the P_{spin}–P_{orb} diagram. The arrow represents a lower limit of the Hα equivalent width for 4U 1258-61

nickent et al. (1994), Slettebak & Reynolds (1978) and Slettebak et al. (1992). When a star appeared in more than one paper we took the highest value. The Be/X-ray sample consists of 20 sources taken from the Southampton/Valencia archive (Reig et al. 1996). The comparison was made only with O9-B2 Be stars because the spectral type of the optical primary in Be/X-ray binaries seems to be restricted to this interval. Since the sample of isolated Be stars was obtained from the Bright Star Catalogue they are well studied stars and are limited in magnitude (<7 mag). Thus, one can assume with quite confidence that all the Be stars below that limit, even those with the weakest emission, have been detected. Therefore, we avoid possible selection effects that would make the detection of strong Hα emitters easier. Moreover, one might expect selection effects in the Be/X-ray sample since there is no magnitude limit. Therefore we should expect to detect those with the highest Hα emission, that is, those with the larger disks. However, the majority of the Be/X-ray systems present small Hα equivalent widths.

On the other hand our sample of isolated Be stars could be affected by the fact that some of these systems are actually binary systems. An apparent emission profile can be caused by the superposition of two absorbing profiles from two components of similar spectral type in a binary system, mimicking the behaviour of a Be star (Coté & Kerkwijk 1993). However, this apparent emission profile is never strong enough to emerge above the continuum and hence the equivalent width is never negative. We have not condidered such systems in our sample. Also, one could argue that the secondary star would act in the same sense as in the case of Be/X-ray binaries, that is, by preventing the development of the disk. If it would be the case the statistics of Fig. 2, which would include the supposed binaries, show that the sample of strong Hα emitters from the Bright Star Catalogue have a higher average. Again, this would favour our hypothesis since those stars with larger equivalent widths must not be binary systems.

Fig. 2 indicates, then, that isolated Be stars can develop bigger disks than Be stars in X-ray binary systems.

3. Discussion

We attribute the existence of the above relationships to the presence of the compact star which prevents its optical counterpart from developing a large circumstellar disk. The neutron star is continuously orbiting round the Be star in a moderate elliptical orbit so that when the envelope radius approximately equals the periastron distance, i.e. $R_d \approx a(1-e)$, the compact star interacts with the disk and disrupts it. The neutron star would sweep up the circumstellar material and mark the limits of the envelope size. In other words, the neutron star orbit determines the maximum size that the envelope can have. The material forming the disk is accreted onto the neutron star, giving rise to an X-ray outburst and producing a change in the emission characteristics of this material. Since the signature of the circumstellar material is its Hα line and infrared continuum emission, any disruption of the disk must manifest as a change in the Balmer emission lines and the infrared luminosity. For those Be/X-ray binaries with short orbital periods ($\sim$ a few tens of days), i.e. with close orbits, the number of periastron passages is larger, precluding the formation of an extended envelope. Those Be/X-ray binary systems with longer orbital periods ($\sim$ a few hundred of days), i.e. wider orbits, can develop bigger circumstellar disks and hence higher values of the Hα equivalent width.

The quiescent X-ray state would be that of an envelope whose radius is smaller than the periastron distance. When the envelope inflates and $R_d \approx a(1-e)$, the neutron star gets inmersed in the envelope and begins to disrupt the disk, giving rise to the giant Type II outburst. Type I outburst are more likely to occur because the neutron star will be accreting in a much lower density wind emitted either from the polar region of the Be star, or from an intermediate region between the envelope and the interstellar medium which is likely to exist beyond the limits of the Hα emitting region. Within this interpretation, the Hα equivalent width measured in quiescence is a lower limit of the maximum that the star can reach during outburst. Consequently, the point in Fig. 1 for 4U 1258-61 (marked with an arrow) corresponding to observations in quiescence represents a lower limit.

Evidence of the circumstellar disk disruption during Type II outburst can be found for some stars in the literature. Coe et al. (1994) describe the 1992 January outburst of A1118-616. In Fig. 7 and Table 1 of this reference it can be seen that the Hα equivalent width slowly increases before the outburst, and reach its maximum value during it, peaking at –89 Å (averaged over four spectra). After the outburst, the equivalent width decreased to values lower than –60 Å. Kriss et al. (1983) also present X-ray and optical observations of 4U 0115+63 during the 1980 December outburst. As can be seen in their Table 2, the Hα equivalent width increases from the end of October, reaching its maximum value in January 2 during the X-ray outburst and decreasing afterwards. On the other hand, Norton et al. (1994) obtained simultaneous X-ray data, Hα spectroscopy

Table 1. Be/X-ray binaries used in this work

X-ray source	Alternative name	Spectral type	P_{orb} (days)	EW(Hα) (-Å)	Reference
4U 0115+63	V636 Cas	O9.5III-V	24.3	12	This work
GT 0236+61	LSI+61 303	B0.5III	26.52	18	Paredes et al. (1994)
V 0332+53	BQ Cam	Be	34.2	10	Kodaira et al. (1985)
A 0535+26	V725 Tau	O9.7V	111	30	Giovanelli & Sabau (1992)
A 0535-668		B2IV	16.65	15	Pakull & Parmar (1981)
GRO J1008-57		Be	100*	26	This work
A 1118-616	Hen 3-640	O9.5IV-V	215*	89	Coe et al. (1994)
4U 1145-619	V801 Cen	B1V	188	45	Stevens et al. (1996)
4U 1258-61	V850 Cen	B2V	132.5	27	Corbet et al. (1986)
4U 1417-624		Be	42.12	16	This work
EXO2030+37		Be	46	18	Norton et al. (1994)

* These values are obtained by interpolation in the P_{orb}-P_{spin} diagram.

and IR photometry of EXO 2030+375 during a Type I outburst at the periastron passage. No variations of the circumstellar disk structure, as measured through the Hα equivalent width and the IR flux, were detected. This is fully consistent with the above assumption that in Type I outburst the neutron star is accreting material well outside the Hα emitting region.

An alternative interpretation of the relationship between the orbital period and the equivalent width of the Hα line could be that among the Be + neutron star binaries only those systems which have orbits within (or touch the outer regions of) circumstellar disks are observable as Be/X-ray binaries. In this case Be/X-ray binaries with long orbital periods necessarily have extended disks, i.e., strong Hα emission. On the other hand, Be stars with small disks are still able to feed a close-by neutron star companion (with corresponding short period) and thus become a Be/X-ray binary.

In order to discern what of the above models is the actual explanation, it is necesary to secure multiwavelength observations, including optical espectroscopy and X-ray data, during the X-ray outbursts. If every outburst is accompanied with a Hα decrease, as described above for A 1118-616 and 4U 0115+63, this would imply the disk disruption. Alternatively, if the two cases described above are not the rule but the exception, then the explanation of the disk size-orbit size selection would be the most likely interpretation.

4. Conclusion

We have reported the discovery of a relationship between the equivalent width of the Hα line and the orbital period which occurs in Be/X-ray binary systems. We explain it by assuming that during Type II outbursts the neutron star interacts with the inner, denser part of the circumstellar Be star envelope and disrupts it, preventing its further expansion. In Type I ouburststhe neutron star interacts with the circumstellar material well outside the region in which the Hα line is formed.

This relation ship however, is based on only a few stars. It would be very important to improve its reliability by adding more points to the diagram in Fig. 1. This has to be done by measuring the orbital period for most of the Be/X-ray binaries, for which this value is not yet known. If confirmed, its interpretation can give important clues to the modelling of the X-ray light curves of Be/X-ray binaries, and to the use of the neutron star as a probe of the circumstellar material structure around Be stars.

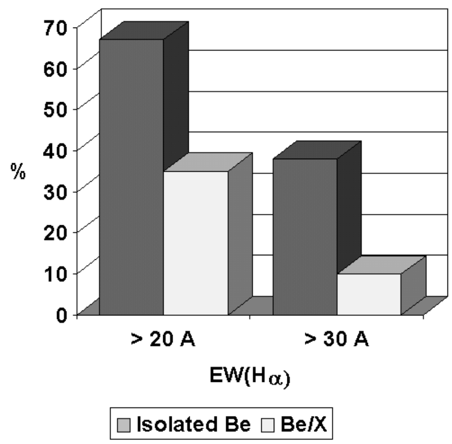

Fig. 2. Comparison of the strength of the Hα emission for isolated Be stars and Be/X-ray systems

Acknowledgements. We wish to thank the anonymous referee for his/her careful reading of the manuscript and for his/her valuable suggestions which improved the final version of this paper.

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