A SPECTROSCOPIC STUDY OF YY GEMINORUM

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ABSTRACT

An extensive series of high and moderate-dispersion spectrograms of the eclipsing, double-lined spectroscopic binary YY Geminorum (spectral type dM1e) has been obtained. Radial-velocity measures show a systematic difference in the velocities derived from absorption and emission lines, confirming earlier results of Struve and Zeberg. A coudé plate obtained during a flare shows the presence of a narrow, central emission component at H δ and H γ . This is interpreted as due to material at the inner Lagrangian point, temporarily ionized by flare light.

From spectroscopic observations of flares and quiescent emission line variations, it is possible to map the location and extent in longitude of the flare-producing and emission-line-enhancing regions on each component of YY Gem. The regions are shown to extend from about 20° to about 60° in longitude, in good agreement with the longitudinal extents of starspots recently calculated for BY Dra and CC Eri by Bopp and Evans. Flare-producing regions on YY Gem can develop and disappear on time scales as short as 1 month.

Subject headings: eclipsing binaries — flare stars — late-type stars — stars, individual

I. INTRODUCTION

The eclipsing, double-lined spectroscopic binary YY Geminorum (Castor C; $P = 0.8142822$) has been known to be a remarkable system since the work of Joy and Sanford (1926). Both components are classified dM1e (Joy and Abt 1974), with the Balmer lines and the Ca II H and K lines visible in emission. Marked variations in the relative strengths of the two components of the Balmer and H and K lines have been seen (Joy and Sanford 1926; Herbig, quoted in Kron 1952). However, in two other investigations (Struve 1952; Struve and Zeberg 1959), evidence for only small, irregular changes in the relative intensities of the hydrogen emission components was found. A photoelectric study by Kron (1952) found distortions in the light curve that could not be explained in terms of the geometrical properties of the eclipses. Kron suggested that these secondary variations might be explicable in terms of patchy bright or dark regions on the stellar surface—"starspots."

Three separate spectroscopic orbital determinations have been made. That of Joy and Sanford found $M_1/M_2 = 1.1$. Later work by Struve, Herbig, and Horak (1950) and Struve and Zeberg (1959) gave equal masses for the components. Recently, both components of YY Gem have been shown to exhibit flare activity (Moffett and Bopp 1971).

The new information regarding the flare characteristics of YY Gem offers further insight into the nature of the emission-line variability and the secondary light variations. Accordingly, an extensive series of spectroscopic observations was obtained at McDonald Observatory during 1971–1972. The aim of the program was twofold: first, to redetermine the orbital parameters, and second, to investigate emission-line variability during both flares and quiescent intervals.

II. OBSERVATIONS

The data are of three types: coudé spectra in the blue (dispersion $18 \text{ \AA mm}^{-1}$); moderate-dispersion Cassegrain image-tube spectra near H α ($28 \text{ \AA mm}^{-1}$); and low-dispersion image tube spectra in the blue ($150 \text{ \AA mm}^{-1}$).

All coudé spectra were obtained using C-camera on the 82-inch (207-cm) Struve reflector. The region $\lambda\lambda 3700\text{--}4500$ was recorded on baked Kodak type IIaO emulsion. With a single exception, all exposures were of approximately 1 hour's duration. During 1971 March, a series of several dozen spectra was obtained at the Cassegrain focus of the 107-inch (272-cm) reflector using the Meinel spectrograph and Carnegie S20 image tube. These spectrograms cover the wavelength region $\lambda\lambda 5900\text{--}6700$; each multiply trailed exposure took ~ 8 minutes. The low-dispersion spectrograms were obtained with the UVITS spectrograph and Westinghouse WL30677 image tube at the Cassegrain focus of the Struve reflector. These singly trailed spectra cover the wavelength region $\lambda\lambda 3800\text{--}5600$, each exposure taking ~ 5 minutes. With the exception of coudé spectra obtained in 1971 February, all the data were obtained while YY Gem was being monitored for flares by T. J. Moffett with a high-speed photometer on the 36-inch (91-cm) reflector at McDonald.

Thirty-five coudé spectra had lines sufficiently unblended for radial velocity measures. These plates were measured on the Grant oscilloscope measuring machine at the Johnson Space Center, Houston, Texas. The emission and absorption lines listed by Struve and Zeberg were used, though at certain phases several of the absorption lines had to be omitted due to blending. The H δ and H γ emission lines were also measured on well-exposed spectra. To study emission-

TABLE 1
Radial Velocities of YY Gem

Plate	HJD 2440000+	Phase	Radial Velocity (km s ⁻¹)				O-C (km s ⁻¹)			
			PRI		SEC		PRI		SEC	
			Em.	Abs.	Em.	Abs.	Em.	Abs.	Em.	Abs.
7118	0988.819	0.8418	+105.6	+121.8	- 96.9	- 86.1	+ 3.2	+16.8	+ 1.9	+11.3
7145	0991.858	0.5739	+ 51.9	+ 39.5	- 50.4	- 63.1	- 3.2	-20.2	+ 2.0	-14.7
7154	0992.792	0.7209	+117.6	+132.9	-122.6	-100.3	- 2.3	+11.1	- 6.5	+15.3
7155	0992.876	0.8241	+113.8	+135.8	-113.2	-116.8	+ 4.7	+24.4	- 7.8	-12.5
7172	0995.741	0.3425	-100.2	- 92.2	+101.9	+131.4	+ 0.1	- 3.1	+ 1.6	+18.7
7173	0995.796	0.4100	- 64.5	- 61.8	+ 67.3	+ 96.2	- 0.6	- 7.5	+ 2.7	+21.2
7188	0996.784	0.6234	+ 81.8	+ 86.6	- 76.0	- 69.5	- 3.8	- 2.4	+ 6.4	+10.5
7189	0996.844	0.6971	+116.2	+124.6	-109.2	-113.7	+ 0.9	+ 7.2	+ 2.4	- 2.9
7209	0998.802	0.1016	- 68.2	- 56.3	+ 68.2	+ 82.2	+ 3.0	+ 5.0	- 3.6	- 0.4
7210	0998.848	0.1581	- 97.2	- 97.5	+103.3	+116.0	+ 3.3	- 8.2	+ 2.7	+ 3.0
7223	0999.827	0.3604	- 94.8	- 85.1	+ 95.8	+117.9	- 2.7	- 3.7	+ 3.4	+13.6
7644	1282.802	0.8751	+ 91.3	-	- 72.3	-	+ 4.8	-	+10.9	-
7645	1282.849	0.9328	+ 66.0	-	- 49.7	-	+15.5	-	- 1.9	-
7648	1282.989	0.1047	- 66.3	-	+ 71.7	-	+ 6.8	-	- 2.0	-
7658	1285.833	0.5974	+ 72.3	-	- 61.3	-	+ 1.9	-	+ 6.1	-
7659	1285.879	0.6539	+ 98.6	+112.3	- 94.8	- 84.0	- 1.9	+ 9.0	+ 2.2	+11.5
7660	1285.923	0.7079	+124.4	+108.9	-113.5	- 86.4	+ 6.7	-10.9	+ 0.4	+26.9
7661	1285.968	0.7632	+124.0	+133.6	-120.7	-	+ 2.5	+10.2	- 3.0	-
7674	1288.782	0.2190	-127.0	-	+114.8	-	- 9.2	-	- 2.8	-
7675	1288.828	0.2755	-119.3	-	+123.7	+107.4	- 0.7	-	+ 5.3	-24.3
7678	1289.869	0.5539	+ 29.8	-	- 29.8	-	-11.3	-	+ 8.8	-
7686	1292.754	0.0969	- 72.3	-	+ 65.5	-	- 4.0	-	- 3.5	-
7687	1292.800	0.1534	- 95.4	-	+ 94.5	-	+ 3.1	-	- 4.1	-
7688	1292.845	0.2086	-122.2	- 96.2	+112.7	+139.1	- 6.1	+ 8.1	- 3.2	+10.0
7689	1292.890	0.2639	-117.7	-109.8	+120.6	+126.5	+ 2.0	- 2.1	+ 1.2	- 6.3
7690	1292.939	0.3241	-113.7	-100.5	+105.7	+136.3	- 6.5	- 4.7	- 1.5	+16.4
7691	1292.965	0.3560	- 87.8	- 78.0	+ 78.0	+ 94.6	+ 6.5	+ 5.4	-16.1	-11.9
7713	1343.661	0.6145	+ 74.6	-	- 79.8	-	- 6.1	-	- 2.3	-
7714	1343.707	0.6710	+105.2	-	-108.9	-	- 2.2	-	-5.2	-
7715	1343.754	0.7287	+114.7	+131.7	-126.2	- 85.1	- 6.2	+ 9.0	- 9.2	+31.4
7718	1345.683	0.0977	- 75.6	- 62.9	+ 60.6	+ 73.6	- 6.8	- 3.9	- 8.8	- 6.5
7719	1345.739	0.1665	-102.8	-	+ 99.6	-	+ 1.0	-	- 4.3	-
7720	1348.689	0.7893	+112.2	+110.8	-124.4	-115.0	- 6.1	- 9.5	- 9.9	- 1.1
7721	1348.768	0.8863	+ 77.1	-	- 82.1	-	- 3.1	-	- 5.1	-
7722	1348.815	0.9440	+ 42.1	-	- 38.9	-	- 0.5	-	+ 1.2	-

line variations, microdensitometer tracings were made of all the unblended coude spectra using the Tull microdensitometer at the University of Texas at Austin.

III. SPECTROSCOPIC ORBIT

We list the radial velocity measures in table 1. The computer program of Wolfe, Horak, and Storer (1967) was used to solve for the orbital elements of the system. The period and epoch have been taken from van Gent (1931). The formal solution indicated a small (~ 0.01) eccentricity. Using the arguments of Lucy and Sweeney (1971), we find this eccentricity not significant. The final solution assumes the orbit to be circular.

We list the orbital elements in table 2; the radial velocity curves are shown in figure 1. It should be noted that the terms "primary" and "secondary" are, strictly speaking, ambiguous. Emission- and absorption-line solutions yield different "primaries." To avoid confusion, we adopt Struve and Zeberg's convention: the primary is defined as the star eclipsed at $\phi = 0.0$, where phases are reckoned from van Gent's period and epoch.

No substantial difference is found between our solution and that of Struve and Zebergs. However, the systematic difference in γ -velocity between absorption and emission lines, suspected by Struve and Zebergs, is confirmed by our more extensive data. We find a difference $V(\text{abs}) - V(\text{em}) = +7 \pm 2$ km s⁻¹. The origin of this velocity difference is unclear.

TABLE 2
ORBITAL ELEMENTS OF YY GEMINORUM
($P = 0.8142822$ days, $T_0 = 2424989.1169$, $e = 0.0$ [assumed])

Emission	Absorption
$\gamma = 0.91 \pm 0.57$ km s ⁻¹ (m.e.)	$\gamma = 7.82 \pm 2.50$ km s ⁻¹ (m.e.)
$K_1 = 121.04 \pm 1.05$ km s ⁻¹	$K_1 = 115.96 \pm 3.24$ km s ⁻¹
$K_2 = 118.98 \pm 1.02$ km s ⁻¹	$K_2 = 125.48 \pm 3.46$ km s ⁻¹
$a_1 \sin i = 1.355 \pm 0.012 \times 10^6$ km	$a_1 \sin i = 1.298 \pm 0.036 \times 10^6$ km
$a_2 \sin i = 1.332 \pm 0.011 \times 10^6$ km	$a_2 \sin i = 1.405 \pm 0.048 \times 10^6$ km
$M_1 \sin^3 i = 0.580 \pm 0.006 M_\odot$	$M_1 \sin^3 i = 0.616 \pm 0.025 M_\odot$
$M_2 \sin^3 i = 0.590 \pm 0.006 M_\odot$	$M_2 \sin^3 i = 0.570 \pm 0.020 M_\odot$

FIG. 1.—Orbital elements solution of YY Gem. Curves represent computed radial velocities from emission-line solution: dots, emission-line observations; open circles, absorption-line observations. Phase from van Gent (1931).

Struve and Zeberg suggested that this difference was the result of an isotropic prominence field moving outward in all directions from each component. There is evidence, however, that a significant portion of the emission intensity of YY Gem is localized in disturbed regions (Kron 1950 and below). If such is the case, we would expect the velocity behavior of the emission lines to be considerably more complex.

IV. CIRCUMSTELLAR MATERIAL

Coudé spectrogram 7154, obtained at binary phase 0.721, shows the blueshifted secondary emission to be markedly stronger than the emission from the redshifted primary. In addition, the $\lambda 3905$ line of Si I can be seen in emission in the secondary spectrum only. Balmer and Si I enhancement are characteristic of stellar flares (Bopp 1974b): it is clear that a flare occurred, or was in progress, during the course of the exposure. A second exposure, obtained 2 hours later, shows the blueward component weaker than before, but still clearly enhanced.

However, the H δ and H γ components of spectrogram 7154 are not merely double, but *triple*. Midway between the two stellar components is a weak, narrow third component with an equivalent width (EW) of ~ 0.2 Å (see fig. 2). No central emission was seen at Ca II K. Radial velocity measurements show these features to have a velocity of $+2$ km s $^{-1}$, coincident with the γ -velocity of the YY Gem system. A central component of H γ is weakly evident on spectrogram 7155. This component was never visible when the stars were quiescent; spectrogram 7720 was exposed for twice the normal time near phase 0.75 to search for weak central emission, with null results.

We are led to conclude that there is circumstellar material concentrated at the inner Lagrangian point L_1 of the YY Gem system. It is evident that only a

small amount of material is involved; YY Gem shows no infrared excess, as might be expected from an extensive circumstellar cloud (Gehrz, private communication), nor are the effects of obscuring material evident in the photovisual light curve (Binnedijk 1950). The observations of Pfeiffer and Koch (1973), however, show YY Gem to exhibit time-dependent polarization, and hence some distribution of scattering circumstellar material. In addition (Pfeiffer, private communication), there are suggestions of variability in polarization on a relatively short time scale (less

FIG. 2.—Intensity tracings of H δ and H γ on spectrogram 7154, obtained during a flare. The central emission components are indicated by an arrow.

than 50 minutes), and the polarization has some degree of repetition with orbital phase. Dr. Pfeiffer notes that this suggests the existence of a basic circumstellar envelope that is subject to sudden enhancements or distortions. The effects of possible flares on the polarization measurements must be considered, however (Efimov 1968).

The dynamical arguments of Torres and Ferraz Mello (1973) show that a cloud placed at L_1 would have a lifetime of a few hours at most. There are then two possibilities: the material is a transient feature of the system, possibly ejected as a result of flare activity; or the material is always present, but visible only when excited into emission by a flare. We believe the former possibility to be highly unlikely. The escape velocity at the surface of each component is quite high ($\sim 600 \text{ km s}^{-1}$); the emission-line broadening observed during flares does not indicate velocities sufficient for ejection of material. Further, the extreme narrowness ($\leq 20 \text{ km s}^{-1}$) of the central emission feature argues against its origin in a turbulent ejected cloud. If we take the latter alternative, and assume the material is always present, we must find a way of constantly replenishing it as it flows through L_1 . The difference in absorption- and emission-line velocities suggests that a slow leakage of chromospheric material may be occurring. We may surmise material to exist in much of the circumstellar volume. Its visibility only at L_1 is presumably due to the directional character of the flare and the greater density of material near the inner Lagrangian point.

If we assume the material to be always present at L_1 , some crude lower limits on the electron density can be made. We will assume the cloud to be originally neutral, and then suddenly ionized by a blast of radiation or particles from the flare (we assume the flare to be an instantaneous event, and ignore the effects of any slow, exponential decline). We then have for the variation of the electron density with time (Aller 1956):

$$N_e = \frac{N_e^0}{1 + \alpha_H t N_e^0}$$

where N_e is the electron density, N_e^0 is the initial electron density, α_H is the hydrogen recombination coefficient, and the time t is measured in days. If the electron temperature is taken as $20,000^\circ \text{ K}$ (consistent with the flare temperatures measured by Kunkel 1970), then $\alpha_H = 0.218 \times 10^{-7}$. It is clear that for $N_e^0 \leq 10^7$, days will be required for the material to recombine. The fact that the central emission had disappeared in a few hours argues that $N_e^0 > 10^7$. Further observations of flares with high spectral and time resolution will be needed to determine better the origin and the nature of the central cloud.

V. FLARE MAPPING

Since the geometry of the YY Gem system is explicitly known and since we can identify the flaring component by spectroscopic means, we have available a method of probing the location and extent in

longitude of the flare-producing regions. A flare observed spectroscopically on YY Gem will enhance one Balmer component with respect to the other, and will immediately restrict the flare location to a visible hemisphere of the primary or secondary. If the flare is of sufficiently long duration to allow observations over a considerable portion of the orbital phase, then location of the flaring region is further restricted to the locus of points defined by the intersection of the two hemispheres visible at the beginning and end of the observations. We assume the flaring region to be completely within the visible hemisphere. Part of the flaring region may have extended invisibly around the limb of the flaring component of course, making our estimates of longitudinal extents merely lower limits. Certainly, however, flare events seen very near the limb must be much rarer than those seen on the disk, even considering the large sizes of star spots, which presumably are the seat of flare activity (Bopp and Evans 1973). We have observed several flares spectroscopically on YY Gem; we discuss them below.

Flare 1 (1971 February 10 UT).—This was the flare recorded on spectrogram 7154. Incorporating the information that it was visible two hours later enables us to restrict the flaring region to a longitude extent of 140° or less on the secondary component. The presence of the central emission component, however, enables us to place an additional geometrical restriction on the flare location: it must be within the solid angle visible from the inner Lagrangian point. With this added restriction, we find the flare region to extend no more than $\sim 45^\circ$ in longitude. This is in excellent agreement with the sizes of the theoretical spots that have recently been constructed for the flare stars BY Dra and CC Eri (Bopp and Evans 1973). Figure 3 shows the observed configuration of the system, and the limits on the spot location. (We define the stellar meridian parallel to $\phi = 0.0$ as 0° , with stellar longitude increasing with binary phase.) We summarize the observations of this and other flares in table 3; longitudinal extents have been rounded to the nearest 5° .

Flare 2 (1971 March 24 UT).—A light curve of this flare may be found in Moffett and Bopp (1971). The event was observed spectroscopically on the primary from phases 0.145 to 0.234, when the observations were terminated due to hour angle. The flaring region

FIG. 3.—Longitude limits of the flaring region on YY Gem for flare 1 (1971 February 10 UT). The cross-hatched portion indicates the maximum possible flare extent. The binary phases are indicated by the arrows.

TABLE 3
SPECTROSCOPIC FLARE OBSERVATIONS OF YY GEMINORUM

Flare No.	Date (1971 UT)	Spectrograph	Phase Coverage	Flaring Component	Longitude Limits
1.....	February 10	coudé	0.721–0.824	SEC	205°–250°
2.....	March 24	Meinel	0.145–0.234	PRI	355°–140°
3.....	March 28	Meinel	0.075–0.149	PRI	325°–120°
4.....	March 29	Meinel	0.243–0.344	PRI	40°–180°
5.....	October 31	UVITS	0.870–0.940	SEC	245°– 45°
6.....	November 4	UVITS	0.840–0.888	SEC	230°– 30°

was still visible, however, since emission-line enhancement was still present. Thus, only upper limits on the extent in longitude may be set. No central emission component was visible, but the resolution of the Meinel spectrograms may not have been sufficient to reveal it. We have thus not applied further geometrical restrictions to this flare. The longitude limits are shown in figure 4a.

Flare 3 (1971 March 28 UT).—The observations are similar to those obtained for flare 2, and a light curve of the flare is shown in Moffett and Bopp. The flare was on the primary, and was visible from $\phi = 0.075$ to 0.149, when observations were again terminated due to hour angle. For the longitude limits, see figure 4b.

Flare 4 (1971 March 29 UT).—The presence of thin cloud precluded photometric observations of this flare, but the enhancement of the primary emission component leaves little doubt that a flare was in progress. The flare was observed from $\phi = 0.243$ to

0.344, when weather conditions stopped further spectroscopic observations. The longitude limits are shown in figure 4c.

The occurrence of the three flares 2, 3, and 4 on the primary component of YY Gem, within 5 days and at nearly the same phase, strongly suggests that the same region was responsible for the three events. Further support for this assumption is furnished by the observations of March 26 and 27 UT, which covered phases 0.510 to 0.681 and 0.733 to 0.909 (that is, the hemisphere opposite from the flare-producing region was observed). No flares were observed on these nights. Observations on March 25 were prevented by weather conditions.

If we make the assumption of a single stationary region, we may combine the spectroscopic phase coverage of the three flares, and superpose the possible flare regions. The locus of points defined by the intersection of the three flare limits should further restrict the location of the flare region. Figure 4d illustrates the result of the superposition. With these constraints, the flare-producing region can extend no more than 60° in longitude.

Flare 5 (1971 October 31 UT).—This very large flare was observed photometrically and with the UVITS.

FIG. 4.—(a) Same as fig. 3, for flare 2 (1971 March 24 UT). (b) Same as fig. 3, for flare 3 (1971 March 28 UT). (c) Same as fig. 3, for flare 4 (1971 March 29 UT). (d) Composite flare region from flares 2, 3, and 4.

FIG. 5.—(a) Same as fig. 3, for flare 5 (1971 October 31 UT). (b) Same as fig. 3, for flare 6 (1971 November 4 UT).

The lines of the primary and secondary were not resolved. However, enhancement of one emission component caused a noticeable shift in the observed line center relative to the quiescent spectrum, enabling the secondary to be identified as the flaring component. The coverage in phase was restricted; observations were terminated by sunrise. The longitude of the flaring region may be restricted only to a range of $\sim 160^\circ$ (fig. 5a).

Flare 6 (1971 November 4 UT).—Observations similar to those for flare 5 were obtained. Phase coverage was from $\phi = 0.84$ to 0.89, with termination again due to sunrise. Measurements were made of the eight spectrograms obtained during the flare event in an attempt to establish a velocity shift and thus identify the flaring component. The results were puzzling and inconclusive: the Ca II K line showed a redshift of 30 km s^{-1} , while H δ showed a 50 km s^{-1} blueshift and H γ showed no shift at all. The results may possibly be explained by the presence of red asymmetry (Bopp and Moffett 1973; Gershberg and Shakovskaya 1971) in this particular flare, with an extended red emission wing confusing the measures. If that were the case, the flare would most likely have been produced on the blueshifted secondary. We note that flares 5 and 6 were observed at nearly the same phase and occurred relatively close in time; it is reasonable to assume that the same flare region pro-

duced them both. The geometry of flare 6, assuming it was produced on the secondary component, is illustrated in figure 5b.

VI. EMISSION-LINE VARIATIONS

It has been noted (Bopp 1974a) that emission-line variability is evident in the spectrum of YY Gem even when the stars are photometrically quiescent. The variations can be explained by the existence of a non-uniform, patchy distribution of emitting regions on the stellar surface (Bopp 1974a; Bopp and Evans 1973). These "active regions" in all probability outline or possibly partly cover the darker spot areas. We expect to see the emission lines enhanced when the active region is facing us, and diminished in intensity when the region is turned away. Since the components of YY Gem are known to rotate synchronously (Struve and Zeberg 1959), spectrophotometric observations over the binary phase should enable us to map the line-enhancing regions in a manner similar to flare mapping.

Equivalent width measures of the author's coude data are given in table 4. Unless noted, all spectrograms were obtained when the stars were photometrically quiescent. Only unblended H δ and H γ were measured; higher-order Balmer lines and Ca II H and K had surrounding continua too weakly exposed for

TABLE 4
COUDÉ OBSERVATIONS OF YY GEMINORUM 1971–1972

PLATE NO.	HJD (2,440,000 +)	PHASE	EW(H δ) (Å)		EW(H γ) (Å)		EW(Pri)/EW(Sec)
			Pri	Sec	Pri	Sec	
7118.....	0988.819	0.842	0.68	0.72	0.78	0.49	1.3
7119.....	0988.873	0.908	0.73	0.64	...	...	1.1
7154*.....	0992.792	0.721	0.76	2.73	0.59	2.37	0.3
7155*.....	0992.876	0.824	0.77	1.28	0.66	1.29	0.6
7172.....	0995.741	0.342	0.72	0.89	0.55	0.64	0.8
7188.....	0996.784	0.623	0.76	0.73	0.94	0.91	1.0
7189.....	0996.884	0.697	1.12	1.17	0.77	0.77	1.0
7209.....	0998.802	0.102	0.65	0.73	0.69	0.90	0.9
7210.....	0998.848	0.152	0.72	0.86	0.76	0.91	0.8
7644.....	1282.802	0.875	1.27	0.71	1.30	0.60	2.0
7645.....	1282.849	0.933	1.00	0.46	1.02	0.69	1.8
7647.....	1282.941	0.046	1.03	0.76	1.12	0.72	1.5
7648.....	1282.989	0.104	0.76	0.82	0.80	0.78	1.0
7658.....	1285.833	0.597	0.73	1.28	0.69	0.94	0.7
7659.....	1285.879	0.653	0.75	0.75	0.82	0.79	1.0
7660.....	1285.923	0.703	0.66	0.93	0.76	1.10	0.7
7661.....	1285.968	0.763	0.99	0.75	0.73	0.83	1.1
7674.....	1288.782	0.219	0.60	0.66	0.40	0.44	0.9
7675.....	1288.828	0.275	0.42	0.45	0.46	0.42	1.0
7686.....	1292.754	0.097	0.43	0.50	0.58	0.62	0.9
7687.....	1292.800	0.153	0.52	0.53	0.37	0.42	0.9
7688.....	1292.845	0.209	0.68	0.61	0.55	0.51	1.1
7689.....	1292.890	0.264	0.68	0.67	0.53	0.59	0.9
7690.....	1292.939	0.324	0.41	0.72	0.36	0.72	0.5
7691.....	1292.965	0.356	0.74	1.14	0.52	0.82	0.7
7713.....	1343.661	0.615	0.93	0.57	0.95	0.37	2.1
7714.....	1343.707	0.671	...	...	0.81	0.42	1.9
7715.....	1343.754	0.729	1.13	1.16	0.77	0.83	1.0
7718.....	1345.683	0.098	0.49	0.85	0.91	1.17	0.7
7719.....	1345.739	0.166	0.64	0.78	0.78	0.87	0.9

* Flare in progress.

TABLE 5
COUDÉ OBSERVATIONS OF YY GEMINORUM 1959 (Struve and Zebergs)

PLATE NO.	Date	UT	Phase	EW(H δ) (Å)		EW(H γ) (Å)		EW(Pri)/EW(Sec)
				Pri	Sec	Pri	Sec	
Cd 12571.....	April 10	03:23	0.338	0.27	0.66	0.37	0.87	0.4
Cd 12578.....	April 11	03:20	0.562	0.62	0.48	0.48	0.35	1.3
Cd 12579.....	April 11	04:24	0.616	0.56	0.47	0.98	0.52	1.5
Cd 12581.....	April 11	06:41	0.733	0.85	0.45	0.89	0.53	1.8
Cd 12587.....	April 12	03:22	0.792	0.77	0.78	0.74	0.63	1.1
Cd 12588.....	April 12	04:25	0.846	0.74	0.49	0.72	0.48	1.5
Cd 12589.....	April 12	05:30	0.901	0.70	0.66	0.81	0.51	1.3
Cd 12599.....	April 13	06:32	0.182	0.74	0.80	0.54	0.57	0.9
Cd 12606.....	April 14	04:29	0.306	0.57	0.60	0.49	0.51	1.0
Cd 12607.....	April 14	05:33	0.360	0.60	0.77	0.39	0.56	0.7

reliable measurement. We note that H δ and H γ exhibit a range of variation of about a factor of 3, similar to the behavior seen in several other quiescent flare stars (Bopp 1974*a, b*). There does seem to be a minimum equivalent width ($\sim 0.5\text{--}0.6$ Å) which is seen at several times throughout the orbital cycle. This quantity may represent the emission contributed by the uniform, undisturbed chromosphere as a whole.

In addition to the McDonald data, the spectrograms obtained by Struve and Zebergs were lent to the author through the kind permission of Dr. O. C. Wilson and the Hale Observatories. These spectra (dispersion 20 Å mm⁻¹) were used in the 1959 orbital study, but no equivalent width measures were made. Ten of these spectra had calibrations available, and were traced by the author. Equivalent widths are given in table 5. No systematic differences in equivalent width measures between the McDonald and Mt. Wilson spectra are noticeable, through the earlier spectra exhibit variations in equivalent width similar to those seen in the McDonald data.

Both the data obtained in 1971 November–December and the 1959 spectra show systematic variations of equivalent width with phase (the 1971 February and 1972 January series contain too little data to tell). To illustrate these changes, we plot the average equivalent-width ratio EW(primary)/EW(secondary) for H δ and H γ in 1971 November–December

and 1959 April as a function of phase in figures 6 and 7. The errors in this ratio are estimated as no more than 20 percent; it can be seen that real variations of a factor of 2 or more in this quantity were observed.

The 1971 observations show a peak near $\phi = 0.9$, followed by a monotonic decrease until phase 0.1. The equivalent widths are equal until $\phi \sim 0.3$, when the secondary component seems to strengthen with respect to the primary. By $\phi \sim 0.7$, the components are of equal strength again.

We interpret the peak in figure 6 as representing an active region on the primary facing the observer. The monotonic decrease (see the data for spectrograms 7644, 7645, 7647, and 7648 in table 4) is readily explained as a consequence of varying aspect. The region is no longer visible at phase $\phi \sim 0.1$. The decrease in the equivalent-width ratio seen near phase 0.3 may represent a similar active region on the *secondary*, but lack of data near phase 0.4–0.6 does not allow us to confirm the reality of the second region.

We may construct a map of the region, similar to those maps constructed in the case of spectroscopically observed flares. We note that the region was visible at $\phi = 0.875$ (spectrogram 7644) and remained visible until $\phi = 0.046$ (7647). It was not visible at $\phi = 0.104$ (7648). We may then restrict the location of the active region to the locus defined by the intersection of *three* hemispheres, with the resulting geometry seen in

FIG. 6.—Emission-line variability in YY Gem, 1971 November–December. Orbital phase as in van Gent (1931).

FIG. 7.—Emission-line variability in YY Gem, 1959 April.

FIG. 8.—Maximum possible longitude extent of the active region on the primary component of YY Gem as revealed by emission-line variations, during 1971 November–December.

figure 8. Our result has the region limited to between 285° and 305° in longitude (maximum possible longitude extent 20°). Struve and Zeberg's 1959 data may be fitted by a similar model. Since the peak in the 1959 data occurs near $\phi \sim 0.7$, the active region on the primary should be centered near longitude $\sim 250^\circ$.

VII. CONCLUSIONS

Bopp and Evans (1973) have shown that a rotating star having a large darkened region on its surface may quantitatively explain the quiescent V -band variations that have been seen in the flare stars BY Dra and CC Eri. Associated with these starspots may be stellar active regions characterized by substantial emission-line enhancement relative to the quiescent chromosphere (Bopp 1974a). Such a model applied to YY Gem effectively explains the distortions noticed by Kron (1952) and the nonrandom emission line variations seen by Struve and Zeberg and by the author.

The spot sizes implied agree well with the models of Bopp and Evans, and also with the recent theoretical results of Mullan (1973, 1974).

Mapping of flares and active regions on YY Gem show the disturbed regions to be randomly distributed in longitude; there is no tendency, for example, for these regions to occur preferentially along the line of centers where the gravitational influence of a companion is greatest. In the case of the flares seen in 1971 March, we have demonstrated that a single flare region can produce at least one major flare per day.

Though the baseline of our observations is rather short, we can make some estimates of the lifetime of an active region on YY Gem. The active region prominently visible in 1971 November–December seems no longer to be present on the spectrograms obtained near the end of 1972 January. Similarly, the flare-producing region of 1971 February has disappeared by March of that year, nor is any trace of the flaring region seen in March visible on the February spectrograms. Spots and active regions on YY Gem can evidently develop and disappear on time scales as short as 1 month. In contrast to this, the V -band oscillations of BY Dra and CC Eri are fairly stable over a period of several weeks, but vary from year to year—an indication that these spots change on time scales of a few months.

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REFERENCES

- Aller, L. H. 1956, *Gaseous Nebulae* (New York: Wiley), p. 161.
 Binnendijk, L. 1950, *B.A.N.*, **11**, 203.
 Bopp, B. W. 1974a, *M.N.R.A.S.*, **166**, 79.
 ———. 1974b, *ibid.*, in press.
 Bopp, B. W., and Evans, D. S. 1973, *M.N.R.A.S.*, **164**, 343.
 Bopp, B. W., and Moffett, T. J. 1973, *Ap. J.*, **185**, 239.
 Efimov, Yu. S. 1968, in *I.A.U. Colloquium, Non-periodic Phenomena in Variable Stars*, ed. L. Detre (Dordrecht: Reidel), p. 169.
 Gershberg, R. E., and Shakovskaya, N. I. 1971, *Astr. Zh.*, **48**, 934.
 Joy, A. H., and Abt, H. A. 1974, preprint.
 Joy, A. H., and Sanford, R. F. 1926, *Ap. J.*, **64**, 250.
 Kron, G. E. 1950, *Pub. A.S.P.*, **62**, 141.
 ———. 1952, *Ap. J.*, **115**, 301.
 Kunkel, W. E. 1970, *Ap. J.*, **161**, 503.
 Lucy, L. B., and Sweeney, M. A. 1971, *A.J.*, **76**, 544.
 Moffett, T. J., and Bopp, B. W. 1971, *Ap. J. (Letters)*, **168**, L117.
 Mullan, D. J. 1973, *Ap. J.*, **186**, 1059.
 ———. 1974, *ibid.*, **192**, 149.
 Pfeiffer, R. J., and Koch, R. H. 1973, *Inf. Bull. Var. Stars*, No. 780.
 Struve, O. 1952, *Pub. A.S.P.*, **64**, 117.
 Struve, O., Herbig, G., and Horak, H. 1950, *Ap. J.*, **112**, 216.
 Struve, O., and Zeberg, V. 1959, *Ap. J.*, **130**, 783.
 Torres, C. A. O., and Ferraz Mello, S. 1973, *Astr. and Ap.*, **27**, 231.
 van Gent, H. 1931, *B.A.N.*, **6**, 99.
 Wolfe, R. H., Jr., Horak, H. G., and Storer, N. W. 1967, in *Modern Astrophysics*, ed. M. Hack (New York: Gordon & Breach), p. 251.

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