On the Intrinsic Difficulty of Producing Stellar Coronae With Acoustic Waves

Reiner Hammer
Kiepenheuer-Institut für Sonnenphysik
Schöneckstr. 6, D-7800 Freiburg, FRG

Peter Ulmschneider
Institut für Theoretische Astrophysik der Universität Heidelberg
Im Neuenheimer Feld 561, D-6900 Heidelberg 1, FRG

Abstract. We discuss theoretical limits on the potential of acoustic waves to produce coronae around inactive solar-like stars. For a star of solar mass and radius, short-period shock waves (which are produced most efficiently in the convection zone) could generate a corona only for base pressures and energy fluxes that are smaller than the observed values by several orders of magnitude. The energy budget of solar coronal holes could be supplied only by shock waves of extremely long periods ($\approx 2P_A$), which are difficult to produce in solar-like stars, and which suffer from *propagation restrictions* in the photosphere and chromosphere. This fundamental difficulty to produce coronae with acoustic waves is even aggravated towards stars of smaller gravity.

1. Introduction

Until the mid 1970s, acoustic shock waves were popular candidates for heating not only the chromosphere, but also the corona of the Sun and similar stars. Meanwhile, however, severe *empirical* limits could be placed on the role that these waves play in heating the solar corona, so that even coronal holes are now thought to be energized by magnetic mechanisms. Unfortunately, relevant observations are difficult to interpret and unavailable for stars other than the Sun. Moreover, observations alone do not explain why there are not enough compressive waves left in the upper chromosphere to heat the open corona, even though such waves are certainly abundant in the photosphere. Finally, acoustic waves are still discussed for "basal flux stars", which rotate so slowly or have so shallow convection zones that their activity has settled to a minimum level that is independent of the rotation rate. This has often been interpreted as evidence of nonmagnetic heating of the outer stellar atmosphere (Schrijver 1987).

In this paper we discuss *theoretical* constraints on the contribution of acoustic waves to the energy supply of stellar coronae.

2. Results and Discussion

The velocity amplitude of periodic shock waves is determined by two competing effects: dissipation tends to reduce the amplitude, while the outward decline of the density tends to increase

* Mitteilungen aus dem Kiepenheuer-Institut Nr. 337

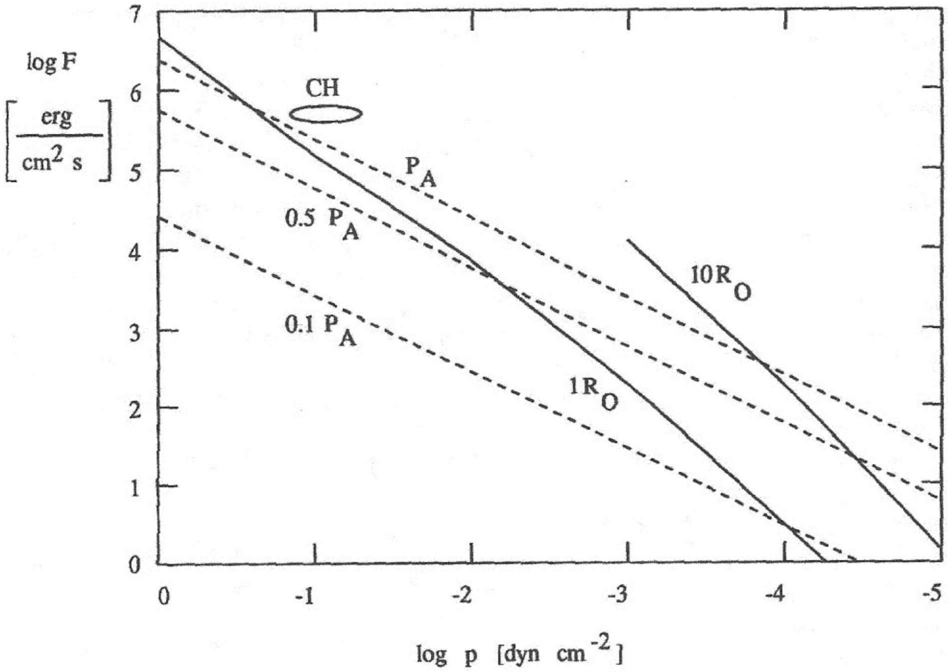

Figure 1. The dashed curves show the maximum energy flux that can be carried by an acoustic wave of a certain period (given as parameter in units of the photospheric acoustic cut-off period P_A). The drawn curves show the minimum coronal energy requirements for two stars of solar mass, but different radii. The intersection points between the two types of curves define upper limits for the base pressure and total energy budget of a corona that is heated exclusively by acoustic waves of the given period. Solar coronal hole parameters (after Withbroe 1988) are centered around the area labeled CH. For low gravity stars, the potential of acoustic waves to sustain a corona is even smaller than for the Sun.

it. Ultimately, both effects balance each other, so that the waves reach a state of constant amplitude (cf. Ulmschneider – these proceedings). The energy flux F_M carri such a wave is proportional to the gas pressure p and to the square of the wave period P,

$$F_M \propto pP^2. \quad (1)$$

Fig. 1 shows the energy flux of constant amplitude waves for three different periods, which are specified in units of the acoustic cut-off period of the photosphere, $P_A = 4\pi c_S/\gamma g$, where c_S is the adiabatic sound speed. Also shown are the minimum coronal energy requirements for two stars of solar mass, but different radii (cf. Hammer – these proceedings). By definition, the actual energy losses of an open corona must always lie above these curves. On the other hand, the wave contribution to coronal heating must lie below the corresponding dashed curves, since the wave energy is partially reflected back at the transition region. Consequently, the intersection of the two types of curves determines *upper limits* for the base pressure and for the total energy losses of a corona that is heated exclusively by such waves.

These theoretical limits are severe. After Bohn (1984), the maximum acoustic energy generation in the convection zone occurs near $0.1P_A$, and virtually no power is generated beyond about $0.5P_A$. According to Fig. 1, waves of period $0.1P_A$ can contribute no more than 0.5% to the energy losses of actual coronal holes; and if no other heating mechanisms were available they could produce only coronae with base pressures and total energy fluxes smaller than those of typical solar coronal holes by three and five orders of magnitude, respectively. Even waves with the longest periods to be reasonably expected, $P \approx 0.5P_A$, could only produce an extremely faint corona.

For low gravity stars it is even more difficult to sustain a corona with acoustic shock waves. This is caused by the fact that in such stars the minimum coronal energy losses consist mainly of radiation from the transition region and inner corona. The emission scale height is proportional to the gravitational scale height; hence the emitting volume is much larger on a giant than on a dwarf. For the same value of the base pressure, therefore, the minimum energy requirements of a giant are larger than those of a dwarf (cf. Fig. 1).

In order to balance the energy requirements of a solar coronal hole, one would formally need shock wave periods of at least twice the cut-off period. For long period waves, however, Eq. (1) tends to become unreliable (Cuntz and Ulmschneider 1988). Moreover, as long as such waves are linear, they are evanescent over the entire photosphere and lower chromosphere. Therefore, they can transport energy upward only

- if they are able to *tunnel* as linear waves through the cool part of the atmosphere, like the solar chromospheric 3 min oscillations (e.g., Mihalas and Mihalas 1984). The upward energy transport is particularly easy
- if the waves become nonlinear shock waves already *below* photosphere, because then they are no longer affected by propagation restrictions. Such waves likely exist in long-period or semiregular variable stars like Miras.
- if they are generated in the chromosphere by the coalescence of *non*monochromatic shocks, where stronger shocks overtake weaker ones. As a result of this coalescence, the average shock period increases with height and can ultimately exceed the cut-off period. However, this process takes so long (cf. the calculations of Cuntz, 1987) that it cannot alleviate the fundamental problem of acoustic waves to produce a corona. Shock coalescence is probably important in the extended chromospheres of noncoronal giants, but inefficient in the compact chromospheres of solar-like stars.

3. Conclusions

As a potential heating mechanism for stellar coronae, acoustic shock waves suffer from the following intrinsic difficulty: The balance of the effects of stratification and dissipation forces such waves into a state of constant amplitude, in which they carry an energy flux that decreases rapidly with height, namely linearly proportional to the gas pressure. The minimum energy requirements of an open corona, on the other hand, decrease only slightly stronger than linearly with the pressure. Consequently, the two types of curves in Fig. 1 intersect under a small angle – and thus at very small pressures and energy fluxes, unless the wave period is sufficiently large. Long period waves, however, are difficult to produce and suffer from propagation restrictions. The discrepancy between energy supply and coronal energy requirements increases towards low gravity stars.

References

Bohn, H. U.: 1984, *Astron. Astrophys.* **136**, 338.

Cuntz, M.: 1987, *Ap. J.* **188**, L5.

Cuntz, M. and Ulmschneider, P.: 1988, *Astron. Astrophys.* **193**, 119.

Mihalas, D. and Mihalas, B. W.: 1984, *Foundations of Radiatio Hydrodynamics*, Oxford Univ. Press.

Schrijver, C. J.: 1987, in *Cool Stars, Stellar Systems, and the Sun*, eds. J. L. Linsky and R. E. Stencel, Lecture Notes in Physics **291**, Springer, p. 135.

Withbroe, G. L.: 1988, *Ap. J.* **325**, 442.