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ASTRONOMY AND ASTROPHYSICS

Long-term changes of the Be star OT Geminorum

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Abstract. We investigate the character of light variability of the bright Be star OT Gem. Two phases of the long-term light changes were distinguished:

- a quiet phase which is characterized by mild light changes; and
- an active phase in which the sudden increases of brightness up to $0\overset{\text{m}}{.}4$ in V occur. During the active phases, a cyclic oscillation of brightness of a period between 70 and 80 days is present, with the most probable value being $71\overset{\text{d}}{.}89$.

A positive correlation was found between the light and colour variations and the emission strength in both phases.

Key words: stars: variables: general – stars: individual: OT Gem – stars: emission-line, Be

1. Introduction

OT Gem (HD 58050, HR 2817, BD +15°1564, MWC 176, B2Ve, V=$6\overset{\text{m}}{.}4$-$6\overset{\text{m}}{.}0$, v sin i = 130 km s^{-1}) is a bright Be star which exhibited strong spectral variations during the past 60 years. The first evidence of the emission changes was presented by Merrill & Burwell (1943). The spectroscopic behaviour between 1954 to 1975 is described by Hubert-Delplace & Hubert (1979), where the strong emission of Balmer and Fe II lines is clearly seen. The strength of the emission is steadily decreasing after the maximum in 1961–62, with intermittent variations. Hubert-Delplace et al. (1982) reported the Hβ line variation and showed that the strength of the emission was secularly fading from 1961, reaching a minimum at the end of 1980. The history of photometric and especially photoelectric observations of OT Gem is not too long. That OT Gem could be a rapid variable was first recognised by Hoffmeister (1934) who, using photographic photometry, detected the rapid light variations ranging from $6\overset{\text{m}}{.}0$ to $6\overset{\text{m}}{.}3$. Until the eighties, only two measurements in the UBV photometric system were obtained: one by Mendoza (1958) ($V = 6.34$, $B - V = -0.13$, $U - B = -0.93$) and one by Crawford et al. (1971) ($V = 6.44$, $B - V = -0.20$, $U - B = -0.81$). Based on visual photometry, Figer (1981) announced two types of variability of OT Gem, a $0\overset{\text{m}}{.}4$ amplitude long-term increase of light from the end of 1980 until the beginning of 1981, and a periodic rapid variation with the strict period of $0\overset{\text{d}}{.}12500$ (or $0\overset{\text{d}}{.}14286$) with an amplitude of $0\overset{\text{m}}{.}15$. Differential UBV photoelectric measurements made at Hvar Observatory during five nights in January 1982 by Božić et al. (1982) did not show the presence of rapid variability. The lack of short periodic light variations was also independently confirmed by differential UBV measurements from Merate Observatory by Poretti (1982), who observed the star during three nights in January and March 1982.

Shortly thereafter, Berthold (1983) published a photographic light curve of OT Gem for the period from 1960 to 1980 based on the 272 Sonneberg Sky Patrol plates. In the first part of this period (JD 2437200–2440000) the light changes were irregular, while later some type of slow cyclic variations appeared. These variations do not exceed 0.4 of photographic magnitude. The last part of this light curve confirmed the light increase observed by Figer at the end of 1980. Alvarez & Schuster (1981) and Schuster & Guichard (1984) classified OT Gem as a possible variable from their 13-colour photometry at San Pedro Mártir. Their subsequent observations between 1980 and 1983 revealed large brightness and colour variations – see Schuster & Guichard (1984). In the summary report on UBV photometry of Be stars carried out at the Hvar Observatory between 1972 and 1990 by Pavlovski et al. (1997) and Harmanec et al. (1997), a small secular brightness decrease of OT Gem over four consecutive seasons was found. Ferro et al. (1998) analysed a set of photoelectric and visual measurements obtained in 1995–96 at La Luz Observatory and announced a light increase of OT Gem in October 1995 followed by a very active phase in which cyclic light variations appeared.

Photometric variations of Be stars usually occur on at least three time scales: long-term, medium-term and short-term ones – see, e.g., Harmanec (1983). Pavlovski et al. (1997) recognized a fourth possible class of photometric variability: a sudden light change. In their analysis of the photometric behaviour of the large set of Be stars based the Hipparcos photometry, Hubert & Floquet (1998) reported also several different types of medium-term changes: outbursts, fadings and quasi-periodic oscillations.

Our intention was to analyze the photometric behaviour of OT Gem over the whole period covered by photoelectric observations and to compare brightness and colour variations with the parallel spectral changes of the object.

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2. Observations and reductions

OT Gem has been observed at Hvar Observatory as a part of the international campaign on photometry of bright Be stars (Pavlovski et al. 1997) from 1982 to 1985. Observations were resumed in 1996 to check on the long-term variations. All Hvar measurements were carefully reduced and transformed to the Johnson UBV system with the help of the reduction program HEC22 – see Harmanec et al. (1994) and Harmanec & Horn (1998). The journal of Hvar observations is presented in Table 1. The long-term light changes, already reported by Pavlovski et al. (1997), are clearly visible in later years. The brightness increase observed in the last seasons is in accordance with the result of Ferro et al. (1998). In order to give a more detailed description of the light and colour changes, we collected all available published photometric measurements of OT Gem. Basic information about the data sets used to study long and medium term variations is collected in Table 2.

In order to transform the 13-colour photometry of Schuster & Guichard (1984) to the standard UBV system, we selected from Table 7 of Johnson & Mitchell (1975) those stars which were used by Harmanec (1998b) to derive the H_p to UBV transformation. They have accurate UBV magnitudes derived from a huge amount of photoelectric observations secured at Hvar and Skalnaté Pleso Observatories (Harmanec et al. 1994) and were checked for constancy by comparing with the Hipparcos photometry. We arrived at the following transformation formulas:

$$\begin{aligned} V &= m_{55} + 0.01930(m_{43} - m_{55}) + 0.01830(m_{35} - m_{43}) \\ &\quad -0.06538(m_{43} - m_{58})^2 + 0.02411(m_{43} - m_{58})^3 \\ &\quad +0.01434 \\ B &= m_{43} - 0.03528(m_{43} - m_{58}) + 0.01464(m_{35} - m_{43}) \\ &\quad -0.02873(m_{43} - m_{58})^2 - 0.03429(m_{43} - m_{58})^3 \\ &\quad +0.00006 \\ U &= m_{35} + 0.10478(m_{43} - m_{58}) - 0.15289(m_{34} - m_{43}) \\ &\quad +0.11294(m_{43} - m_{58})^2 - 0.06538(m_{43} - m_{58})^3 \\ &\quad +0.01686. \end{aligned}$$

To obtain the V magnitudes of OT Gem published by Ferro et al. (1998), we proceeded as follows. First, we derived the mean V magnitude of their comparison star HR 2780 from the transformed Hipparcos H_p magnitude. This value, $6^\mathrm{m}\!.451$, was then added to the magnitude differences OT Gem- HR 2780 from Table 1 of Ferro et al. (1998).

Hipparcos H_p magnitudes published by Perryman et al. (1997) were transformed to Johnson V and B magnitudes with the help of the transformation formulas derived by Harmanec (1998b).

Transformed Hipparcos and 13-colour photometry, La Luz and Hvar measurements are collected in Table 3.[1]

[1] Table 3 is only available in electronic form, see the Editorial in A&AS 103, No.1 (1994)

Table 1. Journal of Hvar UBV observations of OT Gem

Season	Epoch	No. of obs.	Seasonal mean V
1981/82	44977–45069	95	$6^\mathrm{m}\!.443 \pm 0.012$
1982/83	45346–45360	16	$6^\mathrm{m}\!.470 \pm 0.009$
1983/84	45661–45697	6	$6^\mathrm{m}\!.471 \pm 0.020$
1984/84	46095–46159	8	$6^\mathrm{m}\!.484 \pm 0.005$
1994/95	49730–49751	4	$6^\mathrm{m}\!.458 \pm 0.003$
1995/96	50087	2	$6^\mathrm{m}\!.097 \pm 0.005$
1997/98	50863–50910	39	$6^\mathrm{m}\!.195 \pm 0.053$
1998/99	51075–51102	11	$6^\mathrm{m}\!.421 \pm 0.005$
Star	V	$B-V$	$U-B$
1 CMi	5.393	0.100	0.132
HR 2858	6.252	-0.047	-0.109

Comment: All observations were made by 0.65 m Cassegrain reflector at Hvar Observatory with uncooled EMI 6256S photomultiplier. UBV magnitudes for the comparison star 1 CMi and for the check star HR 2858 are from Harmanec et al. (1994).

Table 2. Published photoelectric observations of OT Gem

Source	Epoch (JD-2400000)	No. of obs.	Phot system	Comparison /Check star
1	45000–45045	28	UBV	HR 2858 /HD 60107
2	50093–50195	38	UBV	HD 60107 /HR 2858
3	45013–45016	1	UBV	-
4	47966–49046	96	H_p	-
5	45400–45443	3	13-C	-

Sources: 1. Poretti (1982); 2. Ferro et al. (1998); 3. Dachs et al. (1988); 4. Perryman et al. (1997); 5. Schuster & Guichard (1984)

3. Analysis

In Fig. 1 we plot the nightly mean V magnitudes vs. HJD for all observations from Table 3. of OT Gem (middle panel) and the check star HR 2858 (bottom panel). The larger scatter in the check star in the last two seasons of Hvar measurement is due to a bad weather conditions. From HJD 2444977 to 2446259 the brightness of OT Gem moderately decreases. After the period not covered with measurements the star passed through three active phases. The first sudden brightening was detecteded by the Hipparcos satellite (HJD from 2448705 to 2449046), the second one by the measurements from La Luz and Hvar Observatories (HJD from 2450087 to 2450195) and the third one from Hvar Observatory (HJD from 2450863 to 2450910). Between the second and third active phase, OT Gem reached its minimum brightness as reported by Ferro et al. (1998).

During the first two outbursts, the brightness of OT Gem obviously exhibited cyclic variations. Ferro et al. (1998) formally derived the 83 and 45 day periods from the full set of individual observations or the 77 and 48 day periods from the nightly means. They interpreted these “periods” as characteristic times of the long-term variations but not as a strict periodicity.

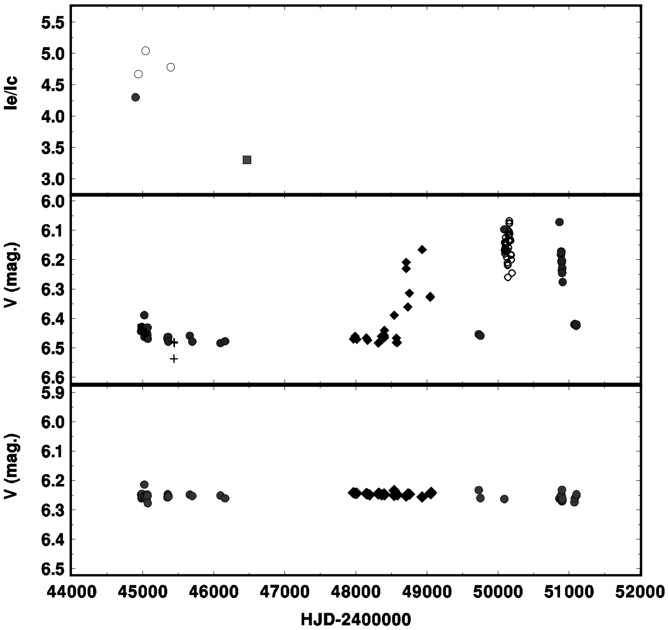

Fig. 1. Upper panel – Hα intensities of OT Gem vs. time (solid circle – Andrillat (1983), open circles – Dachs et al. (1986), solid box – Doazan et al. (1991). Middle panel – The nightly means of photometric measurements of OT Gem vs. time (solid circles – Hvar, open circles – La Luz, solid diamonds – Hipparcos, solid triangles – Merate, pluses – San Pedro Mártir). Bottom panel – The nightly means of the check star HR 2858

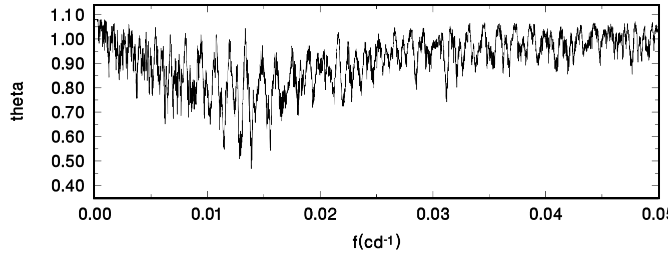

Fig. 2. Stellingwerf's θ statistics of OT Gem for the bin/cover structure (10,4)

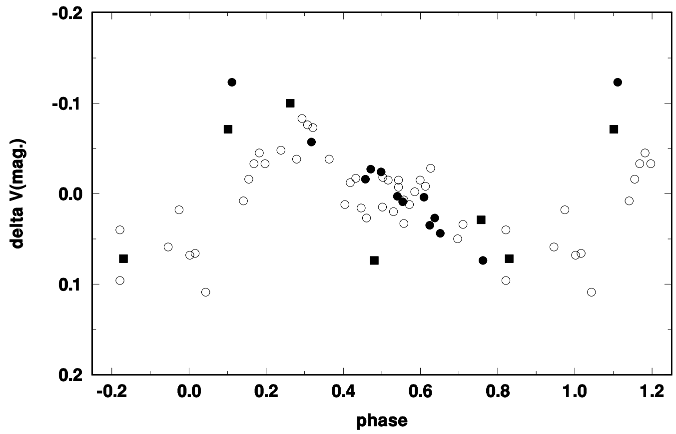

Fig. 3. Phase diagram of the light variations of OT Gem for $71\overset{\mathrm{d}}{.}8907$ period. The prewhitened V magnitudes are plotted on the Y-axis. The following symbols are used: solid circles... Hvar, open circles... La Luz, solid boxes... Hipparcos

To check on their results, we used all nightly means of La Luz, Hvar and Hipparcos V magnitudes and carried out the frequency analysis, taking into account measurements from the active phases only. We removed the long-term trend by the program HEC13 (Harmanec, private communication), based on the smoothing technique derived by Vondrák (1969) and Vondrák (1977), and using the smoothing parameter $\epsilon = 10^{-16}$. The prewhitened values were submitted to Stellingwerf's (1978) PDM period search technique as well as to Deeming (1975) Fourier analysis over the frequency range from 0 to 0.05 c d^{-1} and with a frequency step of 10^{-5}. The PDM method detected as the best frequences the values of 0.01388 c d^{-1} ($72\overset{\mathrm{d}}{.}0461$) and 0.01391 c d^{-1} ($71\overset{\mathrm{d}}{.}8907$) for the bin/cover structure (5,2) and (10,4) respectively, whereas the Fourier analysis gave 0.01295 c d^{-1} ($77\overset{\mathrm{d}}{.}2201$). In Fig. 2 we plot Stellingwerf's Θ statistics. We believe that such variations are cyclic rather than strictly periodic. From Fig. 1 in Ferro et al. (1998) it is obvious that the oscillations of OT Gem are non-sinusoidal, so we prefer the $71\overset{\mathrm{d}}{.}8907$ period as the best representation of the cyclic variations. The corresponding phase diagram is in Fig. 3.

The presence of the $0\overset{\mathrm{m}}{.}15$ short-term variations announced by Ferro et al. (1998) was already questioned by Božić et al. (1982) and Poretti (1982) but they did not carry out the frequency analysis because of their limited data sets. Ferro et al. (1998) reported that they were not able to find a short term period from their frequency analysis. Because of the large light variations in the later seasons, we restricted our analysis to the "quiet" period. Performing the Fourier and PDM analysis in the frequency range from 0.5 to 10 c d^{-1} we did not find any significant period. On the other hand, a close look at the Hipparcos measurements reveals the presence of the one day increasing and one day fading of the brightness of the order of $0\overset{\mathrm{m}}{.}05$. The character of these variations is not clear because of the lack of longer series of observations.

4. Discussion

The character of light and spectral changes of Be stars and their mutual correlation has been the subject of a number of statistical investigations. Nordth & Olofson (1977) and Hirata (1981) showed that for the majority of Be variables the light increase is connected with the reddening of $B-V$ index and blueing of $U-B$. Dachs (1982) found a correlation between the light changes and the intensity of emission and shell lines in the sense that the light maxima correspond to larger equivalent widths, while the light minima are connected with the intensity-maxima of the shell lines.

The concept of a positive and inverse correlation was formulated by Harmanec (1983) and Harmanec (1994). The positive correlation is characterised by simultaneous increase of both the Balmer emission and the brightness, while in the colour diagram the star is changing its luminosity but not the spectral class. A light decrease along with the strengthening of the Balmer emission and, at the same time, a change of spectral but

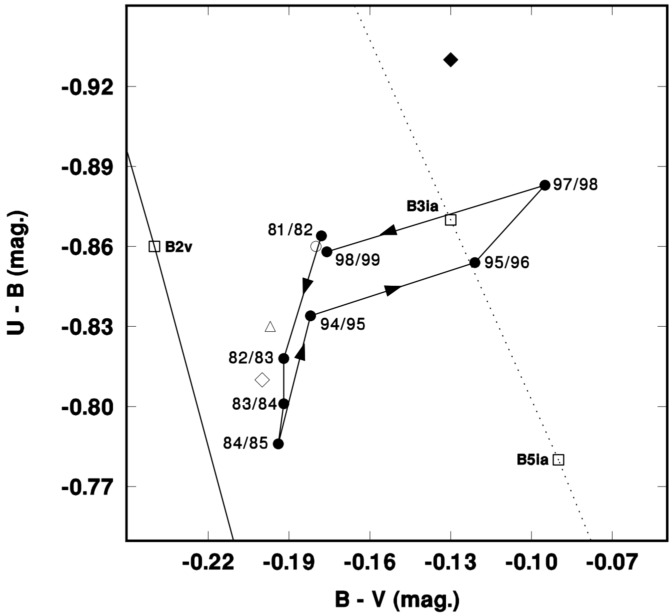

Fig. 4. The U-B vs. B-V diagram for OT Gem.The following symbols are used: solid boxes... Hvar, solid diamond... Mendoza (1958), open circle... Dachs et al. (1988), open triangle... Schuster & Guichard (1984), open diamond... Crawford et al. (1971)

not luminosity class is the characteristic of inverse correlation. Harmanec (1983) interpreted the existence of the two types of correlation as the aspect effect, the inverse correlation being observed for stars seen roughly equator-on. This hypothesis was supported by Hubert & Floquet (1998) who have shown that the brightenings are characteristic for Be stars having small v sin i values while the fadings are associated with the rapid rotators.

In Fig. 4 we present the $U-B/B-V$ diagram for the seasonal means of OT Gem. It is seen that during the first four seasons of Hvar measurements, the star is becoming redder in $U-B$ and slightly bluer in $B-V$. From 1992 to 1998 (HJD 2448705–2450195) OT Gem passed through at least three major brightenings with an amplitude up to $0\overset{m}{.}4$ in V. It is seen from Fig. 4 that the star in the active phases moved toward the supergiant sequence of the $U-B/B-V$ diagram. Such behaviour is typical for the positive correlation in Harmanec's scheme. The lack of spectroscopic data at the time of outbursts does not allow us to search for the correlation between the emission and the position of OT Gem in the colour diagram.

According to Hubert & Floquet (1998) sudden brightenings in Be stars are more frequent in early Be stars and there are three categories of their manifestation: i) reccurent short-lived outbursts, ii) long lived outbursts and iii) outbursts closely linked to a temporary Be phase or strong emission line variations. OT Gem should be classified as a member of the second class that is characterized by amplitude variations from 0.15 to 0.35 in $H_{\rm p}$ and by the duration of an outburst that exceed several hundreds days.

There are several other Be stars that exhibit behaviour similar as OT Gem. Pavlovski et al. (1997) have found that 2 out of 48 objects from their set of well observed Be stars show occasional sudden brightenings, o Cas Horn et al. (1985) and QR Vul Pavlovski et al. (1983). The measurements secured at Hvar Observatory indicate a positive correlation in the $U-B/B-V$ diagram for these stars.

The well known rapid light and spectroscopic Be variable ω CMa shows outbursts with a maximum amplitude of $0\overset{m}{.}4$ as well as a positive correlation between the emission strength and the brightness - see Harmanec (1998a) and Štefl et al. (1998). Mennickent et al. (1994) announced that at the active phase the light changes of the star showed quasi-periodic oscillations up to $0\overset{m}{.}1$ with a mean period of 25 days. Using a larger data sets Harmanec (1998a) was able to uncover the $34\overset{d}{.}67$ period both from spectroscopic and photometric data. He has also pointed out the possibility that those variations could be explained by the orbital motion in a binary system with a highly eccentic orbit.

Recently, Carrier et al. (1999) have discovered the new Be variable HR 2968 in the the open cluster NGC 2451. They showed that the luminosity of the star started to increase in 1990 after a longer period of constancy. The increase of brightness was accompanied with oscillations around the mean light curve with a period of 371 days and an amplitude of $0\overset{m}{.}08$ to $0\overset{m}{.}10$. In the colour-colour diagram the star is moving from the main sequence toward the supergiant sequence indicating again a positive correlation.

There are convincing arguments that OT Gem is observed under an inclination far from $90°$. An estimate made by Rusalep (1989) put the value of the inclination in the range from $60°$ to $80°$. Slettebak (1994) derived a rather low rotational velocity v sin i = 130 km s^{-1} for OT Gem. Hanuschik (1996) classified OT Gem as a non-shell star and concluded that a significant part of the disk is projected against the sky. The variation of the dimension and/or density of the inner disk may then act as an apparent change of the radius of the object causing both the light and colour variations (see Harmanec 1983). Harmanec (1998a) describes the long-term variability and the outbursts of ω CMa as a manifestation of the formation and gradual dispersal of the circumstellar gaseous envelope. Variations of OT Gem are in many aspects similar to that of ω CMa and we believe that they can be explained by the same physical process. Such an idea was also suggested by Koubský et al. (1997) for the explanation of the spectral and photometric variations of the Be binary 4 Her, though for the case of an inverse correlation. In that scheme, the new optically-thick envelope that is created near the photospere in the equatorial region can simulate the stellar photosphere. Consequently, the apparent radius of the object grows and the brightness increases. At the same time, the star moves toward the supergiant sequence in the $U-B/B-V$ diagram. As the envelope expands and rarifies, it becomes optically thin and brightness fades while in the $U-B/B-V$ diagram the star goes back to the main sequence.

Such a scenario is in good agreement with the light and colour changes of OT Gem. The precursor to the quiet phase was the sudden light increase observed by Figer (1981) in 1980–81. Hubert-Delplace et al. (1982) reported that the Balmer discontinuity in 1979 had been seen in absorption but in November

1980 it was in emission. According to Divan et al. (1982), Be stars have two Balmer discontinuities, one belonging to the underlying star and another one corresponding to a low density plasma in the envelope. The variations occur only in the later. A rise of the Balmer discontinuity may be an indication of the formation of the new envelope.

It should be mentioned that in the concept described above, the emission reaches a maximum *after* the light maximum as is certainly observed in the case of ω CMa– see, e.g., Harmanec (1998a). In the later stages of the envelope evolution when the disk is rarified, the brightness and emission both decrease. This closely resembles the spectral and photometric behaviour of OT Gem during the quiet phase from HJD 2444977 to 2446159. The previous episode of a large brightening of the star (not shown in the diagram, but documented by visual and photographic observations by Figer (1981) and Berthold (1983)) was obviously followed, with some delay, by a steep increase and a gradual decrease of the Hα emission (see Fig. 1). In the $U-B/B-V$ diagram, the star was moving towards the main sequence changing its photometric luminosity class with $B-V$ remaining nearly constant.

Notably, a binary interpretation of the *cyclic* light variations was put forward in all above-mentioned cases. Ferro et al. (1998) investigated the possibility that the cyclic light variations of OT Gem during the active phase with a period between 70 and 80 days are caused by tidal effects of the unseen companion in an eccentric orbit but they were not able to find any evidence of binarity. As an explanation of the $34\overset{\rm d}{.}67$ period in ω CMa Harmanec (1998a) has suggested that the object could be a binary in an eccentric orbit. To explain the 371-d photometric period of the Be star HR 2968 Carrier et al. (1999) proposed also a binary model in which the secondary in a highly eccentric orbit interacts gravitationaly and radiatively with the disk around the primary. At the moment, because of the lack of spectral observations, we were unable to check on the possible duplicity of OT Gem. Such a possibility should, however, be tested by dedicated observations of all above-mentioned objects.

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