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IUE-newsips spectra of σ Geminorum★

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Abstract. The IUE spectra of σ Gem have been taken from the NASA IUE archive using IDL (Interactive Data Language). The spectra have been observed in 1979–1986 period. All the spectra analysed in the present study have NEWSIPS reductions and consist of 25 LWP, 8 LWR and 5 SWP images in high resolution, and 2 LWP and 14 SWP images in low dispersion. The emission lines, identified as activity indicators and originating in the chromosphere and transition region, are seen in the spectra. The emission line fluxes and equivalent widths are computed based on Gaussian profile fitting procedures to examine the existence of any line flux variation that depends on time or orbital phase. It was found that there is a flux variation with time and orbital phase that is in good agreement with the photometric light curve variation. By comparing the flux variation with simultaneous light curve variation, it can be shown that there is a relation between the ultraviolet flux variation and the spot activity of the system, as shown by Ayres et al. (1984) and Engvold et al. (1988) based on their IUE (with IUESIPS reduction) spectral analysis. Moreover, it was inferred that there is no ultraviolet excess in σ Gem by comparing the spectra of β Gem taken as a comparison star. The Mg II h and k radial velocity curves of σ Gem were in a good agreement with data obtained by Eker (1986) and Duemmler et al. (1997). The sinusoidal Mg II radial velocity curve solutions of the system give $e = 0$, $P_{\rm orb.} = 19.607 \pm 0.008$ days, $K = 34.86 \pm 2.33$ km s^{-1}, $\gamma = 49.42 \pm 1.87$ km s^{-1} and $T_{\rm o} = 2445972.53 \pm 0.28$. Since the ultraviolet flux data are not conveniently distributed and are insufficient to determine the activity cycle, the evaluation of the ultraviolet flux activity cycle was not successful.

Key words. stars: activity – stars: atmospheres – stars: binaries: spectroscopic – stars: chromospheres – stars: individual: σ Gem – stars: late-type

1. Introduction

σ Gem (HR 2973/ HD 62044) is a long period ($P_{\rm orb} = 19.^{\rm d}6$), non-eclipsing RS CVn-type binary system (Hall 1978). The spectral type of the primary star is K1 III and shows strong emission lines in the far ultraviolet. The system also has soft X-ray emission (Walter et al. 1978) and substantial coronal microwave radiation (Gibson 1980). By using optical photometric observational data, it was found that the chromospherically active component of the system has a large spot region that has longitudinal motion (Strassmeier et al. 1988). Since the orbital period and the rotational period of the cooler component were almost equal, the system was defined as a synchronized system (Linsky 1984). Some photometric and orbital characteristics of σ Gem are summarized in Table 1. By using $v \sin i = 27$ km s^{-1}, $P_{\rm rot.} = 19.54$ days and $i = 60°$, Eaton (1990) found the radius of the spotted (primary) component to be $R = 12.0\ R_{\odot}$. Strassmeier et al. (1993) found $v \sin i = 25$ km s^{-1} from the rotationally broadened line profiles of σ Gem which is in agreement with the value used by Eaton (1990). Bopp & Talcott (1980) showed that there is no relation between the equivalent width of H_{α} and orbital phase, but the detailed spectral analysis by Eker (1986) showed that the line center of H_{α} has some variations in time and orbital phase in agreement with the position of spotted regions.

The first analysis of the IUE spectra (with the IUESIPS reduction procedure) of σ Gem by Ayres et al. (1984) indicates that there is no evidence for circumstellar absorption features or blueward asymmetries in the chromospheric O I, Mg I and Mg II emission cores. And, by using two consecutive IUE observations (1982 May 10 and 11), they concluded that the significant changes in the high-excitation Si IV and C IV profiles which likely were produced by the rotation of a large-scale active region off the visible hemisphere of the primary, are in agreement with the spot (namely A and B) orientations deduced from the photometric study by Fried et al. (1983). Also, IUE and EXOSAT observations of σ Gem were obtained in 1984 by Engvold et al. (1988). From the photometric data they also derived two starspot regions, A and B, relative to the central meridian. From the analysis of the UV line fluxes they concluded that the high temperature ($T \sim 10^5$ K) line emissions were associated with the B spot region and the low temperature ($T < 10^4$ K) lines with a less conspicuous spot region (spot A). They also indicated that the transition region emission lines were strengthened relative to the chromospheric

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★ Tables 3 to 11 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/391/641. Figures 1 to 10 are only available in electronic form at http://www.edpsciences.org

Table 1. The characteristics of σ Gem.

Parameter		References
α_{2000}	$07^h43^m19^s$	The Hipparcos & Tycho Catal.
δ_{2000}	$+28°52'01''$	The Hipparcos & Tycho Catal.
$P_{orb.}$	$19^d.60447$	Eker (1986)
$P_{rot.}$	$19^d.423$	Fried et al.(1983)
Eccentricity	0.02	Bopp & Dempsey (1989)
Masses [$M_\odot$]	$f(m) = 0.0857$	Bopp & Dempsey (1989)
Spectral Type	K1 III	Strassmeier et al. (1993)
Distance [pc]	58.8	Jenkins (1952)
Radii [$R_\odot$]	14.7	Allen (1973)
V	$4^m.14$	Strassmeier et al. (1988)
$B-V$	$1^m.122$	Strassmeier et al. (1988)
$U-B$	$0^m.937$	Strassmeier et al. (1988)
$V-R$	$0^m.92$	Johnson et al. (1966)

emission by more than 50% as the darkest spot region rotated into view during the observational period between Sep. 29 and Oct. 5, 1984.

In this study 54 IUE spectra of σ Gem observed between 1979 and 1986 and reduced by means of NEWSIPS were analysed and some of them were reviewed in detail together with the IUESIPS spectra analysed by Ayres et al. (1984) and by Engvold et al. (1988). The new calibration together with the new image processing techniques have been summarized by Nichols & Linsky (1996). They pointed out that the wavelength and absolute flux errors in the IUESIPS processing could be corrected by NEWSIPS progressing. Chromospheric and transition region line fluxes and equivalent widths were found to vary with time or orbital phase in good agreement with the photometric light curve variation. The results were compared with the Ayres et al. (1984) and Engvold et al. (1988)'s conclusions and it was seen that there are some differences in the line fluxes and radial velocities of the K1 III component that arise mainly from the different reduction procedures (NEWSIPS/IUESIPS). The ultraviolet continuum level of σ Gem does not show any ultraviolet excess compared to the ultraviolet continuum level of β Gem (K0 III). From the Mg II h and k radial curve analysis of σ Gem, we found that the circular primary orbit has $P_{orb.} = 19.607 \pm 0.008$ days, $K = 34.86 \pm 2.33$ km s^{-1}, $\gamma = 49.42 \pm 1.87$ km s^{-1} and $T_o = 2445972.53 \pm 0.28$.

2. IUE data and spectral analysis

The IUE spectra of σ Gem have been taken from the NASA IUE archive using the IDL (Interactive Data Language) Program. All the spectra have a NEWSIPS reduction and consist of 25 LWP, 8 LWR and 5 SWP images in high resolution, and 2 LWP and 14 SWP images in low dispersion. The log of images are given in Table 2. IUE obtained both low dispersion (6 Å resolution) and high dispersion ($\lambda/\delta\lambda \sim 10\,000$) spectra with the short-wavelength prime (SWP: 1150–2000 Å), long-wavelenght prime (LWP: 1850–3400 Å), and long-wavelength redundant (LWR: 1850–3400 Å) cameras (Nichols & Linsky 1996). The spectra show emission lines originating in the chromosphere and transition region. The flux in a given line was obtained by computing the area contained in the spectral region above the continuum or background levels near the wings of the line. The emission line fluxes and their equivalent widths are computed based on Gaussian profile fitting procedures. The fitting procedures were made by means of the CURFIT program of Bevington (1969). Some results of the Gaussian fits are shown in Figs. 1–2. Multiple Gaussian fits were made to the centrally reversed line profiles shown in these figures. The centrally reversed feature was characterized by an absorption. The overall shapes of the line profiles can be reasonably well matched by the sum of 2 or 3 Gaussian components. The absolute integrated line fluxes measured on the Earth for low dispersion spectra are given in Table 3, and the Mg II h and k line fluxes for high dispersion spectra in Tables 4 and 5 respectively, together with their equivalent widths. The orbital phases that correspond to mid-time of IUE observations are computed with the ephemeris

$$\mathrm{JD(Hel)} = 2447227.08 + 19^d.60447E \quad (1)$$

for which the zero phase corresponds to conjunction with the primary (K1 III) component in front (Bopp & Dempsey 1989).

Figure 3 shows that the low dispersion emission line flux variation depends on time and orbital phases obtained from the low dispersion spectra while Figs. 4 and 5 show the Mg II h and k line flux variation with time and orbital phase together with their equivalent width variations. Figure 6 shows the high dispersion line flux variation from SWP images obtained in May 1982 and in Oct. 1984. The high dispersion line fluxes obtained from SWP images taken in May 1982 and Oct. 1984 are given in Table 6. The Mg II h and k radial velocities are given in Table 7 and the radial velocity curves are shown in Fig. 7. In Fig. 8 the Mg II radial velocity curves are compared with the Fe I λ 6173 Å curve of Duemmler et al. (1997) obtained from the SOFIN spectra. By a sinusoidal fitting procedure for the Mg II radial velocity curves we estimate some orbital elements of the primary component of σ Gem. The results are given in Table 8 together with the results of Duemmler et al. (1997) and those of Bopp & Dempsey (1989) for comparison.

The long-wavelength low dispersion spectra were examined for ultraviolet excess, if any, by comparing the ultraviolet continuum level of σ Gem with the level of β Gem (HD 34198) in the same spectral range between 2200 Å and 3350 Å. β Gem was defined as a normal star without chromospheric activity by Fekel & Balachandran (1993). For the continuum level analysis, the flux measured on Earth (=f_λ) can be converted to the surface flux (= F_λ) of a star by means of

$$F_\lambda/f_\lambda = \left(\frac{d}{R}\right)^2 \quad (2)$$

where d is the distance and R is the radius of the star (Gray 1992). If R is in units of solar radii and d in parsecs this relation can be written as

$$F_\lambda/f_\lambda = 1.96555 \times 10^{15}\left(\frac{d(\mathrm{pc})}{R(R_\odot)}\right)^2. \quad (3)$$

With the distance of 58.8 pc (Jenkins 1952) and radius of =14.7 $R_\odot$ (Allen 1973) for σ Gem this relation is

$$F_\lambda/f_\lambda = 3.1449 \times 10^{16} \quad (4)$$

Table 2. The log of IUE observations of σ Gem.

Image	Date	JD(24.000.00+)	Disp.	Exp. Time (min)
LWR05841	15.10.1979	44161.81	H	06
LWR05862	18.10.1979	44164.88	H	06
SWP16943	10.05.1982	45099.86	H	420
LWR13216	10.05.1982	45100.16	H	60
LWR13217	10.05.1982	45100.22	H	25
LWR13218	10.05.1982	45100.26	H	10
SWP16944	11.05.1982	45100.86	H	425
LWR13226	11.05.1982	45101.16	H	60
LWR13227	11.05.1982	45101.23	H	25
LWR13228	11.05.1982	45101.27	H	10
SWP24078	29.09.1984	45973.13	H	757
LWP04450	29.09.1984	45973.44	H	25
LWP04451	30.09.1984	45973.72	H	25
LWP04471	01.10.1984	45974.87	H	25
LWP04472	01.10.1984	45974.94	H	08
LWP04473	01.10.1984	45974.99	H	05
LWP04474	01.10.1984	45975.02	H	23
LWP04480	02.10.1984	45975.93	H	10
LWP04481	02.10.1984	45975.98	H	05
LWP04482	02.10.1984	45976.03	H	08
LWP04487	03.10.1984	45976.74	H	60
LWP04488	03.10.1984	45976.81	H	25
LWP04489	03.10.1984	45976.85	H	10
LWP04490	03.10.1984	45976.88	H	25
LWP04491	03.10.1984	45976.92	H	25
LWP04492	03.10.1984	45976.97	H	10
LWP04493	03.10.1984	45976.99	H	25
SWP24107	03.10.1984	45977.43	H	808
LWP04496	04.10.1984	45977.67	H	25
LWP04506	05.10.1984	45979.39	H	25
SWP24124	05.10.1984	45979.41	H	360
LWP04507	06.10.1984	45979.68	H	25
LWP04573	14.10.1984	45987.74	H	25
LWP04574	14.10.1984	45987.79	H	25
LWP04575	14.10.1984	45987.84	H	10
LWP04582	15.10.1984	45988.75	H	25
LWP04583	15.10.1984	45988.81	H	25
LWP04584	15.10.1984	45988.86	H	10
SWP06872	15.10.1979	44161.75	L	70
SWP06873	15.10.1979	44161.85	L	20
SWP06899	18.10.1979	44164.89	L	25
SWP07265	29.11.1979	44207.04	L	40
SWP07970	17.02.1980	45287.04	L	30
SWP24090	01.10.1984	45974.91	L	10
SWP24091	01.10.1984	45974.97	L	10
SWP24099	02.10.1984	45975.91	L	25
SWP24100	02.10.1984	45975.95	L	10
SWP24101	02.10.1984	45976.00	L	25
SWP24171	14.10.1984	45987.77	L	25
SWP24172	14.10.1984	44987.81	L	25
SWP24173	14.10.1984	45987.86	L	10
SWP24178	15.10.1984	45988.79	L	25
SWP24179	15.10.1984	45988.83	L	25
SWP29306	24.09.1986	46698.03	L	06
LWP15076	22.02.1989	47580.33	L	01
LWP15077	22.02.1989	47580.36	L	05

and for β Gem with d(pc) = 10.34 (The Hipparcos and Tycho Catalogues Sp-1200, JUNE 1997, ESA Hipparcos Space Astrometry Mission) and $R = 11.3\ R_{\odot}$ (McClintock et al. 1975) this relation is

$$F_{\lambda}/f_{\lambda} = 1.6458 \times 10^{15}. \quad (5)$$

LWP 15070 image of β Gem and, LWP 15076 and LWP 15077 images of σ Gem were studied for the investigation of the ultraviolet excess of the σ Gem system. After the polinomial fitting for the continuum levels (see Fig. 9), the integrated fluxes between 2200 Å and 3350 Å were computed for each image. The results are given in Table 9. With the assumption of negligible ultraviolet radiation from the secondary component of σ Gem, we find the surface flux ratio

$$\Delta = (F_{\sigma\mathrm{Gem}})_{\mathrm{av.}}/F_{\beta\mathrm{Gem}} = 0.9288 \quad (6)$$

where $(F_{\sigma\mathrm{Gem}})_{\mathrm{av.}}$ is the average value obtained from the two images of σ Gem. Since σ Gem and β Gem do not have the same effective temperature, this flux ratio must have the value of

$$(T_{\mathrm{e}}(\sigma\mathrm{Gem})/T_{\mathrm{e}}(\beta\mathrm{Gem}))^4 = 0.8435 \quad (7)$$

with $T_{\mathrm{e}}(\sigma\mathrm{Gem}) = 4600$ K and T_{e} (βGem) = 4800 K (Fekel & Balachandran 1993). In the case of no additional radiation or absorption effect, it would be

$$\Phi = [(F_{\sigma\mathrm{Gem}}/F_{\beta\mathrm{Gem}})_{\mathrm{av.}}/(T_{\mathrm{e}}(\sigma\mathrm{Gem})/T_{\mathrm{e}}(\beta\mathrm{Gem}))^4] = 1. \quad (8)$$

But this ratio with the values given above has a value of 1.1012. This means that it may reflect excess radiation in the system but since this evaluation depends strongly on the distances and the radii of the stars , the distances and the radii of both stars must be verified.

With the values of d(pc) = 58.8, $R = 14.7\ R_{\odot}$ (Allen 1973) and $R = 12\ R_{\odot}$ (Strassmeier et al. 1988) for σ Gem, and d(pc) = 10.34 ± 0.11, $R = 9 \pm 1\ R_{\odot}$ (Faucherre et al. 1983) and $R = 11.3\ R_{\odot}$ (McClintock et al. 1975) for β Gem, the results are given in Table 10. On the other hand, in the Hipparcos and Tycho catalogues of the ESA Hipparcos Space Astrometry Mission (1997) the distance for σ Gem (HIP 37629) is given as d(pc) = 37.5 ± 1.2 (π = 26.68 ± 0.79 mas) which is a very different value from the previously published value (d(pc) = 58.8). Based on the confirmation of the value of 37.5 ± 1.2 pc by Perryman (2000) and by using the $\log(L_{\mathrm{x}}/L_{\mathrm{bol.}}) = -3.87$ (Walter et al. 1978) and $T_{\mathrm{e}} = 4600$ K, the radius of the K1 III component of σ Gem is 8.8 $R_{\odot}$. With the radii of 8.8 $R_{\odot}$ and 12 $R_{\odot}$ and the distance of 37.5 pc for σ Gem, and the radii of 9.0 $R_{\odot}$ and 11.3 $R_{\odot}$ and the distance of 10.34 pc for β Gem, the values of Δ and Φ have been obtained as given in Table 11. For different distances and radii, the ultraviolet continuum level comparisons for three images (LWP 15070, LWP 15076, and LWP 15077) are shown in Fig. 10. According to the d(pc) = 58.8 and $R = 12\ R_{\odot}$ or $R = 14.7\ R_{\odot}$ for σ Gem the evaluations gave an excess of the order of 12% but with the evaluations for the d(pc) = 37.5 and $R = 8.8\ R_{\odot}$ or $R = 12\ R_{\odot}$, it can be easily seen that there is no ultraviolet excess in the σ Gem system. These evaluations of excess radiation show that it is very difficult to conclude that an ultraviolet excess exists in σ Gem.

3. Conclusions and discussion

The integrated emission line fluxes of low dispersion spectra show a clear variation with time and orbital phase (see Fig. 3). For the high resolution Mg II emission lines (Figs. 4 and 5) this variation appears more scattered than the variation of the low-dispersion emission lines. In spite of this scattering it can be clearly seen that the fluxes and equivalent widths of Mg II lines varied with time and orbital phase that shows the activity phenomena of σ Gem in UV. These flux variations with orbital phase are seen in close relation to the photometric light curve variation of the system. Thus, when the spotted region moves into the line of sight, the strength of the emission lines is increased. For example, when the spot B was dominant on the 1984 light curves of σ Gem (Strassmeier et al. 1988) around 0.2 P (in the −63th epoch), all the chromospheric and transition-regional lines were at their highest flux levels (see Figs. 3–5). This relation of the flux enhancement-spot visibilities are well-known characteristics of chromospherically active binaries. But the He II (λ1640) fluxes may contribute due to collisional excitation (Athay 1965; Jordan1975) indicating a temperature of $\sim 8 \times 10^4$ K and recombination following photo ionization by coronal X-rays (Zirin 1976). The contribution of recombination to the He II flux increases up to 80% in the more active region (Rego et al. 1983). Another contributor to He II is the Fe II λ1640.15 emission (Jordan 1975; Kohl 1977). Therefore, this 1640 Å feature cannot be considered as a pure chromospheric indicator for σ Gem.

Integrated fluxes of emission lines appeared in the spectra observed on May 10 and May 11, 1982 (SWP16943, SWP16944, LWR13216, LWR13217, LWR13218, LWP13226, LWP13227 and LWP13228) show a decreasing trend (see Fig. 6 and Tables 4–6). This variation appeared in a higher order for the lines originating in the transition-region than for the chromospheric lines. The ratios of variation for the lines originating in the transition-region were 1.54 for N V, 1.97 for Si IV and 1.27 for C II, and for chromospheric lines the ratios were 1.04 for O I and 1.05 for Si II (see Table 6). For chromospheric Mg II lines these ratios (Tables 4 and 5) were 1.03 for Mg II h and 1.06 for Mg II k in agreement with the ratios of the other chromospheric lines. This trend was first seen by Ayres et al. (1984) by analysing the same spectra but with IUESIPS reduction procedures. They found that the variations were of the order of 1.42 for N V and C II lines, of 1.11 for O I, Si II and C I lines and for Mg I and Mg II lines were of the order of 1.06. There are noticeable differences between our ratios and the ratios of Ayres et al. (1984) especially for the lines originating in the transition-region which could have arisen from different reduction procedures (IUESIPS/NEWSIPS). On the other hand Engvold et al. (1988) have pointed out the relation between this flux decrease and the locations of dominant two star-spots. The spotted region designated as B (Fried et al. 1983) was located near the receding limb of the star on May 10. As the star rotates, the dark spot B moved behind the visible hemisphere of the primary component on May 11. As this active region disappears on the visible hemisphere, the UV line fluxes will change and diminish. But the spotted region designated as "A" by Fried et al. (1983) was located on the visible hemisphere on these two days (May 10 and 11). However, it is pointed out that spot B had a more dominant effect than spot A on the photometric light curves in 1982 (Fried et al. 1983). Increased diminishing of the transition regional lines relative to the chromospheric lines suggests that the diminishing of the transition regional lines are closely related to the longitudional position of spot B as the star rotates. In addition, there are asymmetries in the N V, C II, Si IV and C IV profiles toward the long wavelength in the spectra observed on May 10 while no asymmetries were observed for the same profiles on May 11. As indicated by Engvold et al. (1988), the sign of the asymmetry would imply a red-shift of this feature in the UV spectra, and it is in agreement with the receding of spot B.

The variation of the integrated line fluxes obtained from the spectra taken in 1984 also show a relation between this flux variation and the longitudinal positions of the spotted regions designated as "A" and "B". On Sep. 29, 1984 spot A was located on the approaching limb of the star while spot B was located behind the approaching limb (see Engvold et al. 1988). At this time the chromospheric lines were in enhancement which is associated with the appearence of spot A. On Oct. 3, 1984 both of the chromospheric and transition regional lines have some enhanced flux that could be attributed to the appearance of spot B on the visible hemisphere of the star together with the location of spot A in the direction of the line of sight. There are some decreases in the chromospheric lines while the lines of the transition region (N V, SiIV and C IV) show a progressive enhancement on Oct. 5, 1984. This decreasing of the chromospheric line fluxes associated with the disappearance of spot A from the line of sight, and the enhancement of the N V, Si IV and C IV line fluxes (see Fig. 6), occur due to the location of spot B close to the line of sight at the same time. Moreover, the correlations between Mg II flux/equivalent width variation and the location of spot A are clearly seen by close examination of the values given in Tables 4 and 5. The Mg II fluxes and equivalent widths begin to increase around 0.14 P and they reach maximum values around 0.18 P. Finally, they reduce to the initial values (at 0.14 P) around 0.23 P (see Figs. 4 and 5). At this epoch the effect of spot A appeared between 0.14 P and 0.23 P phases on the light curves of the system (Strassmeier et al. 1988). The same characteristics are seen in the low dispersion SWP24099, SWP24100 and SWP24101 images which correspond to the 0.18 orbital phase (see Table 3).

From the analysis of the sinusoidal radial velocity curves of Mg II h and k lines, the following orbital parameters have been found:

$P_{\rm orb.} = 19.607 \pm 0.008$ days
$K = 34.86 \pm 2.33$ km s^{-1}
$\gamma = 49.42 \pm 1.87$ km s^{-1}
$T_{\rm o} = 2445972.53 \pm 0.28$.

These results are in agreement with the results of Eker (1986) and of Duemmler et al. (1997) except for γ. From the optical spectral lines it was found that the γ is of the order of 44 km s^{-1} (see Table 8). By using the H_α lines, Eker (1986) found the value of 45.48 km s^{-1} for γ.

From the comparison of the ultraviolet continuum level of σ Gem with the level of β Gem in the range $\lambda\lambda$2200 Å–3350 Å, it was concluded that it is very difficult to say that there is an ultraviolet excess in the σ Gem system. Ayres et al. (1984) has found no evidence for circumstellar absorption features.

Searches for cyclic changes by Henry et al. (1995) gave the cycle of 8.5 years of σ Gem based on spot rotation period and cyclic changes in mean brightness and $B - V$ color index. Unfortunately, since the ultraviolet flux data are not conveniently distributed and are insufficient to determine the activity cycle, we are unable to find similar cyclic changes for chromospheric activity based on the flux variations.

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