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The Transition Region Structure of κ Ceti*

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Summary. Observations of κ Ceti (HD 20630), G5 V, obtained with the IUE satellite have been analysed to determine the structure of its outer atmosphere. This analysis is used to derive a model of transition region and to examine the terms of energy balance equation.

Key words: EUV spectra – stellar chromospheres – transition region

1. Introduction

The main sources of information about the outer stellar regions of intermediate and late type stars arise from far ultraviolet observations. The IUE satellite has provided a valuable opportunity to study the ultraviolet spectra of cool stars.

The star κ Ceti (HD 20630), G5 V, is one of the few dwarf stars for which indications of chromospheric activity have been observed in the visible range. Wilson and Bappu (1957) measured the Ca II emission in κ Cet which was assigned an intensity 3 in a scale whose maximum value was 5. Later in the same star Zirin (1976) identified the He I line λ10830 Å in absorption. He obtained an equivalent width of 200 mÅ, this value placing κ Cet among the 52 stars with an He I λ10830 Å equivalent width bigger than 100 mÅ out of a sample of about 125 G and K stars. According to Zirin the helium line is an indicator of the existence of a stellar corona rather than a chromosphere. Recently, Rego et al. (1979) have carried out a first analysis comparing the behaviour of the *h* and *k* magnesium emission lines in a sample of dwarf stars including κ Cet. They observed that these lines were present with a remarkable intensity in κ Cet.

In this paper we analyse the ultraviolet emission lines in κ Cet in order to study the higher chromospheric, transition region and low corona structure as in solar analyses.

2. Observations

IUE low resolution ($\simeq$6 Å) observations of κ Cet were obtained in the spectral range λ1150–2000 Å (SWP camera). The exposure times used are 70 min on July 7, 1978 (SWP 1926) and 50 min on July 5, 1980 (SWP 9462).

The most prominent lines are those of C IV (λ1549), Si II ($\lambda\lambda$1808 and 1817), C II (λ1335), O I (λ1304), N V (λ1240), and H Lyα. These lines are indicative of a chromosphere and a transition region similar to those seen in the sun.

The H Lyα and O I (λ1304) emission lines were not considered since the former is strongly contaminated by geocoronal H Lyα emission and the latter may be due to a fluorescent mechanism by H Lyβ.

We have used the C II (λ1334, 1335), Si IV (λ1394, 1402), C IV (λ1548, 1550), N V (λ1240), Si II ($\lambda\lambda$1309, 1526, 1534, 1808, 1817) lines which all appear to be optically thin. The observed line fluxes are listed in Table 1.

3. Line Fluxes

Methods previously used to analyse solar EUV line fluxes (Jordan et al., 1971) have been applied to stellar spectra. Observed line fluxes have been transformed into surface fluxes at the star, with the angular diameter $\phi' = 1''.08\ 10^{-3}$ obtained by the relation of Barnes and Evans (1976), and hence the emission measures have been calculated. In Table 2 are listed the surface fluxes, the emission measures, $\int N_e^2\, dh$, and the peak formation temperatures for the lines used. The atmospheric parameters and abundances

Table 1

λ (Å)	Elem.	F_{ob} (erg cm^{-2}s^{-1})
1240	N V	6.215 (-14)
1304	O I	7.057 (-14)
1309	SiII	1.330 (-14)
1335	C II	1.374 (-13)
1357	O I	2.723 (-13)
1394	SiIV	7.657 (-14)
1403	SiIV	7.044 (-14)
1482	S I	5.964 (-14)
1526	SiII	6.318 (-14)
1533	SiII	6.344 (-14)
1548	C IV	1.578 (-13)
1550	C IV	6.001 (-14)
1640	HeII	6.001 (-14)
1657	C I	1.466 (-13)
1808	SiII	2.185 (-13)
1817	SiII	2.871 (-13)
1892	SiIII	2.516 (-13)
1909	C III	3.022 (-13)

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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 2

λ (Å)	Elem.	F_{surf}	$\frac{N(el)}{N(H)}\int N_e^2\,dh$	g_m	log T_m	f_{lu}	$\bar{g}$
1240	N V	9.8052 (3)	7.38 (22)	9.33 (-4)	5.2	0.234	0.78
1304	O I	1.1134 (4)	1.76 (28)	8.71 (-7)	4.1	0.031	0.03
1309	SiII	2.0970 (3)	4.00 (24)	1.07 (-5)	4.4	0.09	0.33
1335	C II	2.1683 (4)	1.66 (24)	9.55 (-5)	4.5	0.27	0.65
1394	SiIV	1.2081 (4)	1.35 (23)	3.09 (-4)	4.9	0.53	0.43
1403	SiIV	1.1113 (4)	2.50 (23)	3.09 (-4)	4.9	0.26	0.43
1526	SiII	9.8682 (3)	3.78 (25)	2.19 (-5)	4.3	0.076	0.20
1533	SiII	1.0009 (4)	3.85 (25)	2.19 (-5)	4.3	0.076	0.20
1548	C IV	2.4902 (4)	2.89 (23)	8.13 (-4)	5.0	0.194	0.60
1550	C IV	9.8540 (3)	2.30 (23)	8.13 (-4)	5.0	0.097	0.60
1657	C I	2.3136 (4)	8.80 (25)	6.61 (-5)	4.1	0.17	0.03
1808	SiII	3.4475 (4)	4.88 (24)	4.57 (-5)	4.3	0.004	0.33
1817	SiII	4.5292 (4)	6.26 (24)	4.68 (-5)	4.3	0.003	0.33

have been determined by Hearnshaw (1974) from optical data, $\log g = 4.44$ and $[\mathrm{Fe/H}] = 0.08$. The colours $B-V=0.68$ and $V-R=0.57$ have been obtained from Johnson et al. (1966).

It is evident that the emission measures from the region of temperature $2\,10^4$–$1.6\,10^5$ K are between 9 and 2 times larger than the corresponding values for the quiet sun.

4. Model of the Transition Region

The distribution of the emission measures, $\int N_e^2\,dh$, with temperature can be used to find a range of models of the outer atmosphere which would satisfy the observations. The method of analysis derived by Jordan (1965) and Evans et al. (1975) has been used. The emission measure is given by

$$\int_R N_e^2\,dh = \frac{[P_e^2]_{\Delta T}}{T_e^2}\left[\frac{dh}{d\log T_e}\right]_{\Delta T} \times 0.32, \tag{1}$$

where T_e and $P_e = N_e T_e$ are the temperature and the electron pressure (cm^{-3} K).

The assumptions of hydrostatic equilibrium and a fully ionized gas with a mean molecular weight $\mu = 1.26$ give

$$\frac{d\log P_e}{d\log T_e} = -9.21\,10^{-5}\frac{1}{T_e}\frac{dh}{d\log T_e}. \tag{2}$$

When starting from a given pressure at a temperature, the temperature and pressure gradients can be found through the iteration of Eqs. (1) and (2).

The pressure at $T_e \simeq 1.6\,10^5$ K, which is the formation temperature of the N v line, is not known. At the top of the solar chromosphere Ayres et al. (1974) find a total gas pressure of 0.15 dyn cm^{-2}. This value can be used to give an upper limit to the electron pressure at $T_e = 1.6\,10^5$ K of $\log P_e = 14.74$ ($P_e = 5.5\,10^{14}$ cm^{-3} K). But Cook and Nicolas (1979) in their model of solar transition region with a constant pressure have used a total gas pressure of 0.25 dyn cm^{-2}. This value gives an upper limit to the electron pressure of $\log P_e = 14.96$ at the same temperature.

A lower limit to the electron pressure at $T_e = 1.6\,10^5$ K can be found by assuming that the N v emission line is formed in an isothermal medium at this temperature. The scale height in such a medium would be $H = 1.04\,10^4$ km. Combining this value with emission measure for N v leads to $N_e = 1.3\,10^9$ cm^{-3} and $\log P_e = 14.31$ would be a lower limit.

Table 3. Models for κ Cet

Model a : log P_e = 14.74, log T_e = 5.2

log T	$\log\frac{dh}{d\log T}$	log P_e	log N_e	$\int N_e^2\,dh$	P_g	H (km)
5.2	8.67	14.74	9.54	1.78(27)	1.09(15)	1950
5.1	8.48	14.77	9.67	2.09(27)	1.17(15)	1648
5.0	8.33	14.79	9.79	2.57(27)	1.23(15)	1434
4.9	8.19	14.80	9.90	3.24(27)	1.26(15)	1279
4.8	8.10	14.82	10.02	4.57(27)	1.32(15)	1082
4.7	8.06	14.84	10.14	7.24(27)	1.38(15)	967
4.6	8.07	14.86	10.26	1.26(28)	1.45(15)	849
4.5	8.12	14.89	10.39	2.57(28)	1.55(15)	717
4.4	8.20	14.92	10.52	5.89(28)	1.66(15)	559
4.3	8.41	14.97	10.67	1.82(29)	1.87(15)	302
4.2	8.48	15.09	10.89	5.88(29)	2.46(15)	0

Model b : log P_e =14.96 , log T_e = 5.2

log T	$\log\frac{dh}{d\log T}$	log P_e	log N_e	$\int N_e^2\,dh$	P_g	H (km)
5.2	8.22	14.96	9.67	1.78(27)	1.82(15)	992
5.1	8.07	14.97	9.87	2.09(27)	1.87(15)	875
5.0	7.95	14.98	9.98	2.57(27)	1.91(15)	786
4.9	7.83	14.99	10.09	3.24(27)	1.95(15)	718
4.8	7.77	14.99	10.19	4.57(27)	1.95(15)	659
4.7	7.75	15.00	10.30	7.24(27)	2.00(15)	603
4.6	7.77	15.01	10.41	1.26(28)	2.05(15)	547
4.5	7.85	15.03	10.53	2.57(28)	2.14(15)	475
4.4	7.96	15.04	10.64	5.89(28)	2.19(15)	384
4.3	8.19	15.08	10.78	1.82(29)	2.40(15)	229
4.2	8.36	15.15	10.95	5.88(29)	2.83(15)	0

Model c : log P_e = 14.31 , log T_e = 5.2

log T	$\log\frac{dh}{d\log T}$	log P_e	log N_e	$\int N_e^2\,dh$	P_g	H (km)
5.2	9.52	14.31	9.11	1.87(27)	4.08(14)	3676
5.1	9.01	14.50	9.40	2.09(27)	6.32(14)	2653
5.0	8.76	14.57	9.57	2.57(27)	7.43(14)	2078
4.9	8.55	14.63	9.73	3.24(27)	8.53(14)	1724
4.8	8.41	14.67	9.87	4.57(27)	9.35(14)	1467
4.7	8.34	14.71	10.01	7.24(27)	1.02(15)	1248
4.6	8.30	14.75	10.15	1.26(28)	1.12(15)	1048
4.5	8.32	14.79	10.29	2.57(28)	1.23(15)	849
4.4	8.36	14.84	10.44	5.89(28)	1.38(15)	619
4.3	8.48	14.93	10.63	1.82(29)	1.70(15)	316
4.2	8.50	15.08	10.88	5.88(29)	2.40(15)	0

Table 4

log T	F_C	ΔF_C	F_R	ΔF_R	ΔF_m
5.2	2.20 (4)	8.10 (3)	2.56 (5)	-4.50 (4)	3.69 (4)
5.1	1.39 (4)	5.74 (3)	3.01 (5)	-6.90 (4)	6.33 (4)
5.0	8.16 (3)	3.36 (3)	3.70 (5)	-9.70 (4)	9.36 (4)
4.9	4.81 (3)	2.35 (3)	4.67 (5)	-1.91 (5)	1.84 (5)
4.8	2.46 (3)	1.31 (3)	6.58 (5)	-3.82 (5)	3.80 (5)
4.7	1.15 (3)	3.58 (2)	2.04 (6)	-6.70 (5)	7.69 (5)
4.6	4.92 (2)	3.04 (2)	1.81 (6)	-1.89 (6)	1.89 (6)
4.5	1.83 (2)	1.19 (2)	3.70 (6)	-4.78 (6)	4.78 (6)
4.4	6.34 (1)	4.67 (1)	8.48 (6)	-1.83 (7)	1.83 (7)
4.3	1.67 (1)	1.17 (1)	2.68 (7)	-5.79 (7)	5.79 (7)
4.2	5.03		8.47 (7)		

The models derived for the upper limit (Models a and b) and for the lower limit (Model c) in electron pressure are tabulated in Table 3. In the three models derived the temperature gradient goes through a maximum in the region between $T_e = 1.6\,10^4$ and $T_e = 1.6\,10^5$ K. In the sun this gradient has a maximum in the same region.

Our best fit model has a pressure of $\log P_e = 14.96$ at $T_e = 1.6\,10^5$ K. This pressure is larger than that in the model of Ayres et al. (1974) but is the same than that in the model of Cook and Nicolas (1979) for the sun. We consider the last value better because κ Cet is a dwarf of spectral type G5.

5. Energy Balance

By assuming (Evans et al., 1975) that over each region of atmosphere the energy dissipated is balanced by the sum of the radiation losses, thermal conduction and stellar wind losses then

$$\Delta F_m + \Delta F_r + \Delta F_c + \Delta F_w = 0 \qquad (3)$$

and

$$\Delta F_r = 0.80 \int N_e^2 P_{\mathrm{rad}}\, dh$$

$$F_c = \frac{1.8\,10^{-5}}{\ln \Lambda} T^{5/2} \frac{dT}{dh} \simeq 10^{-6}\, T^{5/2} \frac{dT}{dh} \quad \text{(Spitzer, 1956)}$$

where ΔF_w was neglected since any stellar wind from κ Cet must be weak. In Eq. (3) we have assumed that P_{rad} is constant and takes a value of $1.8\,10^{-22}\,\mathrm{erg\,cm^3\,s^{-1}}$ (McWhirter et al., 1975) over the whole temperature range of our models.

The convective flux, the radiation losses, and the mechanic energy for our best fit model are given in Table 4. It is clear that the effect of conduction is very much smaller than that of the radiative losses.

6. Conclusions

We have calculated three models from the emission measure distribution for the outer stellar atmosphere of κ Cet, the best fit model has a pressure of $\log P_e = 14.96$ at $\log T_e = 5.2$ since the pressure-temperature distribution is more linear and the region height is about 800 km which is consistent with the assumptions made initially.

The energy balance for this model has shown that the transport of energy by conduction is negligible compared with radiation losses, which at all heights are larger than those from the sun.

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