THEORETICAL STUDIES OF CHROMOSPHERES AND WINDS IN COOL STARS

Grant NAGW-100

Semiannual Progress Report No. 4

For the period 1 April 1982 through 30 September 1982

Principal Investigator

Dr. A.K. Dupree

January 1983

Prepared for
National Aeronautics and Space Administration
Washington, D.C. 20546

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
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The NASA Technical Officer for this grant is Dr. Edward J. Weiler, Code SC-7, Headquarters, National Aeronautics and Space Administration, Washington, D.C. 20546.

(NASA-CR-169975) THEORETICAL STUDIES OF CHROMOSPHERES AND WINDS IN COOL STARS Semiannual Progress Report, 1 Apr. - 30 Sep. 1982 (Smithsonian Astrophysical Observatory) 10 p HC A02/MF A01 CSCL 03A G3/89
N83-19665
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Semi-Annual Report

I. Program Development

During 1982 work was finished on the computer program development needed for our basic non-LTE radiative transfer modeling. As a result it is possible for the first time to determine the formation of spectral lines in expanding spherical atmospheres in a physically realistic way, taking into account multilevel atomic processes, partial frequency redistribution, and other non-LTE transfer effects that affect the formation of optically thick lines. This program development work has been documented by Avrett and Loeser (1983).

II. Results

We have begun an exploration of the formation of Mg II and Ca II circumstellar absorption lines in late-type giants and supergiants. This work is based on the wave-driven wind theory of Hartmann and MacGregor (1980), as modified by Hartmann, Edwards, and Avrett (1982) and Hartmann, MacGregor, and Avrett (1983) to include solution of a realistic energy equation. In this theory, the mass loss rate from a star is specified by the choice of the initial magnetic field strength and Alfven wave flux. This choice is guided by observational estimates of stellar mass loss rates. In the context of this theory, in which the waves are assumed to dissipate exponentially with a constant damping length λ, the terminal velocity is set by the value of λ. Although in this schematic treatment there is no theoretical reason to choose a specific value for λ, it is found that the only way that low terminal velocities in agreement with observation can be produced is by setting $\lambda \sim 1R_*$. With the wave flux and the damping length fixed, the wave heating rate is determined. In these winds, the temperature is determined from balancing wave heating with radiative cooling. We have calculated the radiative cooling rate as a function of density and temperature from the results of plane-parallel chromospheric models and use these results to approximate the radiative cooling in an extended wind (preliminary calculations indicate that this is roughly correct). This permits the run of temperature to be calculated along with the density and velocity profiles.

The most important prediction of these models is that a warm zone in the wind must exist as a result of the wave heating. Within this zone, the Ca II and Mg II atoms can be ionized to Ca III and Mg III, so that the gas is transparent in the resonance transitions. At large distances, the wind cools adiabatically, and the Mg III and Ca III can recombine to the lower stage of ionization. Since the gas is differentially expanding, this behavior gives rise to "double" circumstellar absorption. Close to the star, the gas temperature is not high because the high densities lead to efficient radiative cooling. Thus, low-velocity Mg II and Ca II absorption is formed. As the wind expands, the gas heats up and becomes transparent. At large distances and high velocities, the wind cools, and the recombination once again results in observable circumstellar absorption, in this case with a large blueshift.

The line profiles resulting from this wind behavior are shown in Figs. 1, 2, and 3. The atmospheric model--the run of density, temperature, and velocity--has been computed with a program solving the energy and momentum equations self-consistently (Hartmann, Edwards, and Avrett 1982). This model provides the input to the radiative transfer code.

The ionization balance is solved for hydrogen using a model atom with three levels plus continuum. The resulting solution provides the starting point for calculations for a 3-level Ca II model atom and a 6-level Mg II model atom, solving the transfer problem in partial redistribution in a moving atmosphere as described above.

The results show the sensitivity of the high- and low-velocity absorption to variations in the mass loss rate and in the maximum wind temperature. Comparison with some observed line profiles shows a striking resemblance between theory and observation.

Another feature worthy of notice is that the low-velocity absorption component is slightly blueshifted by ~ -10 to -20 km s^{-1}. A similar shift is observed in many stars with high-velocity circumstellar shells (cf. Reimers 1982). Although there is some confusion in the analysis of the low-velocity Mg II and Ca II features due to the possibility of interstellar absorption, no such contamination exists for Hα. Figs. 1 and 2 show a similar, small blueshift in the line core; there is a great deal of observational evidence for shifts in G and K supergiants (Mallik 1982; Zarro 1982), indicating that the flow is beginning in the low chromosphere.

Note that in the low mass loss rate case, model 1, the high-velocity absorption is much less prominent than in model 2. The high-velocity circumstellar absorption in model 1 may be overestimated, because at the radius where recombination is beginning, the flow times are comparable to the recombination times. This convective effect, which has not been included in the statistical equilibrium equations, will tend to reduce the Ca II and Mg II absorption. Thus it is clear that minor changes in the properties of model 1 could result in no high-velocity absorption at all. The only indication of mass loss would be the asymmetry observed in Mg II, which is not present in Ca II. Stencel and Mullan (1981) have shown that stars exist which show no high-velocity absorption, and have Mg II mass-loss asymmetries but no Ca II asymmetry. This is naturally explained by the warm wind model.

Our results suggest that the warm wind model is correct in outline, which has important implications for the physical understanding of late-type stellar winds. It may be possible to investigate the required damping length empirically through calculations of the type demonstrated here.

We are continuing an investigation into the wind of α Ori. We showed previously that the warm wind theory predicts Hα and free-free emission in approximate agreement with speckle data (Goldberg *et al.* 1982) and radio observations (Newell and Hjellming 1982). This work is continuing in an effort to determine wind temperatures more precisely. Our prior calculations assumed detailed balance in the Lyman lines. This assumption is not adequate for accurate estimation of the wind temperature, and we are recomputing these models. Ultimately we hope to derive the electron temperature and hence the importance of thermal effects in the wind dynamics, as well as determine the amount of mechanical energy required to heat the wind.

III. Further Work

In addition to exploring further the α Ori series of models, we wish to reexamine the T Tauri series of models (Hartmann, Edwards, and Avrett 1982). These models were originally computed with the statistical equilibrium calculated from a static model, and we wish to check the effects of expansion on the source functions, as well as departures from detailed balance in the Lyman lines.

References

Avrett, E.H., and Loeser, R. 1983, "Line Transfer in Expanding Spherical Media," in *Methods in Radiative Transfer,* ed. W. Kalkofen, Cambridge Univ. Press.

Goldberg, L., Hege, E.K., Hubbard, E.N., Strittmatter, P.A., and Cocke, W.J. 1982, in *Second Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun.* SAO Special Report No. 397, Eds. Mark Giampapa and Leon Golub, p. 131.

Hartmann, L., and MacGregor, K.E. 1980, *Ap. J.* **242**, 260.

Hartmann, L., Edwards, S., and Avrett, E.H. 1982, *Ap. J.* **261**, 279.

Hartmann, L., MacGregor, K.E., and Avrett, E. 1983, *Ap. J.* (submitted).

Mallik, S.V. 1982, *J. Astrophys. Astr. India*, **3**, 39.

Newell, R.T., and Hjellming, R.M. 1982, *Ap. J. (Letters)* **263**, L85.

Reimers, D. 1982, *Astr. Ap.*, in press.

Zarro, 1982, thesis

Publications

Stellar Winds and Spindown - Observations, L. Hartmann, invited review, IAU Sympsoium 102, in press.

Cool Star Winds - Recent Observations and Theoretical Implications, L. Hartmann, invited review, **Highlights of Astronomy**, in press.

Wave-Driven Winds from Cool Stars. III. Energy Balance, L. Hartmann, C.B. MacGregor, and E.H. Avrett, *Ap. J.* (submitted).

Line Transfer in Expanding Spherical Media, E.H. Avrett and R. Loeser, in *Methods in Radiative Transfer*, ed. W. Kalkofen, Cambridge Univ. Press, 1983.

Wave-Driven Winds from Cool Stars. II. Models for T Tauri Stars, L. Hartmann, S. Edwards, and E. Avrett, *Ap. J.* **261**, 279.

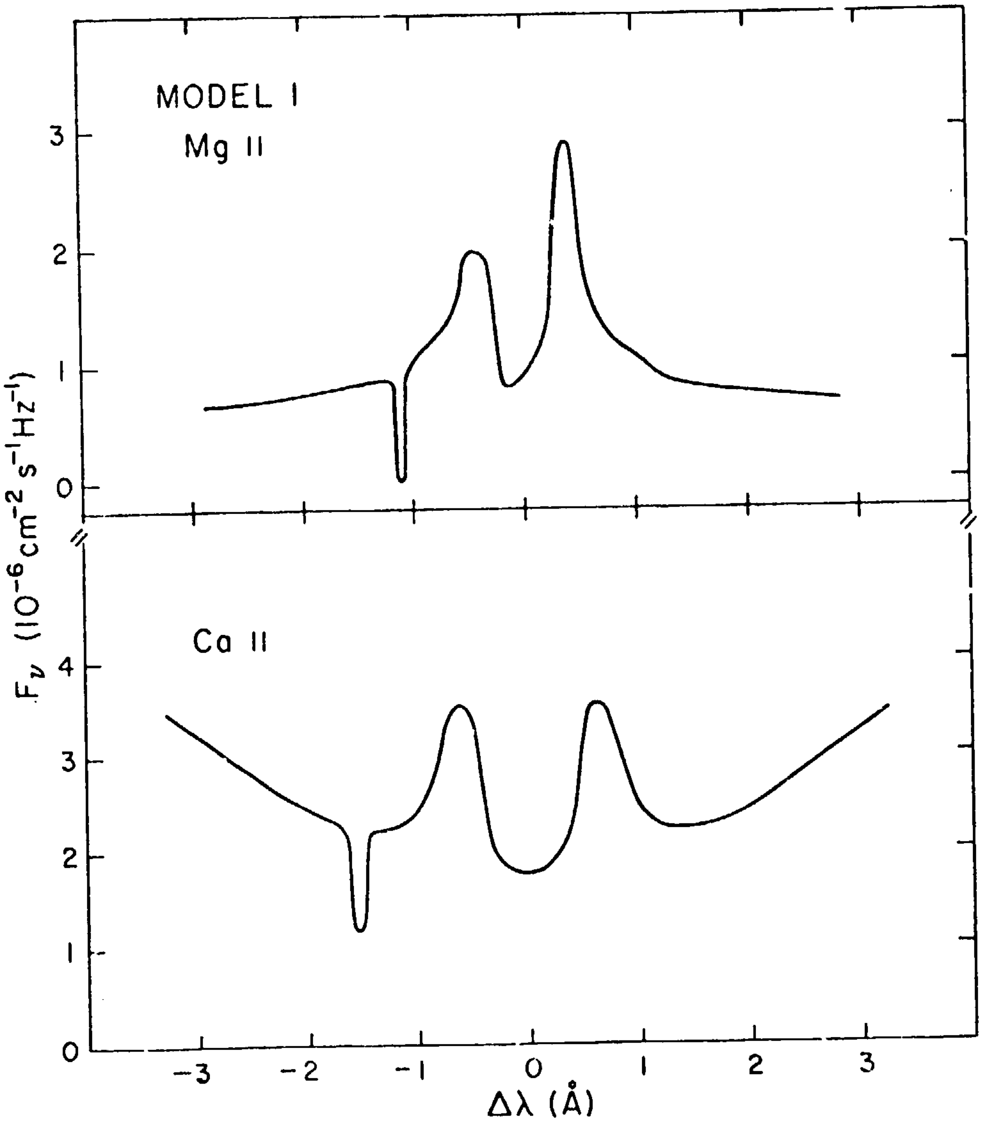

Fig. 1. Calculated Mg II and Ca II line profiles for a star with a mass loss rate of 3.8 x 10^{-9} $M_\odot$ yr^{-1} (model 1).

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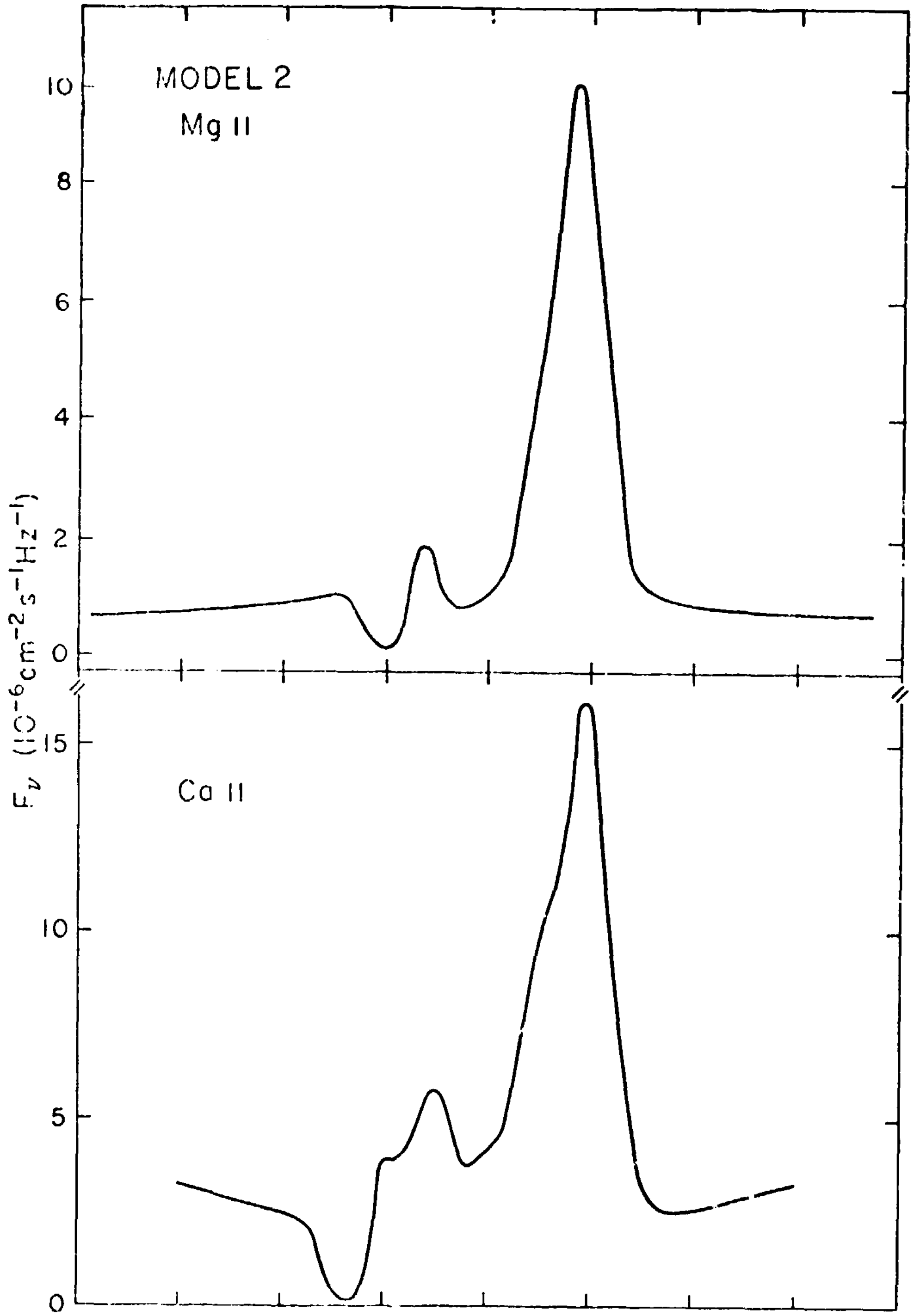

Fig. 2. Calculated Mg II and Ca II line profiles for $\dot{M}$ = 2.9 x 10^{-8} $M_\odot$ yr^{-1} (model 2).

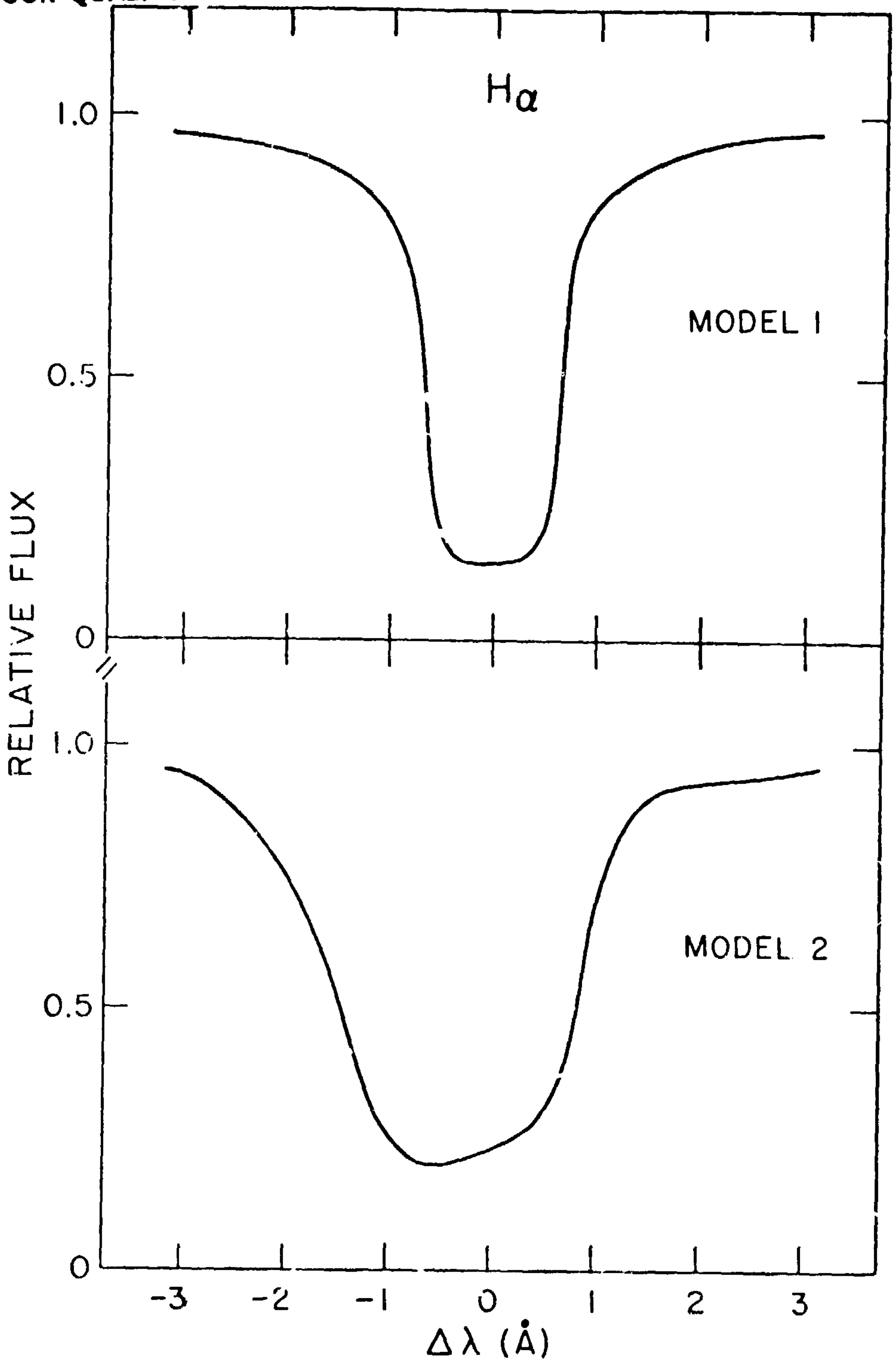

Fig. 3. Hα line profiles for the two model winds.