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OUTER ATMOSPHERES OF COOL STARS. I. THE SHARP DIVISION INTO SOLAR-TYPE AND NON-SOLAR-TYPE STARS

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ABSTRACT

IUE short-wavelength (1175–2000 Å) spectra of late-type stars clearly indicate two separate and distinct groups of stars. The solar-type group shows spectral lines formed at temperatures of 5×10^3–2×10^5 K, indicative of chromospheres, transition regions, and by implication unseen coronae at hotter temperatures. The non-solar-type group shows lines formed at temperatures no hotter than 10,000–20,000 K, indicative of chromospheres only. We interpret this acute change in character of the outer atmospheres of stars on either side of the sharp dividing line between the two groups as due either to the absence of hot material resulting from the rapid onset of large stellar winds, a hypothesis recently suggested on theoretical grounds by Mullan, or to very low transition-region densities, as suggested by a model stellar wind corona we have calculated for Arcturus.

Subject headings: stars: chromospheres — stars: coronae — stars: emission-line — stars: late-type — stars: winds — ultraviolet: spectra

I. INTRODUCTION

The existence of analogs of the solar chromosphere in a wide range of late-type stars is indicated by the well-studied Ca II and Mg II resonance-line emission features in their spectra. Similarly, extended cool circumstellar envelopes are known to exist in late-type supergiants on the basis of blueshifted asymmetric absorption features (Deutsch 1960), infrared excesses, and K I resonance-line emission by gas above the limb of α Ori (Bernat *et al.* 1978). Further study of the outer atmospheres of late-type stars requires observations of emission-line spectra below 2000 Å, where lines indicative of plasma hotter than 10^4 K exist. While a few glimpses of the important 1175–2000 Å spectral range have come from *Copernicus* and rocket experiments, this spectral range can now be studied in a large number of late-type stars by using the *International Ultraviolet Explorer* (*IUE*), as indicated by the initial observations of Capella, HR 1099, λ And, and ϵ Eri by Linsky *et al.* (1978). We report here and in subsequent papers on the first survey of late-type stars with the *IUE*.

II. OBSERVATIONS

We have obtained useful low dispersion spectra with the short-wavelength spectrograph on the *IUE* of 21 stars ranging in spectral type from A7 III (γ Boo) to M2 Iab (α Ori). These spectra cover the wavelength region 1175–2000 Å with a spectral resolution of approximately 6 Å. The design of the *IUE* spacecraft is described by Boggess *et al.* (1978*a*) and its in-flight performance by Boggess *et al.* (1978*b*).

We list in Table 1 the stars observed, their spectral types, *IUE* image numbers, and exposure times. Most of these spectra were obtained with the SWP camera through the $10'' \times 20''$ large aperture to permit an absolute calibration of the flux. Although many of these stars were observed several times, we discuss here only those spectra which are best exposed to show a wide range of emission lines. As a result, many of these spectra are saturated at Lα and at long wavelengths.

Spectra of 10 luminous G–M stars are given in Figure 1. We have included in Figure 1 vertical lines designating important spectral features which are diagnostic of different temperature regimes. Plasma at temperatures less than 10^4 K is indicated by C I $\lambda\lambda$1561, 1657; Si II $\lambda\lambda$1808, 1817; and O I λ1357. Lα is formed at temperatures of 6000–20,000 K in the Sun (Basri *et al.* 1979), but it could be formed at temperatures as cool as 6000 K in stars that have no hotter material. The O I λ1304 resonance triplet is formed by a Lβ pumping process in Arcturus (Haisch *et al.* 1977), and is thus not directly indicative of the local plasma temperature.

Plasma at temperatures hotter than 20,000 K is indicated by lines of ions from C II to N V. The important spectral features noted in Figure 1 and approximate temperatures of formation (Kelch and Linsky 1978; Doschek *et al.* 1978) are C II λ1335 (20,000 K); C III λ1175 (40,000 K); Si IV $\lambda\lambda$1394, 1403 (80,000 K); C IV λ1549 (1×10^5 K); and N V λ1240 (2×10^5 K).

It is apparent in Figure 1 that stars fall into one of two very different groups. In the first group the spectra contain chromospheric lines (Lα, C I, O I, Si II) as well as the hotter-temperature lines (He II, C II–IV, Si III–IV, N V). In addition, the ratio of intensities among the hotter lines is roughly comparable to that seen in the Sun, as shown by the comparison quiet Sun rocket spectrum of Rottman (1978). There are no cases of

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TABLE 1

SUMMARY OF IUE LOW DISPERSION SHORT-WAVELENGTH OBSERVATIONS

Star	Spectral Type	*IUE* Image	Exp. Time (Min.)	V	$V-R$	π (arcsec)	B.C.	$M_{\rm bol}$	Group*
γ Boo	A7 III	SWP 2395	24	+3.02	0.14	0.016	+0.12	−0.84	*n*
α Car	F0 Ib-II	SWP 2302†	30	−0.75	0.24	0.018	+0.03	−4.44	*n*
β Cas	F2 IV	SWP 2372	26	+2.27	0.31	0.072	+0.11	+1.67	*s*
α CMi	F5 IV–V	SWP 1320‡	20	+0.37	0.42	0.288	+0.06	+2.73	*s*
α Cen A	G2 V	SWP 2317	10	−0.01	0.53	0.751	−0.02	+4.35	*s*
HR 1099	G5–K0 V+G5 V	SWP 2321	60	+6.01	(0.54)	0.030	(−0.02)	(+3.38)	*s*
UX Ari	G5 V+K0 IV	SWP 2336	90	+6.60	(0.54)	0.020	(−0.02)	(+3.09)	*s*
α Aur	G5 III+G0 III	SWP 2296	6	+0.08	0.60	0.073	−0.08	−0.68	*s*
ξ Boo A	G8 V	SWP 2347	90	+4.54	0.63	0.145	−0.11	+5.24	*s*
α Cen B	K1 V	SWP 2320	40	+1.33	0.67	0.751	−0.14	+5.57	*s*
β Dra	G2 II	SWP 2349	60	+2.78	0.68	0.009	−0.19	−2.6	*s*
μ Vel	G5 III	SWP 2338	15	+2.69	0.68	0.022	−0.19	−0.79	*s*
ϵ Eri	K2 V	SWP 2376	60	+3.73	0.72	0.303	−0.20	+5.94	*s*
β Cet	K1 III	SWP 2371	40	+2.02	0.72	0.057	−0.24	+0.56	*s*
λ And	G8 III–IV	SWP 2400	60	+3.82	0.78	0.043	−0.32	+1.67	*s*
α UMa	K0 II–III	SWP 2396	50	+1.79	0.81	0.031	−0.36	−1.11	*n*
α Ser	K2 III	SWP 2397	101	+2.64	0.81	0.046	−0.36	+0.59	*n*
ϵ Sco	K2 III–IV	SWP 2401	80	+2.29	0.86	0.049	−0.44	+0.30	*n*
ξ Boo B	K4 V	SWP 2347	90	(+6.8)	(0.90)	0.145	(−0.41)	(+7.20)	*s*
ϵ Gem	G8 Ib	SWP 2337	48	+2.98	0.96	0.009	−0.54	−2.8	*n*
α Boo	K2 III	SWP 1316‡	240	−0.05	0.97	0.090	−0.62	−0.90	*n*
α Ori	M2 Iab	SWP 1312‡	180	+0.42	1.64	0.005	−2.19	−8.3	*n*

* *s*, solar type; *n*, non–solar type.

† High dispersion.

‡ Small aperture.

spectra for which lines hotter than, say, C II, C III, or C IV are missing. Also there are no clear examples of stars with lines of one ion anomalously bright compared with other ions formed at different temperatures. A possible exception is β Cet, for which the N V line appears to be comparable in strength to C IV and Si IV, contrary to all the other examples. We refer to stars with this spectrum as solar type in view of the close similarities to the solar spectrum.

The second group of stars contains the same chromospheric lines (Lα, C I, O I, Si II) but *none* of the hotter lines, not even C II λ1335. There are emission features close to the wavelengths of the hotter lines in several of these spectra, but a careful examination of the spectra has shown that the lines are in all cases at significantly different wavelengths. For example, α Boo and α Ori have emission lines at 1340 Å, which are not C II λ1335. Also α Boo has a line at 1643 Å and α Ori has a line at 1637 Å. In both cases the identification is probably Fe II multiplet 42 rather than He II λ1640 (see van der Hucht *et al.* 1979). Additional lines are evident in the more deeply exposed α Ori and α Boo spectra, but they are due to Fe II, C I, Si II, and perhaps Ni II, and indicate cool material. These spectra will be discussed in more detail in a later paper. Alpha Orionis appears to be the most extreme example of this class of non–solar-type stars, since weak O I λ1304 emission indicates a weak Lβ line and thus little material in the high-temperature portion (6000–20,000 K) of its chromosphere. We do not wish to imply that the non–solar-type stars form a homogeneous class because α Ori has an extensive dust shell whereas the K giants do not. The two hottest stars, γ Boo and α Car, do not show any emission lines, and they will be discussed in a subsequent paper.

The observed stars are plotted in a H-R diagram (Fig. 2). The main-sequence and subgiant stars later than $V - R = 0.31$ (F2 IV) are all of solar type. In the region of the G and K giants there appears a clear, sharp distinction between the two types of stars. The straight, nearly vertical line is our best estimate of where the dividing line lies between the two types of stars, based on our sample of 10 stars in the region. However, two of the five stars immediately to the left of the dividing line, α Aur and λ And, are well-known RS Canum Venaticorum–type binary systems with bright emission-line spectra. Thus there are only three single stars to the left of the line and the line may not be as clearly defined as it appears in the figure. We have no data upon which to determine the extension of the dividing line for $M_{\rm bol}$ greater than −3 or smaller than +2.

Among the G–K giants and supergiants, α Boo exhibits variations in its K line profile (Chiu *et al.* 1977), and ϵ Gem exhibits variable He I λ10830 absorption and emission (Zirin 1976). Thus it is possible that the non–solar-type stars may occasionally exhibit solar-type spectra. Zirin (1975) has argued that λ10830 absorption occurs following recombination to the 2 ^3S metastable state after photoionization of neutral helium by coronal soft X-rays. Thus λ10830 absorption may be a good indicator of hot stellar coronae. We

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note that four of the five stars immediately to the left of the dividing line have strong λ10830 absorption features (Zirin 1976), while the fifth star, μ Vel, was not observed. By comparison, among the six stars to the right of the dividing line, α UMa, α Ser, and α Boo have no detectable λ10830 absorption in Zirin's (1976) survey, α Ori and ε Gem appear to show weak and variable absorption or emission, and ε Sco was not observed. Thus the λ10830 data are consistent with coronae to the left of the dividing line and no coronae or very low density coronae to the right of the dividing line.

III. SPECULATIONS CONCERNING THE ABSENCE OF HOT SPECTRA IN α ORIONIS-TYPE STARS

a) Absence of Transition Regions and Coronae

In the Sun the region above the chromosphere consists of a transition region, characterized by steep temperature gradients and little material between, say, 30,000 K and 1×10^6 K, and a corona at $T > 1 \times 10^6$ K, where the temperature gradients are small. Unfortunately, the *IUE* cannot observe plasma much hotter than about 2×10^5 K (N v) and thus cannot directly observe coronae at hotter temperatures. Such

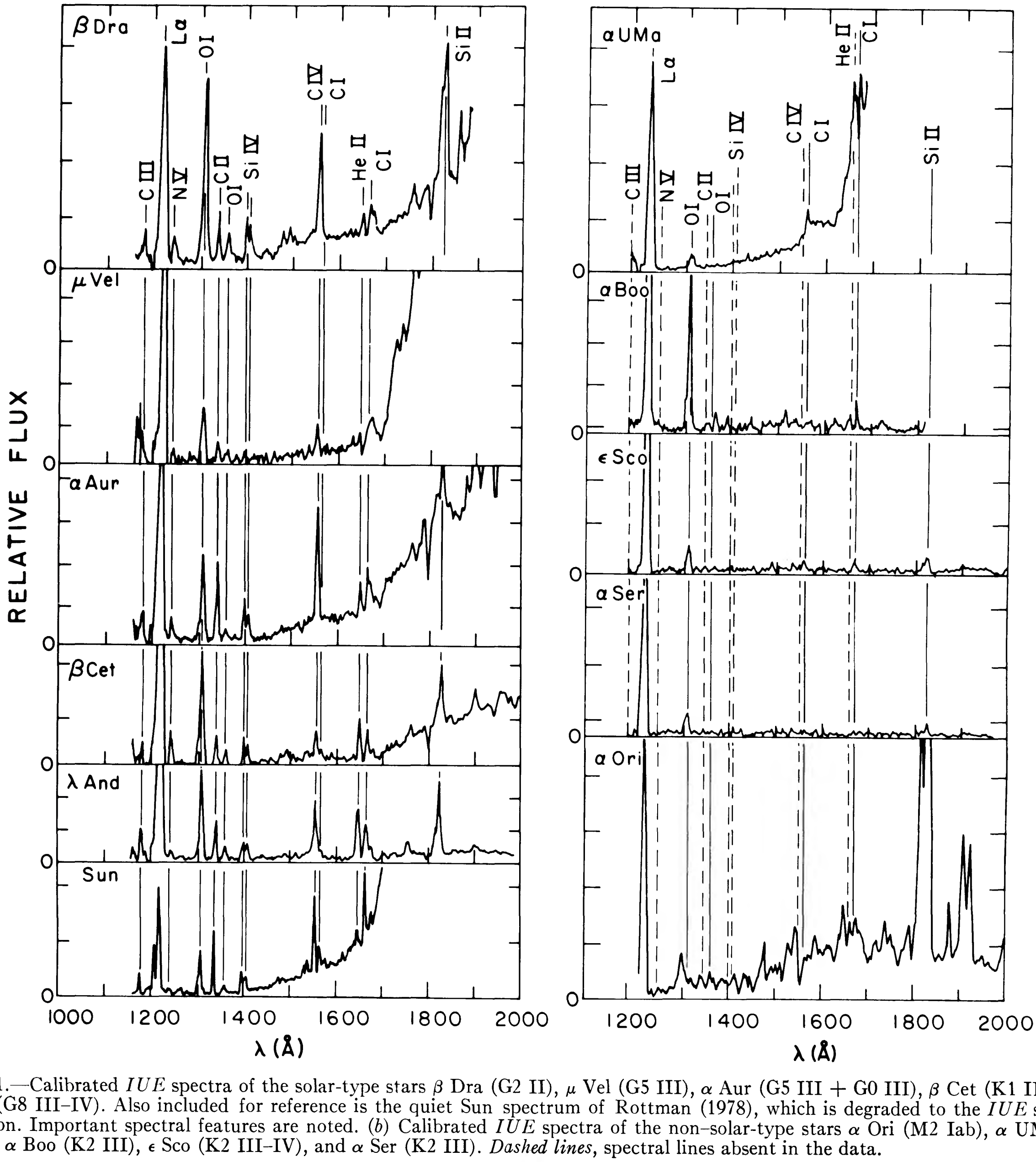

FIG. 1.—Calibrated *IUE* spectra of the solar-type stars β Dra (G2 II), μ Vel (G5 III), α Aur (G5 III + G0 III), β Cet (K1 III), and λ And (G8 III–IV). Also included for reference is the quiet Sun spectrum of Rottman (1978), which is degraded to the *IUE* spectral resolution. Important spectral features are noted. (*b*) Calibrated *IUE* spectra of the non-solar-type stars α Ori (M2 Iab), α UMa (K0 II–III), α Boo (K2 III), ε Sco (K2 III–IV), and α Ser (K2 III). *Dashed lines*, spectral lines absent in the data.

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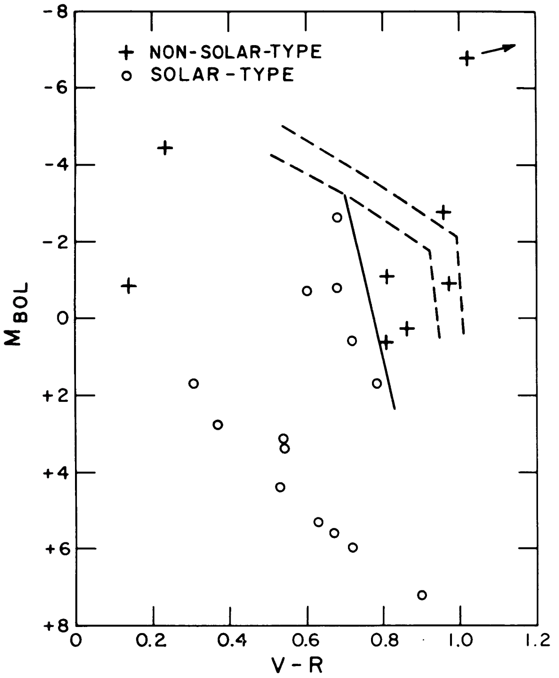

FIG. 2.—Location of stars in the H-R diagram. The symbols refer to stars with solar-type or non-solar-type spectra. The solid line is our estimate of the dividing line between the two types of spectra. The dashed lines refer to Mullan's (1978) computed supersonic transition locus (STL) lines for his assumed parameters of $\Delta = 0.5$ (*left line*) and $\Delta = 0.8$ (*right line*).

coronae are implied by the existence of "transition-region" spectra and X-ray observations. Among our stars α Aur, α Cen, and the RS Canum Venaticorum stars HR 1099 and UX Ari have been identified as soft X-ray sources.

Relatively cool coronae in the temperature range 2.4–6.6 $\times 10^5$ K have been predicted by Mullan (1976) for G and K giants of luminosity class III, and even cooler temperatures are expected for luminosity classes II and Ib based upon the minimum flux coronae thesis. If such cool coronae at $T < 2 \times 10^5$ K exist, we would expect to see spectra with emission lines for ions important at temperatures greater than the coronal temperature to be missing or conspicuously weak in our spectra. Also those lines formed at temperatures near the coronal temperature should be conspicuously strong, as they are no longer formed in a region of steep temperature gradient. We see no evidence for either effect in our data and conclude that cool coronae are somehow forbidden. The one possible exception is β Cet, for which N V is anomalously strong.

We now wish to speculate on why stars to the right of the dividing line in Figure 2 may have no coronae or transition regions, but instead may only have material cooler than 20,000 K and perhaps cooler than 10,000 K. In the Sun the coolest regions of the corona are coronal holes. Coronal holes are not relatively cool compared with quiet Sun regions due to decreased nonradiative heating. On the contrary, Withbroe and Noyes (1977) show that the total coronal energy loss is greater in coronal holes than quiet Sun regions, and thus the compensating heating rate must be larger. Instead, coronal holes are relatively cool due to the cooling provided by the expansion of the solar wind, which becomes the dominant cooling term in the open magnetic field geometry of coronal holes. Thus the geometry of the coronal magnetic field determines whether expansion or radiation is the dominant cooling term in the solar corona. It seems natural to speculate that the outer atmospheres to the right of the dividing line in Figure 2 are cool due to the sudden onset of strong winds at the dividing line.

One can speculate further on the apparent absence of coronae at temperatures of 2×10^4–3×10^5 K. At the present time calculations of the nonradiative energy deposited in stellar coronae are not sufficiently reliable to say whether this quantity is larger or smaller in K giants than in the Sun (Linsky and Ayres 1978). However, the chromospheric radiative losses in the Mg II and Ca II lines (Linsky and Ayres 1978; Linsky *et al.* 1979) are much smaller in K giants than in the Sun, and it is reasonable to assume that the energy input to the coronae of K giants is considerably smaller as well. If so, then the amount of energy available to heat the corona, less the energy converted into the expansion of the wind, may be insufficient to maintain a hot ($T \sim 10^6$ K) corona. Then due to thermal instability (see, e.g., Cox and Tucker 1969), the next lower equilibrium plasma temperature is near 10^4 K.

Our scenario is consistent with and implied by Mullan's (1978) suggestion of a supersonic transition locus (STL) in the H-R diagram. Mullan has argued that along the STL, stellar winds should become supersonic at the base of the stellar corona, implying that the mass-loss rate should increase discontinuously by a factor of order 50 as a star evolves across the STL. A plausible consequence of this large increase in the stellar wind is a large decrease in the energy available to heat the corona which can result in 10^4 K material as just described. Empirical evidence for the onset of large winds in the middle K region of the H-R diagram is found in the K line asymmetry studies of Reimers (1977) and Stencel (1978).

The dashed lines in Figure 2 are Mullan's predicted STL converted to the theoretical H-R diagram for two assumed values of his parameter, Δ, the logarithmic decrease in pressure across the transition region. We note that the minimum flux corona concept of Hearn (1975), upon which Mullan's (1978) analysis is based, has been criticized by several authors (e.g., Vaiana and Rosner 1978; Antiochos and Underwood 1978) on the grounds that the theory is inconsistent with the closed loop geometries typical in the solar corona, it neglects relevant length scales, and the stability argument used to obtain the coronal temperature is invalid for decreases in temperature. We also note that it is not possible to simply feed additional material through a critical point as proposed by Mullan. The location of a critical point will be drastically altered by any increase of outflowing matter, and may in fact disappear entirely, making it impossible for any stellar wind solution to exist. Nevertheless, we take the idea of Mullan's STL as suggestive of a connection between cool coronae and large winds, and we are at present investigating the possibilities of cool winds. The predicted STL curves and our empirical dividing line are only roughly in agreement. It is our opinion that they represent different aspects of the same physical phenomenon and that our ultraviolet spectra may provide a precise location of the end of coronae and the beginning of large stellar winds.

b) Very Low Density Transition Regions and Coronae

One of the stars to the right of the dividing line in Figure 1 is Arcturus (α Boo, K2 IIIp). We have modeled the wind of this star for various initial velocities, subsonic and supersonic, and acoustic fluxes, using as boundary conditions the upper chromospheric structure of the Ayres and Linsky (1975) model chromosphere. We solved the mass, momentum, and energy conservation equations for a transonic (solar wind type) flow, including conduction and optically thin radiative losses. We found that a stellar wind, having a density consistent with the Ayres-Linsky model chromosphere and $v_0 = 0.44$ km s^{-1} at the top of the chromosphere, has a critical point at $R_c = 1.25\ R_*$ with velocity $v(R_c) \approx 250$ km s^{-1} and temperature $T(R_c) \approx 3.7 \times 10^6$ K. We included no acoustic flux dissipation, but implicit in our calculation is the assumption that nonradiative energy is needed to balance the energy which the conductive flux has fed into the flow and radiative losses. To our surprise this hot corona wind model is consistent with the absence of observed transition-region emission lines. A comparison of emission measures for this model and the solar model of McWhirter, Thonenmann, and Wilson (1975) shows that for various intervals (T_1, T_2) in the range of 20,000–250,000 K, $\mathrm{EM}_{\mathrm{Arcturus}} \approx 0.002$–$0.005\ \mathrm{EM}_{\mathrm{Sun}}$. Thus the high-temperature material computed to be in the transition region would emit emission line fluxes below the detection threshold in our data, which are roughly $0.015\ \mathrm{EM}_{\mathrm{Sun}}$ (see Weinstein, Moos, and Linsky 1977).

Solutions with subsonic velocities throughout were rejected because of the well-known problem of matching boundary conditions with the interstellar medium. Supersonic solutions require $v_0 > 400$ km s^{-1}, and are thus unrealistic. We also computed models including acoustic flux dissipation just above the stellar surface, to see whether a wind could be accelerated without a steep rise in temperature. The effect of this additional energy source may indeed drive a wind under certain conditions, and it is possible to produce narrow plateaus at 10,000–20,000 K, but in all cases conduction eventually produces a steep drop in temperature at the top of any plateau, resulting in a sharp loss of energy from the wind flow and collapse of the wind solution. This is true for all solutions regardless of whether v_0 is greater than, less than, or equal to $(2kT_0/m_{\mathrm{H}})^{1/2}$. The only reasonable physical solution at this point thus seems to be the transonic wind.

For Arcturus, the transonic model predicts a critical point only $\frac{1}{4}\ R_*$ above the stellar surface, which may be close enough to the surface of this giant to be consistent with Mullan's (1978) scenario in which the corona is "fed" by outward-flowing chromospheric material (but note comments in § III*e*). As discussed above, spherically symmetric models having a large chromospheric velocity (10–20 km s^{-1}) are not physically possible. However, if such flow velocities occur only over a portion of the stellar surface in rising cells, then the expansion of the gas will not be purely radial, and a high density, low-temperature flow above regions of upwelling matter may be physically plausible. The freedom to expand transversely may permit a cool wind to balance its energy requirements without undergoing a temperature collapse. The observation by Chiu *et al.* (1977) of variable chromospheric outflow of 10–20 km s^{-1} argues against a spherically symmetric transonic wind with $v_0 = 0.44$ km s^{-1}. This suggests that, as in the Sun, a realistic treatment of the wind structure must include inhomogeneities. Various diverging flow models are under investigation.

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Note added in proof.—Subsequent calculations show that scattering of Lα in an optically thin envelope may bring about a supersonic flow near the stellar surface.

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