Final Report

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Astrophysics Theory Program

On the Origin and Evolution of Stellar Chromospheres, Coronae and Winds

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SUMMARY OF COMPLETED WORK

This grant was awarded by NASA to The University of Alabama in Huntsville (UAH) to construct state-of-the-art, theoretical, two-component, chromospheric models for single stars of different spectral types and different evolutionary status. In our proposal, we suggested to use these models to predict the level of the "basal flux", the observed range of variation of chromospheric activity for a given spectral type, and the decrease of this activity with stellar age. In addition, for red giants and supergiants, we also proposed to construct self-consistent, purely theoretical wind models, and used these models to investigate the origin of "dividing lines" in the H-R diagram. In the following, we describe our completed work.

We have accomplished the first main goal of our proposal by constructing **first purely theoretical, time-dependent and two-component models of stellar chromospheres.** The models require specifying only three basic stellar parameters, namely, the effective temperature, gravity and rotation rate, and they take into account non-magnetic and magnetic regions in stellar chromospheres. The non-magnetic regions are heated by acoustic waves generated by the turbulent convection in the stellar subphotospheric layers. The magnetic regions are identified with magnetic flux tubes uniformly distributed over the entire stellar surface and they are heated by longitudinal tube waves generated by turbulent motions in the subphotospheric and photospheric layers. The coverage of stellar surface by magnetic regions (the so-called filling factor) is estimated for a given rotation rate from an observational relationship. The constructed models are time-dependent and are based on the energy balance between the amount of mechanical energy supplied by waves and radiative losses in strong Ca II and Mg II emission lines. To calculate the amount of wave energy in the non-magnetic regions, we have used the Lighthill-Stein theory for sound generation modified by Musielak, Rosner, Stein & Ulmschneider (1994). The acoustic wave energy fluxes for chromospherically active stars located in different regions of the H-R diagram have been computed (Ulmschneider, Theurer & Musielak 1996; Ulmschneider, Theurer, Musielak & Kurucz 1998). The wave energy fluxes carried by longitudinal waves along magnetic flux tubes have also been calculated by using both analytical and numerical methods. Our analytical approach is based a theory developed by Musielak, Rosner, & Ulmschneider (1989) and Musielak, Rosner, Gail & Ulmschneider (1995) which allows computing the wave energy fluxes for linear waves. A numerical approach has been developed by Ulmschneider & Musielak (1998) to compute the energy fluxes for nonlinear waves. Both methods have been used to calculate the wave energy fluxes for stars located in different regions of the HR diagram (Musielak, Rosner & Ulmschneider 1998; Ulmschneider, Musielak & Fawzy 1998). Having obtained the wave energy fluxes carried by acoustic and longitudinal tube waves, we have investigated the behavior of these waves in the solar and stellar atmospheres (Theurer, Ulmschneider & Cuntz 1996; Theurer, Ulmschneider & Kalkofen 1997; Sutmann, Musielak & Ulmschneider 1998; Fawzy, Ulmschneider & Cuntz 1998) and use the results to construct theoretical models of stellar chromospheres (Cuntz, Ulmschneider & Musielak 1998; Buchholz, Ulmschneider & Cuntz 1998). We have used these models to predict theoretically the "basal flux" in late-type dwarfs and giants, and the decrease of the Ca II emission with decreasing stellar rotation rate. **The first purely theoretical, two-component and time-dependent models of stellar chromospheres** have been constructed by Cuntz, Rammacher, Ulmschneider, Musielak & Saar (1998).

The first theoretical, two-component chromospheric models have been constructed for K2 V stars with $T_{\rm eff} = 4900$ K, log $g = 4.5$ and the radius $R = 0.8$ R$_\odot$. The magnetic field strength B_o inside magnetic flux tubes at the photospheric level $\tau_{5000} = 1$ is calculated by assuming that the gas pressure inside and outside the tube (p_i and p_e, respectively) is given by $p_i/p_e = 1/5$, which holds for the Sun (Solanki 1996) and is extended here to the considered stars. This gives $B_o = 2100$ G which is independent of stellar rotation. We assume that the magnetic flux tubes with B_o are uniformly distributed over the entire stellar surface. To construct our two-component chromospheric models, we have to know the area of the stellar surface that is covered by magnetic and non-magnetic regions; this can be done by specifying the photospheric magnetic filling factor f_o. Since we are interested in the effects of stellar rotation rate $P_{\rm rot}$ on the level of chromospheric activity, we have to relate $B_o f_o$ to $P_{\rm rot}$. The relationship of our choice is based on the results of Rüedi et al. (1997) who presented a very recent analysis of 13 high-quality optical spectra for late-type dwarfs (G1–K5) with different levels of activity. The derived relationship has been used to constrain the shape of the flux tubes (see Cuntz, Ulmschneider & Musielak 1998 for details). Fast rotating stars are expected to have higher coverage of flux tubes than slow rotating stars implying increased photospheric and chromospheric magnetic filling factors. As a consequence the tube spreading in fast rotating stars should be smaller.

Having specified the structure of magnetic regions, the wave calculations are performed by solving a set of time-dependent, nonlinear and ideal MHD equations for thin magnetic flux tubes. The equations are solved using the method of characteristics (Fawzy, Ulmschneider & Cuntz 1998) and the wave energy fluxes obtained by Ulmschneider, Musielak and Fawzy (1998) are used. In non-magnetic regions, the wave calculations are performed by solving time-dependent and nonlinear hydrodynamic equations for acoustic waves and the wave energy fluxes computed by Ulmschneider, Theurer & Musielak 1996) are used. In both cases of magnetic and non-magnetic regions, only *monochromatic waves* are considered. In addition, the models for both regions are computed separately, which means that there is no mutual interaction between both components and there is no energy leakage from one component to the other. Simultaneously with these wave calculations, we perform the computations of radiative losses in H$^-$ continuum and in Mg II and Ca II emission lines by solving the appropriate radiative transfer equations together with the statistical equilibrium equations for NLTE populations. The time-dependent energy balance between the wave dissipation due to the formation of shocks and the emitted radiative losses is calculated at different heights in the atmosphere and it is used to determine the local values of temperature, density and pressure. The time-averaged chromospheric models of magnetic and non-magnetic regions are calculated by averaging over a timespan of many wave periods. Since the heating in magnetic regions is much more efficient than in non-magnetic regions, the increase in the level of chromospheric activity in stars of the same spectral type is obtained by increasing the coverage of the stellar surface by magnetic regions. To achieve this, higher magnetic filling factors are required, which imply higher stellar rotation rates — a trend fully consistent with the observational data.

The first theoretical, two-component chromospheric models have been constructed for K2 V stars with $T_{\rm eff} = 4900$ K, log $g = 4.5$ and the radius $R = 0.8$ R$_\odot$. The magnetic field

strength B_o inside magnetic flux tubes at the photospheric level $\tau_{5000} = 1$ is calculated by assuming that the gas pressure inside and outside the tube (p_i and p_e, respectively) is given by $p_i/p_e = 1/5$, which holds for the Sun (Solanki 1996) and is extended here to the considered stars. This gives $B_o = 2100$ G which is independent of stellar rotation. We assume that the magnetic flux tubes with B_o are uniformly distributed over the entire stellar surface. To construct our two-component chromospheric models, we have to know the area of the stellar surface that is covered by magnetic and non-magnetic regions; this can be done by specifying the photospheric magnetic filling factor f_o. Since we are interested in the effects of stellar rotation rate P_{rot} on the level of chromospheric activity, we have to relate $B_o f_o$ to P_{rot}. The relationship of our choice is based on the results of Rüedi et al. (1997) who presented a very recent analysis of 13 high-quality optical spectra for late-type dwarfs (G1–K5) with different levels of activity. The derived relationship has been used to constrain the shape of the flux tubes (see Cuntz, Ulmschneider & Musielak 1998 for details). Fast rotating stars are expected to have higher coverage of flux tubes than slow rotating stars implying increased photospheric and chromospheric magnetic filling factors. As a consequence the tube spreading in fast rotating stars should be smaller.

Having specified the structure of magnetic regions, the wave calculations are performed by solving a set of time-dependent, nonlinear and ideal MHD equations for thin magnetic flux tubes. The equations are solved using the method of characteristics (see Herbold et al. 1985; Rammacher & Ulmschneider 1989; Fawzy, Ulmschneider & Cuntz 1998) and the wave energy fluxes obtained by Ulmschneider, Musielak and Fawzy (1998) are used. In non-magnetic regions, the wave calculations are performed by solving time-dependent and nonlinear hydrodynamic equations for acoustic waves (see Ulmschneider, Muchmore & Kalkofen 1987; Rammacher & Ulmschneider 1992) and the wave energy fluxes computed by Ulmschneider, Theurer & Musielak 1996) are used. In both cases of magnetic and non-magnetic regions, only *monochromatic waves* are considered. In addition, the models for both regions are computed separately, which means that there is no mutual interaction between both components and there is no energy leakage from one component to the other. Simultanously with these wave calculations, we perform the computations of radiative losses in H^- continuum and in Mg II and Ca II emission lines by solving the appropriate radiative transfer equations together with the statistical equilibrium equations for NLTE populations (Ulmschneider, Muchmore & Kalkofen 1987; Rammacher & Cuntz 1991). The time-dependent energy balance between the wave dissipation due to the formation of shocks and the emitted radiative losses is calculated at different heights in the atmosphere and it is used to determine the local values of temperature, density and pressure. The time-averaged chromospheric models of magnetic and non-magnetic regions are calculated by averaging over a timespan of many wave periods. Since the heating in magnetic regions is much more efficient than in non-magnetic regions, the increase in the level of chromospheric activity in stars of the same spectral type is obtained by increasing the coverage of the stellar surface by magnetic regions. To achieve this, higher magnetic filling factors are required, which imply higher stellar rotation rates — a trend fully consistent with the observational data.

Figure 1. The decrease of Ca II fluxes with decreasing stellar rotation rate. (a) Theoretical Ca II fluxes (squares) calculated by using our theoretical, two-component chromospheric models are directly compared to the observational data (triangles) for a set of stars with spectral type between K0 V and K3 V. (b) The comparison between the observations at low activity phases of the stars (triangles) and the theoretical basal flux limit is shown (after Cuntz, Rammacher, Ulmschneider, Musielak & Saar 1998).

The computed purely theoretical chromospheric models are then used to calculate the emergent Ca II H+K line fluxes and profiles, and compare them with the observational results (see Fig. 1). Note that for the purpose of calculating these emergent fluxes and profiles, the magnetic and non-magnetic regions must be composed together (see Cuntz, Rammacher, Ulmschneider, Musielak & Saar 1998). The results presented in panel (a) of Figure 1 show the decrease of Ca II flux with decreasing stellar rotation rate. Theoretically calculated Ca II fluxes (denoted by squares) are directly compare to the observational data (denoted by triangles) for a set of stars with spectral type between K0 V and K3 V. In panel (b) of the same figure the comparison between low activity phases of the stars obtained via long-term monitoring programs (triangles) and the theoretical basal flux limit (Buchholz, Ulmschneider & Cuntz 1998) is shown. In both cases the agreement between the theoretical results and the observational data is very good, which shows that our models are able to reproduce empirical chromospheric emission – stellar rotation relations as well as chromospheric basal flux limits for stars of low activity. This gives us confidence that our **two-component chromospheric models are consistent with observations** and that we are on the right track to explain the origin and evolution of stellar chromospheres.

We have also accomplished our second main goal of the proposed research by constructing **theoretical, time-dependent and self-consistent wind models** based on the momentum deposition by nonlinear Alfvén waves. The full set of single–fluid MHD equations with the background flow has been solved by using a modified version of the ZEUS MHD code. The constructed wind models are radially symmetric with the magnetic field decreasing radially and the initial outflow is described by the standard Parker wind solution. In contrast to previous studies, no assumptions regarding wave linearity, wave damping, and wave-flow interaction are made; the models thus naturally account for the backreaction of the wind on the waves as well as for the nonlinear interaction between different types of MHD waves. The models have been already used to explain the origin of fast speed streams in solar coronal holes (see Ong, Musielak, Rosner, Suess & Sulkanen 1997). The obtained results clearly demonstrate that the momentum deposition by Alfvén waves in the solar wind can be sufficient to explain the origin of fast stream components of the solar wind. The range of wave amplitudes required to obtain the desired result seems to be in good agreement with recent observations. After obtaining these encouraging results, we intended to use the developed code to construct self-consistent models of cool massive winds observed from late-type giants and supergiants. The work was supposed to be done by Mr. Ong as part of his Ph.D. research. Unfortunately, Mr. Ong, who had been working on this project for the last two years and was partially supported by this grant, decided to accept a position in the computer industry and discontinued working on his dissertation. In the following, we briefly describe these results and then show how to apply them to cool massive winds observed from the evolved stars.

Figure 2. Time-averaged wind velocity profiles for four different solar wind models. In each model, the initial flow is assumed to be the thermally-driven (Parker) wind. Alfvén waves with the same period (1 hour) but different amplitudes, A, are generated at the base of each model (corresponding to the base of solar coronal holes) and allowed to interact with the initial flow for 278 hours. After this time, the resulting time-averaged wind velocity profiles are calculated. The obtained results show that the presence of Alfvén waves with amplitudes ranging from 40 km s^{-1} to 75 km s^{-1} is required in the solar wind in order to explain the origin of fast streams (after Ong, Musielak, Rosner, Suess & Sulkanen 1997).

To calculate our wind models, we start with a standard Parker model of thermally driven winds (Parker 1958) and treat it as the initial flow. The structure of an atmosphere computed with this initial flow is then perturbed by radially-propagating toroidal Alfvén waves of a finite amplitude. The interaction between these waves and the flow is treated self-consistently, e.g., the structure of the wind and atmosphere is modified by the waves and, in turn, the wave behavior is influenced by this newly modified structure. The physical parameters describing the background medium are recorded (as they fluctuate on time scales of the Alfvén wave period), and then time-averaged over the Alfvén wave crossing time in order to obtain estimates for the corresponding parameter values of the flow on time scales long when compared to the Alfvén wave period. In order to perform these calculations, we modified the original ZEUS code (Stone & Norman 1992a, b), and use it to solve the full set of ideal single fluid compressible MHD equations in one-dimension; we consider a single magnetic field line along which the field decreases radially. At the lower boundary of our computational domain the field line is perturbed in such a way that toroidal ($\partial/\partial\phi = 0$) Alfvén waves are continuously generated. The upper boundary is transparent, which means that the wind and waves freely leave the computational domain. Since we are solving the single-fluid MHD equations without any further simplifications, processes such as wave reflection, nonlinear coupling between the various MHD waves, and shock formation are automatically accounted for.

Our results are presented in Figure 2, which shows the distribution of the time-averaged wind velocity with distance. The following physical parameters at the base of the solar corona ($r = 1R_\odot$) are used: the strength of the magnetic field $B_o = 10$ G, temperature $T_o = 1.0 \times 10^6$ K and density $\rho_o = 1.3 \times 10^{-15}$. The obtained results clearly show that Alfvén wave amplitudes ranging from 40 km s^{-1} to 75 km s^{-1} at the coronal base of the solar wind to explain the acceleration of fast speed streams in the solar wind. This range of required Alfvén wave amplitudes is in agreement with observations of line broadening of Mg coronal emission lines (Hassler et al. 1990), with more recent Ulysses observations (e.g., Phillips et al. 1995), and with very recent independently performed numerical simulations by Ofman & Davila (1998).

In addition to these major accomplishments, we have completed our analytical (Musielak, Rosner & Ulmschneider 1998a) and numerical (Huang, Musielak & Ulmschneider 1995) investigation of the generation of transverse magnetic tube waves in stellar convection zones; note that these waves have not yet been incorporated in our stellar chromosphere models described above. The results of these studies will be used to calculate the wave energy fluxes carried by these waves in stars located in different regions of the HR diagram (Musielak, Rosner & Ulmschneider 1998b; Musielak, Ulmschneider & Fazwy 1998). We have also investigated the efficiency of the energy transfer along magnetic structures (Huang 1996; Wu, Xiao, Musielak & Suess 1996; Ziegler & Ulmschneider 1997a,b; Huang, Musielak & Ulmschneider 1998a,b). The primary goal of this study is to investigate the validity of the thin flux tube approximation used in our chromospheric models. The relevant work to our wind modeling project has been done by Krogulec & Musielak (1998) and by R. Rosner (in several papers published with different collaborators - see Section I.C) who have investigated the behavior of linear and nonlinear Alfvén waves in solar coronal holes and stellar atmospheres and the effects caused by these waves on the background medium. M. Cuntz has also worked on ab-initio models for outer atmospheric flows in α Ori (Cuntz 1997) and the interpretation of chromospheric velocity fields in various late-type (super-)giants considering proposed heating mechanisms (Harper, Bennett & Cuntz 1998).

The results described above have been obtained by the P.I. (Dr. Z. E. Musielak), Co-I's (Drs. R. Rosner and P. Ulmschneider), one senior research associate (Dr. M. Cuntz, who joined UAH in Jan. 1996), one junior research associate (Dr. P. Huang, who joined UAH in Jan. 1996 and left in May 1996 to work for industry), and two graduate students in physics; one of them, Mr. K. K. Ong, has recently left UAH to work for industry without completing his Ph.D. Dr. Cuntz has devoted all his time to work on the project and has been fully supported by the grant. He has been closely working with the P.I. and Dr. Ulmschneider, and with Mr. Ong while he was at UAH. He also worked with Dr. Huang during her stay at UAH. The Co-I's visited UAH several times and the P.I. spent some time at both the University of Chicago and the University of Heidelberg. In Fall of 1996, Mr. Ong spent three months at the Univeristy of Chicago working with Dr. Rosner on construction of self-consistent and time-dependent stellar wind models. Finally, the P.I. has been working on several problems directly related to the project during the regular academic year when his salary is fully paid by UAH and during the academic year 1997/98 when he was on sabbatical leave.

REFEREED PAPERS RESULTING FROM THIS NASA SUPPORT

"On the Efficiency of Energy Transfer by Nonlinear Magnetohydrodynamic Waves Propagating Along Magnetic Slabs", Huang, P., *Phys. Plasmas*, 3, 2579 (1996)

"Propagation of MHD Body and Surface Waves in Magnetically Structured Regions of the Solar Atmosphere", Wu, S. T., Xiao, Y. C., Musielak, Z. E., and Suess, S. T., *Solar Phys.*, 163, 291 (1996)

"Wave Resonances and Induced Flow Due to Nonlinear Alfvén Waves in a Stratified Atmosphere", Stark, B. A., *J. Geophys. Res.*, 101, 15,615 (1996)

"Acoustic Wave Energy Fluxes for Late-Type Stars", Ulmschneider, P., Theurer, J. and Musielak, Z. E., *Astron. Astrophys.*, **315**, 212 (1996)

"Acoustic Wave Propagation in the Solar Atmosphere. IV. Nonadiabatic Wave Excitation with Frequency Spectra", Theurer, J., Ulmschneider, P., and Cuntz, M., *Astron. Astrophys.*, **324**, 587 (1996)

"Propagation of Three-Dimensional Alfvén Waves in a Stratified, Thermally-Conduction Solar Wind", Orlando S., Lou Y.-Q., Rosner R., and Peres G., *J. Geophys. Res.*, **101**, 24443 (1996)

"Self-Consistent and Time-Dependent Solar Wind Models", Ong, K. K., Musielak, Z. E., Suess, S. T., and Sulkanen, M. E., *Astrophys. J. Letters*, **474**, L143 (1997)

"Dynamic Response of Magnetic Tubes to Transverse Perturbations. I. Thick Flux Tubes", Ziegler U. and Ulmschneider P., *Astron. Astrophys.*, **324**, 417 (1997)

"Acoustic Wave Propagation in the Solar Atmosphere. V. Observations versus simulations", Theurer J., Ulmschneider P., Kalkofen W., *Astron. Astrophys.*, **324**, 717 (1997)

"Chromospheric Velocity Fields in α Orionis (M2 Iab) Generated by Stochastic Shocks", Cuntz, M., *Astron. Astrophys.*, **325**, 709 (1997)

"The Sun as an X-ray Star: Overview of the Method", Peres G., Orlando S., Reale F., Rosner R., and Hudson H., *Solar Phys.*, **172**, 239 (1997)

"Dynamic Response of Magnetic Tubes to Transverse Perturbations. II. Towards Thin Flux Tubes", Ziegler U. and Ulmschneider P., *Astron. Astrophys.*, **327**, 854 (1997)

"Alfvénic Fluctuations in the Fast and Slow Solar Winds", Orlando S., Lou Y.-Q., Peres G., and Rosner R., *J. Geophys. Res.*, **102**, 24139 (1997)

"Self-Consistent and Time-Dependent Magnetohydrodynamic Chromosphere Models for Magnetically Active Stars", Cuntz, M., Ulmschneider, P., and Musielak, Z.E., *Astrophys. J. Letters*, **493**, L117 (1998)

"Basal Heating in Main-Sequence Stars and Giants: Results from Monochromatic Acoustic Wave Models", Buchholz, B., Ulmschneider, P., and Cuntz, M.,*Astrophys. J.*, **494**, 700 (1998)

"Alfvén Wave Transmission and Heating of Solar Coronal Loops", Litwin C., and Rosner R., *Astrophys. J.*, **499**, 945 (1998)

"Reflection Coefficient and Non-WKB Effects for Alfvén Waves Propagating in the Solar Wind", Krogulec, M., and Musielak, Z. E., *Acta Astron.*, **48**, 77 (1998)

"The Heating of Solar Magnetic Flux Tubes. I. Adiabatic Longitudinal Tube Waves", Fawzy, D.E., Ulmschneider, P., and Cuntz, M., *Astron. Astrophys.*, in press (1998)

"On the Generation of Nonlinear Magnetic Tube Waves in the Solar Atmosphere. II. Longitudinal Tube Waves", Ulmschneider, P., and Musielak, Z. E., *Astron. Astrophys.*, in press (1998)

"Acoustic Wave Propagation in the Solar Atmosphere. IV. Analytical Solutions for Adiabatic Wave Excitations", Sutmann, G., Musielak, Z. E., and Ulmschneider, P., *Astron. Astrophys.*, in press (1998)

"Numerical Simulation of Nonlinear MHD Body and Surface Waves in Magnetic Slabs", Huang, P., Musielak, Z. E., and Ulmschneider, P., *Astron. Astrophys.*, in press (1998a)

"Acoustic Wave Energy Fluxes for Late-Type Stars. II. Nonsolar Metallicities", Ulmschneider P., Theurer J., Musielak Z.E., and Kurucz R., *Astron. Astrophys.*, in press (1998).

"MHD Wave Energy Fluxes for Late-Type Stars. I. Longitudinal Tube Waves", Ulmschneider, P., Musielak, Z. E., and Fawzy, D.E., *Astron. Astrophys.*, submitted (1998)

"MHD Surface Waves on Magnetic Interface Embedded in a Compressible Medium", Huang, P., Musielak, Z. E., and Ulmschneider, P., ***Astron. Astrophys.***, submitted (1998b)

"On Chromospheric Velocity Fields of Evolved Late-Type Stars", Harper, G. M., Bennett, P. D., and Cuntz, M., ***Astrophys. J.***, submitted (1998)

" Two-Component Theoretical Chromosphere Models for Stars of Different Magnetic Activity: The Ca II Emission — Stellar Rotation Relation of K Dwarfs", Cuntz, M., Rammacher, W., Ulmschneider, P., Musielak, Z. E., and Saar, S. H., ***Astrophys. J.***, submitted (1998).

"Time-Dependent Hydrogen Ionization in Time-Dependent Hydrodynamic Flows: A Numerical Method within the Method of Characteristics", Cuntz, M. and Höflich, P., ***Astron. Astrophys.***, submitted (1998)

"On the Generation of Flux Tube Waves in Stellar Convection Zones. III. Transverse Tube Waves Driven by Forced Turbulence", Musielak, Z. E., Rosner, R., and Ulmschneider, P. ***Astrophys. J.***, submitted (1998a)

"MHD Wave Energy Fluxes for Late-Type Stars. II. Transverse Tube Waves", Musielak, Z. E., Ulmschneider P., and Fawzy, D.E., ***Astron. Astrophys.***, to be submitted (1998)

"On the Generation of Flux Tube Waves in Stellar Convection Zones. IV. Wave Energy Fluxes for Late-Type Stars", Musielak, Z. E., Rosner, R., and Ulmschneider, P. ***Astrophys. J.***, to be submitted (1998b)

"Evolution of Solar-Type Activity: MHD Flux Tube Models for β Hydri (G2 IV)", Cuntz, M., Ulmschneider, P., Fawzy, D.E., & Musielak Z.E., ***Astrophys. J.***, to be submitted (1998)

CONTRIBUTED AND REVIEW PAPERS RESULTING FROM THIS NASA SUPPORT

"Chromospheric Heating in Late-Type Stars: Evidence for Magnetic and Nonmagnetic Surface Structure", Cuntz, M., ***Stellar Surface Structure***, Proc. IAU Symposium 176, Eds. K.G. Strassmeier and J.L. Linsky (Dordrecht: Kluwer), 393 (1996)

"Chromospheric and Coronal Heating Mechanisms", Ulmschneider P., ***Astronomical Society of the Pacific Conference Series: Cool Stars, Stellar Systems and the Sun***, Eds. R. Pallavicini and A. K. Dupree, p. 71 (1996)

"Modeling of Temporal Variations in the Solar Chromosphere", Hoeflich P., Avrett E., Uitenbroek H., Ulmschneider P., ***Astronomical Society of the Pacific Conference Series: Cool Stars, Stellar Systems and the Sun***, Eds. R. Pallavicini and A. K. Dupree, p. 105 (1996)

"New Acoustic Wave Energy Computation for Late-Type Stars", Theurer, J., Ulmschneider, P. and Musielak, Z. E., ***Astronomical Society of the Pacific Conference Series: Cool Stars, Stellar Systems and the Sun***, Eds. R. Pallavicini and A. K. Dupree, p. 169 (1996)

"Effects of Thermal Conduction on the Energy Balance of Open Coronal Regions", Hammer, R., Nesis, A., Moore, R. L., Suess, S. T., and Musielak, Z. E., ***Astronomical Society of the Pacific Conference Series: Cool Stars, Stellar Systems and the Sun***, Eds. R. Pallavicini and A. K. Dupree, p. 254 (1996)

"Alfvén Wave Resonances and Flow Induced by Non-Linear Alfvén Waves in a Stratified

Atmosphere", Stark, B. A., Musielak, Z. E. and Suess, S. T., *Solar Wind Eight*, p. 153 (1996)

"Chromospheric and Coronal Heating Mechanisms", Ulmschneider P., *Theoretical and Observational Problems Related to Solar Eclipses*, Eds. Z. Mouradian and M. Stavinschi (Dordrecht: Kluwer), p. 95 (1997)

"Dynamics of Flux Tubes in the Solar Atmosphere: Theory", B. Roberts and Ulmschneider P., *Solar and Heliospheric Plasma Physics*, Eds. G.M. Simett, C.E. Alissandrakis and L. Vlahos (Berlin: Springer-Verlag), p. 75 (1997)

"MHD Waves and Turbulence in the Solar Wind", Musielak, Z. E., *Proceedings of the Third SOLTIP Symposium on Solar and Interplanetary Transient Phenomena*, Eds. M. Dryer and S. Wang, p. 118 (1997)

"First Time-Dependent MHD Heating Models for Chromospheres of Magnetically Active Stars", Cuntz, M., Ulmschneider, P. and Musielak, Z. E., *Tenth Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, p. 60 (1997)

"Self-Consistent and Time-Dependent MHD Heating Models for Chromospheres of Magnetically Active Stars", Cuntz, M., Musielak, Z. E. and Ulmschneider, P., *The 191st Meeting of AAS*, Washington, DC, *Bulletin of AAS*, **29**, 1228 (1997)

"Acoustic and MHD Wave Energy Fluxes for Late-Type Stars", Musielak, Z.E., Cuntz, M., Ulmschneider, P., Theurer, J. and Kurucz, R., *The 191st Meeting of AAS*, Washington, DC, *Bulletin of AAS*, **29**, 1228 (1997)

"Generation of Linear and Nonlinear Magnetic Tube Waves in the Solar Atmosphere", Musielak, Z. E., Rosner, R., and Ulmschneider, P., *Proceedings of the IAU Colloq. No. 153 on Magnetodynamic Phenomena in the Solar Atmosphere — Prototypes of Stellar Activity*, Eds. Y. Uchida, T. Kosugi, and H. S. Hudson, p. 89 (1997)

"UV Spectroscopy of α Ori (M2 Iab) and Implications Regarding Heating Mechanisms", Cuntz, M., *The Scientific Impact of the Goddard High Resolution Spectrograph*, Eds. J.C. Brandt, T.B. Ake III, and C.C. Petersen, *A. S. P. Conference Series*, p. 356 (1998)

"Heating of Chromospheres and Coronae", Ulmschneider P., *Space Solar Physics: Theoretical and Observational Issues in the Context of SOHO Mission*, Eds. J.C. Vial, K. Bocchialini and P. Boumier, in press (1998)

"Heating of Chromospheres and Coronae", Ulmschneider P., *Highlights of Astronomy*, IAU/JD19, Ed. Engvold O., in press (1998)