

STELLAR CHROMOSPHERES AND CORONAE IN THE URSA MAJOR CLUSTER STARS

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ABSTRACT

We discuss *IUE* spectra of 18 proposed members of the Ursa Major Cluster and *Einstein* X-ray images of 11 of these stars. We find that 13 of these stars (six in the Nucleus and seven in the stream) exhibit bright ultraviolet and/or X-ray emission indicating that they are bona fide members of the young Ursa Major Cluster, whereas four stars (one in the Nucleus and three in the Stream) exhibit weak emission and are probably old field stars that have space velocities similar to the Cluster. The X-ray surface fluxes and luminosities of the bona fide Ursa Major Cluster stars appear to lie intermediate between the older Hyades Cluster and the younger Pleiades stars as expected on the basis of the general decay of outer atmosphere emission with age. The surface fluxes in the ultraviolet emission lines of the Ursa Major stars are comparable to the most active Hyades stars and thus are presumably larger than for typical Hyades stars as expected. We argue that chromospheres and transition regions could be present in dwarf stars hotter than $B-V = 0.30$ (F0 V), but are unobservable in *IUE* spectra due to the rapid increase in the photospheric flux in hotter stars.

Subject headings: clusters: open — stars: chromospheres — stars: coronae — ultraviolet: spectra — X-rays: sources

I. INTRODUCTION

The study of galactic clusters has played a crucial role in our understanding of stellar evolution because such clusters consist of a variety of stars that lie at a common distance and are presumably coeval (see, however, Stauffer 1982). Such clusters as NGC 2264, the Pleiades, and the Hyades have been studied to provide empirical checks on stellar evolution calculations and to derive the cosmic distance scale.

In his classic study of Ca II H and K emission in late-type main sequence stars in the Hyades, Praesepe, Coma, and Pleiades clusters, Wilson (1963) concluded that the Ca II intensity, and hence the general degree of chromospheric activity, in main-sequence stars decreases systematically with cluster age. Data on the four clusters he observed are given in Table 1 (taken from Allen 1973, Duncan 1981, and references therein). Subsequently, Skumanich (1972) argued on the basis of Wilson's cluster data and data on field stars, that the Ca II emission strength decreases with age as $t^{-1/2}$ for late-type main-sequence stars.

As stars age on the main sequence, they lose angular momentum through their stellar wind, and the rotational velocity (and angular velocity) of their convection zone decreases with time. This is clearly shown in Kraft's (1967) data, and Skumanich (1972) showed that $v_R \sin i \sim t^{-1/2}$. Since magnetic fields are regenerated by dynamo processes that are driven by differential rotation (which presumably increases

with stellar rotation), it is likely that the decrease in Ca II emission for stars of a given spectral type on the main sequence is a consequence of decreased magnetic fields in the chromosphere. In the Sun, for example, there is an excellent correspondence between magnetic flux and Ca II emission.

While this qualitative scenario is probably correct in its coarse outline, we know little about how the outer atmospheric structure and parameters differ in main-sequence stars of different ages. Field stars are of some value, but their ages (determined, for example, from surface lithium content) are highly uncertain. We must therefore study a statistical sample of stars in clusters of different ages in order to begin to answer this question in a meaningful way.

Recently, Stern *et al.* (1981) and Zolcinski *et al.* (1982a, b) obtained *Einstein* X-ray images and *IUE* spectra of many stars in the Hyades cluster. These data show a pattern of enhanced emission from their coronae ($T > 10^6$ K), transition

TABLE 1
PARAMETERS FOR NEARBY CLUSTERS

Name	Distance (pc)	Absorption A_v	Log Age	Typical m_v for a G1 V Star
NGC 2264	800	0.1	6-7 ^a	11.7 ^b
Pleiades	126	0.2	7.9 ^c	10.3
UMa Nucleus.....	23	0.0	8.5 ^c	5.5
Praesepe	159	0.0	8.4 ^d	10.5
Coma.....	80	0.0	8.5 ^d	9.4
Hyades	41	0.0	8.8 ^c	7.7

^a Adams, Strom, and Strom 1983.

^b These stars lie above the main sequence.

^c Duncan 1981.

^d Allen 1973.

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regions ($T \sim 10^5$ K), and chromospheres compared to the Sun and other relatively older main-sequence field stars. Typical flux enhancements compared to the quiet Sun are a factor of 100 for the coronal X-ray emission and a factor of 30 for the transition region emission lines.

It is important to extend this study of the age dependence of stellar coronal, transition region, and chromospheric emission to clusters of different ages. Unfortunately, the visual magnitude of solar type stars in the Hyades is about 7.7, and their ultraviolet emission line fluxes are near the sensitivity limit for *IUE* in its low-dispersion, short-wavelength mode; and most other clusters are significantly more distant and thus fainter (see Table 1). The broad-band X-ray imaging capability of *Einstein* does permit observations of more distant clusters, and studies of the Pleiades and the Orion Nebula are now becoming available (Caillault and Helfand 1981; Micela *et al.* 1982).

However, there is a cluster that is both appreciably younger and closer than the Hyades. This cluster, Ursa Major, consists of a compact Nucleus (often referred to as the Ursa Major cluster) with dimensions (240 pc^3 volume) similar to an ordinary loose galactic cluster, and the Ursa Major Stream, which extends over a radius of 100 pc. The Nucleus consists of 14 stars, including five of the seven stars in the Big Dipper, all on the main sequence with spectral types A0 V to K3 V (Roman 1949). Eggen (1965) and Roman (1949) argue that the Nucleus is unstable to disruption, but the stars have common space motions and are presumably coeval. The Ursa Major Stream shares a common space motion with, but no concentration in density toward, the Nucleus (Roman 1949), and consists of approximately 69 members including the A0–G2 main-sequence and a number of G and K giants. The Stream is a real association even though it is often difficult to decide whether a particular star is a bona fide member rather than an interloper from the field, because common space motion heretofore has been the only criterion for membership. Presumably the Stream is coeval with the Nucleus, but this point is unproven. The Sun lies well within the volume of space occupied by the Stream.

The main advantages of studying Ursa Major are its proximity and youth. Roman (1949) gives the mean distance of the Nucleus as 23 pc, nearly a factor of 2 closer than the Hyades. Thus at a given spectral type the stars in the Nucleus and many of those in the Stream are 2 mag brighter than their counterparts in the Hyades. The age of the UMa Nucleus is a factor of 2.5 younger than the Hyades (e.g., Duncan 1981). This young age estimate is confirmed by the strong Ca II intensities of cluster members. For example, HD 115043 (G2 V), a Nucleus member, has a Wilson Ca II intensity of 4, and ξ Boo A (G8 V), a Stream member, has a Wilson Ca II intensity of 5. The Stream members π^1 UMa (G0 V) (Vaiana *et al.* 1981) and ξ Boo A (Walter 1982) are extremely luminous X-ray sources. In addition, several Nucleus members have large lithium abundances, another indicator of youth. Barry and Schoolman (1982) obtained low-dispersion LWR spectra of UMa Nucleus members HD 111456 and HD 115043, and showed that they have strong Mg II emission. Thus the UMa Cluster appears to be the ideal younger cluster to compare with the Hyades and older field stars.

Given the unique advantages of the UMa cluster, we initiated observing programs with the *IUE* and *Einstein* satellites. We report here on the results of these programs, as well as the analysis of additional Nucleus and Stream stars

for which observations are available from the data archives. While the data sample is not complete at this time, enough stars have been observed to make meaningful statements concerning cluster membership and the age dependence of stellar chromosphere and coronal properties. Of particular importance is the question of whether chromospheres and transition regions turn on quickly near $B - V = 0.30$ (spectral type F0 V) as suggested by Böhm-Vitense and Dettman (1980), or whether ultraviolet emission lines indicative of these layers first become visible near this spectral type due to the rapidly decreasing photospheric ultraviolet background with later spectral types against which these emission lines must be measured.

II. OBSERVATIONS

a) The *IUE* Data

We obtained ultraviolet spectra with the *International Ultraviolet Explorer* satellite (Boggess *et al.* 1978) of eight out of the 14 UMa Nucleus stars, including all of the stars between spectral types A5 V (80 UMa) and K3 V (HD 110463). The six unobserved Nucleus stars are of spectral type of A0 V–A3 V. In addition we observed five dwarf members of the Stream and reduced archival spectra of five additional Stream members. The Stream stars cover the spectral range F2 IV (α Crv) to K2 V (HD 45088). Within this spectral range the sample of dwarf stars in the Stream is not complete as spectra for seven additional dwarf stars (from the compilation of Roman 1949) in this spectral range are not available. Parameters for the 13 Nucleus and Stream stars we observed are summarized in Table 2, together with a log of the *IUE* observations. Table 3 provides the same information for the five Stream stars (ι Leo, χ^1 Ori, π^1 UMa, ξ Boo A, and HD 45088) whose *IUE* spectra come from the archives.

For most of the stars we were able to obtain a pair of exposures consisting of a low-resolution short-wavelength (SWP, 1200–2000 Å) spectrum and a high-resolution long-wavelength (LWR, 2000–3200 Å) spectrum well exposed in the region of the Mg II *h* and *k* lines near 2800 Å. For the fainter stars, however, available time limited us to obtaining only low-dispersion LWR spectra.

We reduced the *IUE* spectra at the Colorado Regional Data Analysis Facility, using standard *IUE* software and calibrations to obtain spectra in absolute flux units. The photometric accuracy of the *IUE* data is limited to $\sim 20\%$ by uncertainties in the intensity transfer function and fixed pattern noise. We measured line fluxes by integrating above a best fit quadratic background extrapolated under the emission line. Uncertainties in the line fluxes are estimated from the variance in a nearby continuum region that should be free of real features. Except for the Mg II lines (discussed below) and the weakest lines, photometric errors are dominated by the $\sim 20\%$ systematic uncertainties.

We present the chromospheric and transition region emission line surface fluxes in Table 4. Upper limits to the emission-line fluxes are approximately 2σ confidence and were evaluated by adding a weak emission line with instrumental shape to the data and then increasing its flux until it was positively detected. The SWP images were deliberately overexposed longward of 1600 Å in order to bring out the weak emission lines at shorter wavelengths. We have used the Barnes-Evans (1976) relation between $V - R$ and the stellar angular diameter to convert observed fluxes to surface fluxes.

TABLE 2
OBSERVING LOG

Star Name	HD	Spectral Type ^a	<i>V</i>	<i>B</i> − <i>V</i>	<i>V</i> − <i>R</i>	<i>V</i> sin <i>i</i> (km s ^{−1})	Reference ^b	<i>IUE</i> Image Number ^c	Exposure Time (minutes)	<i>Einstein</i> Sequence Number ^d	Exposure Time (minutes)
80 UMa	116842	A5 V	4.01	0.16	0.17	218	U	LWR 11712H SWP 15180L SWP 15195L	8 18 8	...	...
α Crv	105452	F2 IV	4.02	0.32	0.30	16	U	LWR 19421H SWP 13789L	15 60	I5538	149.5
37 UMa	91480	F1 V	5.16	0.34	0.33	87 100 ± 9	U BP	LWR 11689H SWP 15181L	30 60	...	...
78 UMa	113139	F2 V + G0 V	4.93	0.36	0.37	92 103 ± 10	U BP	LWR 11661H SWP 15178L	18 70	...	...
18 Boo	125451	F5 IV	5.41	0.38	0.34	42 39	K U	SWP 20635L LWR 16457H	120 25	I9705 ^e	56.5
HR 4867	111456	F6 V	5.85	0.46	0.44	35 37 ± 3 36	K BP U	LWR 11654H SWP 15150L	55 180	I7913 ^f	78.8
34 Leo	88355	F6 V	6.44	0.46	0.41	...	...	LWR 10409H	60	I5367	27.7
γ Lep	38393	F6 V	3.60	0.47	0.45	11	U	LWR 10423H LWR 11717H SWP 13790L	50 9 60	H5481	124.0
9 Pup	64096	G1 V + G8 V	5.16	0.60	(0.52)	<17	U	LWR 10410H SWP 15179L	53 160	I10669	71.9
	115043	G2 V	6.83	0.60	0.52	7.7 ± 0.8	S	LWR 11675L	6	...	...
	109011	K2 V	8.3	0.94	(0.74)	...	...	LWR 11713L LWR 11740L	12 18	...	...
	124752	K2 V	8.2	(0.94)	(0.74)	...	...	LWR 11738L	18	I10429	13.9
	110463	K3 V	8.1	(1.00)	(0.82)	...	...	LWR 11739L	16	...	...

^a Known binary companions within 4" (blended at the *IUE* resolution) are included.

^b *V* sin *i* reference: U = Uesugi 1976; K = Kraft 1967; S = Soderblom 1982; BP = Bernacca and Perinotto 1970.

^c The suffix denotes high dispersion (H) or low dispersion (L).

^d The prefix denotes IPC(I) or HRI(H).

^e Walter 1983.

^f Schrijver 1983.

Where *V*−*R* colors are unavailable, we have used the similar relation for *B*−*V*. Where both colors are unpublished, we have estimated *B*−*V* colors based on the published spectral type. (Estimated colors are in parentheses in Table 2.) The ratios of surface to observed flux (\mathcal{F}/f) are included in Table 4.

In the short-wavelength region of the *IUE* spectra, measurement of the line fluxes is fairly straightforward, as the

lines sit atop a fairly smooth background of noise, scattered light, and, toward longer wavelengths, stellar photospheric continuum. (We ignore all aspects of line blending.) This is not the case for the chromospheric Mg II resonance lines, which exhibit emission cores at the bottom of the deep, broad photospheric absorption lines (see Fig. 1). Of particular concern are the F stars where the chromospheric Mg II emission is superposed on a strong photospheric continuum.

TABLE 3
OBSERVATIONS FROM THE *IUE* DATA ARCHIVES

Star Name	HD	Spectral Type ^a	<i>V</i>	<i>B</i> − <i>V</i>	<i>V</i> − <i>R</i>	<i>V</i> sin <i>i</i> (km s ^{−1})	Reference ^b	<i>IUE</i> Image Number ^c	Exposure Time (minutes)	<i>Einstein</i> Sequence Number ^d	Exposure Time (minutes)
ι Leo	99028	F4 IV + G5 V	3.94	0.41	0.39	20	U	SWP 11311L LWR 1559H	4.83 25	...	...
χ ¹ Ori	39587	G0 V	4.41	0.59	0.51	9.4 ± 0.4	S	SWP 15205L ^e LWR 10210H	50 15	I4347 ^f	34.3
π ¹ UMa	72905	G1.5 V	5.64	0.62	0.52	9.5 ± 0.6	S	SWP 8582L LWR 7348H	35 20	I4456 ^g	35.7
ξ Boo A	131156	G8 V	4.74	(0.74)	(0.58)	2.5 ± 0.7	S	SWP 16797L LWR 13051H	90 15	H3498 ^h	35.6
	45088	K2 Ve	6.79	0.94	(0.74)	6	...	SWP 15954L LWR 10213H	155 18	I5484	27.1

^a Known binary companions within 4" (blended at the *IUE* resolution) are included.

^b *V* sin *i* reference: U = Uesugi 1976; S = Soderblom 1982.

^c The suffix denotes high dispersion (H) or low dispersion (L).

^d The prefix denotes IPC (I) or HRI (H).

^e Boesgaard and Simon 1984.

^f Mewe, Schrijver, and Zwaan 1981.

^g Vaiana *et al.* 1981.

^h Walter 1982.

TABLE 4
SURFACE FLUXES ($\times 10^5$ ergs $\text{cm}^{-2} \text{s}^{-1}$)

Star	HD	$10^{-17} \mathcal{F}/f$	O I 1302	C II 1334	Si IV 1393 1400	C IV 1549	He II 1640	C I Fe II 1656	Al II Fe II 1670	Mg II k	Mg II h	Mg II h+k	X-rays (0.1-3 keV)	$\log L_x$	Membership ^a
80 UMa	116842	3.70	abs.	abs.	...	<10	+	+	+	<48	<28	<100	...	...	N?
α Crv	105452	2.23	1.0	1.7	0.8	+	+	+	+	22	<76	<76	3	28.9	S
37 UMa	91480	5.67	0.8	1.4	<0.3	1.2	<0.5	<0.5	+	24	45	45	...	...	N
18 Boo	125451	6.86	0.8	1.7	1.2	3.2	(0.9)	...	+	13	9	22	10	29.4	S
78 UMa	113139	3.92	0.8	1.8	1.4	2.5	<2.6	+	+	35	20	55	...	...	N
ι Leo	99028	1.46	2.1	1.6	...	2.2	...	...	...	...	...	50	...	...	S
HR 4867	111456	6.93	0.8	1.2	0.4	1.1	1.5	0.4	<0.2	22	20	42	28	29.4	N
34 Leo	88355	13.4	...	...	...	...	...	...	...	3.0	6.3	9.3	<0.45	<29.0	SF
γ Lep	38393	0.84	0.1	<0.1	<0.1	<0.2	<0.05	+	+	2	7	9.0	0.25	27.6	SF
χ^1 Ori ^c	39587	1.40	0.4	0.6	0.6	0.7	0.3	...	...	...	...	40	44	29.6	S
9 Pup	64096	2.68	<0.4	0.05	...	<0.2	<0.05	...	0.2	...	3.4	6.8	0.4	27.4	SF
	115043	12.5	...	...	...	...	...	...	...	...	...	39 ^b	...	...	N
π^1 UMa	72905	4.17	0.45	1.1	1.1	1.1	0.32	...	...	...	...	36	18	29.1	S
ξ Boo A	131156	1.43	0.42	0.59	(0.19)	0.85	...	...	...	...	...	35.6	31	29.2	S
	109011	20.2	...	...	...	...	...	...	...	...	...	30 ^b	...	...	N
	124752	18.5	...	...	...	...	...	...	...	...	...	...	...	...	NF
	45088	4.52	0.36	0.72	...	0.90	0.45	...	...	12 ^d	17 ^d	29 ^d	<4	<28.2	S
	110463	12.3	...	...	...	...	...	...	...	...	...	22 ^b	36	29.0	N

NOTES.—abs. = absorption line; + = overexposed.

^a N = Nucleus; S = Stream; NF = probable field star originally proposed for the Nucleus; SF = probable field star originally proposed for the Stream; N? = proposed nucleus star but membership uncertain.

^b From low-resolution spectra.

^c From Boesgaard and Simon 1984.

^d Mg II emission is present from both stars in this spectroscopic binary system.

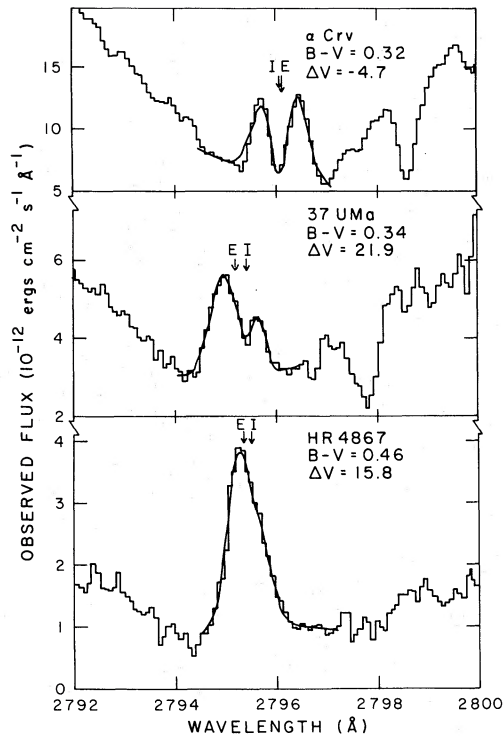


FIG. 1.—Mg II k line profiles for three UMa Cluster stars. The α Crv data are smoothed with a boxcar over three bins, the other data are unsmoothed. The fit to the data consists of a Gaussian emission core and a superposed Gaussian absorption reversal on a quadratic background. There are nine free parameters in the fit. The arrow labeled E indicates the Gaussian emission centroid. The arrow labeled I indicates the expected position of the interstellar absorption, on the assumption that the Mg II k emission centroid is located at the stellar radial velocity. The wavelength measurements are relative; uncertainties in absolute registration evident here are due to lack of corrections for spacecraft motions and other effects.

In these stars a summation of the flux between the k_1 and k_3 features will include a large photospheric contribution, in addition to scattered light from the IUE optics. We find for 80 UMa (A5 V), which does not exhibit detectable Mg II emission cores, that we can approximate the shape of the bottom of the Mg II photospheric absorption lines with a quadratic function. We have therefore adopted a quadratic absorption model for the shape of the Mg II absorption; we have fitted this to the data on either side of the emission core and have extrapolated the background under the emission.

Among the F stars in our sample, the Mg II emission cores are broad and often exhibit a reversal that is not central to the emission features. We can model these data by a broad Gaussian emission component with a width commensurate with the stellar rotational velocity and a superposed Gaussian absorption component. This absorption feature is generally unresolved (i.e., comparable with the instrumental width). Assuming that the emission component is centered at the stellar radial velocity, we find that the radial velocity of the absorption component is consistent with the expected line-of-sight velocity of the local interstellar medium (Böhm-Vitense 1981; Freeman *et al.* 1980). As a result, we assume that this absorption is interstellar and not circumstellar or due to chromospheric self-reversals. Therefore, we compute the stellar Mg II emission flux from the best fit emission Gaussian. (This is similar to the method used by Böhm-Vitense 1982.) Because the superposed absorption component is well off center in

most cases, the amplitude of the core emission can be well determined. Only in the case of α Crv (see Fig. 1), where the emission line is relatively narrow and the velocity offset is small, is the extrapolated Mg II flux highly uncertain. Our method for deducing the chromospheric Mg II emission for the F stars differs from that previously used in studying cooler stars in that we measure the emission above the extrapolated broad photospheric absorption line rather than above zero. We have adopted this different approach for the F stars because in these hotter stars the chromospheric Mg II optical depths are much smaller than for the cooler stars. The differences between the derived stellar Mg II fluxes using the two different approaches are small for the late F stars, but are about a factor of 2 of the early F stars like α Crv (see Fig. 1). Given these errors, our assumption of a quadratic absorption profile rather than another profile does not add significant additional errors into the Mg II emission fluxes.

We have obtained low-resolution (~ 8 Å) LWR spectra of the Mg II lines in four fainter stars. Not only are the h and k lines unresolved at this resolution, but they are severely blended with the photospheric features. A straightforward measurement of the emission flux above the local continuum would therefore underestimate the true Mg II emission flux by an amount that depends on both the spectral type and the true amount of Mg II flux. To calibrate this effect, we have degraded high-resolution (0.28 Å resolution) LWR spectra to low-resolution (~ 8 Å resolution) and have compared the fluxes measured in each case. We have also degraded the spectra of chromospherically inactive stars and subtracted them from the low-resolution scans to look for residual emission. The two methods give results that agree to within $\sim 50\%$. The low-resolution flux measured above the background must be increased by about a factor of 5 at G0 V and a factor of 2 at K0 V, for stars with moderately active chromospheres, such as ξ Boo A.

Because of all the corrections we have had to apply to the Mg II lines, the quoted surface fluxes are likely accurate to $\sim 50\%$. We adopt 20% uncertainties for the well-exposed short-wavelength lines.

b) The Einstein X-Ray Data

We have obtained X-ray observations of six stars (one in the Nucleus and five in the Stream) and include in our sample previous observations of one Nucleus star (HR 4867) and four Stream stars: all these observations were made with the *Einstein X-Ray Observatory* (Giacconi *et al.* 1979), using either the Imaging Proportional Counter (IPC) or the High Resolution Imager (HRI). We have used flux conversion factors of 2 and 4×10^{-11} ergs s^{-1} count $^{-1}$, for the IPC and HRI, respectively (Vaiana *et al.* 1981). According to Golub *et al.* (1983), however, for the A stars and probably also the early F stars, the standard flux conversion factors may be too small. The *Einstein* observing sequence numbers are listed in Tables 2 and 3, and the derived 0.1–3 keV surface fluxes are included in Table 4. Systematic uncertainties of order 20% in the IPC flux calibration are the dominant source of error in these data. The X-ray luminosities in Table 4 are derived using the parallaxes in Hoffleit (1982).

III. DISCUSSION

a) Membership in the Ursa Major Cluster

The surface fluxes of the chromospheric and transition region emission lines are presented in Table 4. It is evident

that the stars fall into two groups: an active group with surface fluxes $F_{\text{Mg II}} \approx 20\text{--}70 \times 10^5 \text{ ergs cm}^{-2} \text{ s}^{-1}$ and $F_{\text{C IV}} \approx 1\text{--}2 \times 10^5$, and an inactive group with $F_{\text{Mg II}} \lesssim 10 \times 10^5$ and $F_{\text{C IV}} \lesssim 0.2 \times 10^5$. The X-ray luminosities of these two groups also differ by a factor of 100. We take this as evidence for two distinct populations in this sample, an active group containing the true members of the young UMa Cluster, and a sample of field stars that share the same space velocity as the Nucleus but are much older. While the large difference in surface flux makes the separation of stars into these two groups clear cut, it is possible that a young star could be observed at a low point in its activity cycle or when most of its active regions are on the unobserved hemisphere and thus be misclassified as a field star. The absence of any variation in the Mg II flux from χ^1 Ori during a monitoring program (Boesgaard and Simon 1984) suggests that the latter interpretation is unlikely, and there is no evidence that the amplitude of flux variation during activity cycles is as large as factors of 20–100.

We plot in Figure 2 the Mg II surface fluxes for the Nucleus and Stream stars separately, together with $F_{\text{Mg II}}$ for the Hyades stars (Zolcinski *et al.* 1982a, b; Böhm-Vitense 1982) and other dwarf field stars observed by Böhm-Vitense (1982) and Ayres, Marstad, and Linsky (1981). This plot shows that the active stars in the Nucleus and Stream have surface fluxes that are comparable with those of the Hyades stars and the top of the field star distribution (presumably the youngest stars in this heterogeneous sample), at similar values of $B-V$. Thus we feel that the active stars in the Nucleus and Stream are likely coeval and members of the same UMa cluster. An approximate empirical upper bound to $F_{\text{Mg II}}$ defined by the top of the field star distribution, active Ursa Major stars, and Hyades stars in units of $10^5 \text{ ergs cm}^{-2} \text{ s}^{-1}$ is $F_{\text{Mg II}} \approx 70 - 50(B-V)$ or $F_{\text{Mg II}} \approx 170(\log T_{\text{eff}} - 3.588)$, using a relation between T_{eff} and $B-V$ for dwarfs from data tabulated by Popper (1980). On the other hand, the inactive putative

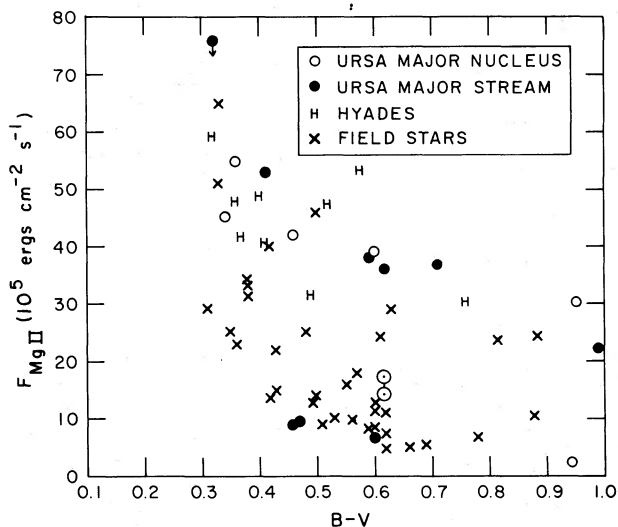


FIG. 2.—Mg II surface flux in units of $10^5 \text{ ergs cm}^{-2} \text{ s}^{-1}$ plotted as a function of $B-V$. Note that the upper bound consists mainly of members of the two young clusters. γ Lep, 34 Leo, and 9 Pup, as well as HD 124752, are inactive and probably are not bona fide UMa Cluster members. The spread in $F_{\text{Mg II}}$ at a given $B-V$ is roughly what one expects if $F_{\text{Mg II}}$ decays as the stellar age $t^{-1/2}$. The upper limit plotted is for α Crv (see text and Fig. 1), and the values for the quiet and active Sun are indicated.

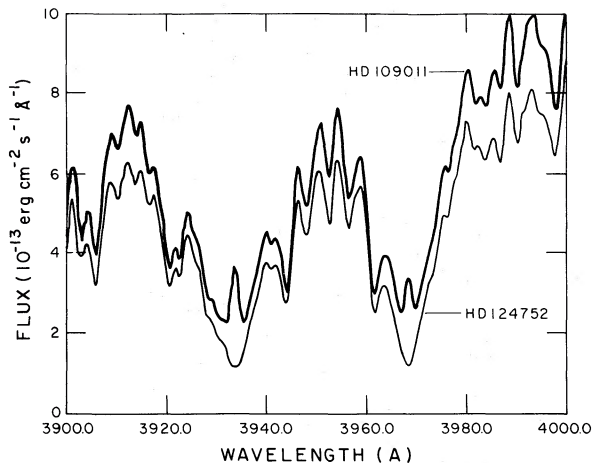


FIG. 3.—Optical spectra in absolute flux units of HD 109011 and HD 124752, early K dwarfs in the UMa Nucleus. HD 109011 exhibits prominent Ca II H and K emission cores, while HD 124752 does not. The offset between the spectra is mainly due to the ~ 0.1 mag brightness difference. These spectra were obtained with the Kitt Peak 2.1 m telescope and IIDS detector on 1983 June 3.

Ursa Major stars lie at the bottom of the field star distribution and are thus likely old field stars that by chance have space motions similar to that of the UMa cluster.

Excluding 80 UMa, all the members of the Nucleus, with the sole exception of HD 124752, clearly fall into the active category. HD 124752, however, exhibits both very weak Mg II emission (about one-sixth that of the quiet Sun) and very weak Ca II emission (Roman 1949), unlike the other two K stars in the Nucleus. Its X-ray luminosity falls an order of magnitude below that of the other stars in the Nucleus. We obtained spectra of the Ca II H and K lines of the K dwarfs in the UMa Nucleus using the Kitt Peak 2.1 m telescope IIDS system, and of HD 124752 using the 2.1 m coude spectrograph with the RCCD detector (camera 5, grating D). At IIDS resolution (1.7 \AA) there is clearly far more chromospheric emission in HD 109011 than in HD 124752 (see Fig. 3). The excess Ca II chromospheric surface flux in HD 109011, computed by scaling the continuum fluxes and subtracting the spectrum of HD 124752, is $\sim 2 \times 10^6 \text{ ergs cm}^{-2} \text{ s}^{-1}$. There is a noticeable emission feature in the coude spectrum of HD 124752 (0.22 \AA resolution). When this high-resolution spectrum is calibrated in absolute flux units using the IIDS spectrophotometry ($\sim 10\%$ accuracy), the emission surface flux between the K_1 features and above zero is $1.6 \times 10^5 \text{ ergs cm}^{-2} \text{ s}^{-1}$. The expected flux from a radiative equilibrium model is $\sim 3 \times 10^4 \text{ ergs cm}^{-2} \text{ s}^{-1}$ (Linsky *et al.* 1979). The Ca II flux ratio between these stars indicates an age for HD 124752 about 100 times that of HD 109011, or $\sim 3 \times 10^{10} \text{ yr}$. A measurement of the Li age of HD 124752 star is needed to confirm this old age. We have measured only upper limits to the ultraviolet emission line fluxes for the hottest Nucleus star 80 UMa (A5 V), and on a spectroscopic basis alone we cannot determine whether or not this star is a bona fide member of the UMa Cluster. We will discuss this point further in § IIIc.

Of the five proposed members of the Stream we observed, only α Crv and 18 Boo appear to be young active stars. The chromospheric fluxes (e.g., Mg II or C II) of α Crv are comparable to those of 37 UMa and 78 UMa, which are

Nucleus members of similar colors; its X-ray surface flux appears low compared to other cluster members but is typical of that observed in other F0–F2 V stars (Walter 1983). The Mg II flux is large, but highly uncertain because the stellar radial velocity and the line-of-sight velocity of the interstellar medium in that direction coincide, with the result that the interstellar Mg II absorption feature is nearly central. The emission-line profile is therefore determined only by the wings of the emission, and hence the amplitude of the emission core (assumed Gaussian) is poorly determined. The observed emission flux itself only yields a lower limit of 16×10^5 ergs $\text{cm}^{-2} \text{s}^{-1}$ in the Mg II lines. The chromospheric surface fluxes of 18 Boo are comparable to those of HR 4867.

In addition to our *IUE* observations, we have obtained from the *IUE* and *Einstein* data archives spectra and/or X-ray images of five additional proposed members of the Stream. On the basis of their ultraviolet and X-ray surface fluxes (see Table 4), it is likely that ξ Boo A (Hartmann *et al.* 1979; Walter 1982), χ^1 Ori (Boesgaard and Simon 1983), ι Leo (Böhm-Vitense and Dettman 1980; Böhm-Vitense 1982), π^1 UMa (Vaiana *et al.* 1980), and HD 45088 are all bona fide members of the Stream and presumably coeval with the Nucleus.

The other three supposed members of the Stream that we observed are all very inactive. For example, γ Lep (F6 V), which has a Li age of 3.8×10^9 yr (Duncan 1981), over an order of magnitude older than the nuclear age of the UMa Cluster, has a Mg II surface flux about a factor of 4 lower than that of HR 4867, a star of similar spectral type, a very low upper bound on transition region emission, and a small X-ray surface flux. The star 34 Leo (F6 V) has a Mg II surface flux comparable to that of γ Lep, while 9 Pup (G1 V) also has a Mg II surface flux less than the solar value, a C IV surface flux upper limit consistent with the solar value, weak X-ray emission, and a lithium age of 2.1×10^9 yr. We note that Soderblom and Jones (1984) found that 9 Pup is not a kinematic member of the Stream, and that the space velocity of ξ Boo also differs from the mean value for the Stream by greater than 3σ .

We conclude that these three stars (γ Lep, 34 Leo, and 9 Pup) are not true members of the Stream, and that HD 124752 is unlikely to be a true member of the Nucleus. Instead these stars are probably interlopers with similar space velocities. Roman (1949) and Eggen (1965) both stressed that space velocities alone cannot be used to decide whether proposed members of the Stream are coeval with the Nucleus. Whether or not 80 UMa is a spectroscopic as well as a kinematic member of the Nucleus cannot be determined at this time.

Henceforth we will no longer distinguish between Nucleus and Stream stars, but will refer to the 13 active stars as members of the UMa Cluster and the four inactive stars as probable field stars. We stress, however, that independent evidence, such as Li ages, is needed to confirm our assessment that the inactive stars are indeed old field stars rather than young stars that are inactive due to unusually slow rotation or their being at a minimum in their magnetic cycles.

We have investigated the variation of the f_l/l_{bol} ratios to see if the relative radiative loss rates in lines formed at different temperatures are similar to the relations that Ayres, Marstad, and Linsky (1981) and Basri, Laurent, and Walter (1984) have previously found for field stars and RS CVn systems, respectively. We find that the ultraviolet and X-ray fluxes for the Ursa Major stars fall on these established relations.

b) Comparison of the Ursa Major Cluster with Clusters of Different Ages

Now that we have identified a sample of 13 UMa Cluster stars that appear to be coeval with an age of 3×10^8 yr (Duncan 1981), we can compare their properties with those of stars in other clusters with different nuclear ages. The most extensively studied cluster is the Hyades located at a distance of 41 pc with an age of 7×10^8 yr (Duncan 1981 and references therein). Stern *et al.* (1981) published soft X-ray fluxes for 33 Hyades dwarfs with $B - V < 1.0$. Soft X-ray surface fluxes for these stars are plotted versus $B - V$ color in Figure 4. Also plotted are X-ray surface fluxes for seven UMa cluster stars and for four probable field stars identified in the UMa sample. Clearly the Hyades and UMa stars have similar X-ray surface fluxes, whereas the three probable field stars lie far below the distributions for both clusters.

We would like to proceed to a more quantitative comparison of the UMa and Hyades clusters, but we face two problems: the UMa data set is small, and the Hyades data set is biased by observational selection of stars brighter than $L_x = 10^{28.4}$ ergs s^{-1} . Furthermore, there are very few stars hotter than $B - V = 0.40$ that have measured X-ray fluxes and for these stars the X-ray emission is either very weak or due predominantly to known or suspected cool star companions (Golub *et al.* 1983). We therefore restrict ourselves to the large sample of stars in the range of $0.4 < B - V < 1.0$. Within this range $\langle F_x \rangle_{\text{Hyades}} = 1.8 \times 10^6$ ergs $\text{cm}^{-2} \text{s}^{-1}$ and $\langle F_x \rangle_{\text{UMa}} = 3.1 \times 10^6$ ergs $\text{cm}^{-2} \text{s}^{-1}$. Since observational selection requires that $\langle F_x \rangle_{\text{Hyades}}$ be an upper limit, it is likely that the younger UMa cluster stars statistically have brighter X-ray emission than the Hyades stars. However, additional observations of UMa stars are needed to confirm this tentative conclusion.

Zolcinski *et al.* (1982a, b) and M.-C. Zolcinski (1983, private communication) obtained *IUE* spectra of ten stars in the Hyades X-ray survey, but in order to increase the probability of obtaining usable spectra they selected Hyades stars with the largest X-ray luminosities. The X-ray surface fluxes of these stars are specially indicated in Figure 4. The mean X-ray surface flux of this sample $\langle F_x \rangle_{\text{Hyades, IUE}} = 3.4 \times 10^6$ ergs $\text{cm}^{-2} \text{s}^{-1}$, nearly double $\langle F_x \rangle_{\text{Hyades}}$ and slightly larger than $\langle F_x \rangle_{\text{UMa}}$. Thus the Hyades observed by Zolcinski *et al.* constitute a sample biased toward the most active stars in the cluster.

We also plot in Figure 4 the C IV $\lambda 1550$, C II $\lambda 1335$, and Mg II h and k line surface fluxes for the Hyades, UMa, and probable field stars (observed in the UMa program). We again note that the probable field stars lie well below the UMa Cluster stars in C II, C IV, and Mg II. Also the UMa star surface fluxes are consistent with and show a similar trend with $B - V$ as the Hyades stars observed by Zolcinski *et al.* But since these Hyades are from the most active group within the Hyades sample, it is likely that the mean of the distribution of surface fluxes for the UMa stars in C IV, C II, and Mg II would lie above the corresponding mean for the full Hyades sample. Given our small sample of stars, we cannot make this statement quantitative at this time.

If the Skumanich scaling law were valid for the Mg II lines ($F_{\text{Mg II}} \approx t^{-1/2}$), then we would expect the UMa clusters to lie 40% above the Hyades stars on the average in Figures 2 and 4. The observations do not clearly verify this prediction. However, the range in $F_{\text{Mg II}}$ in Figure 2 for solar type stars ($B - V \approx 0.6$) is about a factor of 7 between the least active field stars and

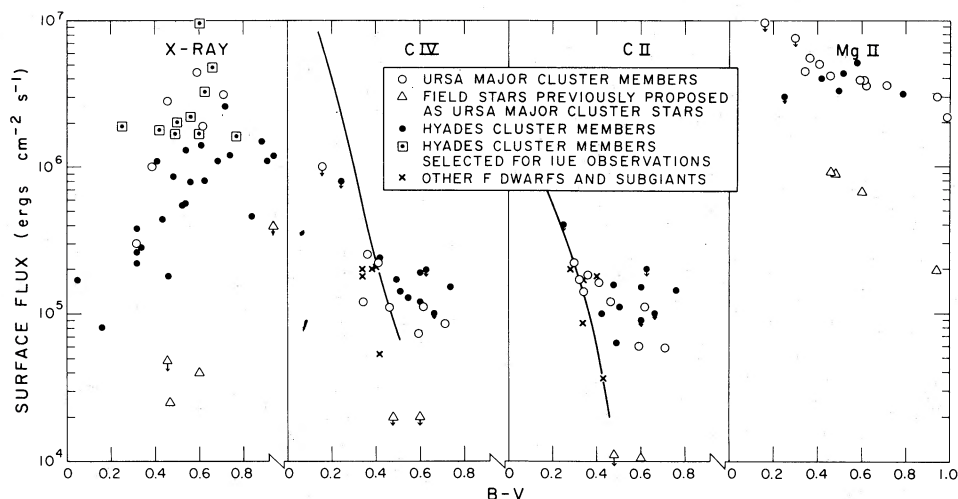


FIG. 4.—Surface fluxes in soft X-rays, C IV 1550 Å, C II 1335 Å, and the Mg II 2800 Å doublet for UMa Cluster members, probable field stars previously identified as Ursa Major members, Hyads, and selected field stars (see text). X-ray surface fluxes of the ten Hyads that Zolcinski *et al.* (1982*a, b*) selected for *IUE* observations are denoted by boxes. The solid lines indicate the photospheric continuum emission and scattered light (per 6 Å interval) at a C IV 1550 Å and C II 1335 Å obtained by averaging the measured flux for Ursa Major stars in 20 Å bands on both sides of the C IV and C II lines.

the UMa stars ($t \approx 3 \times 10^8$ yr) near the peak of the $F_{\text{Mg II}}$ distribution. This is consistent with the Skumanich scaling law if the oldest early G dwarf field stars have an age of $t \approx 15 \times 10^9$ yr. On the other hand, the spread in $F_{\text{Mg II}}$ at $B-V = 0.35$ is only a factor of 2.3, and this would imply that the oldest F2 V stars have an age $t \approx 1.6 \times 10^9$ yr. These ages are consistent with the main-sequence lifetimes of these stars.

To our knowledge the only ultraviolet spectra available for late-type dwarf stars in clusters other than Ursa Major and the Hyades are low-dispersion LWR spectra of five Coma and Pleiades stars obtained by Barry and Schoolman (1982). The measured Mg II residual intensities are sufficient to indicate that stars in these clusters are young, but uncertainties in blanketing corrections make it difficult to derive a relative age sequence from such data. However, *Einstein* data are available for other clusters. Stern (1982) compared the *Einstein* soft X-ray luminosities L_x of the Hyades, Pleiades, and Orion Nebula stars and noted a rapid increase in typical values of L_x with decreasing cluster age. Because the younger Orion and Pleiades clusters are systematically more distant, the minimum detectable L_x also systematically increases toward the younger clusters. This can bias the observed *mean* cluster X-ray luminosity toward higher values for the younger clusters to the extent that the faint cluster members are not detected. However, the peak L_x detected does increase with decreasing cluster age at a given $B-V$. For example, the L_x range is $28.3 \lesssim \log L_x \lesssim 30.1$ for the Hyades, is $29.3 \lesssim \log L_x \lesssim 30.4$ for the Pleiades, and is $30.4 \lesssim \log L_x \lesssim 31.5$ for Orion. In our sample the X-ray luminosities (see Table 4) lie below $\log L_x < 28.2$ for the three probable field stars (γ Lep, 9 Pup, and HD 124752), and lie in the range $28.9 \leq \log L_x \leq 29.6$ for the seven UMa Cluster stars. The latter stars have roughly 100–400 times the soft X-ray luminosity of the quiet Sun. The values of L_x for the seven UMa stars lie near the top of the Hyades distribution (as previously noted when discussing F_x), well below most of the detected Pleiades stars, and far below the even younger Orion stars. These data are consistent with the age of the UMa Cluster being intermediate between those of the Hyades and the Pleiades.

c) Do Chromospheres and Transition Regions Cease to Exist or Become Unobservable in the Early F Dwarfs?

Several studies have now addressed the important question of whether the nonradiatively heated outer layers of a star do not exist in stars hotter than the early F stars, or whether these layers exist but are unobservable due to the loss of contrast of emission lines with respect to the bright photospheric absorption line spectrum and scattered light. Warner (1968) and Dravins (1981) were able to detect Ca II K line emission at high spectral resolution in dwarf stars only as early as spectral type F0 V ($B-V \approx 0.30$). Böhm-Vitense and Dettmann (1980) in their systematic study of A–F stars using both the SWP and LWR cameras of *IUE* and Böhm-Vitense (1982) in her subsequent survey of Mg II emission observed Mg II and transition region emission lines in stars only as early as $B-V \approx 0.30$ on the main sequence (spectral type F0 V) and at later spectral types in the more luminous stars lying to the right of the Cepheid instability strip. They argued that chromospheres and transition regions are not present in main-sequence stars hotter than about $B-V \approx 0.30$, but they state that this conclusion is in doubt because the photospheric continuum is very bright for the late A dwarfs. An important point in their argument is that other evidence points to the rapid onset of convection at about the same $B-V$ color where the emission lines are first detected. This coincidence and the belief that acoustic waves (a consequence of convection) play a major role in heating stellar chromospheres and transition regions provide the conceptual framework upon which their conclusions are based.

Linsky and Marstad (1981) arrived at the opposite conclusion in their study of four early F and late A stars. They detected bright emission lines of C IV and other high temperature species in α CMi (F5 IV–V, $B-V = 0.42$) and β Cas (F2 IV, $B-V = 0.34$), but not in α Car (F0 Ib, $B-V = 0.15$) and γ Boo (A7 III, $B-V = 0.19$). The essential point of their analysis is that structure in the bright photospheric absorption line spectra and scattered light in *IUE* spectra of the late A type stars sets the upper limit on C IV emission lines that could be detected unambiguously. Further

complications are that rotational broadening might smear out weak chromospheric emission features located within the photospheric absorption lines and thus appear as filling in of the absorption lines. The corresponding upper limits for α Car and γ Boo are 6 and 22 times the quiet Sun values of F_{CIV} , respectively. Thus chromospheres and transition regions with C IV surface fluxes substantially brighter than for the quiet Sun could exist in the late A stars yet be undetectable in *IUE* spectra. We show in Figure 5 SWP spectra of four UMa cluster stars. Emission lines of C II (1335 Å) and C IV (1550 Å) are clearly present in the cooler stars, are weakly present in 37 UMa ($B-V = 0.34$), and are not apparent in 80 UMa ($B-V = 0.16$). At the same time the strength of the photospheric continuum increases rapidly with decreasing $B-V$.

To make the comparison of emission-line surface fluxes and background continuum quantitative, we plot in Figure 4 C IV and C II surface fluxes for five UMa stars (80 UMa, α CrV, 37 UMa, 78 UMa, and ι Leo), five Hyads (71 Tau, BD +14°690, BD +15°640, BD +16°577, BD +17°731), and five field stars (β Cas, α CMi, α Cae, μ Vir, and η Sco) that lie in the interval $0.16 \leq B-V \leq 0.42$ (Zolcinski *et al.* 1982a; Linsky and Marstad 1981; Böhm-Vitense and Dettmann 1980). Unfortunately there are no UMa stars with $0.16 < B-V < 0.34$. Also plotted for comparison are solid lines indicating the photospheric and scattered light flux (per 6 Å interval) at C IV 1550 Å and C II 1335 Å obtained by averaging the measured flux for UMa stars in 20 Å bands on both sides of the C IV and C II lines. These data clearly show that the background surface flux rises extremely rapidly

with decreasing $B-V$ color near spectral type F0 V ($B-V \approx 0.30$). In well-exposed SWP low-dispersion spectra, we have been able to determine surface flux upper limits as small as 13% of the background by determining the smallest 6 Å FWHM Gaussian emission-line profile that would be clearly detectable above the observed spectrum. However, in this extreme case (80 UMa) the C IV surface flux upper limit is 1×10^6 ergs $\text{cm}^{-2} \text{s}^{-1}$, which is 5 times brighter than the detected lines in the stars at $0.34 \leq B-V \leq 0.42$ and 170 times brighter than the quiet Sun surface flux. The data plotted in Figure 4 show that the mean surface fluxes for the active stars actually increase with decreasing $B-V$, with no evidence of a turnover for $B-V \gtrsim 0.30$. Thus emission lines from the most active transition regions and chromospheres could be hidden in the spectral "noise" in dwarf stars hotter than $B-V \approx 0.30$.

Because of this contrast problem, evidence for chromospheres and transition regions must be searched for by different observational techniques, e.g., coronal X-ray data which do not suffer from this contrast problem. Golub *et al.* (1983), Schmitt *et al.* (1983), and Walter (1983) do find a real decrease in the X-ray flux in the few detected single dwarf stars near $B-V = 0.30$. Apparently the hottest single star with solar like chromospheric and coronal emission is α Aql (A7 IV-V, $B-V = 0.22$) on the basis of detected X-ray (Golub *et al.* 1983), Mg II (Blanco *et al.* 1982), and Ly α (Blanco *et al.* 1980) emission. The hottest rapidly rotating W UMa systems with transition region emission lines (Eaton 1983) are V535 Ara (A8-9) and S Ant (A9 V, $B-V = 0.33$). Thus the question of how far chromospheres and transition regions ($T < \sim 10^5$ K) extend toward the hotter stars is still open.

IV. CONCLUSIONS

We have obtained *IUE* spectra of 18 proposed members of the UMa cluster and *Einstein* X-ray images of 11 of these stars in order to study the evolution of stellar outer atmosphere regions among dwarf stars. Of particular interest is the comparison with the well-studied Hyades cluster, which is a factor of 2.5 older than Ursa Major, and with the field stars that range in age up to perhaps 50 times older than Ursa Major. As a result of this study, we have arrived at the following tentative conclusions:

1. Thirteen stars, six in the Nucleus and seven in the extended comoving Stream, are likely true members of the UMa cluster in that their bright ultraviolet and X-ray surface fluxes indicate youth. Presumably these stars are nearly coeval with an age of $\approx 3 \times 10^8$ yr as indicated by the cluster turnoff point and the measured Li equivalent widths in several cases. On the other hand, four stars, one in the Nucleus and three in the Stream, exhibit weak ultraviolet and/or X-ray emission suggesting that they are old field stars that have the same space motion as the UMa cluster. Independent evidence is needed to confirm this hypothesis as these four stars could perhaps be inactive Cluster members because they are at the minimum of their magnetic cycles or are abnormally slow rotators.

2. The X-ray surface fluxes of the UMa cluster stars appear to be brighter than those of the Hyades Cluster stars, consistent with their relative ages, although the Ursa Major data sample (seven detections for likely cluster members) is small and should be augmented. It is difficult to make a similar statement concerning the chromospheric and transition

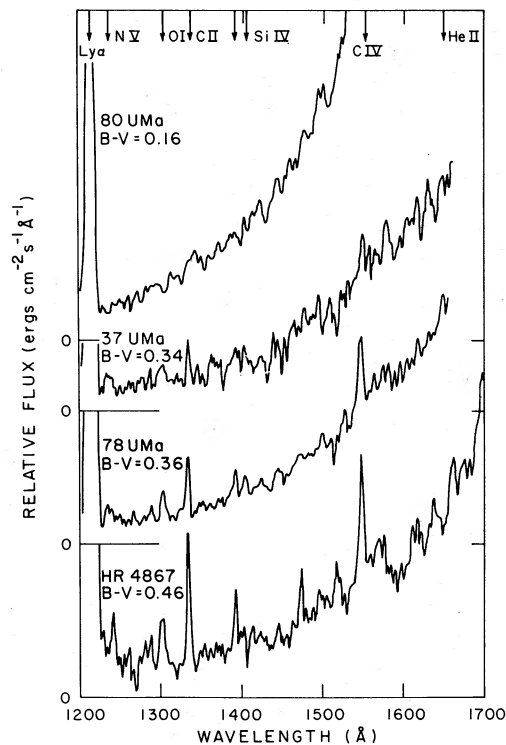


FIG. 5.—Short wavelength *IUE* spectra of four members of the UMa nucleus. The zero level is indicated for each spectrum, but the vertical scales are different for each. Strong chromospheric and transition region emission is visible in 78 UMa and HR 4867. Emission in the C IV and C II lines is prominent in 37 UMa, but no emission, and possible absorption at O I and C II, are evident in 80 UMa.

region emission lines because the *IUE* observations of Hyades cluster members are only for the most active stars as determined from the X-ray data. However, the surface fluxes for the Ursa Major stars are similar to those of the most active Hyads, and thus are probably brighter than the mean of the Hyades distribution, as expected. The X-ray luminosities of the Ursa Major stars lie between those of the Hyads and the Pleiads, also consistent with the generally accepted decay of activity with age and the relative ages of these three clusters. Assuming that the Skumanich (1972) $t^{-1/2}$ scaling law is valid also for the Mg II surface flux, the range of $F_{\text{Mg II}}$ values between the Ursa Major and field stars is consistent with the ages of the oldest F2 V field stars being $\sim 1.6 \times 10^9$ yr and the oldest G2 V field stars being $\sim 15 \times 10^9$ yr.

3. We have tested and confirmed the previously proposed hypothesis that chromospheres and transitions regions could exist in dwarf stars hotter than $B-V \approx 0.30$ (F0 V), but are unobservable because of low contrast with respect to the photospheric spectrum which increases rapidly in brightness below 2000 Å with decreasing $B-V$ for $B-V \lesssim 0.30$. The surface flux upper limit in our well-exposed spectrum at C IV of 80 UMa ($B-V = 0.16$), which is probably a young Ursa

Major star, is 170 times the quiet Sun value and 5 times that of the detected Ursa Major stars near $B-V = 0.30$. Thus other spectral regions such as the EUV ($\lambda < 912$ Å) and soft X-ray regions must be used in searching for chromospheres and transition regions in the A stars.

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APPENDIX

LOW-RESOLUTION MEASUREMENTS OF THE N v DOUBLET

One diagnostic of the transition region that we have not tabulated in Table 4 is the flux in the N v doublet, which arises at a temperature of $\sim 2 \times 10^5$ K. This is because we are not convinced that the emission near 1240 Å is always N v. In HR 4867 (Fig. 5) there is a strong single line near 1240 Å that is likely to be due to N v. However, in the F stars 37 UMa, 78 UMa, and α Crv, as well as in the inactive star γ Lep, there is a broad emission feature just barely above the noise level near this wavelength that resembles a blend of two emission lines with mean wavelengths near 1234 and 1240 Å (with uncertainties of ~ 1.5 Å). The wavelength scale was determined from the position of the O I and C II resonance lines. The longer wavelength component coincides with N v (mean wavelength ~ 1240.5 Å), but there are no strong emission lines in the solar spectrum near 1234 Å (cf. Burton and Rideley 1970; Cohen 1981). Some of this emission may be

unresolved molecular bands or low-temperature lines. We note that all the stars in which this particular profile is seen are early- to mid-F stars. In 9 Pup, ξ Boo A, and other G stars, the feature appears to have two peaks centered at wavelengths ~ 1240 Å and 1245 Å. The latter peak may be due to the confluence of C I lines at 1243–1248 Å in the solar spectrum (Cohen 1981), while the former may be N v.

Determination of exactly which species are responsible for the complicated emission near $\lambda 1240$ will require high spectral resolution, high S/N observations. The mixture of high- and low-temperature lines may explain why the 1240 Å feature often behaves more like a low-temperature diagnostic (Basri, Laurent, and Walter 1984) than would be expected for N v. We therefore suggest that N v fluxes from low-dispersion spectra in the literature be viewed cautiously.

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