THE STRUCTURE AND ENERGY BALANCE IN MAIN SEQUENCE STARS

[+] C. Jordan, [*] T.R. Ayres and [+] A. Brown
[+] Department of Theoretical Physics, Oxford University, UK
[*] LASP, University of Colorado, Boulder, USA
[+] Department of Physics, Queen Mary College, London, UK

ABSTRACT

High-resolution spectra obtained with the IUE satellite have been used to study the structure and energy balance in the main sequence stars ξ Boo A, α Cen A, α Cen B and ε Eri. The EUV observations are combined with X-ray fluxes to predict the coronal temperatures, the electron pressures and energy lost or transferred by radiation and thermal conduction

1. INTRODUCTION

In our IUE programmes we have been studying the brighter main-sequence stars for which high-resolution spectra may be obtained. The aim is to compare the structure and energy input requirements of their chromospheres and coronae and thus elucidate the physical processes operating.

Methods established for interpreting solar emision line fluxes in terms of the atmospheric structure (eg. Jordan and Wilson, 1971), should be applicable to stars of similar gravity. Line fluxes alone do not yield unique models, the electron density must also be measured. Because suitable lines are blended or are in a region of strong continuum high resolution observations become necessary. The line fluxes and subsequent models can be used to calculate the radiative losses and net conductive flux through the atmosphere and hence the energy input required to balance these losses can be deduced. Also, line widths allow the non-thermal energy density to be examined and compared with wave-carried energy fluxes. The methods for carrying out the above analysis have been set out by Jordan and Brown (1981) and have already been applied to a α CMi (F5IV-V). (Brown and Jordan, 1981). At present the results are limited by the lack of reliable temperature measurements for the stellar coronae, in most cases only broad-band fluxes or approximate temperature estimates are available.

In the present work we use new high resolution observations of ξ Boo A and ε Eri obtained with exposure times of 952 min and 447 min respectively. We use observations of α Cen A and α Cen B that have been published by

P. B. Byrne and M. Rodonò (eds.), Activity in Red-Dwarf Stars, 61–65.
Copyright © 1983 by D. Reidel Publishing Company.

https://doi.org/10.1017/S0252921100095932 Published online by Cambridge University Press

TABLE 1.

Stellar Parameters & Results for Pressures, Temperatures & Energy Fluxes

Star	$R/R_\odot$	log g	log a	log P_o	log T_c	log F_{R1}	log F_{R2}	log $F_c(T_o)$
α Cen A (G 2V)	1.23	4.2	17.6	14.5 (14.5)	6.1	6.1	4.2	5.2
α Cen B (K 0V)	0.87	4.5	17.6	15.0 (15.1)	6.4	6.2	4.9	6.2
ξ Boo A (G 8V)	0.98	4.4	18.6	16.0 (15.9)	6.8	7.0	6.5	7.2
ε Eri (K 2V)	0.82	4.5	18.3	15.5 (15.5)	6.5	6.6	5.8	6.5

Ayres et al. (1982). X-ray fluxes and temperature estimates are from observations by Vaiana et al. (1980), Walter et al. (1980), Golub et al. (1982) and Johnson (1981). The stellar parameters adopted are given in Table 1.

2. RESULTS

The line fluxes have been used to construct the emission measure distributions between 6300K and $2x10^5$K. These all have essentially the same shape between ~$2x10^4$K and $2x10^5$K. The position of the density sensitive CIII (1909A) and SiIII (1982A) intersystem lines relative to each mean distribution around $5.6x10^4$K has been used to determine or limit the electron pressure. In ξ Boo A the ratio of the SiIII lines at 1206A and 1892A can also be used to estimate the pressure. (Details of atomic data will be given in the fuller paper to be submitted to MNRAS). Solar abundances were adopted since individual values for the relevant elements are not known.

The similar shape of the emission measure distributions shows that the energy input has the same dependance on T_e in these four stars. If energy input balances radiation losses, in the absence of conduction, the best single power function would be

$$dF_m/dT_e = A\ T_e^{\ x} \qquad \text{where } -1 < x < 0. \tag{1}$$

However the large conductive fluxes found would require a dynamic not a static model; this point will be discussed in the fuller paper.

The X-ray fluxes and temperature estimates for ξ Boo A (10^7K) and the α Cen A + α Cen B system ($2.1 \pm 0.4x10^6$K from Golub et al. 1982) may be used to determine the mean coronal pressure, P_c. These pressures ($1.2x10^{16}$ and $8.9x10^{14}$ cm^{-3}K for ξ Boo A and α Cen B respectively) may be adequately reproduced by adopting an emission measure scaling between $2x10^5$K and T_c, such that $E_m(T_e) = a\ T_e^{3/2}$, as found also in the Sun. (Jordan 1980). The scaling law between P_o (at $2x10^5$K), a, g_* and T_c is then

$$T_c^{\ 5/2} - T_o^{\ 5/2} = 1.2x10^8\ P_o^{\ 2}/a\ g_* \tag{2}$$

(Jordan and Brown, 1981). The values of P_o for all four stars may then

https://doi.org/10.1017/S0252921100095932 Published online by Cambridge University Press

be determined. (See Table 1). They are in reasonable agreement with the estimates from line ratios. The ratio of the CI (1944A) line, which is pumped by the optically thick CI (1656A) multiplet (Jordan, 1967) to CII (1334A + 1335A) is also density sensitive. The relative density values show remarkably good agreement with the relative values of P_o and are shown in brackets below P_o in Table 1.

The total radiation losses between 6300K and $2x10^5$K (F_{R1}) may be found directly from the observed emission measures and power loss calculations (eg. Raymond et al. 1976). Above $2x10^5$K the radiative loss (F_{R2}) depends mainly on $E_m(T_c)$. The net conductive flux, $Fc(T_o)$ back at $2x10^5$K is found from the local emission measure and P_o. (See Jordan and Brown, 1981 for details).

To match the temperature variation of the non-thermal widths of the optically thin lines, if these do represent a wave-carried energy flux in a region where P_e and B are constant, then the power of the heating function (equation 1) must be $-0.10<x<0$. For acoustic waves $A = 10^{-11}a$. Interpreted as an acoustic wave flux the energy carried by the observed non-thermal motions is comparable with the radiation losses; only very small (~10 gauss) magnetic field strengths would be required to provide sufficient Alfvén wave flux. However the non-thermal motions may be related to the large conductive flux or energy from the magnetic field. The radiative losses and conductive fluxes are given in Table 1. Neither the temperatures, pressures or ratio of radiative and conductive fluxes fit the predictions of the scaling laws proposed by Rosner et al. (1978) or Hearn (1977), which imply a fixed ratio for these fluxes. The total energy losses do scale as P_o in the way predicted by these scaling laws because the total is insensitive to the split between radiation and conduction (Jordan, 1980).

REFERENCES

Ayres, T.R., Linsky, J.L., Moos, H.W., Stencel, R.E., Basri, G.S., Landsman, W, & Henry, R.C., 1982, Ap. J. In Press.
Brown, A. & Jordan, C: 1981, M.N.R.A.S. 196, pp. 757-779.
Golub, L., Harnden, F.R., Pallavacini, R., Rosner, R. & Vaiana, G.S: 1982, Ap. J. 253, pp. 242-247.
Hearn, A.G., 1977, Sol. Phys, 51. pp. 159-168.
Johnson, H.M., 1981, Ap. J. 243, pp. 234-243.
Jordan, C., 1967, Sol. Phys. 2, pp. 441-450.
Jordan, C., 1980, Astron. Astrophys. 86, pp. 353-363.
Jordan, C. & Brown, A., 1981, in 'Solar Phenomena in Stars and Stellar Systems' (Eds. R.M. Bonnet and A.K. Dupree) D. Reidel. pp. 199-225
Jordan, C. & Wilson, R., 1971, in 'Physics of the Solar Corona' (Ed. C.J. Macris) D. Reidel, pp. 211-236.
Raymond, J.C., Cox, D.P. & Smith, B.W., 1976, Ap. J. 204, pp. 290-292.
Rosner, R., Tucker, W.H., Vaiana, G.S., 1978, Ap. J. 220, pp. 643-665.
Vaiana, G.S. et al. 1981, Ap. J. 245, pp. 163-182.
Walter, F.M., Linsky, J.L., Bowyer, G.S. & Garmire, G., 1980, Ap. J. (Letts) 236, pp. L137-141

https://doi.org/10.1017/S0252921100095932 Published online by Cambridge University Press

DISCUSSION

Rosner: I have a point to make about the calculation of emission measures. Several groups (Los Alamos & Shube at Stanford) have made calculations as follows. They take a prescribed temperature gradient and, initially, a Maxwellian distribution. They then do a Fokker-Planck calculation i.e. a particle calculation in which one calculates the electron distribution function as a function of height. The interesting result of this calculation is that when one looks at the electron distribution at low temperatures (i.e. as defined by the ions' thermal distribution e.g. at 20,000°K) one finds a superabundance of electrons in the high-energy Maxwellian tail. This superabundance is by many orders of magnitude and is density and pressure sensitive. So higher excitation species such as C IV, O VI, etc. are locally produced not by thermal electrons but by what are essentially coronal electrons. So if one compares emission-measure curves from these calculations with those derived from the observations one finds that the calculated curves are virtually flat, independent of temperature instead of concave up. This suggests that in a low-density atmosphere, such as the quiet Sun's, one does not have a temperature diagnostic from these lines. Would you like to comment?

Jordan: Yes. It was in fact I who first pointed out that He II was sensitive to this effect and so I was delighted to see that a proper calculation was done. He II is particularly sensitive to this effect. I have looked for it deliberately and systematically in solar work for the other lines but the exponential factor exp (-kT) in the excitation rate is so temperature insensitive for the Li-like resonance lines such as N V, O VI that I would maintain it is not effecting those lines. It is, however, clearly affecting He II and I am glad you pointed this out. There is a huge spread in the He II line λ1640 and this is because it is sensitive to the local temperature gradient. This is true whether or not one has coronal X-rays controlling the ionization balance or the electron tail from the corona. One cannot distinguish between the two from the spread of the He II line. So He II is very sensitive to the temperature gradient. The temperature gradient goes up as the pressure goes up and so (referring to Table 1) He II increases from α Cen B, ε Eri to ξ Boo A because in ξ Boo A the temperature gradient is greater than in ε Eri, for instance. So this effect is controlling the He II emission and perhaps the energy balance lower down but I do not believe it affects lines with small values of (W/kT) in the line factor.

Rosner: Yes, but this also means that the evaluation of the conductive flux cannot be done in the simple-minded way by evaluating $kT^{5/2}$ times the temperature gradient.

https://doi.org/10.1017/S0252921100095932 Published online by Cambridge University Press

Jordan: No, this will give you simply an indication for each star that you have to go back and do a proper evaluation of the turbulent carrying of energy. So I agree with you entirely but to my knowledge nobody is able to do a turbulent, convective, conductive calculation at the moment. This kind of work can tell us those stars where we are going to have to do that.

https://doi.org/10.1017/S0252921100095932 Published online by Cambridge University Press