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On the Physics of Waves in the Solar Atmosphere: Wave Heating and Wind Acceleration

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CONTINUATION OF STUDIES INITIATED IN 1990

I. Solar Physics

New calculations of the acoustic wave energy fluxes generated in the solar convective zone have been performed by Dr. Z. Musielak in collaboration with Drs. R. Rosner (University of Chicago), R. Stein (Michigan State University), and P. Gail and P. Ulmschneider (University of Heidelberg). The original theory developed by R. Stein in 1967 has been corrected by including a new frequency factor describing temporal variations of the turbulent energy spectrum. These new frequency factors have been obtained by large-scale numerical simulations of convection carried out by Dr. Rosner's group at the University of Chicago. We have modified the original Stein code by including this new frequency factor and have tested the code extensively. Then, we have calculated the acoustic wave energy fluxes for the Sun finding much higher fluxes than those previously obtained. Alos, we have demonstrated that with the new frequency factor, the calculated acoustic wave energy fluxes are not sensitive to the shape of this factor. Two papers containing these results are presently in preparation and will be soon submitted to *The Astrophysical Journal* before the summer. The obtained results are important in solving the longstanding problem of solar physics, namely, what is the role of the acoustic wave energy in the heating of the solar atmosphere and in the excitation of the solar p-mode oscillations.

Another possible source of the mechanical energy generated in the solar convective zone is the excitation of magnetic flux tube waves which can carry energy along the tubes far away from the region of their origin. The problem how efficiently these waves are generated in the Sun has been recently solved by Z. Musielak, R. Rosner and P. Ulmschneider. The obtained results indicate that the magnetic tube wave energy fluxes are sufficient to supply energy to heat lower parts of the solar chromosphere and may be especially importnat in the energy balance in the chromospheric network. Investigations are being presently performed to estimate how much of this wave energy can reach upper chromospheric layers and also whether these waves can contribute to the heating of the solar corona. We are preparing a series of papers (six !) on this subject for publication in *The Astrophysical Journal.* The obtained results have been presented at the AAS Meeting held in Atlanta in Jan. 1992.

In order to understand transfer of the wave energy originated in the solar convective zone to the outer atmospheric layers, one has to compute wave propagation and dissipation in highly nonhomogeneous solar atmosphere. This sort of calculations usually requires time-dependent and nonlinear codes. P. Ulmschneider and Z. Musielak have calculated the propagation of nonlinear magnetic tube waves in the solar atmosphere and studied mode coupling, shock formation and heating of the local medium. In a paper recently published in *Astronomy and Astrophysics* they showed that these waves may indeed efficiently heat the solar atmosphere and that the heating will be especially significant in the chromospheric network. Presently, these studies are being extended to include reflection of magnetic tube waves in a more realistic solar atmosphere model.

The propagation of waves in the solar outer atmospheric layers is also important for explaining the observed spectrum of the solar p-mode oscillations. Drs. J. Fontenla (UAH/CSPAR), Z. Musielak and R. Moore (NASA/MSFC) have been working on the wave trapping problems and on evaluation of critical frequencies for wave reflection in the solar atmosphere. The problem of the observed short period tail for the p-mode spectrum is likely to be explained by using these results.

The fact that the solar wind is originated in solar coronal holes has been well-known for many years, however, the mechanism for acceleration of the wind from these holes is still unknown. Also, it is unclear what is the main physical mechanism responsible for heating of the coronal holes. Recent work done by Drs. R. Moore, Z. Musielak, S. Suess (NASA/MSFC) and C. An (Applied Research, Inc.) has shown that the role played by

Alfven waves in the wind acceleration and the coronal hole heating is dominant. The results of these calculations were already published in *The Astrophysical Journal* . In addition, the authors indicate that the main source of these waves for the heating and the wind acceleration are very likely solar microflares extensively observed in the UVSP data. New extensive studies of the physical processes responsible for the solar wind acceleration are being undertaken as a result of this support. First obtained results are being prepared for publication in *The Journal of Geophysical Research.* We intend to construct self-consistent models of the solar coronal wind based on the reflected Alfven waves and compare the theoretical range of physical parameters required by these models to observational data.

The results discussed above have been obtained for the Sun. Presently, we are performing calculations of wave energy fluxes generated in late-type dwarfs stars and studying physical processes responsible for the heating of stellar chromospheres and coronae. This will allow us to investigate solar-stellar connections.

II. Physics of Waves

A new analytical approach for studying linear Alfven waves in smoothly nonuniform media has been recently developed by Drs. Z. Musielak, J. Fontenla and R. Moore. The approach formally takes into account continuous, arbitrary structure of the background medium and allows transforming the wave equation to the form of the Klein-Gordon equation which displays a critical frequency for wave propagation. It has been shown that the wave equation can be always transformed to a Klein-Gordon equation and that the latter displays the critical frequency below which reflection is strong; the results of these studies have been recently published in *Physics of Fluids.* This approach is presently being extended to study the propagation of linear and nonlinear magnetohydrodynamic (MHD) waves in stratified, non-isothermal and solar atmosphere. Dr. Z. Musielak and a graduate student are presently working on developing a numerical code to carry out these calculations and the research is supported by this NASA grant. The motivation for these studies is to investigate in detail the problem of chromospheric and coronal heating, wind acceleration, damping of p-mode oscillations by energy lekage and other problems related to the solar and stellar activity.

Dr. Z. Musielak and his graduate student have also extended the Lighthill theory of sound generation to nonisothermal media (with a special temperature distribution) and a paper with these results is being prepared for submition to *Physics of Fluids.*

Dr. Z. Musielak and a graduate student are presently conducting studies of energy cascade by nonlinear MHD waves and possible chaos driven by these waves. The first obtained results show that chaotic behavior occurs in the system of reflected Alfven waves nonlinearly coupled to magnetoacoustic waves. The results will be prepared for publication in *Physics of Fluids.*

Publications Resulting From This Support

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"Magnetic Confinement, Alfven Wave Reflection, and the Origins of X-ray and Mass Loss 'Dividing Lines' for Late-Type Giants and Supergiants" Rosner, R., An. C. H., Musielak, Z. E., Moore, R. L., and Suess, S. T., *Astrophys. J. Letters*, **372**, L91-L94 (1991).

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"Recent Developments in Theories of Wave Generation" Musielak, Z. E. *Mechanisms of Chromospheric and Coronal Heating*, Eds. P. Ulmschneider, E. Priest and R. Rosner (Springer-Verlag, Heidelberg) p. 369-379 (1991).

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"A Regularization Method for the Extrapolation of the Solar Potential Magnetic Fields" Gary, G. A. and Musielak, Z. E., *Astrophys. J.*, **392**, 722-735 (1992).

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"Heating of Solar and Stellar Chromospheres and Coronae by MHD Waves"
Musielak, Z. E. *Highlights in Astronomy*, Ed. J. Bergeron, Volume 9 (1992) in press.

"Alfven Wave Trapping and Heating in Coronal Holes: Theory and Observation"
Suess, S. T., Moore, R. L., Musielak, Z. E. and An, C. H., *Solar Wind Seven* (1992) in press.

"Alfven Wave Heating in Solar Coronal Holes"
Moore, R. L., Musielak, Z. E., Suess, S. T. and An, C. H., *Memorie della Societa Astronomica Italiana*, (1992) in press.

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"On Reflection of MHD Fast Mode Waves in an Isothermal Atmosphere"
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Presentations Resulting From This Support

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