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Title: *Test of an acoustic mechanism for atmospheric heating in dynamo-deficient F stars*

I. General

In a *qualitative* sense, the heating of chromospheres and coronae has long been ascribed to either acoustic or magnetic heating. However, *quantitative* discussions of the energy balance with detailed comparison to the fluxes of chromospheric emission lines have begun to appear only recently. The aim of this work is *to observe F stars where magnetic effects might be expected to be rather small, thereby allowing us hopefully to access acoustically heated atmospheres.*

Mechanical energy in acoustic form is *inevitably* present in all stars with convective envelopes. Once the acoustic waves are generated, their propagation and dissipation in the chromosphere and corona can be computed by *ab initio* models, again using the well defined equations of compressible hydrodynamics (e.g. Mullan and Cheng 1993,1994a,b: Papers I-III).

In contrast to the ubiquitous acoustic modes, magnetic modes need *not* be present. And even in stars where magnetic heating is at work, the atmospheric heating *always* includes an acoustic component as well. In order to evaluate the magnetic contribution in such stars, we need to separate out the acoustic contribution.

To address the "acoustic-magnetic" mixture, and separate the components, our strategy in this work has been to select stars in those parts of the HR diagram where the magnetic contribution is "turning on". By studying such stars, we hope to quantify the acoustic component which pervades the atmospheres of all cool stars, and characterize how the magnetic components alter the emission measure distribution in the atmosphere.

Here we report on an observing program of warm stars, i.e. F stars where we might expect that the magnetic component is of little importance. We shall see from EUVE data that this expectation is NOT realized.

II. Warm stars: chromospheres and coronae

Previous evidence for chromospheres and coronae in warm stars (spectral classes A and F) comes from the CII 1335 line and X-rays: both have been detected in stars as early as A7 (Simon et al. 1994; Walter et al. 1995). The X-rays are rather soft $T \leq 10^6$ K (Golub et al. 1983). Moreover, several F stars appear in the ROSAT/WFC catalog (Pounds et al. 1993) and in the EUVE all-sky survey (Malina et al. 1993; Bowyer et al. 1994). The non-magnetic nature of heating in stars of spectral type A to early F is suggested by the lack of rotation-activity connection (Walter 1983): e.g. Altair's X-ray emission is highly constant (J. Schmitt, pers. comm.). EUV filter ratios for A stars suggest temperatures of 10^{5-6} K, consistent with acoustic heating (Paper III).

Warm stars are much stronger acoustic sources than the Sun. To see this, note that vigorous convection occurs in A and F stars, as proven by large microturbulence ξ (Coupry and Burkhart 1992) and large amplitude of the C-shaped bisectors of spectral lines: both are indicators of convection (Nordlund 1980; Gray 1992). Since acoustic energy generation rates are very sensitive to ξ ($\sim \xi^8$), acoustic generation is highly efficient in A and F stars.

The shape of the DEM contains information on the energy balance in the atmosphere (Jordan 1980). Predictions of the distribution of emission measure (DEM) as a function of temperature in an acoustically heated F star have been published (Paper III). In the case of the F5 star Procyon, the DEM predictions included a minimum at log T_m = 5.4, with steep slopes on either side of this minimum: in a subsequent analysis of EUVE data, Drake et al. (1995) found that the predictions provide an "impressive" fit to their data.

The present study is aimed at evaluating DEM in various warm stars in order to examine the energy balance.

III. Observations of two EUVE targets

Of the 6 F stars for which we proposed to make EUVE spectral observations, we were awarded observing time for one star (HR120: F2), and data rights to two other stars. Of the two others, only one was actually observed (HR1817: F7: PI J. Linsky).

For the star HR120, observations were started on 07-05-95 at 13:31 GMT, with the plan to obtain 100Ks exposure. However, the exposure was interrupted on 07-08-95 at 04:30 GMT for a target of opportunity program. The star HR120 had been exposed for only 58-59Ks. Therefore, the star was re-observed from 11:51 GMT on 08-09-95 to 20:25 GMT on 08-16-95 in order to obtain a full length exposure (180Ks). In order to improve the signal to noise, we combined the two exposures into a single spectrum, with a total exposure time of 239-240 Ks.

For the star HR1817, we examined two spectral data strings: one started on 10-23-95 at 08:17 GMT and lasted until 10-26-95 at 21:37 GMT. Exposures in the three EUVE spectral channels were about 96000 seconds. The second exposure started at the end of the above session and lasted until 10-30-95 at 07:20 UT: exposures in the 3 EUVE channels were each of order 91000 seconds. The reason for analyzing the HR1817 data in two pieces was that a flare event occurred during the overlal exposure. Therefore, one piece corresponds to quieter conditions than the second piece. the very fact that a flare was noticeable in the data indicates that HR1817 is magnetically active. Therefore, our hopes of finding a purely acoustically heated atmosphere were unfortunately not realized in this star.

IV EUVE analysis: the technique

We have developed a code for efficient analysis of line fluxes in EUVE spectra. Line fluxes are extracted from archival data tapes using standard IRAF/EUV software. In order to determine which lines in the spectrum are above the noise, we also extract a "spectrum" of the background in the EUVE image by scanning across the image at a position well removed from the stellar photons. We process this background "spectrum" in exactly the same way as we do the actual stellar spectrum, and extract "line fluxes" for all the features in the 'spectrum". We fit these "background line fluxes" as a function of wavelength using a least squares technique to a Chebyshev series: we increase the length of the series until we reach a point where the fit is numerically independent of a linear combination of Chebyshev polynomials. In order to accept a line in the stellar spectrum as "real", we require that the flux in that line exceed 3 times the value of the best fitting curve to the "background line fluxes".

The fluxes of the accepted lines are converted to stellar surface values. To correct for interstellar absorption, we use a tool provided by the EUVE archives: the ISM hydrogen column density table. To use this, we insert the position of the star in question, and its distance, and the program responds with a list of the ten stars which are nearest (in space) to the target star for which column densities N_H are available in the literature. For each extracted line, we enter the Landini and Monsignori-Fossi (1990: LMF) table of line emissivities and search for possible line identifications within the nominal uncertainties of the EUVE wavelength scale (± 0.5, ± 1.0, and ± 2.0 A for short, medium, and long wave spectrometer respectively). Possible lines in these ranges are arranged in order to peak emissivity: those which lie within a factor of 3 of the maximum emissivity are assumed to contribute to the observed line, with a contribution proportional to the emissivity. This is clearly not as precise as the process of individual profile fitting which has been described by (e.g. Drake et al. 1995). However, our work is aimed at stars where the lines are weak, and close to noise level. Thus, a more sophisticated approach to line-fitting is not warranted for these faint lines. Moreover, our approach is more automated, and can be applied to a broad class of targets.

The LDF emissivity tables are listed in intervals of 0.1 in $\log_{10}$ T. The flux of each identified line is converted to an emission measure as if emissivity were constant over ± 0.05 on either side of the tabulated log $_{10}$ T. In this sense, the output can be thought of as proportional to the emission measure integrated over a certain interval $\Delta \log_{10} T = 0.43 \Delta T/T = 0.1$.

We group the lines according to stage of ionization: if two or more lines of a given stage of ionization of a given element are found to have DEM within a factor of ± 2 of their mean, we classify them as "good lines". The remaining lines, which we refer to as "leftover" lines, are grouped according to temperature, and mean DEM are constructed at each temperature: the r.m.s. deviations σ of these means for the "leftover" lines are distinctly larger than those for the "good lines", partly because of possible alterations in chemical abundances among the elements in our target star compared to the standard abundances which enter into the LDF tables. For the star HR120, we list the "goodlines" in Table 1: there are 24 of them, spanning a temperature range from log $T = 5.6$ to 7.1. We list the "leftover" lines in Table 2: there are 54 of them, spanning a temperature range from log $T = 5.0$ to 7.3. Thus, the DEM is determined with more precision in the intermediate range of temperatures: the closer we get to either the hot or the cold end of the DEm curve, the less precise the results become. The "goodlines" include lines from NeVII, SiV, SiVII, and six charge states of iron. The "leftover" lines include lines from nine elements in various charge states. Tables analogous to tables 1 and 2 have also been created for HR1817 (1) and (2): they contain 45 and 37 "goodlines" and 49 and 45 "leftover" lines respectively.

Weights are assigned to the DEM in both "good lines " and "leftover" samples according to $1/(\sigma^2)$. Regression analysis is used to obtain the best fit of a series of Chebyshev polynomials to the DEM. The quality of fit is assessed by the mean separation between the fitted curve and each point, expressed in units of the r.m.s. deviation of each point: this provides a sort of reduced χ^2 (RCS) for the fit.

V EUVE analysis: results for two F stars

The DEM for our 2 target stars are presented in Fig. 1. The plotted curves are the weighted best fitting Chebyshev polynomial series to the results. Also plotted in Fig. 1 are scaled DEM results for quiet and active Sun obtained from SERTS rocket data (Brosius et al. 1996).

The two DEM's for HR1817 differ from each other mainly at the extremes of the temperature range. Exposure (1) shows a large amount of cool material, with DEM rising steeply towards lower temperatures for log T <5.75 (analogous to the solar results), and a hot peak at temperatures of log T = 6.75 (close to the peak in the solar active region). In contrast, exposure (2) shows much less cool material (especially at log T < 5.5, where it falls far below DEM(1)) but an increase at log T = 5.5-6.1. And there is a clear increase in the maximum temperature which is present in (2) relative to (1): the high-T peak is now at temperatures which are well in excess of 10^7 K. These temperatures are much higher than those which are ever seen in solar active regions unles a flare is in progress. Thus, the high temperatures in HR1817(2) is a sure sign of flaring activity, consistent with the higher count rates in exposure (2). Thus, the EUVE data demonstrate clearly that HR1817 is certainly NOT a star where acoustic heating of the atmosphere dominates: HR1817(2) may be in a flaring state, and even HR1817(1) contains gas which is somewhat hotter than a solar active region.

For HR120, there are similarities to both exposures of HR1817: at low temperatures (log T < 5.6), the DEM shows a steep increase towards lower temperatures (analogous to the solar features and HR1817(1)). But at higher temperatures, HR120 exhibits a peak at temperatures in excess of 10^7 K which looks quite similar to that in DEM HR1817(2). This suggests that also HR120 cannot be fitted neatly into the categories of quiet and active solar plasma, but there may be a flaring component in the spectrum.

VI. What has been learned from EUVE

Our DEM results suggest that strong heating to temperatures in excess of 10^7 K is at work in both of the F stars which were observed by EUVE in this program. Temperatures of this magnitude are seen in the Sun only during flares. Thus, the EUVE data suggest that magnetic activity is also at work in the two F stars. This leads us to the conclusion that the two F stars which were observed by EUVE in this program are NOT good candidates for acoustic heating.

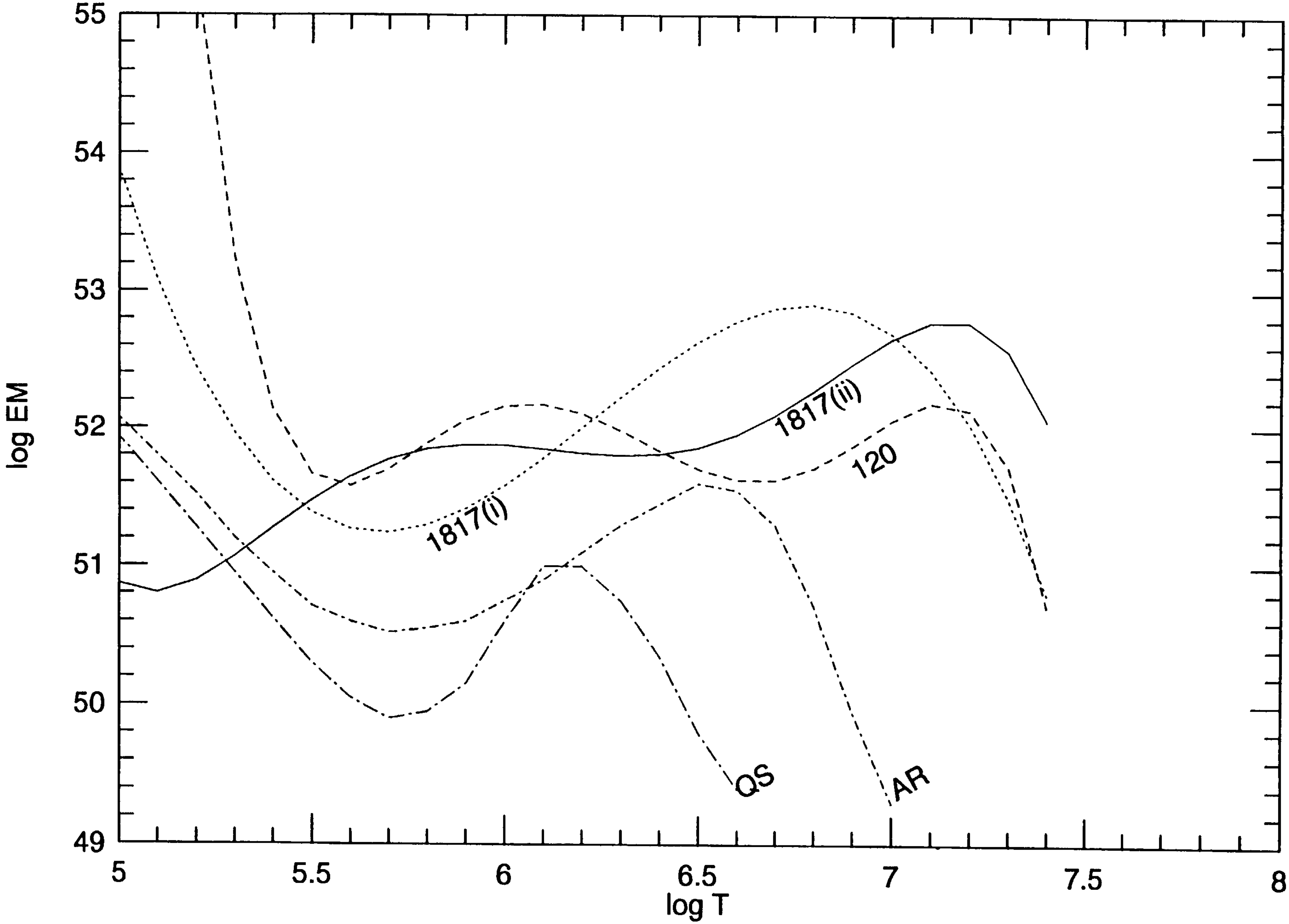
The fact that Procyon (F5) is already known to exhibit some signs of magnetic activity (Drake et al. 1993) suggests that if we want to access a star where the atmospheric heating is purely acoustic, then we will have to observe stars with spectral types which are even earlier than F2 (or F5 or F7).

References

Bowyer, S. et al. 1994, *ApJS* 93, 569
Brosius, J. et al. 1996, *ApJS* 106, 143
Coupry, M. and Burkhart, C. 1992, *A&A Suppl.* 95, 45
Drake, J., Laming, J., and Widing, K. 1995, *ApJ*, 443, 393.
Drake, S., Simon, T., and Brown, A. 1993, *ApJ* 406, 247
Golub, L. et al. 1983, *ApJ* 271, 264
Gray, D. F. 1992, Observation and Analysis of Stellar Photospheres, pp 423-426
Jordan, C. 1980, *A & A* 86, 355
Landini, M. & Monsignori-Fossi, B.C., 1990, *A&AS* 82, 229 (LDF)
Malina, F.M., et al., 1994, *AJ* 107, 751
Mullan, D.J. & Cheng, Q.Q., 1993, *ApJ* 412, 312 (Paper I)
Mullan, D.J. & Cheng, Q.Q., 1994a, *ApJ* 420, 392 (Paper II)
Mullan, D.J. & Cheng, Q.Q., 1994b, *ApJ* 435, 435 (Paper III)
Nordlund, A. 1980, Stellar Turbulence (eds. Gray&Linsky), p. 213
Pounds, K., et al., 1993, *MNRAS* 260, 77
Simon, T., Landsman, W. and Gilliland, R. 1994, *ApJ* 428, 319
Walter, F. 1983, *ApJ* 274, 794
Walter, F., Matthews, L. D., and Linsky, J. L. 1995, *ApJ* 447, 353.

Figure captions

Fig. 1. Emission measure (EM) *versus* temperature (T) extracted from EUVE spectra of HR120 (labelled 120) and of HR1817 (two different exposures). The units of EM are cm^{-3}. The units of T are degrees K. The curves are weighted best fits of Chebyshev series to log (EM) versus log T. Also shown are EM curves for quiet sun (QS) and a solar active region (AR) obtained with the SERTS program (Brosius et al. 1996)


log EM
log T
55
54
53
52
51
50
49
5
5.5
6
6.5
7
7.5
8
1817(i)
1817(ii)
120
QS
AR

Good lines in EUVE spectra of HR120 (F2)

Element	Ioniz State	Wavelength A	log T	EM cm^{-3}
NE	7	97.5800	5.8	51.8011
NE	7	106.1000	5.8	51.6456
NE	7	115.5000	5.8	51.5220
SI	5	80.0000	5.7	53.0513
SI	5	96.1400	5.6	51.1590
SI	5	96.4400	5.6	51.5630
SI	7	79.5000	6.0	52.8533
SI	7	81.9000	6.0	52.7173
FE	8	112.4800	5.8	52.3367
FE	8	112.9300	5.8	52.1687
FE	9	83.4600	6.0	51.7369
FE	9	105.2100	6.0	52.3116
FE	9	217.1000	5.9	52.6927
FE	10	96.3400	6.1	51.4340
FE	10	206.5000	6.1	52.1580
FE	12	192.4200	6.2	51.6687
FE	12	195.1400	6.2	50.5863
FE	12	208.1400	6.2	51.7920
FE	12	208.4300	6.2	51.9200
FE	18	93.9300	6.9	51.7010
FE	18	103.9500	6.9	52.0877
FE	21	91.2800	7.1	52.2043
FE	21	102.2200	7.1	52.2108
FE	21	128.7300	7.1	51.9380

Leftover lines in EUVE spectra of HR120 (F2)

Element	Ioniz State	Wavelength Å	log T	EM cm^{-3}
O	2	430.0900	5.0	52.5859
O	4	203.0000	5.4	50.7227
O	6	129.8000	5.6	51.6499
Ne	4	208.6000	5.5	52.1351
Ne	5	119.0100	5.7	50.8374
Ne	5	132.0400	5.7	52.0452
Ne	6	111.1000	5.8	51.3381
Ne	6	120.0000	5.8	51.3535
Ne	6	138.5500	5.8	52.4972
Ne	8	98.3100	5.9	51.8501
Na	4	410.4000	5.4	52.7111
Na	8	411.1500	6.0	52.6621
Mg	4	130.0000	5.5	51.1669
Mg	6	111.6000	5.8	51.1161
Mg	8	75.0000	6.0	51.8532
Mg	9	77.7000	6.1	52.6188
Al	4	161.7000	5.4	52.9889
S	7	72.4000	5.9	52.5455
S	7	72.6600	5.9	51.4124
S	8	199.9100	6.0	51.7283
S	9	224.7400	6.1	51.8003
Ca	16	208.0000	6.7	52.0910
Ni	10	144.2100	6.2	52.9656
Ni	11	77.8000	6.3	52.3288
Ni	24	126.7000	7.2	53.0089
Ni	25	119.9000	7.3	51.4825
Fe	11	206.8400	6.2	52.0210
Fe	13	75.8400	6.3	51.8319
Fe	13	201.1300	6.3	51.1323
Fe	13	202.0500	6.3	50.4051
Fe	13	202.0500	6.3	50.0585
Fe	13	209.9200	6.3	51.4525
Fe	14	91.0800	6.4	51.9763
Fe	14	211.2800	6.4	51.3639
Fe	14	219.1600	6.4	52.4093