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SIGMA GEMINORUM (K1 III + ?): VARIABILITY OF THE ULTRAVIOLET EMISSION LINES NEAR CONJUNCTION

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ABSTRACT

We report far-ultraviolet *IUE* echelle spectra of the moderate-period RS CVn system σ Geminorum (K1 III + ?). Despite the location of the red giant primary of σ Gem in a portion of the H-R diagram where cool stellar winds are common, we find no evidence for circumstellar absorption features or blueward asymmetries in the chromospheric O I (or Mg I and Mg II) emission cores. However, observations on two consecutive days indicate significant changes in the profiles of high-excitation species, such as Si IV and C IV, which likely were produced by the rotation off of the visible hemisphere of the primary of a large-scale magnetic active region identified in a previous photometric study.

Subject headings: stars: chromospheres — stars: late-type — ultraviolet: spectra

I. INTRODUCTION

The remarkably intense far-ultraviolet and soft X-ray emissions of the RS Canum Venaticorum systems (Hall 1978) are thought to derive from vigorous surface magnetic activity resulting from the interaction of convection and the rapid synchronous rotation of these tidally locked binaries (see, e.g., Ayres and Linsky 1980 and references therein). Here we report high-dispersion, far-ultraviolet spectra of the $19^{\rm d}.6$ single-line spectroscopic binary Sigma Geminorum (=HD 62044 = HR 2973; K1 III + ?), the first such observations of an RS CVn system containing a red giant.

II. OBSERVATIONS

We observed σ Gem with the *International Ultraviolet Explorer* (Boggess *et al.* 1978) on two consecutive days, 1982 May 10 and 11, bracketing the times of conjunction (single-line phase) predicted by the ephemerides of Luyten (1936) and Harper (1935). A catalog of the *IUE* exposures is provided in Table 1.

We reduced the two SWP (1150–2000 Å) and six LWR (2000–3000 Å) echellograms at the *IUE* Regional Data Analysis Facility in Boulder using standard procedures (see Schiffer 1982). We spliced together the graded sequences of three LWR images by retaining at each wavelength the flux from the longest exposure which was not beyond the top level of the Intensity Transfer Function.

We measured the stationary interstellar absorption components in the two LWR composite spectra of the Mg II $\lambda\lambda2796(k)$, $2803(h)$ lines. The inferred ISM velocity, $+17 \pm 3$ km s^{-1}, is compatible with the value predicted by the empirical relationship of Böhm-Vitense (1981).[3] The velocities of the well-exposed Mg I $\lambda2852$ and Mg II emission cores suggest that the epochs of observation were close to phases 0.54 and 0.59 on 1982 May 10 and 11, respectively, implying an orbital period $P = 19^{\rm d}.604$ with the Luyten (1936) T_0. The inferred period is midway between the values proposed by Harper (1935) and Luyten. We therefore adopted the ephemeris of Table 1, based on the revised period and the Luyten T_0.

The appearance of the Mg I and Mg II features on the two days is illustrated in Figure 1, and selected portions of the far-ultraviolet emission spectra are depicted in Figure 2. The prominent features were measured using a least squares Gaussian fitting technique, and the results are given in Table 2. Errors were estimated using the algorithms of Landman, Roussel-Dupré, and Tanigawa (1982). The rms deviation of the fitted Gaussian from the observed profile provided an empirical measure of the noise level.

III. DISCUSSION

At $V-R = 0.92$ (Johnson *et al.* 1966), the σ Gem primary lies in the portion of the red giant branch where high-temperature emissions, like C IV and soft X-rays, are rare among single stars (Linsky and Haisch 1979; Simon, Linsky, and Stencel 1982; Ayres *et al.* 1981), but cool ($\lesssim 10^4$ K) winds with significant mass loss rates are common (e.g., Reimers 1975; Stencel and Mullan 1980). The figures and Table 2 reveal that the ultraviolet emission lines of σ Gem are bright and broad like those of the $2^{\rm d}.8$ RS CVn system

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[3] The cited error (1 σ) is the quadratic sum of the standard error of the mean of the four measurements (two each, h and k), the ± 2.5 km s^{-1} internal consistency of the LWR wavelength scale (Holm 1982), and the ± 1.4 km s^{-1} *minimum* uncertainty in the centering of the target in the large aperture.

TABLE 1

CATALOG OF OBSERVATIONS

Image No.[a]	JD 2,445,000+ (mid-exposure)	Phase[b]	V_1[c]	Exposure Time (minutes)
SWP 16943	100.008	0.528	39.8	420
LWR 13216, 13217, 13218	100.178, 100.231, 100.266	0.54	37.5	60, 25, 10
SWP 16944	101.012	0.579	29.5	425
LWR 13226, 13227, 13228	101.183, 101.238, 101.270	0.59	27.5	60, 25, 10

[a] All exposures through the 10″ × 20″ aperture in the echelle mode. SWP spectral range 1150–2000 Å; LWR spectral range 2000–3000 Å.

[b] JD = 2,418,957.53 ± 0.07 + 19.604E; phase 0 is the conjunction with the K giant in front. The time of conjunction and its uncertainty are based on the T_0 cited by Luyten (1936).

[c] Predicted velocity of primary in km s^{-1}: $V_1 = \gamma + K_1 \sin 2\pi E$; $\gamma = 45.8$, $K_1 = 34.2$ (Batten, Fletcher, and Mann 1978).

V711 Tauri = HR 1099 (Ayres and Linsky 1982), are relatively symmetric (except for Lyα and Mg II h and k, which are affected by interstellar absorption), and are near the rest velocity of the K giant, or perhaps slightly redshifted. Indeed, there is no evidence for blueshifted circumstellar absorption components or blueward asymmetries in the high signal-to-noise profiles of the O I λ1305 triplet, or in the Mg II h and k lines, like those seen in the "hybrid" spectrum yellow supergiants α Aqr and β Aqr (Hartmann, Dupree, and Raymond 1980), and in the red giant Arcturus (α Boo, K2 III). The latter is a near neighbor to σ Gem in the Hertzsprung-Russell diagram but exhibits no C IV or soft X-ray emission to very small upper limits (Ayres, Simon, and Linsky 1982) and rotates much more slowly than σ Gem since it is a single star.

However, many of the line profiles in the far-ultraviolet spectrum of σ Gem appear to have changed between the two sets of observations. In particular, the emissions formed

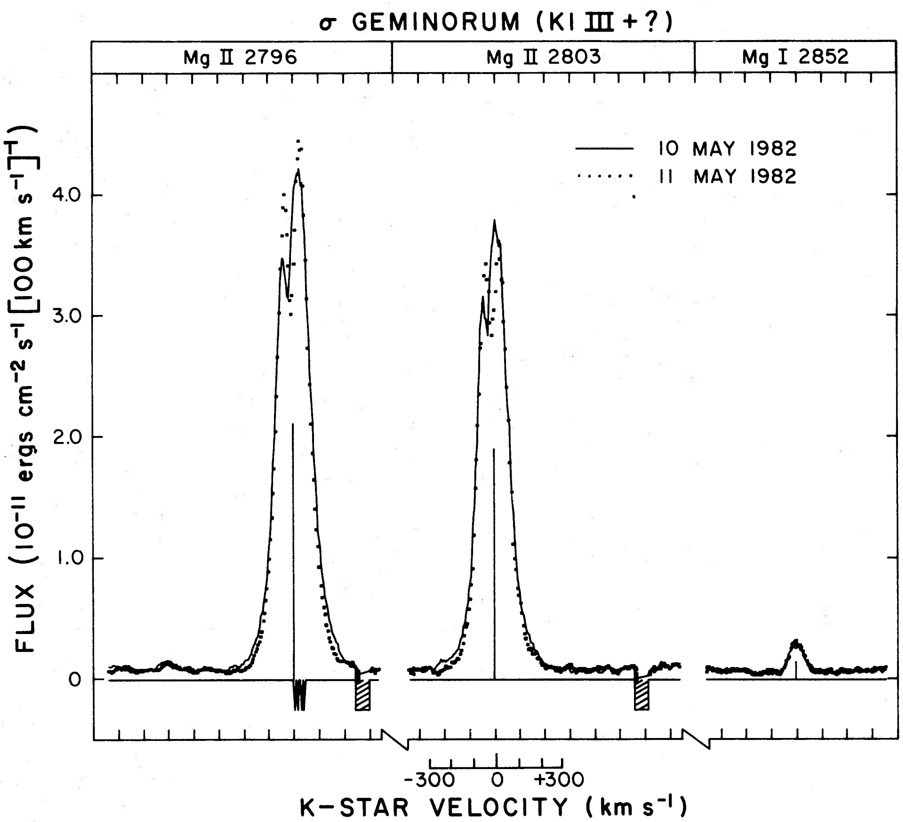

FIG. 1.—The resonance lines of neutral and ionized magnesium from the middle-ultraviolet spectrum of σ Gem, observed on two consecutive days in 1982 May. The profiles are superpositions of three independent LWR images that span a factor of 6 in exposure time. The monochromatic flux scale of the ordinate has units compatible with those of the velocity scale of the abscissa. The profiles have been smoothed with a five-point running mean and registered to the velocity frame of the active K type giant of the system. Vertical tick marks denote the rest velocities of the emission lines in that reference frame. Underscoring below the zero flux line indicates portions of the spectrum affected by overexposure or reseau marks. The weak central reversals in the h and k lines are interstellar, and their apparent shifts are an artifact of the orbital motion of the primary star.

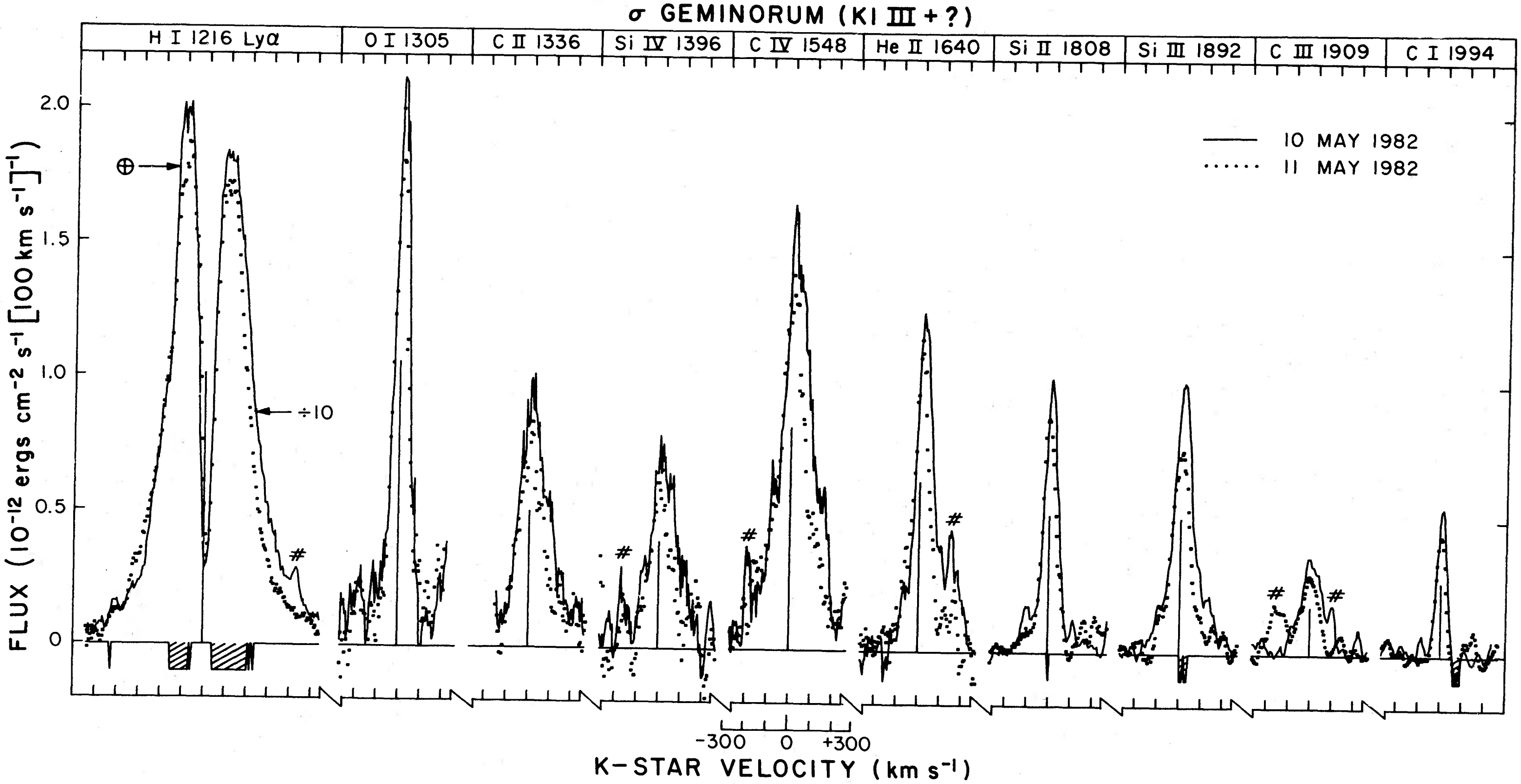

FIG. 2.—Selected emission lines from the far-ultraviolet spectrum of σ Gem, depicted in the same manner as Fig. 1. In addition, cosmic-ray spikes or blemishes are indicated by "#" symbols, and the location of the geocoronal hydrogen emission is denoted by a "$\oplus$" symbol. Note, also, that the stellar Lyα emission has been scaled down by a factor of 10.

TABLE 2

GAUSSIAN PROFILE PARAMETERS

Spectrum	Wavelength[a] (Å)	V_0	FWHM	f_L	V_0	FWHM	f_L
		Phase 0.53			Phase 0.58		
H I	1215.668[b]	27	380	85	3	350	81
N V	1238.821	17	170	1.6	22	140	1.1
O I	1304.858	12	80	1.6	4	80	1.4
	1306.029	8	75	1.6	3	75	1.5
C II	1335.708	21	160	1.3	2	110	0.9
Si IV	1393.755	17	170	1.1	13	150	0.7
C IV	1548.185	30	190	2.6	9	160	1.9
	1550.774	38	170	1.6	6	130	1.0
He II	1640.4	25	87	1.1	8	100	1.0
Si II	1808.012	10	68	0.75	1	65	0.63
	1816.928	5	65	1.35	−3	72	1.27
	1817.451	−2	61	0.63	−12	73	0.56
Si III]	1892.030	15	89	0.97	4	85	0.73
C III]	1908.734	6	128	0.45	−1	111	0.32
C I]	1993.620	5	50	0.30	−1	45	0.24
		Phase 0.54			Phase 0.59		
Mg II	2795.528[b]	+4	141	69	+3	131	66
	2802.705[b]	−3	124	55	−2	121	51
Mg I	2852.126	−0	72	1.9	+2	64	1.7

NOTES.—V_0 is the emission centroid velocity (in the reference frame of the primary) in km s^{-1}; FWHM is the full width at half-peak intensity in km s^{-1}; and f_L is the line flux at Earth in 10^{-12} ergs cm^{-2} s^{-1} (Cassatella, Ponz, and Selvelli 1981 calibration, continuum version). Estimated errors ($\pm 1\ \sigma$) in the Gaussian parameters, based on Landman, Roussel-Dupré, and Tanigawa 1982, are (same units as above): Lyα (2, 4, 2); N V–C IV (6, 15, 0.3); He II–Si II (2, 3, 0.1); Si III]–C I] (2, 3, 0.03); Mg II (1, 2, 2); Mg I (2, 4, 0.2).

[a] $\lambda < 2000$: (Kelly and Palumbo 1973; vacuum wavelengths); He II λ1640 is an unresolved blend of several components. $\lambda > 2000$: (Kurucz and Peytremann 1975: air wavelengths).

[b] Interstellar absorption cores ignored in fitting procedure.

at temperatures between 3×10^4 K (C II) and 2×10^5 (N V) were a factor of 1.42 ± 0.05 times brighter on 10 May than on 11 May, and the far-ultraviolet, low-excitation lines of O I, Si II, and C I were a factor of 1.11 ± 0.03 brighter. Nevertheless, the middle-ultraviolet lines of Mg I and Mg II (which were a factor of 1.06 ± 0.04 times brighter) appear not to have changed significantly between the 2 days of observations.[4]

Although we cannot rule out the possibility that the far-ultraviolet profile changes were produced by a stellar flare, a more likely explanation is that a stellar "active region" was on or near the receding limb of the K giant on May 10 and had rotated over the limb by May 11. A similar model has been proposed to account for profile variations in high-dispersion SWP spectra of HR 1099 (Ayres and Linsky 1982), and to explain the bimodal phase dependence of the C IV emission of the $6^d.7$ system II Peg (Marstad *et al.* 1982). Indeed, Fried *et al.* (1983), in a recently completed 5 year photometric study, identified two persistent "starspots" on the σ Gem primary. The authors' photometric ephemeris predicts that region B had just crossed over the receding limb on May 10 and was well behind the limb the following day, while the other spot (A) was in full view on both days near the opposite limb. If, like solar active regions, arcades of magnetic loops having enhanced high temperature emissions overlie the photospheric starspot, the longward asymmetry of the Si IV and C IV profiles on 10 May could be explained by the $v \sin i \lesssim 40$ km s^{-1} ($= v_{\rm synch}$) Doppler shift of spot B at the limb.

An important test of the model would be a high-dispersion *IUE* monitoring program covering a number of projected orientations of spots A and B. In particular, when the spots rotate *onto* the visible hemisphere from behind the limb, are *blueshifted* emission enhancements seen in the high-excitation emission lines? The advantage of high-dispersion observations, over the simple monitoring at low dispersion of the line fluxes, is that the radial velocity of the emission enhancement can be used to more tightly constrain the latitude and longitude of the active region and thereby test the physical association of the far-ultraviolet "activity" with the optically dark starspots. An important subsidiary question is: Why did the high-temperature lines exhibit a significantly larger change in flux than the low-excitation species (cf. Ayres, Marstad, and Linsky 1981)? High-dispersion measurements of emission enhancements at different projected velocities in the line profiles provide an opportunity to estimate the C IV/Mg II contrast *within* the active regions themselves.

Concerning the nature of the unseen secondary of σ Gem, the lack of significant continuum emission in the far-ultraviolet region and the lack of a perceptible influence on the optical spectrum suggest that the secondary is a cool main-sequence star, probably a G or K. If so, the companion very likely does not contribute significantly to the ultraviolet and X-ray emission owing both to its small surface area and its comparatively long rotational period (if the secondary rotates synchronously) for its inferred luminosity class.

Finally, we emphasize that the primary of σ Gem is a striking anomaly among the luminosity class III red giants: high-temperature emissions are quite prominent in its far-ultraviolet spectrum, and there is no evidence for the cool, low-velocity wind that is typical of single red giants like Arcturus. The dichotomy in far-ultraviolet emissions and wind properties between σ Gem and Arcturus almost certainly is due to very different configurations and strengths of surface magnetic fields on the two evolved stars, very likely as a result of their vastly different rotation rates. The quantitative investigation of that dichotomy should be an important goal in the exploration of the effects of stellar evolution and binary environment on chromospheric and coronal activity in the red giant branch. In particular, the binary nature of σ Gem may be significant only insofar as it induces rapid rotation in a red giant that otherwise would be a slow rotator, and magnetically inactive, if single.

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[4] For each excitation group, the flux-weighted mean and standard error were calculated for the fluxes of 10 May/11 May. The number of samples were 8, 6, and 3, respectively. The uncertainty for each group is the quadratic sum of the standard error of the mean and an estimate of the high-dispersion photometric error based on low-dispersion repeatability tests in broad bands (Holm 1982), scaled according to the square root of the effective areas of the camera tube ($A_{\rm low}/A_{\rm high} \approx 1$ for the SWP groups; ≈ 2 for the LWR group).

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