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# THE NARROW ULTRAVIOLET EMISSION LINES OF THE RED DWARF AU MICROSCOPII (dM1.6e)

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## ABSTRACT

We present the first high-dispersion, vacuum-ultraviolet (1150-3000 Å) observations of a red dwarf star—AU Microscopii (dM1.6e)—obtained with the *International Ultraviolet Explorer*. *Subject headings:* stars: chromospheres — stars: individual — ultraviolet: spectra

### I. INTRODUCTION

The red dwarfs are the smallest, coolest, faintest, least massive, but most common of normal main-sequence stars. At the same time, the dMe (H $\alpha$ -emission) subclass of the red dwarfs exhibits the largest median soft X-ray to bolometric luminosity ratio of any group of late-type stars (Johnson 1981; Vaiana *et al.* 1981). The enormous quiescent X-ray emission levels and sporadic flare outbursts of the dMe stars are thought to originate in large areas of intense magnetic activity analogous to solar coronal active regions and sunspots (Bopp 1974; Worden 1975; Kunkel 1975). Accordingly, the red dwarfs provide an important arena for exploring the response of cool stellar atmospheres to extremes of magnetic phenomena that rarely, if ever, are encountered on the Sun (cf. Golub 1983).

In this *Letter*, we report the first high-dispersion spectra of the chromospheric  $(6 \times 10^3 \text{ K})$  and higher temperature (up to  $10^5 \text{ K}$ ) emissions of a dMe star, AU Microscopii (GL 803; dM1.6e),<sup>4</sup> in the far-ultraviolet (1150–2000 Å) and middle-ultraviolet (2000–3000 Å) bands accessible to the *International Ultraviolet Explorer* (*IUE*) (Boggess *et al.* 1978).

#### II. OBSERVATIONS

AU Mic is one of the most luminous of lower mainsequence stars in C IV and soft X-ray emission (Linsky et al. 1982; Golub 1983). We therefore undertook a

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 $^{4}$ A discussion of the stellar parameters of AU Mic is provided by Linsky *et al.* (1982). We adopt their values here.

series of IUE echelle exposures of AU Mic in order to study the line shapes of the brightest emissions in the 1150-3000 Å region. We maneuvered IUE to AU Mic near the end of the NASA No. 2 shift on 1982 June 23 and obtained a 10 minute low-dispersion exposure with the LWR (2000-3000 Å) camera. Prior to and following the exposure, we measured the visual magnitude of AU Mic, to check for flare activity, utilizing the acquisition camera (the fine error sensor [FES]) in its fast-track mode with the target at the reference point. Next, we exposed an SWP (1150-2000 Å) echellogram, in 2 hr segments separated by FES magnitude measurements, through the VILSPA shift, the NASA No. 1 shift, and about 4 hr into the NASA No. 2 shift on June 24. A total of 18 hr exposure was accumulated on the SWP image. Finally, we utilized the remainder of the No. 2 shift to obtain a 4 hr high-dispersion exposure of the middle-ultraviolet region, also in 2 hr segments bracketed by FES magnitudes. The circumstances of the IUE exposures are summarized in Table 1.

During the periods of observation, we found no evidence for significant fluctuations in the optical light of AU Mic. The ultraviolet spectra therefore likely correspond to quiescent conditions in the outer atmosphere of the red dwarf.

Despite the length of the SWP exposure—one of the longest attempted with *IUE*—only a few emission lines are clearly visible in the far-ultraviolet spectrum: faint, extended emission wings of  $Ly\alpha$  on both edges of the saturated geocoronal core, and sharp features of C II  $\lambda$ 1336, C IV  $\lambda$ 1548, and He II  $\lambda$ 1640. Additional weak emissions, such as O I  $\lambda$ 1306, are visible in the extracted spectrum when it is smoothed with a five-point running mean to suppress high-frequency noise. The 4 hr LWR

L18

TABLE 1						
CATALOG OF <i>IUE</i> EXPOSURES						

Image	No. <sup>a</sup>	Dispersion	Date JD 2,445,000 + (mid-exposure)	Exposure Time (minutes)	
LWR	13552	low	144.37	10	
SWP	17291	high	144.80	1080 <sup>b</sup>	
LWR	13553	high	145.25	240 <sup>b</sup>	

<sup>a</sup>All exposures through  $10'' \times 20''$  aperture: SWP spectral range, 1150–2000 A; LWR spectral range, 2000–3000 Å.

<sup>b</sup>In 120 minute segments separated by FES visual magnitude measurements.

spectrum is overexposed at the core of the Mg II k line, well-exposed at the h line, and lightly exposed at the  $\lambda 2600$  multiplet of Fe II. The last appears as a broad, prominent feature in the low-dispersion LWR spectrum of AU Mic and other dMe stars (Linsky *et al.* 1982). The initial visual impression of the SWP and LWR echelle images is that the emission lines, with the exception of Ly $\alpha$ , are quite narrow. The Mg II doublet is especially striking in this regard.

We reduced the echelle spectra of AU Mic at the *IUE* Regional Data Analysis Facility in Boulder utilizing standard procedures (see Schiffer 1982). Profiles of prominent emission lines from the two images are illustrated in Figure 1. We measured line shape parameters (emission centroid, FWHM, and integrated intensity) by a least squares Gaussian technique, using error estimates based on the work of Landman, Roussel-Dupré, and Tanigawa (1982). The resulting parameters are listed in Table 2 and compared in Table 3 to representative values for quiet-chromosphere and active-chromosphere dwarfs of earlier spectral type (G-K) from Ayres *et al.* (1983).

#### III. DISCUSSION

For the sake of brevity, we limit our discussion to two aspects of the AU Mic spectra: the line shapes and the line intensities.

On the one hand, the resolved high-temperature emission lines are similar in shape to those of active and quiet dwarf stars of earlier spectral type (G–K): the lines are symmetric, narrow, and exhibit no large differential velocity shifts (see Ayres *et al.* 1983). Since the high-temperature lines like C IV probably are optically thin, or at worst barely optically thick, their widths must indicate unresolved motions in the  $10^5$  K layers of the stellar outer atmosphere. The empirical similarity in the amplitudes of these motions in the early-G to early-M dwarfs covering a wide range of chromospheric activity



FIG. 1.—Profiles of selected emission lines from the far-ultraviolet (1150–2000 Å) and middle-ultraviolet (2000–3000 Å) spectra of AU Microscopii (dM1.6e), smoothed with a five-point running mean. The ordinate is monochromatic flux measured at Earth with units compatible to those of the velocity scale of the abscissa. Cross-hatching below the zero line indicates saturated or extrapolated intensity transfer function (e.g.,  $\lambda$  2803) pixels, or reseau marks; # symbols designate prominent particle radiation events or blemishes; and  $\oplus$  and Sa denote geocoronal Ly $\alpha$  emission through the large and small apertures respectively. Vertical tick marks designate expected rest velocities for each feature (see Table 2). Despite the domination of the geocoronal emission in the 18 hr SWP spectrum, much of the unsaturated portion of the Ly $\alpha$  feature is genuinely stellar. The feature just shortward of Fe II  $\lambda$ 2599 is a weaker component of the same multiplet, and the long-wavelength shoulder on the Mg II  $\lambda$ 2803 profile is a blemish that appears in echelle order 82.

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Spectrum	Rest Wavelength <sup>a</sup> (Å)	$\frac{V_L}{(\mathrm{km}\mathrm{s}^{-1})}$	FWHM (km s <sup>-1</sup> )	$f_L$ (10 <sup>-13</sup> ergs cm <sup>-2</sup> s <sup>-1</sup> )
Н 1	1215.668	+24 <sup>b</sup>	380 <sup>b</sup>	$> 71 \pm 10^{b}$
N v	1238.821	$+15 \pm 8$	$52 \pm 18$	$1.9 \pm 1.3$
01	1306.029	$+7 \pm 5$	$66 \pm 28$	$1.2 \pm 1.0$
Сп	1335.708	$-2 \pm 3$	$59 \pm 8$	$1.7 \pm 0.3$
С і	1548.185	$+6 \pm 3$	$74 \pm 8$	$2.9 \pm 0.5$
	1550.774	$-10 \pm 3$	$51 \pm 5$	$1.3 \pm 0.3$
Не п	1640.4	$0 \pm 3$	$68 \pm 3$	$3.0 \pm 0.3$
Si 11	1808.012	$0 \pm 3$	$30 \pm 3$	$0.23 \pm 0.05$
	1816.928	$-1 \pm 3$	$36 \pm 3$	$0.58 \pm 0.10$
Fe II	2598.368	$-1 \pm 3$	$40 \pm 5$	$0.9 \pm 0.3$
	2599.395	$0\pm 3$	47 <u>+</u> 5	$1.9 \pm 0.3$
	2625.666	$0\pm 3$	$43 \pm 5$	$1.8 \pm 0.3$
	2628.287	$0\pm 3$	$58 \pm 5$	$1.4 \pm 0.3$
	2631.049	$+5 \pm 3$	$52 \pm 5$	$1.6\pm0.3$
Mg II	2795.528	$+7 + 1^{c}$	$47 + 1^{c}$	$12.3 + 0.5^{\circ}$
0	2802.705	+2 + 1	38 + 3	13.4 + 1.9

TABLE 2 MEASURED ULTRAVIOLET EMISSION-LINE PARAMETERS FOR AU MICROSCOPII

NOTES.-Line parameters determined by least squares Gaussian fits; error estimates indicate quality of fits; velocity scale was registered by subtracting the mean velocity of the prominent features in each echellogram (excluding H I, N v in SWP region; Fe II λλ2631.0, 2631.3, and Mg II  $\lambda$  2796 in LWR region); spectra were smoothed with five-point running mean prior to measuring, with exception of Mg II h and k.

 $^{a}\lambda < 2000$ ; Kelly and Palumbo 1973.  $\lambda > 2000$ ; Kurucz and Peytremann 1975.

<sup>b</sup>Gaussian profile was fitted to extreme outer wings of stellar Ly $\alpha$  emission, beyond saturated geocoronal core. The flux cited probably is a lower limit, and the  $V_L$  and FWHM are quite uncertain.

<sup>c</sup>Uncertain owing to overexposure of line core.

Transition	λ (Å)	Approx. T <sub>max</sub> (K)				G0–K2 Dwarfs <sup>a</sup>				
			AU MIC (dM1.6e)			Active		Quiet		
			FWHM <sup>b</sup> (km s <sup>-1</sup> )	$\frac{F_L}{(10^4 \text{ cgs})}$	$f_L/l_{\rm bol}$ (10 <sup>-7</sup> )	FWHM <sup>b</sup> (km s <sup>-1</sup> )	$\frac{F_L}{(10^4 \text{ cgs})}$	$f_L/l_{\rm bol}$ (10 <sup>-7</sup> )	$\frac{F_L}{(10^4 \text{ cgs})}$	$f_L/l_{bol}$ (10 <sup>-7</sup> )
Mg II	2803	6,000	$29 \pm 3$	56	740	52 ± 2	290	640	79	170
Si II	1817	10,000	$36 \pm 3$	1.3	17	$29 \pm 6$	6.0	13	1.4	2.9
С п	1336	30,000	$59 \pm 8$	3.7	49	49 ± 6	2.1	4.8	0.3	0.7
Неп	1640		68 + 3	6.5	86	56 + 7	2.8	4.8	0.03	0.06
С і	1548	$1 \times 10^{5}$	74 + 8	6.2	83	49 + 10	3.0	6.5	0.4	0.8
Soft X-rays	4-80	$\geq 10^6$		1600 <sup>c</sup>	22,000 <sup>c</sup>		180	400	2.6	5.5

TABLE 3 COMPARISON OF FLUXES AND LINE SHAPES

NOTES.  $-F_L$  is the surface flux, and  $f_L/l_{bol}$  is the (dimensionless) ratio of the line flux measured at Earth to the bolometric luminosity of the star also measured at Earth in units commensurate to  $f_L$ . Therefore,  $f_L/l_{bol}$  is the fraction of the stellar luminosity that is provided by the radiative power loss in the particular spectral line.

<sup>a</sup>From Ayres et al. 1983. Standard deviations for UV line fluxes  $\leq 0.2$  dex; for soft X-rays  $\leq 0.5$  dex. Active dwarfs are  $\chi^1$ 

Ori (G0 V),  $\xi$  Boo A (G8 V), and  $\epsilon$  Eri (K2 V). Quiet dwarfs are  $\alpha$  Cen A (G2 V) and  $\alpha$  Cen B (K1 V). <sup>b</sup>Only Mg II is corrected for instrumental broadening (FWHM<sub>LWR</sub>  $\approx 25$  km s<sup>-1</sup>); SWP instrumental width is probably close to FWHM (Si II), since that feature is narrow in the solar spectrum. Line widths for the active and quiet dwarfs are similar, and a mean FWHM is given.

<sup>c</sup>X-ray flux from Helfand and Caillault 1982.

L20

levels is remarkable and must be addressed by proposed heating mechanisms for the stellar transition region. On the other hand, the Mg II h line emission core is very much narrower than those of the hotter dwarfs. On this basis, we propose that the Mg II width-luminosity relation (cf. Weiler and Oegerle 1979), like the so-called Wilson-Bappu effect (Wilson and Bappu 1957) for the Ca II lines (see Giampapa et al. 1981), extends at least to the early-M portion of the lower main sequence. The factor of 2 width decrease in Mg II h between typical G-K dwarfs and AU Mic is consistent with that predicted by the generalized Wilson-Bappu relation (see Weiler and Oegerle 1979), given the 4-5 mag difference between the absolute visual magnitudes of middle-G and early-M dwarf stars. Accordingly, explanations of the width-luminosity relations in Ca II and Mg II (cf. Ayres 1979) must address the extraordinary range in visual magnitudes over which the systematic broadening mechanism for the very optically thick resonance lines operates.

While the X-ray surface flux of AU Mic is an order of magnitude larger than that typical of the active G-K dwarfs (see Table 3), and the transition-region line surface fluxes are a factor of 2 larger, the Mg II and Si II fluxes surprisingly are somewhat smaller than those of the quiet G-K dwarfs. Indeed, only when compared with the small bolometric luminosity of the red dwarf do the chromospheric emissions of AU Mic merit the description "active." Furthermore, the estimated H I Ly $\alpha$ emission of the red dwarf (see Table 2) significantly exceeds that of the Mg II doublet, as does the H $\alpha$  flux (Linsky et al. 1982). A very different situation is encountered among the earlier type dwarfs: the Ly $\alpha$  emission always is many times smaller than that of h and k(e.g., Linsky and Ayres 1978), and H $\alpha$  is strongly in absorption.

Finally, like Ly $\alpha$ , the He II  $\lambda$ 1640 Balmer- $\alpha$  emission appears to share the large enhancement of X-ray normalized and surface fluxes.

## IV. SUMMARY AND CONCLUDING REMARKS

Line widths of high-temperature species like C II, He II, and C IV in *IUE* echelle spectra of the red dwarf AU Mic are very similar to those of active (and quiet) dwarfs of earlier spectral type, including the Sun itself. It is possible, then, that the kinematics and excitation mechanisms of the red dwarf outer atmosphere are basically similar to those of solar magnetic active regions. Even the Mg II resonance lines, which are a factor of 2 narrower in AU Mic than in earlier type dwarfs, provide additional corroboration that the red dwarf chromosphere is governed by essentially the same physical mechanisms as those of the G and K dwarfs. In particular, the narrowing of the optically thick Mg II features is predicted by the Wilson-Bappu effect, one of the major unifying themes of late-type chromospheres. Other differences, like the enhancement of H I Ly $\alpha$  and He II B $\alpha$  emission, perhaps due to X-ray heating of the lower atmosphere by the bright corona (cf. Cram 1982; Schindler et al. 1983, and references therein), can be interpreted as exaggerations of fundamentally solar-like phenomena and not the result of entirely new physical processes (cf. Golub 1983). Despite the solace one might find in the plausible extension of the solar-stellar connection to the lower main sequence, one nevertheless should not lose sight of how extreme the coronal properties of the dMe stars truly are: the dim, red dwarf AU Mic is a thousand times more luminous in its 0.1-4 keV X-ray emission than the Sun.

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## REFERENCES

- Ayres, T. R. 1979, Ap. J., 228, 509. Ayres, T. R., Linsky, J. L., Simon, T., Jordan, C., and Brown, A. 1983, Ap. J., submitted.

- 1983, Ap. J., submitted.
  Boggess, A., et al. 1978, Nature, 275, 377.
  Bopp, B. W. 1974, M. N. R. A. S., 46, 108.
  Cram, L. E. 1982, Ap. J., 253, 768.
  Giampapa, M. S., Worden, S. P., Schneeberger, T. J., and Cram, L. E. 1981, Ap. J., 246, 502.
  Gliese, W. 1969, Catalog of Nearby Stars, Veröff. Astr. Rechen-Inst., No. 22
- No. 22
- Golub, L. 1983, in IAU Colloquium 71, Activity in Red-Dwarf Stars, ed. P. B. Byrne and M. Rodono (Dordrecht: Reidel), in press (CFA preprint No. 1704). Helfand, D. J., and Caillault, J. P. 1982, *Ap. J.*, **253**, 760.

- Johnson, H. M. 1981, Ap. J., 243, 234.
  Kelly, R. L., and Palumbo, L. J. 1973, "Atomic and Ionic Emission Lines Below 2000 Angstroms," NRL Report 7599.

- Kunkel, W. E. 1975, in IAU Symposium 67: Variable Stars and Stellar Evolution, ed. V. E. Sherwood and L. Plaut (Dordrecht:
- Reidel), p. 15. Kurucz, R. L., and Peytremann, E. 1975, "A Table of Semiempiri-"*Curitheonian An Obs. Spec. Rept.*, No. 362. cal gf Values," Smithsonian Ap. Obs. Spec. Rept., No. 362. Landman, D. A., Roussel-Dupré, R., and Tanigawa, G. 1982, Ap.
- J., 261, 732
- Linsky, J. L., and Ayres, T. R. 1978, Ap. J., 220, 619.
- Linsky, J. L., Bornmann, P. L., Carpenter, K. G., Wing, R. F., Giampapa, M. S., Worden, S. P., and Hege, E. K. 1982, Ap. J., 260, 670.
- III. 1982, "Data Analysis Procedures for the Schiffer, F. H., International Ultraviolet Explorer Regional Data Analysis Facilities: Part 1: Guidelines for Determining the Wavelengths and Fluxes from Extracted Spectra," Computer Sciences Corporation TM-82/6207.

No. 1, 1983

Weiler, E. J., and Oegerle, W. R. 1979, *Ap. J. Suppl.*, **39**, 537. Wilson, O. C., and Bappu, M. K. V. 1957, *Ap. J.*, **125**, 661. Worden, S. P. 1975, Ph.D. thesis, University of Arizona.

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