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Comments on the Acoustic Heating of Stellar Coronae

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Summary. Recent claims that UV and X-ray observations allow to reject the acoustic heating theory of stellar coronae are shown to be unfounded. In particular, the argument that in late type stars the acoustic flux is insufficient to balance the observed X-ray flux is contradicted by new calculations which use Lighthill's theory corrected for density stratification and for strong magnetic fields.

Key words: coronal heating – acoustic waves – magneto-hydrodynamic waves – X-ray observations

1. Introduction

Recent observations of stellar X-ray emission with the Einstein satellite (Vaiana et al., 1981; Linsky, 1980) have led to an almost unanimous refutation of acoustic waves as an important mechanism for the heating of stellar coronae. Linsky (1980) e.g. presented "arguments to *demonstrate* that the acoustic wave heating theory of stellar coronae is inadequate to explain Einstein observations". The forceful rejection of the acoustic heating theory culminates in the statement by Vaiana et al. (1981) that from Einstein *observations* can even be concluded that "it seems unlikely that the quantitative differences (between observations and theory) can be resolved by considering more sophisticated acoustic heating theories in the context of revised convection theories and acoustic conversion and propagation models". Here the reader remains puzzled about whether one could deduce from observations alone what future theoretical developments may do or may not do, especially if one thinks about the present poor state of development of coronal heating theories.

What does the term acoustic heating theory mean? Clearly this term does not have the same meaning to all workers in the field of stellar coronae. Acoustic heating theory in a restricted sense means that coronae are supposed to be heated by purely hydrodynamic shock waves that form out of acoustic waves which are generated in a convection zone. This narrow concept of acoustic heating is taken to be distinctly different from mechanisms involving magneto-hydrodynamic waves and mechanisms where the acoustic energy is not generated by convective motions. This view appears to be exemplified in Linsky's (1980) work.

Such a narrow definition of the term acoustic heating theory is in many ways unrealistic. For instance, it has long been known (Hearn, 1973; Berthomieu et al., 1976; Nelson and Hearn, 1978; Martens, 1979) that in early type stars radiative amplification of acoustic waves from observed surface turbulence must be possible. In these stars therefore the mechanism of radiative acoustic energy generation could replace the mechanism of convective energy generation that operates in late type stars. As shock dissipation does not depend on the manner by which the acoustic waves are generated it seems unduely narrow to restrict the term acoustic heating theory exclusively to convective energy generation. Indeed many workers (e.g. Lamers and De Loore, 1976; Vaiana et al., 1981) if not the majority, decouple the acoustic heating theory from convective energy generation. The somewhat broader concept of the acoustic heating theory thus sees the corona heated by purely hydrodynamic shocks that develop out of acoustic waves, which are generated by any suitable mechanism.

Taking the acoustic heating theory in this somewhat broader sense is still not very realistic. It is well known that most stars possess extensive magnetic fields and that on the Sun in almost any situation magnetic fields of various strength are present. Strictly speaking, due to the action of the three restoring forces (magn. field, pressure and gravity) in stars, the waves which we consider should be called magneto-acoustic-gravity (mag) waves (Stein and Hartunian, 1981). For frequencies large compared to the acoustic cut-off frequency and for weak magnetic fields do these mag waves degenerate into acoustic waves. Alfvén and Fälthammar (1963, p. 98) showed, however, that in strong magnetic fields the waves that correspond to the acoustic waves are the modified sound waves or more commonly called slow mode waves.

In view of the importance of magnetic fields on the surface of stars a restriction of the term acoustic heating theory exclusively to non-magnetic situations would largely by definition exclude this theory from a meaningful explanation of the heating of stellar coronae. In addition such a narrow definition would exclude any possible enhancement of the acoustic energy generation by the presence of magnetic fields. We conclude that to avoid an unrealistic definition and to conserve the idea of the acoustic heating theory (generation of compression waves and dissipation by hydrodynamic shocks) we must allow the presence of magnetic fields.

Generally there is no compelling reason why the other *mhd* wave modes, the fast mode and Alfvén mode waves should be excluded if they dissipate eventually by hydrodynamic shocks. But such a broad concept would probably cause a considerable confusion in the literature. We thus take the term acoustic heating theory to mean the heating of the corona by dissipation of hydrodynamic shocks which develop out of acoustic or modified

Send offprint requests to: P. Ulmschneider acoustic waves (slow mode waves in strong fields) generated by a suitable mechanism. The acoustic heating theory in this sense is thus seen to be distinctly different from a fast mode (Habbal et al., 1979) or Alfvén mode heating theory (Uchida and Kaburaki, 1974; Ionson, 1978; Wentzel, 1979), from a steady current dissipation mechanism (Rosner et al., 1978) and from a flare-like explosive heating theory (Brueckner et al., 1978). It is the aim of this work to show that the claims are unsafe that the acoustic heating theory (in the present or in the more restricted meaning) is inadequate and that these claims should be considered with utmost caution. There are several reasons for that.

Firstly, uncertainties of the solar OSO-8 observations are too large to safely exclude the acoustic heating theory.

Secondly, instead of attributing the disagreement between observed X-ray fluxes and theoretical acoustic fluxes to the inadequacy of the particular version of the Lighthill theory an unproven generalization was made that the basic idea of acoustic heating is wrong.

Thirdly, and most significantly recent theoretical developments in the field of acoustic (Bohn, 1980) and magnetoacoustic (Stein and Leibacher, 1980; Stein, 1981) energy generation indicate that older acoustic fluxes given e. g. by Renzini et al. (1977) have to be considerably modified. These order-of-magnitude modifications significantly all occur in the direction of improving agreement with observation.

With the aim of showing that the acoustic heating theory can presently not be dismissed we do not want to demonstrate the validity of this theory in the face of rival theories. Thinking of the complicated magnetic structure of stellar coronae, the lack of high resolution observations and of detailed magnetohydrodynamic computations this can presently not be done. We conclude that the acoustic theory at the present time still remains an important possibility for the heating of stellar coronae.

2. Evidence and Discussion

In Linsky's (1980) presentation of evidence for the rejection of the acoustic heating theory of coronae arguments pertaining to the chromospheric and the possibly different coronal heating mechanisms have unfortunately been mixed. Chromospheric heating mechanisms will be discussed elsewhere (Ulmschneider and Stein, 1981) and thus we do not consider Mg II and Ca II observations here which are clearly chromospheric. The main evidence against acoustic or slow mode *mhd* wave heating of the solar corona appears to be derived from UV line observations of Si II and C IV in the upper chromosphere and the transition layer obtained from OSO-8. Athay and White (1978, 1979) as well as Bruner (1978) found acoustic fluxes which were roughly by a factor of 60 below the average upper chromospheric and coronal energy requirement of $6\ 10^5$ erg/cm^2 s. Here the well known decrease of sensitivity and the relatively low spatial (both horizontal and vertical) resolution of the OSO-8 instrument call for some caution in accepting these fluxes.

It is known that magnetic fields in the network are concentrated into flux tubes with thicknesses considerably below one arc s. Thus the 20″ by 2″ resolution leads to severe spatial averaging which indeed has been recognized by Athay and White. Another difficulty in interpreting the observations is the lack of detailed radiation-hydrodynamic and *mhd* wave calculations which include effects of wave pressure, ionization, diffusion, finite equilibration times, and the detailed line formation process. Moreover most calculations of line formation in the upper chromosphere and the transition layer are made on the basis of a smooth monotonic temperature distribution where e. g. Si II is produced at a certain fixed height. In a dynamic atmosphere where large non-monotonic temperature jumps occur, it is not clear where Si II is formed and how the detailed contribution to the line comes about.

Athay and White (1979) have discussed the systematic reduction of the observed flux values due to spatial and temporal averaging. They estimate that the averaging procedure in the OSO-8 experiment could underestimate the velocity amplitude by a large factor which they, however, estimate to be less than 10. But if we include the above mentioned time dependent effects it is not clear without detailed computations and a realistic estimate of the horizontal distribution of the relevant magnetic flux tubes whether a factor of ten is not indeed reasonable. As the velocity amplitude enters the acoustic flux as a square the missing factor of 60 seems well within the uncertainty.

Recently work by Mein and Mein (1980), Schmieder and Mein (1980), as well as Mein and Schmieder (1981) on the solar Mg I b_2, Ca II K and IRT lines appears to confirm the Athay and White results. In their work the hydrodynamic and radiation treatments of acoustic waves have been greatly improved. Similarly to the Athay and White observations, however, the relatively low spatial resolution of the Ca II observations could lead to severe underestimation of the mechanical flux.

The other important basis for the rejection of the acoustic heating theory is derived from recent X-ray observations obtained from the Einstein satellite. Here the main reasoning against the acoustic theory (Vaiana et al., 1981) is (see Fig. 1) that firstly the the total acoustic flux is insufficient to provide for the observed X-ray flux and secondly that the large variation of the X-ray flux as seen in similar stars cannot be explained by the acoustic theory. Thirdly large X-ray emission of O and B stars "cannot be explained by the acoustic theory since OB stars are generally thought to be too hot to have significant convective energy transport" (Linsky, 1980).

The insufficiency argument is based on a comparison (see Fig. 1) of observed X-ray fluxes with theoretical acoustic fluxes derived from the Lighthill theory for cases which explicitly exclude magnetic fields. We show in Fig. 1 more recent acoustic fluxes ($\alpha=1.5$) by Renzini et al. (1977) multiplied by a factor of 2 after Schmitz and Ulmschneider (1980). α is the ratio of mixing length to pressure scale height.

The reasoning of Vaiana et al. concerns mainly the large discrepancy (see Fig. 1) for stars of spectral type later than K 5. Here indeed the X-ray flux is seen to be many orders of magnitude larger than the theoretical acoustic flux. This was already recognized by Blanco et al. (1974) and by Cram and Ulmschneider (1978) for the case of stellar chromospheres and prompted a search for the cause of this discrepancy.

In his thesis work Bohn (1980) found three principal reasons for the previously low values of the acoustic flux in late type stars. He found firstly that molecular opacities have to be included, secondly that the treatment of the H_2 dissociation was inadequate, and thirdly that the homogeneous density assumption used in the Lighthill theory breaks down particularly for the late type dwarf stars. Inclusion of molecular opacity brings the top of the convection zone to regions of lower pressure where consequently the convective velocities must be greater. In addition the convective velocities are modified if the adiabatic gradient is changed by the H_2 dissociation. Due to the high dependence of the acoustic energy production on velocity this considerably increases the acoustic flux. Following earlier work of Stein (1968), Bohn (1980) has shown that in late type stars the density stratification becomes

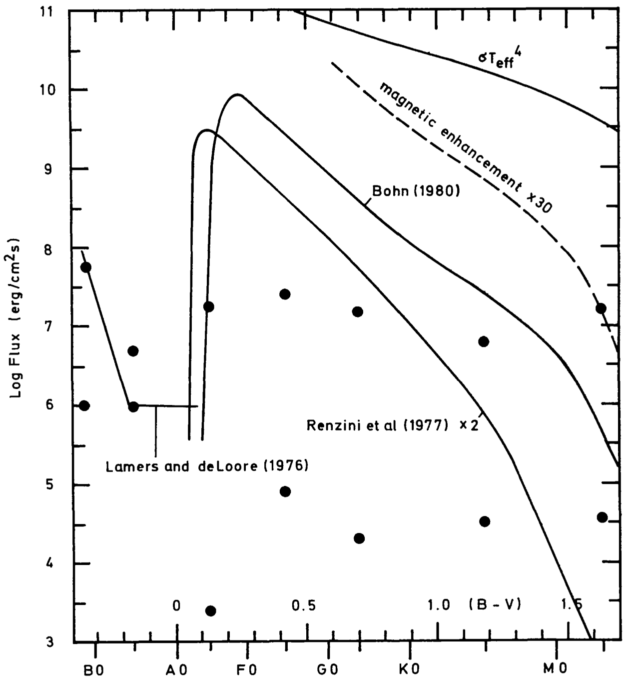

Fig. 1. Comparison of X-ray fluxes of main sequence stars (dots, Vaiana et al., 1981) with theoretical non-magnetic acoustic fluxes (drawn) from various authors. Estimated modified acoustic (slow mode) wave fluxes of stars which are completely covered by kilogauss type magnetic fields are shown dashed. Stars with incomplete magnetic field coverage have fluxes intermediate between the magnetic and non-magnetic cases. The total stellar radiative flux is indicated by the line marked $\sigma T_{\mathrm{eff}}^4$. For the plot of the theoretical fluxes we used tables of Allen (1976, pp. 206, 209)

very important leading not only to dipole but also to very efficient monopole sound generation. Together the three effects increase the acoustic flux by many orders of magnitude as can be seen in Fig. 1. Here it has to be noted that for late M stars the fluxes of Bohn (1980) are very likely only lower estimates as there molecular opacities are not yet adequately included. The greatly increased acoustic fluxes show that the acoustic heating theory taken even in its most narrow meaning has difficulties only with the most efficient X-ray emitting M stars.

Additional acoustic flux arises if magnetic fields are present. Recently Stein and Leibacher (1980) and Stein (1981) have shown that in strong magnetic field regions slow mode waves but also Alfvén waves are very efficiently produced by monopole sound generation. In a homogeneous atmosphere compared to the quadrupole type sound production for acoustic and fast mode waves, both the slow and the Alfvén mode waves in flux tubes are produced more efficiently by a factor of $\left(\frac{c}{u}\right)^4$ and $\left(\frac{a}{u}\right)^4$ respectively, where c is the sound velocity, a the Alfvén velocity and u the mean convective velocity. With $u=0.3\,c$ or $u=0.1\,c$ one has efficiency factors of 120 or 10,000 compared to the acoustic and fast mode fluxes. Stein and Leibacher (1980) publish for the Sun Alfvén flux values ($3\;10^9$ erg/cm^2 s) which are by a factor of 30 larger than the largest acoustic fluxes ($1\;10^8$ erg/cm^2 s) given by Stein (1968). As in kilogauss type magnetic field areas in the solar photosphere the Alfvén velocity is roughly equal to the sound velocity we expect the slow mode flux to be enhanced by a factor similar to the Alfvén flux. Thus very crudely the magnetic field may lead to an enhancement of the acoustic energy flux by a factor of 30. This factor admittedly is quite uncertain and a more detailed investigation is urgently needed.

Nevertheless, as an indication, we have plotted the factor 30 wave flux enhancement for late type dwarf stars in Fig. 1. This factor, by the way, agrees nicely with the factor of ten variation of the Mg II emission fluxes observed by Basri and Linsky (1979) for stars of the same gravity and effective temperature depending on the magnetic field coverage of the star. As we may safely assume that the stars with highest X-ray flux have the largest coverage by magnetic fields we should compare the observed X-ray fluxes with the theoretical fluxes that include magnetic fields. In such a comparison (see Fig. 1) it is seen that the insufficiency argument largely collapses in face of the greatly increased theoretical wave fluxes.

At this point we should discuss the efficiency of conversion of the total wave flux into X-ray flux. For the average Sun one has a total acoustic flux of around 10^8 erg/cm^2 s and about $3\;10^5$ erg/cm^2 s in observed coronal XUV flux. Even assuming that this XUV flux is produced entirely by acoustic heating, which remains doubtful, there would be an efficiency of only $3\;10^{-3}$ for conversion into X-ray flux. Roughly for the Sun an order of magnitude of the total acoustic flux is consumed by photospheric radiation damping and another order of magnitude by chromospheric heating. Depending on the outer boundary condition (open or closed fields) the X-ray and wind conversion efficiencies on the Sun are strong functions of the magnetic field geometry. In the HR diagram the X-ray conversion efficiency is not a constant. As has been shown by Schmitz and Ulmschneider (1981) the amount of radiation damping in the photospheres of *R*-type chromosphere stars (of relatively high T_{eff} and low gravity) is much larger than in *S*-type chromosphere stars (with relatively low T_{eff} and larger gravity) due to the different extent of the radiation damping zone. Likewise we have reason to believe that the fraction of acoustic energy used for the chromospheric heating is also not a constant in the HR diagram. In addition Bohn (1980) has shown that together with the increasing importance of monopole sound generation in late type dwarf stars a change in the emitted acoustic spectrum occurs. The more the monopole source term becomes important, the closer the acoustic spectrum peaks near the cut-off frequency, that is, near long periods. Long period waves in turn are much less damped as has been shown by Ulmschneider and Kalkofen (1977) and Ulmschneider et al. (1978). From the latter processes we thus expect a strong increase of the X-ray conversion efficiency for late type dwarf stars. This together with the increasing importance of magnetic fields towards later type (compare frequency of dMe–dM stars, Joy and Abt, 1974) decreases considerably the strong T_{eff} dependence of the theoretical X-ray flux for late type stars.

Let us now discuss the large X-ray variation seen for stars of the same T_{eff} and gravity as exhibited in Fig. 1. Firstly we know from the Sun that the most intense X-ray emission occurs in closed loop regions while the coronal holes with open field geometries produce X-rays much less efficiently. Thus as discussed above it is obvious that the X-ray conversion efficiency is a strong function of the magnetic field geometry. Secondly it is clear from another discussion above that due to the difference in the average magnetic field coverage of similar stars the ratio of magnetic field enhanced wave generation to non-magnetic wave generation is also highly variable. Both processes together quite likely provide for a large variability in the X-ray emission similar to the variation seen in the solar corona.

Finally let us now discuss early type stars. That these stars emit considerable acoustic flux even in absence of convection zones has been known since some time (Hearn, 1973; Lamers and De Loore, 1976; see also Nelson and Hearn, 1978; Martens, 1979). Here the process variously called κ-mechanism, Hearn mechanism, Eddington valve instability or overstability, replaces the convection zone as energy source for acoustic waves. The waves are amplified by the stellar radiation field. Crude flux calculations (criticized by Berthomieu et al., 1976) have been made by Lamers and De Loore (1974, 1976) and used in the comparison with X-ray observations by Vaiana et al. (1981). As with the acoustic fluxes of late type stars the theory of early type stars is in its infancy. Magnetic fields e.g. have not been considered. It is quite likely that in areas of strong primordial magnetic field strength fast mode-, slow mode- as well as Alfvén mode waves are efficiently produced. We feel that in such a situation no safe conclusion as to the insufficiency of the (magneto) acoustic heating theory can be made. On the contrary the dip in the observed X-ray emission as function of $T_{\rm eff}$ for stars of spectral type A (see Fig. 1) seems indeed to indicate a change in the generation mechanism as suggested by the theories of convective and radiative acoustic energy generation. Thus as opposed to Linsky (1980) we feel that the acoustic heating theory can not be rejected for early type stars.

3. Conclusions

The purpose of this work is not to demonstrate the validity of the acoustic heating theory of stellar coronae in the face of rival theories featuring fast mode-, Alfvén mode heating, flare-like mechanisms or anomalous current dissipation. Our main purpose is to show that recent claims that the acoustic heating theory can now safely be rejected are unfounded. In particular we showed that the erroneous conclusion of insufficiency of the acoustic theory in late type stars rested on a comparison of observations with a theory that is both non-magnetic and inadequate. As shown in Fig. 1 the acoustic energy flux due to the recent theoretical work of Stein and Leibacher (1980), Stein (1981) and Bohn (1980) using a modified version of the Lighthill theory has greatly increased. In addition the decreasing width of the radiation damping zone and the shift of the acoustic spectrum to longer period waves when going to stars of later spectral type lead to a strongly increasing efficiency of conversion of the acoustic flux into X-ray flux. The large variation of the observed X-ray flux in stars of similar type is likely due to the great variation of the X-ray conversion efficiency in closed as compared to open field geometries and to the varying total magnetic field coverage of the stars. An absence of efficient convection zones in early type stars does not preclude the efficient generation of (magneto) acoustic waves in these stars. As a matter of fact the observed conspicuous dip of the X-ray flux as a function of $T_{\rm eff}$ for stars of spectral type A is in good agreement with the location of the transition between convective and radiative acoustic energy generation as was already noticed by Vaiana et al. (1981).

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