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Emissions from the transition regions and coronae of three cool dwarf stars★

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Summary. Ultraviolet emissions of τ Cet, δ Pav, and 61 Cyg A have been analysed to determine the structure of their outer atmospheres.

Emission line fluxes are used to find the emission measure distributions. Using two boundary values of the electron pressure, models of the transition region have been derived. In the two models of τ Cet the net conductive flux is less than the radiation losses at all temperatures. However, for δ Pav and 61 Cyg A the model with the upper boundary value of the electron pressure has a temperature range where the radiative losses are less than the net conductive fluxes.

Measured X-ray fluxes are used to test the coronal temperature values derived from the ultraviolet observations.

Key words: transition region – corona – X-ray emission

1. Introduction

It is well known that a clear knowledge of the physical conditions in stars with hot ($T \geqq 10^5$ K) outer atmospheres ultimately rests on observations from space which can measure ultraviolet and X-ray emissions. Until observations in these spectral ranges became available, conditions in stellar chromospheres were inferred mainly from the emission cores of Ca II H and K lines, which can be observed in most stars later than F 5 (Wilson and Bappu, 1957).

The advent of the IUE satellite (Boggess et al., 1978) has permitted the measurement of chromospheric and transition region lines in a large number of late type stars. Furthermore with the launch of the HEAO satellites (Giaconi et al., 1979) it has been possible to observe the 10^6 K coronae of a large number of stars (Viana et al., 1981).

Observations in the UV spectral range have shown that stars with indicators of 10^5 K plasma in their outer atmospheres, appear to be restricted to a particular region in the H–R diagram (Linsky and Haisch, 1979). The exact division between stars with and without hot outer atmospheres is a subject of debate (Dupree et al., 1980, Ayres et al., 1981). Recently Simon et al. (1982), in a survey of 39 late type stars observed with IUE, conclude that the Linsky-Haisch boundary is a real phenomenon for single stars, and they speculate that a radiative instability may play an important role in the existence of the boundary.

In this paper we present an analysis of the outer atmospheres of three cool dwarf stars (τ Cet, δ Pav, 61 Cyg A) observed with IUE, and for which Einstein X-ray observations are available (Johnson, 1981).

The ultraviolet emission line fluxes have been used to derive the distribution of emission measure as a function of temperature, which provides us a method to interpret the observations in physical terms (Jordan and Wilson, 1971).

The atmospheric parameters of τCet and δPav were taken from Hearnshaw (1974, 1975) and for 61 Cyg A the values reported by Oinas (1977) have been adopted. Colour indices are from Johnson et al. (1966). These data are provided in Table 1.

Existing ground-based chromospheric data of the three stars are varied: the Wilson-Bappu intensity of δPav has not been measured, for τCet and 61 Cyg A it is respectively 0 and 5; Zirin (1976) has measured He I λ10830 absorption in 61 Cyg A; and Linsky et al. (1979) have shown that the chromospheric radiative losses of this star are similar to those of the sun.

The emission line fluxes used in this paper, were obtained from low dispersion observations with the IUE satellite, in the 1150–2000 Å spectral range. All of the spectra were reprocessed with the revised intensity transfer function (ITF) and the calibration of Bohlin and Holm (1980). A catalog of observational data is provided in Table 2.

2. Analysis of solar type lines

The stars in our sample exhibit the characteristic solar transition region emission lines like Si IV and C IV, so they can be included in the group of stars with solar-like outer atmospheres. The stellar

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★ Based on observations by the International Ultraviolet Explorer collected at the Villafranca Satellite Tracking Station of the European Space Agency

Table 1. Stellar parameters

HD	Name	*Sp.T*	m_V	$B-V$	$V-R$	$\theta_{\rm eff}$	Log g	[Fe/H]	$\phi('')$
10700	τCet	G5Vp	3.50	0.72	0.62	0.94	4.5	−0.34	2.1(−3)
190248	δPav	G5V	3.56	0.76	0.61	0.90	4.3	+0.43	2.0(−3)
201091	61CygA	K5V	5.23	1.17	1.03	1.15	4.5	−0.06	2.2(−3)

Table 2. Observational data

Name	Image no.	Aperture	t_{ex} (min)
τCet	SWP 4054	*L*	150
δPav	SWP 3586	*L*	120
61 Cyg A	SWP 3622	*L*	120

Table 3. Surface fluxes in erg cm^{-2} s^{-1}

λ (A)	El	F_λ		
		τCet	δPav	61 Cyg A
1240	N v	1.25(3)	1.18(3)	3.35(2)
1335	C II	4.51(3)	3.83(3)	2.96(3)
1394	Si IV	2.33(3)	5.77(2)	3.35(2)
1403	Si IV		8.30(2)	3.40(2)
1549	C IV	1.42(3)	6.99(3)	3.03(3)
1808	Si II	1.63(3)	1.60(3)	3.65(3)
1817	Si II	6.44(3)	6.54(3)	7.23(3)

Table 4. Emission measure distributions

Log T_e	log ($\int N_e^2\, dh$)		
	τCet	δPav	61 Cyg A
5.2	26.84	25.91	25.92
5.1	26.89	25.92	25.94
5.0	26.95	25.94	26.00
4.9	27.02	26.00	26.16
4.8	27.10	26.11	26.28
4.7	27.21	26.25	26.45
4.6	27.32	26.41	26.67
4.5	27.44	26.64	26.95
4.4	27.63	26.92	27.38
4.3	27.98	27.33	28.00

Table 5. Initial pressures

Star	log P_e	
	"Energy balance" (a)	"Cool corona" (b)
τCet	14.92	14.38
δPav	14.76	13.85
61 Cyg A	14.91	13.92

surface fluxes given in Table 3 were calculated from the fluxes observed at the Earth using angular diameters obtained by the relation of Barnes and Evans (1976) and Barnes et al. (1976). It can be seen that the surface flux values of the three stars predominantly are lower than the solar ones (Ayres and Linsky, 1980). Accordingly, τCet, δPav, and 61 Cyg A can be considered "quiet" stars.

We adopt a method for analysing lines formed in regions with temperatures above $2\,10^4$ K which has been developed in the context of solar work (see e.g. Jordan and Wilson, 1971).

a) *Emission measure distributions*

The starting point is to calculate the emission measure, $E_m = \int N_e^2 dh$, for each line. Assuming effectively thin collisionally excited emission, and a spherically symmetric atmosphere, the surface fluxes are,

$$F_\lambda = \frac{6.86\,10^{-14}}{\lambda(A)} \frac{\Omega_{12}}{g_1} A(\text{el}) G \cdot g(T_m) \int_{\Delta h} N_e^2 dh\,, \tag{1}$$

where A(el) is the element abundance relative to hydrogen; Ω_{12} is the averaged collision strength; g_1 the statistical weight of the lower level; the factor $G \cdot g(T_m)$ is an average value of the function $g(T)$ over the range, $\Delta \log T$, in which the line is formed; and T_m is the temperature at the peak of Pottasch's function $g(T)$. Following Jordan and Wilson (1971) the factor $G \cdot g(T_m)$ has been calculated using a temperature range of $\Delta \log T = \pm 0.15$, and the ion population ($N_{\text{ion}}/N_{\text{el}}$) obtained from Jordan's tabulation (1969). Equation (1) allows us to derive emission measure from the measured stellar surface fluxes assuming uniform coverage of the stellar surface by emitting regions. The emission measure distributions thus obtained are given in Table 4.

b) *Transition region pressures*

If the thickness of the stellar transition region is small compared to the local pressure scale height, as appears to be true in the solar case, then in a first approximation we can assume that the pressure is constant throughout the upper chromosphere and low corona.

In an earlier paper (Castro et al., 1981) we applied several methods to estimate transition region pressures from ultraviolet line fluxes to a larger sample of late type stars. In this paper, we adopt two of those methods to determine lower and upper boundaries to the pressure.

An upper limit to the pressure can be defined by the "energy balance" method, in which the surface flux ratio of the C IV line is given by,

$$\frac{F_*(1549\text{ A})}{F_\odot(1549\text{ A})} = \frac{A_*(C)P_*}{A_\odot(C)P_\odot}, \tag{2}$$

where a balance between the radiative losses and the divergence of the downward conductive flux has been assumed (Haisch and Linsky, 1976).

Alternatively, if we assume that the N v λ1240 emission line comes from an optically thin isothermal region in hydrostatic equilibrium (a "cool corona"), the surface flux is,

$$F_*(1240\text{ A}) = \frac{5.91\,10^{25} A(N) G \cdot g(T_m) \Omega}{g_1 T \lambda} \frac{P_0^2}{g}, \tag{3}$$

where, P_0 is the total pressure at the base of the corona and g is the stellar surface gravity. The "cool corona" method provides a likely lower limit to the transition region electron pressure.

Pressures based on Eqs. (2) and (3) are provided in Table 5 for τCet, δPav, and 61 Cyg A.

c) *Coronal temperatures*

Unfortunately we cannot infer coronal structure directly from observations with the IUE satellite, because there are no strong lines formed at $T > 2\,10^5$ K in the accessible wavelength range.

However, a scaling law that fits different regions of the solar atmosphere has been proposed by Jordan (1980a). Assuming that

Table 6. Coronal temperatures

Star	Log T_c	
	(a)	(b)
τCet	5.8	5.4
δPav	6.1	5.4
61 Cyg A	6.2	5.4

the emission measure $E_m = aT^{3/2}$ above $T_0 = 2\,10^5$ K, the scaling law is,

$$T_c^{5/2} - T_0^{5/2} = 1.2\,10^8\,P_e^2/ga\,,$$

where T_c is the coronal temperature, P_e is the pressure at T_0 and $a = E_m(T_0)\,T_0^{-3/2}$.

Since emission measure distributions of τCet, δPav, and 61 Cyg A are similar to that of the solar below T_0 we assume, for the sake of argument, that the E_m scales as $T^{3/2}$ above $2\,10^5$ K. We have applied the above scaling law to estimate the coronal temperatures given in Table 6. For each star of the sample, two coronal temperatures were calculated according to the highest (a) and lowest (b) pressure. In the case of τCet, the temperature obtained is lower than 10^6 K. Consequently, a low X-ray luminosity is expected.

3. Transition region models

The distributions of the emission measure can be used to derive the density and pressure structures of the transition region.

According to Jordan and Wilson (1971), the electronic pressure P_e, and the temperature gradient, $(dh/d\log T_e)^{-1}$, can be assumed to be constant over the region of line formation. Accordingly,

$$\int_{\Delta h} N_e^2 dh = \frac{P_e^2}{T_e^2}\frac{dh}{d\log T_e} \times 0.31\,. \tag{4}$$

If, in addition, we assume hydrostatic equilibrium,

$$\frac{d\log P_e}{d\log T_e} = -3.26\,10^{-9}\frac{g}{T_e}\frac{dh}{d\log T_e}. \tag{5}$$

Using Eqs. (4) and (5) and the pressure values obtained in Sect. 2, we have derived the pressure and temperature gradient distributions given in Tables 7–9.

In all of the computed models, the temperature gradient reaches a maximum at a particular temperature that depends only on the shape of the emission measure distribution. A similar result was found for other dwarfs stars (Fernández-Figueroa et al., 1982). Furthermore, the models obtained with the lower limit to the electron pressure have lower temperature gradients and larger thickness than the ones derived using the upper limit.

Finally, the energy balance in each temperature regime has been studied. In particular, we have assumed that the energy input ΔF_m must be balanced by radiation losses ΔF_r and the net conductive flux ΔF_c. We assume that the emission arises from closed magnetic structures so that wind energy losses can be neglected. The radiation losses depend only on the emission measure (Brown and Jordan, 1981), but the conductive flux depends on the temperature gradient and thus on the adopted pressure.

Table 7. Models for τCet

Log T_e	$\log\frac{dh}{d\log T_e}$	$\log P_e$	$\log N_e$	$-\Delta F_r$	ΔF_c
Model a: $\log T_e=5.2$, $\log P_e=14.92$					
5.2	7.92	14.92	9.72	9.64(4)	1.55(4)
5.1	7.76	14.93	9.83	1.12(5)	1.04(4)
5.0	7.61	14.93	9.93	1.28(5)	6.90(4)
4.9	7.47	14.93	10.03	1.51(5)	4.55(3)
4.8	7.35	14.94	10.14	1.81(5)	2.83(3)
4.7	7.25	14.94	10.24	2.34(5)	1.60(3)
4.6	7.15	14.95	10.35	3.01(5)	9.20(2)
4.5	7.06	14.95	10.45	3.97(5)	6.15(2)
4.4	7.06	14.95	10.55	6.14(5)	3.48(2)
4.3	7.19	14.96	10.66	1.38(6)	–
Model b: $\log T_e=5.2$, $\log P_e=14.38$					
5.2	9.00	14.38	9.18	9.96(4)	5.42(2)
5.1	8.72	14.46	9.36	1.12(5)	9.03(2)
5.0	8.50	14.49	9.49	1.28(5)	6.70(2)
4.9	8.30	14.52	9.62	1.51(5)	5.60(2)
4.8	8.13	14.55	9.75	1.81(5)	4.28(2)
4.7	8.00	14.57	9.87	2.34(5)	2.48(2)
4.6	7.86	14.59	9.99	3.01(5)	1.70(2)
4.5	7.75	14.61	10.11	3.97(5)	1.05(2)
4.4	7.70	14.63	10.23	6.14(5)	7.53(1)
4.3	7.81	14.65	10.35	1.38(6)	–

Table 8. Models for δPav

log T_e	$\log\frac{dh}{d\log T_e}$	$\log P_e$	$\log N_e$	$-\Delta F_r$	ΔF_c
Model a: $\log T_e=5.2$, $\log P_e=14.76$					
5.2	7.31	14.76	9.56	1.17(4)	5.55(4)
5.1	7.12	14.76	9.66	1.20(4)	4.04(4)
5.0	6.94	14.76	9.76	1.25(4)	3.20(4)
4.9	6.80	14.76	9.86	1.44(4)	2.32(4)
4.8	6.71	14.76	9.96	1.86(4)	1.38(4)
4.7	6.65	14.76	10.06	2.56(4)	7.71(3)
4.6	6.61	14.76	10.16	3.70(4)	3.76(3)
4.5	6.63	14.76	10.26	6.30(4)	1.90(3)
4.4	6.71	14.77	10.37	1.20(5)	8.20(2)
4.3	6.92	14.77	10.47	3.08(5)	–
Model b: $\log T_e=5.2$, $\log P_e=13.85$					
5.2	9.13	13.85	8.65	1.17(4)	2.90(2)
5.1	8.83	13.91	8.91	1.20(4)	5.01(2)
5.0	8.58	13.94	8.94	1.25(4)	6.00(2)
4.9	8.39	13.97	9.07	1.44(4)	5.23(2)
4.8	8.26	13.99	9.19	1.86(4)	3.49(2)
4.7	8.16	14.00	9.30	2.56(4)	2.13(2)
4.6	8.09	14.02	9.42	3.70(4)	1.27(2)
4.5	8.08	14.04	9.54	6.30(4)	6.32(2)
4.4	8.11	14.07	9.67	1.20(5)	3.03(1)
4.3	8.25	14.10	9.80	3.08(5)	–

Table 9. Models for 61 Cyg A

$\log T_e$	$\log \frac{dh}{d \log T_e}$	$\log P_e$	$\log N_e$	$-\Delta F_r$	ΔF_c
Model a: $\log T_e=5.2$, $\log P_e=14.91$					
5.2	7.02	14.91	9.71	1.20(4)	1.13(5)
5.1	6.84	14.91	9.81	1.25(4)	9.00(4)
5.0	6.70	14.91	9.91	1.44(4)	7.40(4)
4.9	6.66	14.91	10.01	2.08(4)	3.28(4)
4.8	6.58	14.91	10.11	2.74(4)	1.99(4)
4.7	6.55	14.91	10.21	4.06(4)	1.05(4)
4.6	6.57	14.91	10.31	6.74(4)	4.83(3)
4.5	6.64	14.92	10.42	1.28(5)	2.18(3)
4.4	6.87	14.92	10.52	3.45(5)	6.44(3)
4.3	7.28	14.92	10.62	1.44(6)	–
Model b: $\log T_e=5.2$, $\log P_e=13.92$					
5.2	9.00	13.92	8.72	1.20(4)	3.30(2)
5.1	8.69	13.98	8.88	1.25(4)	8.60(2)
5.0	8.47	14.03	9.03	1.44(4)	1.01(3)
4.9	8.37	14.06	9.16	2.08(4)	5.35(2)
4.8	8.23	14.09	9.29	2.74(4)	3.85(2)
4.7	8.14	14.11	9.41	4.06(4)	2.45(2)
4.6	8.11	14.14	9.54	6.74(4)	1.27(2)
4.5	8.12	14.17	9.67	1.28(5)	6.64(1)
4.4	8.26	14.22	9.82	3.45(5)	2.41(1)
4.3	8.53	14.29	9.99	1.44(6)	–

Table 10. X-ray observations[a]

Star	F_X	L_X	Detector
τCet	<5(−13)	<7 (26)	IPC
δPav	3(−13)	1.1(27)	IPC
61 Cyg A	2(−12)	2.6(27)	IPC

[a] Johnson (1981)

Table 11. Emission measure and pressure from X-ray data

Star	E_m	$\log P_e$
τCet	<1.90(28)	15.37
δPav	4.27(26)	14.61
61 Cyg A	1.20(27)	14.99

For all of the program stars, at lower temperatures and lower pressures the net conductive flux is far less than the radiation losses. The total energy input required is dominated by radiation losses. For δPav and 61 Cyg A the models constructed with higher pressures yield a "critical" temperature, T_*, above which $\Delta F_r < \Delta F_c$. This critical temperature suggests that either the model geometry must be changed or further energetic processes should be included. For example, the energy deposited by conduction in the region from $2\,10^5$ K to T_* may drive turbulent motions which would transport the energy to lower temperatures. According to Jordan (1980b) the downward energy flux in turbulent motions is,

$$\Phi_T = \varrho \langle V_T^2 \rangle V_T \,\mathrm{erg\,cm^{-2}\,s^{-1}},$$

where ϱ is the mass density. If we identify that energy, Φ_T, with the difference between the net conductive flux and radiative losses in the "critical" region, we obtain an upper limit to the turbulent velocity, V_T. The velocity values are 22.8 km s^{-1} for 61 Cyg A and 19.0 km s^{-1} for δPav, both lower than the calculated for the sun by Jordan (1980b).

4. X-ray emission

The coronal temperature and pressure values obtained in Sect. 2 can be compared to the Einstein X-ray fluxes of our stars taken from the survey of Johnson (1981), and reproduced in Table 10. We assume that the X-ray luminosity of 61 Cyg splits equally between the *A* and *B* components. The upper limit (3σ) to τCet was estimated for no detection. Note that the X-ray luminosities of stars of similar spectral type (τCet and δPav) are quite different, in accord with the general result in the survey by Vaiana et al. (1981) that a property other than spectral type establishes coronal activity levels. We calculate the emission measure of an isothermal corona using the power coefficient of Raymond and Smith (1977) and the temperatures given in Table 6. The results are listed in Table 11. It can be seen that the emission measure in the corona is larger than that at $2\,10^5$ K.

The coronal emission measure provides a method to estimate the pressure at T_c. From Eqs. (1) and (3), the electron pressure of an isothermal corona is given by,

$$P_e = 1.24\,10^{-4} (E_m g T_c)^{1/2}. \quad (6)$$

The pressures obtained using this relation are given in Table 11. In the case of δPav, the pressure value deduced from X-ray emission is in good agreement with the one obtained from ultraviolet observations. For 61 Cyg A the coronal pressure limit is not consistent with the observed UV emissions. Perhaps, then the assumption of a uniformly emitting transition region should be modified.

5. Final remarks

We have presented an analysis of the outer atmosphere structures of three dwarf stars (τCet, δPav, and 61 Cyg A). The emission measure distributions have been established from the ultraviolet observations. From these distributions, the structure of a uniformly emitting region in hydrostatic equilibrium has been derived as a function of P_e at $2\,10^5$ K. The main conclusions of this work can be summarized as follows:

a) τCet

The coronal temperature deduced from ultraviolet emissions is smaller than 10^6 K. The X-ray luminosity predicted is less than 10^{27} erg s^{-1}, which is consistent with the observations reported by Johnson (1981).

In the models with $\log P_e \leqq 14.92$, the net conductive flux is less than the radiation losses at all the temperatures ($10^{4.3}$–$10^{5.2}$ K). Accordingly, the radiative losses likely are balanced by dissipation of mechanical energy.

We can conclude from the above results that there is no reason why the radiation losses from the outer atmosphere of τCet cannot be represented by calculations based upon homogeneous model atmospheres.

*b) δ*Pav

A transition region pressure of $5.75\ 10^{14}\ \mathrm{cm}^{-3}\ \mathrm{K}$ obtained from UV emission lines yields a $10^{6.1}$ K corona. These temperature and pressure values are in good agreement with the X-ray observations.

In the model with $\log P_e = 14.76$ there is a temperature range where the radiation losses are less than the net conductive flux. We have speculated that the energy deposited by thermal conduction in that region is used to drive non-thermal motions which carry the energy to lower temperatures. The derived upper limit to the velocity is smaller than the observed nonthermal motions in the solar transition region.

c) 61 Cyg A

The analysis of the ultraviolet emission lines given an upper and lower limit to the transition region pressure. The coronal temperature ($1.6\ 10^6$ K) estimated from the highest pressure is consistent with the X-ray emission.

From the X-ray flux the pressure of an isothermal corona has been estimated. The inferred pressure value is lightly larger than that deduced form observations. Furthermore, in the transition region model with $P_e = 8.13\ 10^{14}\ \mathrm{cm}^{-3}\ \mathrm{K}$, the energy deposited by thermal conduction is greater than the radiation losses at $4.6 < \log T_e \leqq 5.2$. Like in δPav an upper limit to the velocity of non-thermal motion driven by conduction has been calculated.

Throughout our analysis, we have made the assumption of a uniformly emitting atmosphere, so that the derived pressures are, in some sense, mean values averaged over the stellar surface. Nevertheless, it is well-known that there is a strong UV flux variation on the quiet sun between the supergranulation network and the cell centres owing to the different concentrations of confined magnetic fields. Consequently, the emission from others stars very likely also arise from inhomogeneous regions.

If the ultraviolet emission of 61 Cyg A comes only from a limited area, the pressure in the emitting region will be larger than that calculated in this paper. This is an addition way in which transition region pressures can be reconciled.

The effects of a fractional emitting region in the energy balance will be studied in next papers.

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