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X-ray emission from acoustically heated coronae

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Summary. The limiting shock strength behaviour of acoustic waves permits to estimate the expected X-ray emission from purely acoustically heated coronae. These predicted X-ray fluxes turn out to be very much smaller than the observed fluxes which strengthens the argument that the observed coronae are generated by magnetic heating.

Key words: hydrodynamics – shocks – stellar coronae – X-rays

1. Introduction

Since about ten years it has become widely accepted that the chromospheric UV emission and the coronal X-ray emission of late-type stars arise from magnetically heated atmospheric layers (Linsky, 1980; Vaiana et al., 1981). However, recent investigations of F-stars (Walter and Schrijver, 1987) and of slowly rotating basal flux stars (Schrijver, 1987a, b) have pointed to the possibility that there are stars where the heating is not dominated by magnetic fields and that acoustic waves appear to be a likely nonmagnetic heating mechanism. Moreover, theoretical work indicates that acoustic waves are indeed able to produce chromospheres and coronae (Schmitz et al., 1985; Ulmschneider et al., 1987). But how can one differentiate observationally between a magnetic and a nonmagnetic mechanism? A powerful procedure developed by Oranje and Zwaan (1985), Oranje (1986) as well as Schrijver (1987a, b) is to correlate the chromospheric emission where a basal flux has been subtracted with the observed X-ray emission. This procedure allows to determine the supposedly nonmagnetic basal chromospheric emission which depends only on spectral type and not, like the magnetic mechanisms, on rotation.

One of the basic assumptions made in this procedure is that X-ray emission is a reliable indicator for magnetic heating. However, as the above mentioned theoretical work indicates that X-ray emission can also be produced by purely acoustic means, this assumption has to be critically discussed. In recent work by Ulmschneider (1989) it has been shown that acoustic waves in late-type stars tend to *a common limiting strength* which appears to be largely independent of the effective temperature $T_{\rm eff}$ and of gravity g. In addition, at great heights, the limiting strength acoustic waves attain a flux which is essentially proportional to the ambient gas pressure, independent of the initial wave generation process. The generation of acoustically heated coronae is thus due to the fact, that the chromospheric emission decreases with the square of the density while the heating flux decreases only linearly with pressure. Thus the heating eventually overwhelms the cooling, resulting in unbalanced heating which leads to the formation of a transition layer. Time-dependent examples of this process to form transition-layer-like steep temperature rises have been given by Schmitz et al. (1985) and Ulmschneider et al. (1987).

In the present work we attempt to estimate the importance of the expected purely acoustically generated X-ray emission. For this purpose we estimate the gas pressure at the base of the transition layer of selected stars using available empirical chromosphere models. Based on predicted limiting acoustic fluxes we then estimate expected X-ray fluxes. In Sect. 2 we describe our method and give the results. Section 3 presents our conclusions.

2. Method and results

In this work we want to specifically study the situation where magnetic fields are absent: we want to predict the X-ray flux emitted by purely acoustically heated coronae of late-type stars. For such a prediction we should know the spectrum of the acoustic energy generated in the convection zone. Employing a theoretical time-dependent radiation-hydrodynamic calculation we would then need to follow the propagation and development of this spectrum into the chromosphere and corona. If magnetic fields are absent the situation in the corona is similar as in coronal holes. The acoustic flux at the base of the transition layer would be spent to balance the three important coronal energy losses: the stellar wind loss, the conductive loss (most of which drives the UV-emission of the transition layer) and the X-ray loss.

2.1. Computation of the acoustic flux

The acoustic energy spectrum of late-type stars has been computed by Bohn (1981, 1984). He finds that except for very cool dwarf stars the acoustic spectrum rises from the cut-off period $P_{\rm A}$ to a peak near

$$P=\frac{1}{10}P_{\rm A}=\frac{1}{10}\frac{4\pi c}{\gamma g}, \tag{1}$$

and thereafter falls rapidly to smaller wave periods. Here c is the sound speed at the top of the convection zone, g the gravity and γ

Send offprint requests to: P. Ulmschneider the ratio of specific heats. Bohn's calculations have been criticised because they use the Lighthill theory in atmospheres with gravity (see Ulmschneider, 1989). However, this criticsm is expected to affect more the magnitude of the spectrum rather than its frequency dependence. It is therefore likely that the shape of the spectrum described above is not much changed and is even valid for very cool dwarf stars. In any case, a spectrum of this or similar shape is expected, because it ensures that the acoustic waves are strongly propagating and are able to transport significant energy into the outer layers of the star. Waves with periods comparable to or longer than P_A do not propagate. On the other hand, if the spectrum would extend to much shorter wave periods than given by Eq. (1), then shock dissipation would damp these high frequency waves so quickly, that no significant acoustic energy is transmitted into the outer stellar layers.

To avoid the uncertainty of the magnitude of the acoustic frequency spectrum and the theoretical difficulties of a detailed acoustic wave calculation we employ a powerful property of acoustic shock waves recently discussed by Ulmschneider (1989). It was found that independently of the intial acoustic energy flux, of the effective temperature T_{eff} and of gravity g, acoustic waves in late-type stars attain a common *limiting shock strength*. For isothermal atmospheres this limiting strength is given by

$$M_S^{\text{LIM}} = 1 + \frac{\gamma g}{4c} P = 1 + \frac{\pi}{10} = 1.3 . \tag{2}$$

In Eq. (2) the period P given by Eq. (1) has been used. If the peak of the acoustic power spectrum were moved to $P = 1/5\, P_A$ then M_S^{LIM} would increase to 1.6. For these and even longer period waves the limiting shock strength concept still applies, although, as shown by Cuntz and Ulmschneider (1988, Fig. 4), Eq. (2), based on weak shocks, becomes increasingly unreliable to predict the limiting strength of the waves.

Based on the weak shock theory the limiting flux of the acoustic waves is given by

$$F_M = \frac{4\gamma}{3(\gamma+1)^2}\, \text{pc}\, (M_S^{\text{LIM}} - 1)^2 . \tag{3}$$

where p is the gas pressure (Ulmschneider, 1970, 1989). Here it should be noted that this flux depends only on the assumed frequency spectrum and is reached independently of the intial acoustic flux and of the radiation damping low in the atmosphere. Assuming that the X-ray loss is the fraction 1/80 of the total coronal loss which is valid for coronal holes as determined by Withbroe and Noyes (1977), we are able to predict the coronal X-ray loss using Eq. (3), if the gas pressure p at the base of the transition layer can be estimated.

2.2. Estimate of the X-ray flux using empirical models

For the estimate of the transition layer pressure p theoretical models do not exist at the present time and we are forced to consider stars for which empirical chromosphere models are available. The selected stars and the relevant data are given in Table 1. The temperature at the base of the transition layer was assumed to be $T = 8500$ K. For stars where the gas pressure at this height was not given, p was computed from the mass column density m, using $p = mg$. If necessary m was extrapolated using a linear T vs. $\log m$ relation. The models where extrapolation was necessary are marked in Table 1 by an asterisk. For γ Vir N this extrapolation procedure due to the small slope of the T vs. $\log m$ relation appeared to be extreme and we consider this value of p as unreliable. For the basic stellar parameters we took the values listed by Linsky et al. (1982) or by the respective authors; if they were not given we used estimates. For the observed X-ray fluxes F_X in Table 1 we converted values F_X/F_{bol} given in the literature.

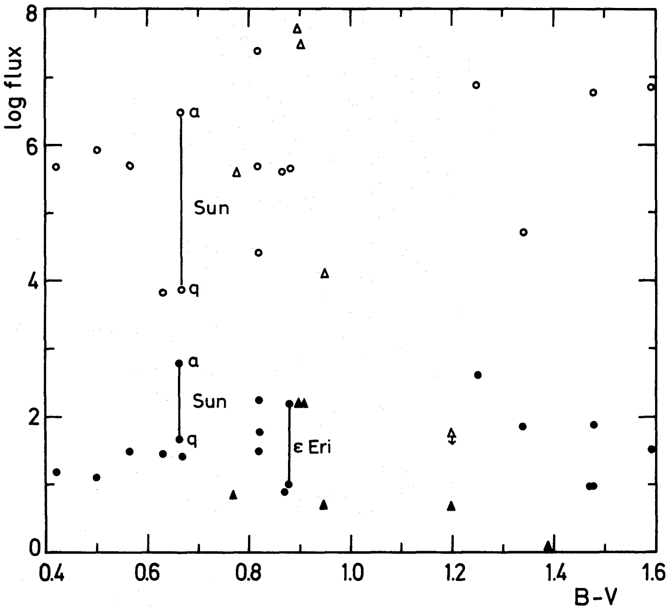

Fig. 1. Observed and predicted X-ray fluxes for purely acoustically heated chromosphere and corona models of selected stars (cf. Table 1). Circles denote dwarf stars and triangles indicate giants. Predicted values are shown solid. Vertical bars join the solar values characteristic of quiet and active regions, and two different predicted values for ε Eri

Large transition layer pressures were found for the RS CVn stars HR 1099 and UX Ari and for the active chromospheric emission stars ξ Boo A and EQ Vir. We consider the obtained transition layer pressures for these stars as representative for active regions (see Sun in Table 1) and not for quiet regions which would be appropriate for purely acoustically heated chromospheres. A comparison of different models for ε Eri shows the uncertainty introduced by different empirical modelling.

Using Eq. (3) with a value $M_S^{\text{LIM}} = 1.3$ as found in Eq. (2) we are able to roughly predict expected X-ray fluxes from purely acoustically heated coronae. With the assumed temperature $T = 8500$ K at the base of the transition layer the predicted X-ray flux is simply the gas pressure p multiplied by the numerical factor 320. Figure 1 shows a plot of the predicted X-ray flux from acoustically heated coronae compared with the observed X-ray flux (with γ Vir N omitted). If the active chromosphere and RS CVn stars are disregarded because of their high transition layer pressures due to the magnetic field, then the X-ray flux of main sequence stars generated by acoustic heating is around 10–20 erg cm^2 s, apparently independent of spectral type. The corresponding flux for giants is found a factor of 3–4 lower and likewise apparently independent of spectral type. Despite the considerable uncertainty due to the assumptions made for the acoustic frequency spectrum, due to the use of empirical chromosphere models and due to the assumed fixed ratio of X-ray to total coronal losses, it is seen from Fig. 1 that the predicted X-ray fluxes are much lower than the observed fluxes. Figure 1 moreover shows that the ratio of observed to predicted acoustic X-ray fluxes is the larger the more active the star is. This demonstrates that the observed X-ray emission is a very good indicator for magnetic heating mechanisms.

Table 1. Basic parameters of stars with empirical chromosphere models together with predicted gas pressures p (dyn/cm^2) at the base of the transition layer and with observed X-ray fluxes F_X (erg cm^2 s). Asterisks indicate values obtained from extrapolated models. Literature references are indicated. Predicted X-ray fluxes in (erg cm^2 s) from purely acoustically heated coronae are obtained by multiplying the values of p with the numerical factor 320

Star	SpT	$B-V$	$\log g$	p	Ref.	F_X	Ref.
Sun q.	G2V	0.66	4.44	0.155	Kelch et al. (1979)	$8\ 10^3$	Vaiana and Rosner (1978)
				0.122	C, Vernazza et al. (1981)		
a.				2.75	Kelch and Linsky (1978)	$3\ 10^6$	Vaiana and Rosner (1978)
				1.5	Haisch and Linsky (1976)		
γ Vir N	F0V	0.34	4.2	0.003 *	Kelch et al. (1979)	$1.4\ 10^6$	Schmitt et al. (1985)
α CMi	F5IV-V	0.42	4.0	0.05	Ayres et al. (1979)	$5\ 10^5$	Schmitt et al. (1985)
θ Boo	F7IV-V	0.50	4.0	0.04 *	Kelch et al. (1979)	$8.7\ 10^5$	Schmitt et al. (1985)
59 Vir	F8-G0V	0.56	4.4	0.1 *	Kelch et al. (1979)	$5.4\ 10^5$	Schmitt et al. (1985)
α Cen A	G2V	0.63	4.25	0.091	Kelch et al. (1978)	$6.6\ 10^3$	Vaiana et al. (1981)
HD 76151	G5V	0.67	4.6	0.09	Kelch et al. (1979)		
ξ Boo A	G8V	0.82	4.4	0.56 *	Kelch et al. (1979)	$2.3\ 10^7$	Walter (1981)
61 UMa	G8V	0.82	4.5	0.18 *	Kelch et al. (1979)	$5.4\ 10^5$	Schrijver (1983)
α Cen B	K1V	0.82	4.5	0.095	Kelch et al. (1978)	$2.6\ 10^4$	Vaiana et al. (1981)
70 Oph A	K0V	0.87	4.4	0.025	Kelch (1978)	$4\ 10^5$	Johnson (1981)
ε Eri	K2V	0.88	4.5	0.5	Simon et al. (1980)	$4.9\ 10^5$	Vaiana et al. (1981)
				0.03	Kelch (1978)		
HR 1099	RS CVn	0.9	~3.5	0.5	Simon and Linsky (1980)	$5.5\ 10^7$	Basri et al. (1985)
UX Ari	RS CVn	0.9	~3.5	0.5	Simon and Linsky (1980)	$3.1\ 10^7$	Basri et al. (1985)
EQ Vir	dK5e	1.25	4.4	1.25	Giampapa et al. (1982)	$7.8\ 10^6$	Vaiana et al. (1981)
				1.38 *	Kelch et al. (1979)		
61 Cyg B	K7V	1.34	4.4	0.22 *	Kelch et al. (1979)	$5.2\ 10^4$	Johnson (1981)
HD 95735	M2V	1.48	4.5	0.03	Giampapa et al. (1982)		
Gl 616.2	dM1.5e	1.48	4.5	0.24	Giampapa et al. (1982)	$6.6\ 10^6$	Agrawal et al. (1986)
Gl 393	dM2	1.48	4.5	0.03	Giampapa et al. (1982)		
YZ CMi	M4.3eV	1.60	4.5	0.1	Giampapa et al. (1982)	$6.6\ 10^6$	Agrawal et al. (1986)
α Aur	G5III	0.77	2.62	0.023	Kelch et al. (1978)	$4\ 10^5$	Vaiana et al. (1981)
β Gem	K0III	0.95	2.9	0.016	Kelch et al. (1978)	$1.2\ 10^4$	Ayres et al. (1981)
α Boo	K2III	1.20	1.7	0.016	Kelch et al. (1978)	<55	Ayres et al. (1981)
α Tau	K5III	1.40		0.0035	Kelch et al. (1978)		

3. Conclusions

We have shown that the acoustic flux at transition layer heights can be estimated using the limiting shock strength property of the acoustic waves. This property originates from a balance between the growth and the decay of acoustic shock waves in atmospheres with gravity and depends almost exclusively on the frequency of the waves. Because the frequency spectrum of propagating acoustic waves in stellar atmospheres has a maximum roughly an order of magnitude above the cut-off frequency of the atmosphere, the limiting acoustic flux at transition layer heights can be predicted. This flux is found to be proportional to the gas pressure at these heights. A small fraction of this acoustic flux will then be used to balance the X-ray emission.

A comparison of the predicted and observed X-ray fluxes shows that the acoustically heated coronae have very much weaker X-ray emission. This supports the picture that the observed X-ray emission from coronae of late-type stars is a good indicator for a magnetic heating mechanism.

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