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PHYSIQUE DES MOUVEMENTS
DANS LES
ATMOSPHÈRES STELLAIRES

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EXTRAIT

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

Colloques internationaux du C.N.R.S.
N° 250 - PHYSIQUE DES MOUVEMENTS DANS LES ATMOSPHÈRES STELLAIRES

THEORETICAL TEMPERATURE MINIMUM FOR THE SUN.

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Method : Under the assumption that the chromospheric temperature rise is due to the dissipation of acoustic shock waves we have computed the development of acoustic waves from the solar convection zone up to the point of shock formation in the high photosphere. For this purpose we have solved the full set of hydrodynamic equations with the method of characteristics which treats both the shock formation and the development of the shock exactly. The transfer equation of radiation was solved simultaneously in the grey approximation with an integral method. We have run extensive tests both on the hydrogen and radiation code and have insured for example that our radiative method goes over into the optically thin approximation at low optical depth and the diffusion approximation at large optical depth. We have employed a sinusoidally oscillating piston at the lower boundary to propagate acoustic waves of various frequencies and fluxes into a radiative equilibrium model of the solar atmosphere. For such models we have modified the Harvard Smithsonian Reference Atmosphere (HSRA, Gingerich et al. 1971) and a recent model of Vernazza, Avrett and Loeser (1975).

Results : In Fig. 1 the heights of shock formation,are shown as function of wave period and acoustic flux. Because of the strong dissipation of the shocks these shock heights represent theoretical temperature minima. The dashed lines are shock heights if no radiative damping is considered. It is seen that long period waves develop shocks at greater heights because the profile distorsion compared to the wavelength is smaller for these periods. Fully drawn lines are shock heights with radiative damping taken into account. Because radiative damping effects small period waves most severely, these waves are weakened and shocks develop only at great heights. Thin lines are shock heights for the model of Vernazza et al. (1975). Because their upper photospheric temperatures are smaller the wave amplitudes grow faster and the shocks develop earlier. It is seen that the HSRA temperature minimum is reproduced by fluxes of between 2.0 and 6.0E7 erg/cm^{2}s. Fluxes of this size are in agreement with those computed by Stein (1968) or Osterbrock (1961).

In Fig. 2 we see the final flux of the acoustic waves after passage of the radiation damping zone as function of wave period and initial flux. The full lines are for the modified HSRA model, the thin lines for the Vernazza et al. model. It is seen that large periods are relatively little effected. The flux of a 50 s wave decreases for example only by a factor of 3. Waves of small period are strongly damped. The flux of a 20 s wave for instance is decreased by a factor of 9. Generally speaking however the effect of radiative damping is much smaller than expected from approximate calculations. Allowing for a factor of 2 uncertainty it is seen that waves with periods of less than 40 sec and initial fluxes of between 1.0 and 4.0E7 reproduce the computed chromospheric radiation loss (Ulmschneider 1974). Periods of this type are in agreement with predictions of Stein (1968).

Another important property of acoustic waves is exhibited in Fig. 2. We note that at a given wave period the final flux is a constant fraction of the initial flux. This scaling law can be understood as follows. For small amplitude acoustic waves the gas velocity, temperature and density perturbation are proportional to the square root of the initial flux. Because in these waves radiative damping depends linearly on the temperature and density perturbation it too is scaled linearly. The mechanical flux of an acoustic wave is a quantity of second order depending e.g. on the gas velocity and the pressure perturbation. Radiation damping being effective only over a limited height interval thus decreases the mechanical flux proportional to the initial flux.
This general scaling property can be used to predict the development of any spectrum of acoustic waves from the convection zone, where it is generated, to the base of the chromosphere. In Fig. 3 we show this transformation applied to the acoustic spectra of Stein (1968, drawn). It is seen that photospheric radiation damping decreases and shifts the spectra (dashed) toward larger periods. This process will continue in the chromosphere where shock dissipation reduces the amplitudes of the small period components.

To summarize our results we want to make the following points :

1.) Radiative damping appears less effective than previously thought.

2.) The acoustic heating theory explains well both the observed position of the solar temperature minimum, and the chromospheric energy requirements.

3.) Because long period waves are little effected by radiative damping a large amount of energy in this frequency band is available for heating in the transition layer and corona. This makes an acoustic heating theory of the corona quite likely.

4.) In order to have sufficient acoustic energy to produce chromosphere and corona the required initial flux in the convection zone may be reduced considerably.

Literature :

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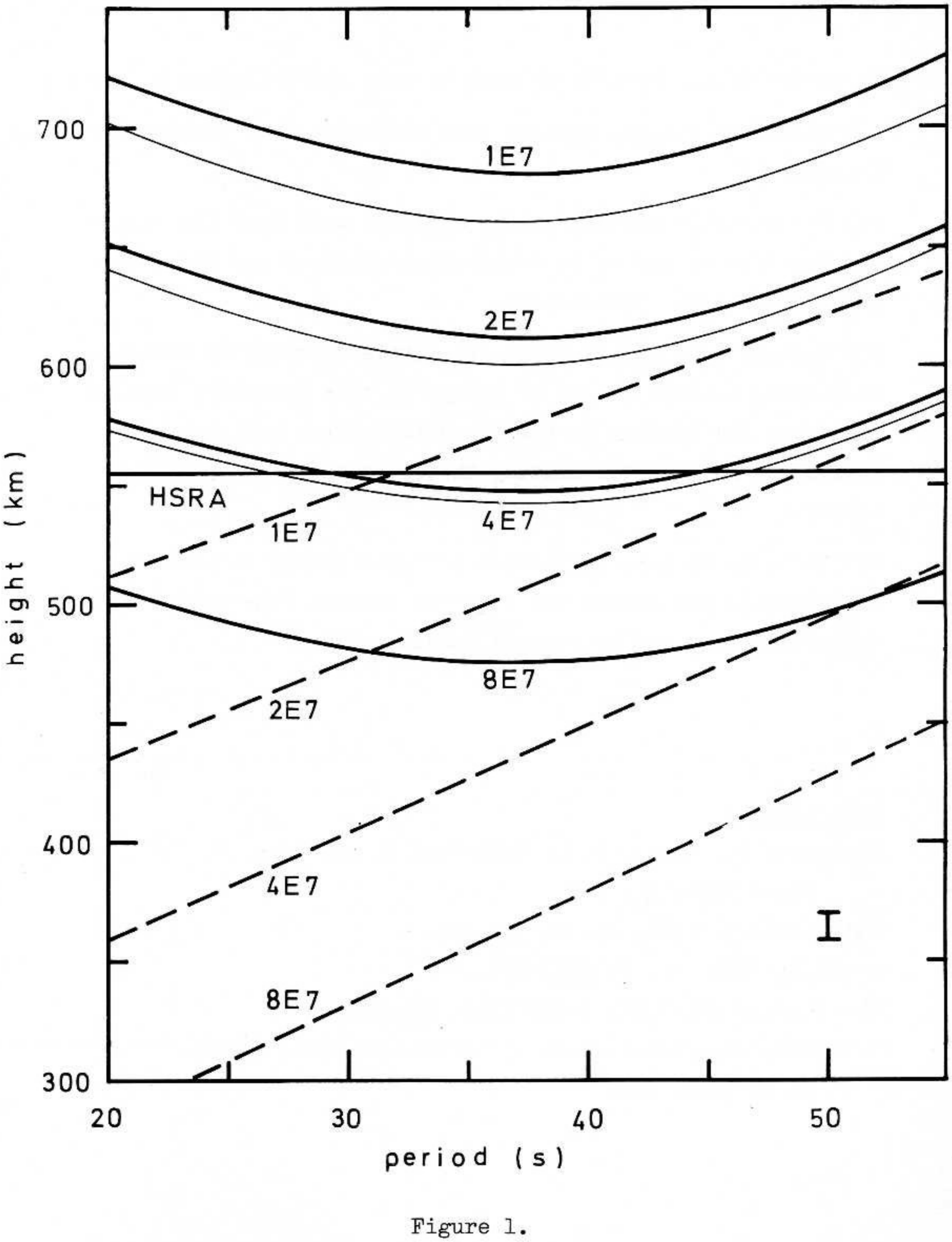
700
600
500
400
300
20
30
40
50
height (km)
period (s)
1E7
2E7
4E7
8E7
HSRA
1E7
2E7
4E7
8E7
I

Figure 1.

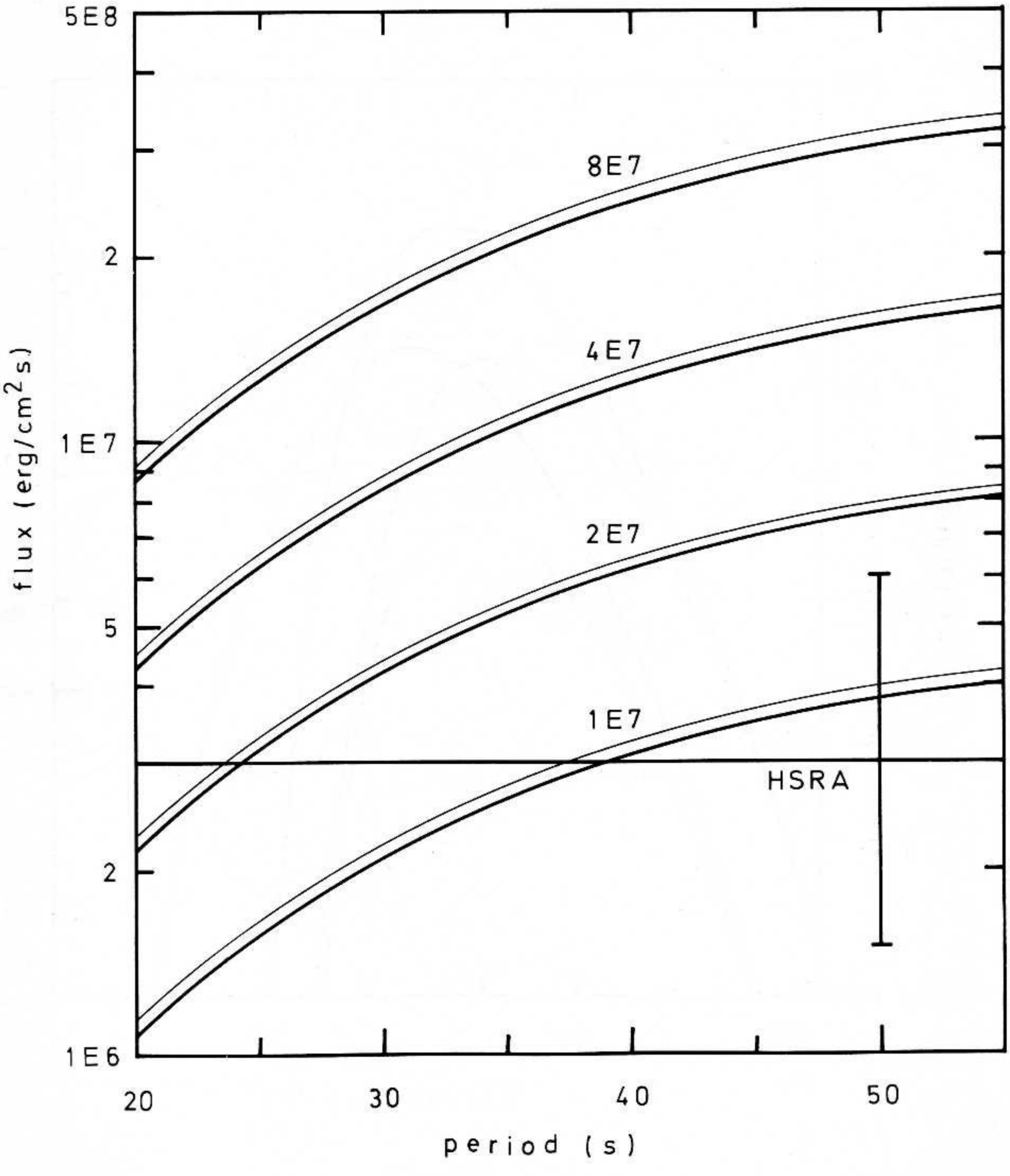
5E8
2
1E7
5
2
1E6
flux (erg/cm^{2}s)
8E7
4E7
2E7
1E7
HSRA
20
30
40
50
period (s)

Figure 2.

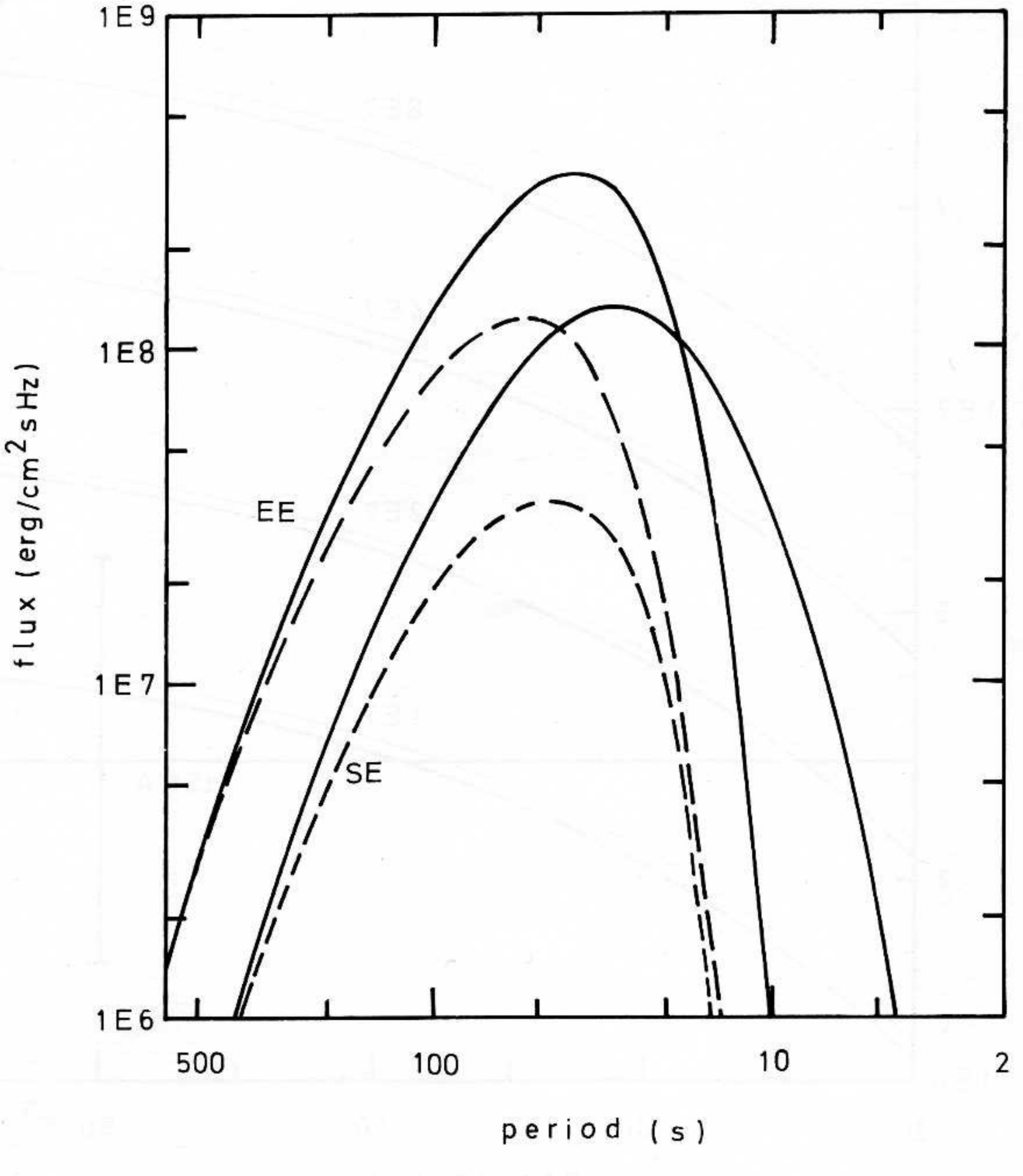

Figure 3.