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Photometry and spectroscopy of the RS CVn system σ Geminorum

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Abstract. We present new UBV photoelectric photometry and high-resolution H_α spectroscopy of the RS CVn system σ Gem made in 1993-1994. A brief photometric analysis for the new light curves is carried out using the Wilson-Devinney method with spot approximation based on the Roche model. The result suggests the probable presence of two cool spots on the K1 III primary around the phases of $\phi = 0.6$ and $\phi = 0.9$. The spot activity is discussed in connection with the chromospheric H_α emission. The enhanced H_α core emission is found to vary with phase and shows distinct anti-correlation with the spot regions. It may be an indication for the existence of plage regions on σ Gem.

Key words: stars: σ Gem; activity — binaries: close

1. Introduction

σ Gem (=HR 2973 = HD 62044) is a well known member of the long-period RS CVn systems. It is a non-eclipsing single-line spectroscopic binary with a long orbital period of 19.605 days (Bopp & Dempsey 1989). The visible primary is a red giant of spectral type K1 III. Little is known about the secondary component.

The light variability of this star was discovered by Hall et al. (1977). Fried et al. (1983) contributed a detailed photometric study of σ Gem and derived a reliable photometric period of 19.423 days, which is shorter than the orbital period. The amplitude of the photometric wave is variable with a maximum value of 0.17 mag in V. As a hyperactive star σ Gem draws much attention of astronomers. Focusing on the starspot changes over an eight-year period, Strassmeier et al. (1988) analyzed the V light curves and discussed the cyclic variations and spot migration. With a simplified light curve modeling method they suggested two cool spot regions on the K1 III primary and found a 2.7 yr period of cyclic variation for both spots and a new photometric period of 19.410 days. Later, Olah et al. (1989) investigated the light curve behavior of σ Gem from 1986 to 1988 with the same method. They also confirmed large spot changes from year to year and the existence of two active longitudes on σ Gem. A detailed study on spot activities of σ Gem was recently published by Henry et al. (1995).

Strong CaII H and K emission, UV line emission and X-ray emission have also been observed, revealing the unusual manifestations of σ Gem with high chromospheric and coronal activity (Schrijver et al. 1995; Elgaray et al. 1997). The H_α core emission has been observed by many authors. First, Smith & Bopp (1982) noted that the H_α absorption line in σ Gem was partly filled in by chromospheric emission. Strassmeier et al. (1986) measured the H_α feature with an average EW of 972 mÅ and an average R_c of 0.51. Strassmeier & Fekel (1990) and Frasca & Catalano (1994) computed the residual emission separately and got different results. A detailed study of the H_α profile by Eker (1986) showed the line core to vary with the orbital phase in agreement with the location of stellar active regions. Bopp et al. (1988) indicated that the H_α EW varied with rotational phase in 1986 but not obviously in 1987.

From 1993 to 1994, we made almost simultaneous photoelectric UBV and spectroscopic observations. In this paper, we present an analysis of the observations. The spot activity and the chromospheric H_α emission will be discussed in the context of the stellar evolutionary status.

2. Observations and data reductions

In the 1993/94 observing season, new UBV photometry of σ Gem was carried out at the Xinglong station of Beijing Astronomical Observatory. On 17 nights from

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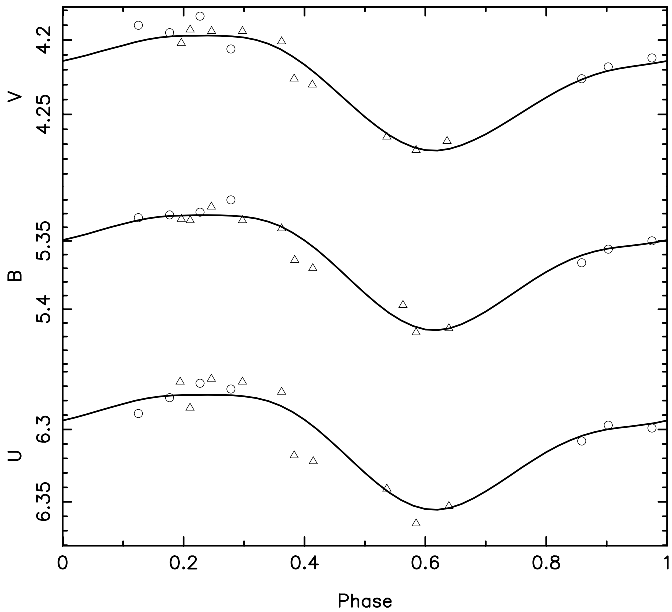

Fig. 1. The new light curves of σ Gem observed in 1993/94. Circles denote the measurements obtained in 1993 Jan.-Feb., and the triangles stand for that observed in 1993 Nov.-1994 Jan. Solid lines represent the computed light curves using W-D method with two-spot model

1993 January to 1994 January, the observations were made on the 60 cm reflector using a single channel photometer with a direct amplification receiver. The star ρ Gem (=HD 58946, $V = 4.18$, $U - B = -0.03$, $B - V = +0.32$, Strassmeier et al. 1988) was adopted as the comparison star. The integration time was 30 s for both the target and comparison stars in all filters. The accuarcy of the observations was estimated to be about 0.01 mag in all V, B and U bands on most nights. All the measurements were transformed to the UBV standard system and combined into light curves using the photometric ephemeris of Fried et al. (1983),

$$\mathrm{JD(hel)} = 2444686\overset{\mathrm{d}}{.}5 + 19\overset{\mathrm{d}}{.}423 \times E.$$

Table 1 gives the dataset of UBV measurements. We combined the data obtained on one night into one average point because of the long period of the system. The UBV light curves are shown in Fig. 1, where circles and triangles represent the measurements observed in early 1993, and from 1993 November to 1994 January.

Table 1. Photometric measurements of σ Gem

JD(Hel) 2440000+	V (mag)	JD(Hel) 2440000+	B (mag)	JD(Hel) 2440000	U (mag)
9015.0712	4.231	9015.0713	5.366	9015.0714	6.312
9015.0848	4.227	9015.0830	5.366	9015.0832	6.308
9015.0925	4.222	9015.0927	5.366	9015.0928	6.304
9015.9334	4.220	9015.9334	5.351	9015.9335	6.300
9015.9412	4.217	9015.9413	5.360	9015.9413	6.294
9017.3190	4.211	9017.3171	5.345	9017.3172	6.298
9017.3422	4.222	9017.3422	5.346	9017.3423	6.293
9017.3615	4.203	9017.3630	5.357	9017.3616	6.307
9020.2452	4.193	9020.2480	5.339	9020.2470	6.295
9020.2628	4.181	9020.2628	5.334	9020.2610	6.287
9020.2726	4.195	9020.2726	5.327	9020.2742	6.284
9021.2612	4.194	9021.2612	5.335	9021.2600	6.286
9021.2767	4.195	9021.2768	5.328	9021.2768	6.270
9022.2440	4.184	9022.2440	5.329	9022.2441	6.268
9023.2365	4.206	9023.2365	5.320	9023.2354	6.272
9313.2216	4.206	9313.2216	5.350	9313.2216	6.299
9313.2392	4.203	9313.2393	5.344	9313.2293	6.284
9313.2586	4.193	9313.2570	5.335	9313.2572	6.281
9313.2858	4.190	9313.2842	5.331	9313.2844	6.278
9313.3033	4.180	9313.3030	5.317	9313.3018	6.270
9313.3208	4.184	9313.3208	5.330	9313.3210	6.297
9316.1706	4.210	9316.1706	5.351	9316.1706	6.276
9316.1803	4.207	9316.1803	5.342	9316.1803	6.268
9316.1992	4.204	9316.1992	5.339	9316.2024	6.272
9316.2114	4.201	9316.2115	5.341	9316.2106	6.290
9316.2366	4.190	9316.2350	5.336	9316.2352	6.268
9316.2463	4.193	9316.2465	5.336	9316.2446	6.270
9317.1592	4.236				
9317.1689	4.250	9317.1690	5.372		
9317.1903	4.224			9317.2118	6.334
9317.2212	4.222	9317.2212	5.365	9317.2212	6.323
9317.2427	4.220	9317.2442	5.375	9317.2442	6.310
9336.0350	4.226	9336.0540	5.370	9336.0350	6.324
9339.0058	4.260	9339.0045	5.397	9339.0046	6.327
9339.0136	4.262	9339.0124	5.398	9339.0126	6.353
9339.0214	4.272			9339.0248	6.343
9339.9479	4.274	9339.9481	5.417	9339.9471	6.374
9339.9595	4.275	9339.9596	5.417	9339.9596	6.364
9340.9806	4.269	9340.9806	5.415	9340.9807	6.357
9341.0330	4.267	9341.0330	5.413	9341.0330	6.348
9371.2486	4.202	9371.2486	5.337	9371.2478	6.269
9371.2583	4.203	9371.2584	5.331	9371.2584	6.265
9372.2164	4.186	9372.2184	5.321	9372.2180	6.274
9372.2356	4.202	9372.2188	5.330	9372.2188	6.255
9373.2030	4.196	9373.2022	5.339		
9373.2186	4.194	9373.2186	5.336	9373.2190	6.267
9373.2362	4.192	9373.2363	5.330		

Spectroscopic observations were made with the 2.16 m telescope also at the Xinglong station in 1993 on eight nights from 1993 Jan. 12 to Jan. 19. The spectra were obtained by using the fiber-fed Cassegrain ISIS spectrograph, which was designed specifically for the international MUSICOS observations by Meudon Observatory (Cuby et al. 1992). With a THX 576×384 CCD detector the ISIS spectrograph yields a resolving power of about 3.6 10^4 at H_α band. The spectrum covers about 35 Å from 6544.5 to 6579.5 Å. The reciprocal dispersion is 2.64 Å mm^{-1}, corresponding to a 2-pixel resolution of 0.122 Å. The star β Gem (K0 III) was used as comparison star.

On most nights, we obtained two spectra of the target, one before midnight and one after midnight. A total of 14 spectra with high S/N ranging from 160 to 300 were obtained. The spectra obtained on Jan. 16 are noisy because of the bad weather. Information about the observations is given in Table 2, where JD of the observations corresponds to the midexposure and the phases were computed from the ephemeris of Fried et al. (1983).) Each spectrum was reduced according to the usual procedures: bias

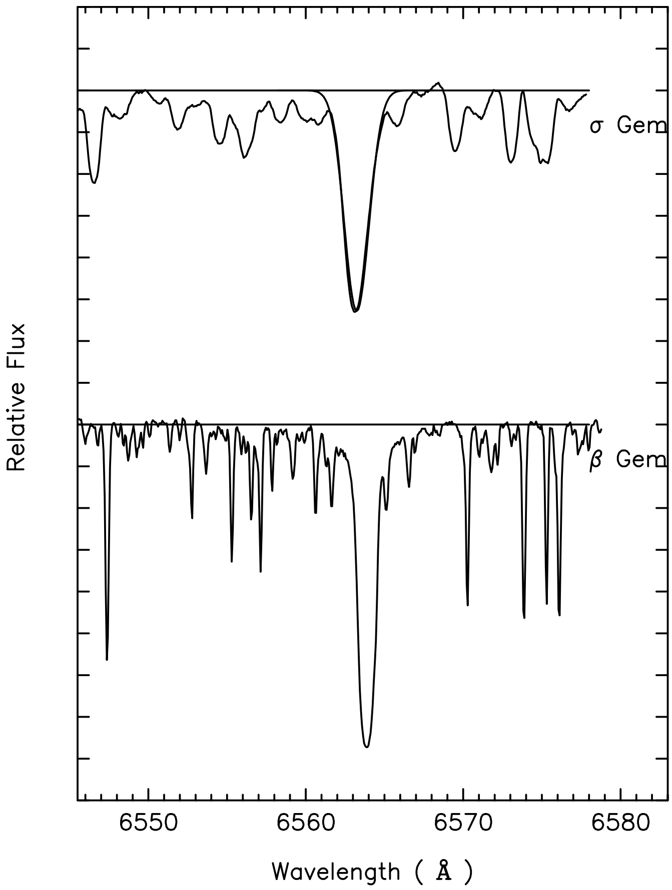

Fig. 2. Average spectrum of σ Gem of the H_α order after velocity shift corrections. The dotted curves illustrate the Gaussian fittings to the H_α profiles

subtraction, dark subtraction, flat-field division, global slope correction and wavelength calibration. The precision of the calibration is better than 0.02 Å. The continuum level is established by choosing two line-free windows, approximately 2 Å wide, centered at 6550 and 6578 Å. A straight line is then drawn through these two regions to define the continuum in each spectrum. Two representative spectra illustrating our continuum definition are shown in Fig. 2. The upper one is the average spectrum of σ Gem and the lower one is of the comparison, β Gem.

3. The new light curves

The new *UBV* light curves (Fig. 1) are single-humped with asymmetry. The maximum brightness located around $\phi = 0.2$ is found to be about 4.18 mag in V, 5.32 mag in B and 6.28 mag in U, respectively. The minimum is located around $\phi = 0.6$. The amplitudes of the light variation of σ Gem in 1993/94 was about 0.1 mag, 0.09 mag and 0.07 mag in V, B and U respectively. Comparing with the light curves of Olah et al. (1989) obtained in 1986, 1987 and 1988, we find that the distortion wave has evidently been migrating steadily.

Table 2. The spectroscopic observations of σ Gem in 1993

No.	HJD 2 440 000+	Date	Phase	Exp. Time (second)
1	9000.131	12.1.1993	0.089	3000
2	9001.075	13.1.1993	0.137	2400
3	9001.274	13.1.1993	0.148	1800
4	9002.076	14.1.1993	0.189	1800
5	9002.231	14.1.1993	0.197	1800
6	9003.253	15.1.1993	0.249	1800
7	9003.306	15.1.1993	0.252	1800
8	9004.257	16.1.1993	0.301	1500
9	9004.346	16.1.1993	0.306	2100
10	9005.227	17.1.1993	0.351	2100
11	9006.242	18.1.1993	0.403	1800
12	9006.340	18.1.1993	0.409	1800
13	9007.226	19.1.1993	0.454	1200
14	9007.294	19.1.1993	0.458	1000

The shape of the light curves implies large-scale spot activity on surface of the star. To study the spot activity furtherly from the light curves, a brief photometric analysis was carried out using the Wilson-Devinney program with spot approximation (Kang & Wilson 1989; Zhai et al. 1994). The major Roche parameters are mainly adopted or estimated from the previous works on this system (Stawikowski & Glebocki 1994; Eker 1986). With a two-spot model, the computed light curves give a good fitting to all the V, B and U light curves as shown in Fig. 1.

The result indicates that probably two cool spots exist on the primary component of σ Gem in the season of 1993/94. The one cooler and larger is located at the phase around $\phi = 0.6$ and the other, smaller one is around the phase of $\phi = 0.9$. Additional spots should also be present on the star to account for the general dimming from the unspotted level ($4.^{m}137$, Strassmeier et al. 1988) to our measured maximum light ($4.^{m}18$). Because of the considerable observational errors and the large gap between our two observational intervals, however, the resulting parameters of the spots are uncertain.

4. H_α variations

The average spectrum of σ Gemis shown in Fig. 2 which is obtained by adding together the 14 individual spectra after velocity shift corrections to the centers of H_α, agreeing to ± 1 pixel. The center of H_α is located by fitting a Gaussian profile as illustrated in Fig. 2. Subtracting the average spectrum from the shifted, individual spectra yields the residual spectra as shown in Fig. 3. Arrows

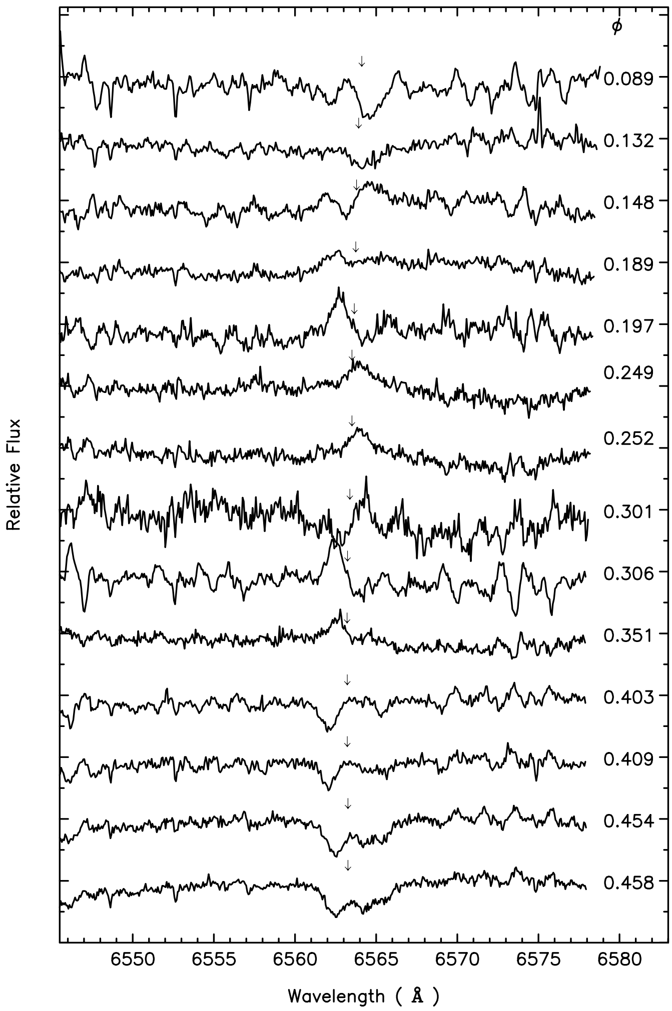

Fig. 3. Residual spectra obtained by abstracting the average spectrum from the individual spectra after velocity shift corrections. Phases are from Table 2. Arrows mark the centers of H_α

mark the centers of H_α. As can be seen in Fig. 3, the residual H_α profiles show variations with phase. It is clearly in emission in scans 6 and 7 with phases around 0.25, which corresponds to the maximum of the light curves. At phases with more spots in view (scans 1, 2 and 13, 14), the residual H_α lines appear obviously in absorption.

Table 5 lists the values of the equivalent width (EW) and the central depth (R_c) of H_α for each of the 14 individual spectra and the average spectrum of σ Gem. These values are obtained by one Gaussian fitting. Figure 4 shows the variations of EW and R_c with phase according to Table 5. The dashed line represents the calculated V light curve. It is obvious that the equivalent width and central depth of the H_α profile show distinct anti-correlation with the light curve, (i.e., with the spot regions), though the spectroscopy covers only half of a period. The H_α equivalent width shows the smallest value at maximum brightness, and tends to increase with the appearance of spots. It agrees well with the result from the analysis of the residual H_α profiles above.

Table 3. The variations of the H_α profile of σ Gem

No.	Phase	EW(H_α) (mÅ)	R_c
1	0.089	1060	0.459
2	0.137	1005	0.469
3	0.148	988	0.478
4	0.189	995	0.479
5	0.197	995	0.475
6	0.249	966	0.502
7	0.252	985	0.495
8	0.301	985	0.495
9	0.306	1007	0.481
10	0.351	1002	0.493
11	0.403	1078	0.473
12	0.409	1082	0.475
13	0.454	1125	0.455
14	0.458	1136	0.452
Average		1042	0.47

In general, for a temperature insensitive spectral line, the appearance of spots cause changes in the shape of the line profile, but not in its equivalent width (Vogt & Penrod 1983). Thus, the variation of the H_α equivalent width in σ Gem is probably due to chromospheric H_α emissions.

Many authors investigated the correlation between H_α core emission and spot regions in RS CVn-type stars, and got different results. Weiler (1978) found a marginal correlation between H_α emission and wave minimum for RS CVn, UX Ari and Z Her. A similar correlation holds for II Peg (Vogt 1981). In the Sun, the enhanced chromospheric emissions are from the plage regions visible in white light. If, according to the suggestion of Walter (1996), the solar analogy is valid, in case of σ Gem there may be bright, spatially distinct plages where the enhanced H_α core emission comes from at the phase of maximum light.

The average equivalent width of the H_α absorption profile is measured to be EW = 1042 mÅ with an average central depth of $R_c = 0.47$ for σ Gem. Strassmeier et al. (1986) gave a value of EW = 972 mÅ with $R_c = 0.51$ while Bopp et al. (1988) gave EW $\simeq$ 1100 mÅ and $R_c \simeq 0.44$. The differences may be due to the variations of the active regions apart from the errors of measurements.

5. Summary

We made new UBV photoelectric photometry and high resolution H_α spectroscopy of the chromospheric active binary system σ Gem in 1993-1994. The analysis of the light curves and the H_α spectra yield the following results:

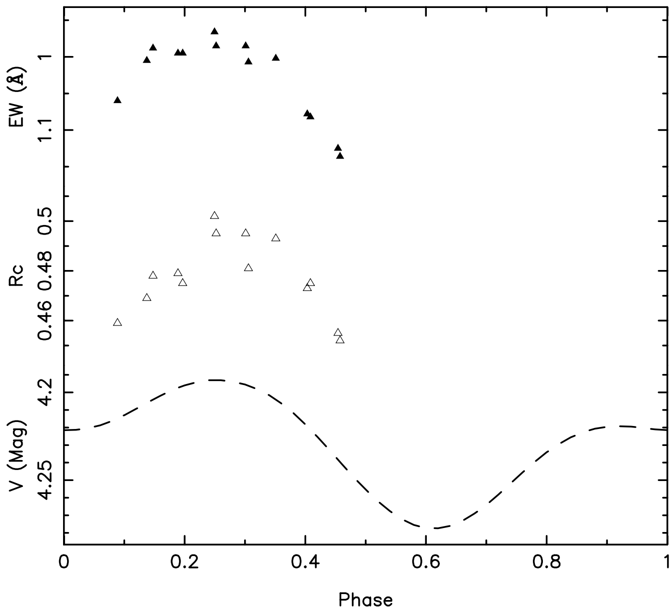

Fig. 4. The anti-correlations of the H_α equivalent width (EW) and the central depth R_c with the distorted wave. The dotted line represents the V light curve of σ Gem

(1) The light curve migrated steadily and the distortion wave varied comparing to the previous observations, though the measurements show a considerable scatter. A brief photometric analysis, carried out using the Wilson-Devinney method, suggests two cool spots on the primary component of σ Gem around phases of 0.6 and 0.9 apart from additional spots causing the general dimming of the star.

(2) In connection with the photometric observation, the H_α spetctroscopy of σ Gem is analyzed. It is found that the core of the H_α profile is varying with phase and time. The near to simultaneous photometry and spectroscopy enable us to find that the enhanced H_α core emissions show distinct anti-correlation with spot regions. Our study suggests that there may be some plage-type regions around the maximum light, where the enhanced H_α emission comes from.

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