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Infrared observations of peculiar carbon stars*

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Abstract. We present a uniform and high quality set of infrared photometric (JHK) observations of the 6 peculiar carbon giant stars V Ari, UV Cam, BD+34 911, TU Gem, BD+57 2161 and BD+34 4134. All of these belong to the small group of known cool CH giants populating the Galactic halo. Comparison of the $J-H$ and $H-K$ colours to "normal" C stars show our stars to be "bluer" (i.e., having lower values of $J-H$ and $H-K$) than the bulk of the Galactic C stars. Comparison with synthetic JHK colours reveal 5 of our 6 stars as having considerably lower metallicities and/or higher temperatures than the bulk. Using standard assumptions we derive estimates of their effective temperatures, gravities, luminosities and distances. Their derived luminosities place them close to (or below) the theoretical first He shell flash luminosity, although other observations indicate their carbon excess to be intrinsic.

Key words: stars: evolution – stars: carbon – infrared: stars – stars: fundamental parameters

1. Introduction

Carbon stars have many molecular bands and often strong circumstellar emission which affect their energy distribution (e.g. Noguchi el al. 1981). Having a characteristic 3 micron absorption, where the main contributors are HCN and C_2H_2, they do not show a minimum in the photospheric continuum absorption at 1.6 micron (i.e. H band), indicating that H^- and H_2O are not major contributors to their opacity, as is the case for K and M stars (Bahng 1969). The presence of circumstellar envelopes is manifested by their IR colours being generally non-photospheric with strong excesses at mid- and far-IR wavelengths (Claussen et al. 1987). Noguchi el al. suggested that circumstellar emission contributed only significantly for those C stars with $I-L$ $\geq$ 3.5 mag.

In the $J-H$ vs. $H-K$ diagram, unlike G, K or M stars, C stars tend to occupy a line close to the black-body (BB) line (Bahng 1969; Gao et al. 1985; Gigoyan et al. 1994). According to Chen et al. (1984) this behaviour indicates that re-radiation by circumstellar dust is smaller in C stars than in M giants. Bergeat & Lunel (1980) found C stars to populate a steep strip for $J-H$ $>$ 1, with the cool Miras populating the reddest part. While the circumstellar contribution to the J band was found very small, increasing reddening by cooler and thicker particles in the shell was the main explanation provided for the strip orientation by Bergeat & Lunel. Most of C stars in the sample studied by Gao et al. (1985) were found to fall in the range 0.7 $< J-H <$ 1.3 and 0.4 $< H-K <$ 0.9, compatible with earlier results. Five of the six stars in our sample fall at the blue side (i.e., smaller $J-H$ and $H-K$). Claussen et al. (1987) noticed that although C stars are common optical variables, only a few of their targets displayed a variation in K larger than 0.5 mag.

The general scenario for carbon stars is that they are formed when the helium shell flashes during the thermally pulsing asymptotic giant branch (TP-AGB) evolution bring sufficient freshly synthesized carbon to the surface. Several groups of carbon stars have luminosities far below the lower luminosity limit for the TP-AGB evolution stage. For them this scenario obviously does not work. Some of these low luminosity stars are believed to have gained their excess carbon and heavy s-process elements by mass transfer in close binary systems from the now post-AGB component which had higher mass and reached the TP stage. The mass transfer scenario is generally believed to apply to the barium stars, sub-giant CH stars and earlier spectral-type CH giants (Lambert 1985, Smith et al. 1993). Some members of the small group of known cool CH stars associated with the Galactic halo, on the other hand, do not fit this scenario (Kipper & Jørgensen 1994). Also, among late type CH stars very few are found to be binaries. The study of late-type CH stars suffers

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* Based on observations made with the Carlos Sánchez Telescope operated on the island of Tenerife by the Instituto de Astrofísica de Canarias in the Spanish Observatorio del Teide.

Table 1. List of observed objects in the JHK bands. Most common names – including their HIPPARCOS Input Catalogue (HIC) number, coordinates (Epoch 2000.0) and published spectral type for program stars are included.

No.	Names					RA			Dec			Sp. type
	C⋆	V⋆	BD	HD	HIC	hh	mm	ss	^{o}	'	"	HD/C/Variab.
1	93	V Ari	+11 305	13826	10472	02	14	59.77	+12	14	20.9	R8,Nb/C4,4 CH/SRb
2	177	UV Cam	+61 667	25408	19115	04	05	53.72	+61	47	39.6	R8/C5,4 J/SR(?)
3	246	-	+34 911	30443	22403	04	49	15.98	+35	00	06.8	R4,Nb/C4,3 CH/
4	461	TU Gem	+26 1117	42272	-	06	10	53.07	+26	00	53.9	N3/C5,4/ SRb
5	2884	-	+57 2161	-	99725	20	14	07.00	+58	05	54.0	R0/C1,1 CH/
6	2925	-	+34 4134	197604	102292	20	43	42.00	+35	05	00.0	R2-3/C3,2 CH/

BD+34 911: only star in this sample known to be binary.
Spectral types from Sleivyté & Bartkevicius (1990).

Table 2. Magnitudes and other physical parameters compiled from the literature.

No.	V	B-V	E(B-V)*	Mv	P(d)+	d(kpc)	refs.
1	8.45-10.8	2.05-2.13	0.05	-2.6	77		1,2 (a,b)
2	7.6-9.9	2.26	0.30:	-2.4	294	0.8	2,3,4
						1.07	5
3	8.89	2.08	0.35	-2.3	2954(77)		2,4,6
4	7.29-12.5	2.77	0.15	-1.7	230	0.8	2,3,7
						0.65	1,3,5
5	9.6	1.75	0.15:	-2.6			8
6	9.17	1.44	0.25	-1.3			2

*(:) after E(B-V) means 'uncertain' value.
+: P(d) corresponds to light variation periods (in days) other than for ref. (6)
(a): $U-B$=2.25-2.43 (SIMBAD). (b): $B-V$=2.03, 2.22 (Mannery & Wallerstein 1970).
(1): Bouigue (1954) (vibrational temperatures).
(2): Sleivyté & Bartkevicius (1990).
(3): Peery (1975).
(4): Baumert (1972) (IR colour temperatures).
(5): Claussen et al. (1987).
(6): McClure & Woodsworth (1990) (orbital period from radial velocities).
(7): Gao et al. (1985).
(8): Bartkevicius & Sleivyté (1983).

from the usual difficulties in knowing their temperatures and luminosities.

We therefore seek to obtain observational data of as high and uniform quality as possible in order to make a good determination of stellar parameters possible. Our computations are based on standard published relationships and assumptions together with comparison with our synthetic JHK colours.

Our objects are presented in Table 1, while Table 2 compiles some basic information about them from the literature together with corresponding references. According to their Harvard classification, the first four stars in Table 1 are quite late type and the last two of earlier type; this is also the case according to C classification (Sleivyté & Bartkevicius 1990, Tsuji 1981). For the calculation of distances, compiled from the literature in Table 2, Claussen et al. (1987) assumed that all C stars have the same luminosity at 2.2 micron (i.e. $M_K=-8.1$).

Our paper is organized as follows: The new JHK magnitudes are presented in Sect. 2, together with particulars about the observations and reductions, and a comparison is made with IR magnitudes from the literature. Sect. 3 deals with the computation of IR colours, distances, luminosities, effective temperatures and gravities. Our results are summarized in Sect. 4.

2. IR observations and data calibration

The JHK photometry was obtained for the objects in Table 1 with the 1.5m *Carlos Sánchez* Telescope (CST) (Arribas & Martínez-Roger 1987) at the Observatorio del Teide (Tenerife), on October 21 (BD+57 2161 and BD+34 911) 22 (BD+34 4134 and V Ari) and 25 (UV Cam and TU Gem), 1994. A 15" aperture was employed and typical exposure times of 1-2 minutes for each filter were used for single integrations. The targets were repeatedly measured in order to minimize errors and averaged JH and K magnitudes are presented in Table 3 together with their corresponding 1 σ counting-statistic uncertainties.

A detailed description of the photometric system at the CST can be found in Alonso et al. (1994), together with the corresponding equations to convert CST values to the Johnson system and vice versa. However, as their standard deviations are larger than our observational errors, our data have not been converted into standard Johnson magnitudes.

Table 3. Results from the Oct. 1994 run at the CST. Each entry is the result of averaging of 3 or more integrations. All values are dereddened. The modified Julian observation dates (MJD) minus 49646.0 are provided.

No.	MJD -49646.0	J	σ_J	H	σ_H	K	σ_K
1	2.190530	5.04	0.01	4.29	0.01	3.96	0.01
2	5.230437	3.47	0.02	2.54	0.01	2.18	0.01
3	1.205424	4.50	0.01	3.62	0.01	3.34	0.01
4	5.167275	2.51	0.01	1.43	0.01	0.88	0.01
5	0.965400	6.90	0.02	6.20	0.01	6.05	0.01
6	1.910745	11.42	0.09	11.07	0.02	11.03	0.05

The data has high quality with typical signal-to-noise ratios of at least 100. Only for the case of BD+57 2161 is it lower, about 37, due to slight cirrus and because the star is the second faintest in J, H and K in the group. IR standard stars were observed nightly in order to ensure proper photometric calibration (Kidger et al. 1990). An accuracy of 0.01 mag is about the best that can be obtained with the equipment employed. Nightly averaged (but not reddening corrected) J, H and K values for the flux standard star HR0508 in the CST system are as follows (± 0.01): 4.99, 4.66, 4.58 – Oct. 21; 5.01, 4.68, 4.62 – Oct. 22; and 5.01, 4.69, 4.62 – Oct. 25, respectively. Catalogue CST JHK values for HR0508 are: 5.010 ± 0.021, 4.688 ± 0.015 and 4.613 ± 0.017.

Standard reductions were performed using the ESO **Snopir** software written by Olivia, Barbier, Schmider and Bouchet (P. Bouchet, private communication) available at the Instituto de Astrofísica de Canarias. The data presented in Table 3 have been corrected for inter-stellar reddening according to the E(B-V) values in Table 2 and Zombeck's (1990) formalism. The corrections are all small and on average equal to 0.020, 0.015 and 0.010 mag in the J, H and K bands, respectively.

Each star positioning in the photometer's aperture has been carefully double-checked with the aid of various astronomical Sky surveys. In no case more than one likely bright target falls within 3' by 3' of the telescope pointing at the coordinates given in Table 1. Given this, the IR magnitudes obtained for star 6 are very faint compared to its V magnitude in Table 2 rendering its $V-J, V-H$ and $V-K$ colours negative. As we are quite certain of having observed the right target we are left with no explanation for the values obtained, except for a possible momentary instrumental failure or appearance of an isolated cloud at the time of this measurement. We recommend to take with caution, therefore, the conclusions derived for this object.

For comparison, a compilation of previous IR magnitudes for our targets from the literature can be found in the various IR catalogues by Gezari et al. (e.g., Gezari et al. 1993). When compared with literature values, our JHK measurements seem to indicate that V Ari and UV Cam have larger variations in their K magnitude than those proposed by Claussen et al. (1987): at least, 0.71 and 0.55 mag, respectively while a variation of $\geq$0.49 mag is found for TU Gem.

3. Analysis

3.1. Colours

Our new JHK values can be compared with those obtained by Bergeat et al. (1976), Bergeat & Lunel (1980), Chen et al. (1984) and Gigoyan et al. (1994). With this purpose, we first find the colour regions spanned by the C stars in their samples, which are 0.9 - 1.47 and 0.38 - 0.85; 0.69 - 1.29 and 0.25 - 0.84; 0.55 - 1.29 and 0.41 - 1.31; 0.6 - 1.1 and 0.21 - 0.9, for $J-H$ and $H-K$, respectively. Caution should be taken in that observations by different authors have been obtained with slightly different photometric systems. Claussen et al. (1987) provide equations to convert Noguchi et al. (1981) JHK values to the standard Johnson system by comparing with the photometry obtained by Bergeat & Lunel (1980).

Given our data in Table 3, we can conclude that only BD+34 4134 falls outside the $J-H$ range proposed by Gao et al. (1985) (see Sect. 1), among our six targets. We should however keep in mind that, in general, $J-K$ values differ for various stars much more than the values of $H-K$ for all carbon stars. For the $H-K$ colour, only TU Gem falls in the Gao et al.'s range. Considering the range in Bergeat et al. (1976), only our TU Gem data matches theirs in both colours simultaneously. Given, on the other hand, all four colour ranges described above plus Gao et al.'s one, only BD+34 4134 would then be outside simultaneously in $J-H$ and $H-K$, with BD+57 2161 also excluded in $H-K$. If the lower limit in $H-K$ for Bergeat & Lunel (1980) data is arbitrarily set to 0.4 and for Gigoyan et al. (1994) to 0.48 – excluding two very discrepant stars of their sample, then all but TU Gem are out in the $H-K$ colour again. It can be concluded that five of our targets have $H-K$ colours systematically smaller than the bulk of C stars in previous works.

For photospheric temperatures of stars, the underlying Planck radiation will result in that stars will move toward the lower right in the $H-K$ versus $J-H$ diagram with increasing temperature. In Fig. 1 this is illustrated by plotting the BB line together with the observed colours of our 6 CH stars from the present work (crosses) and the 13 carbon stars from the work of Gigoyan et al. (1994) (square symbols). It is seen that all the stars fall in a band relatively parallel to the BB line, and that our stars fall in the direction of the diagram corresponding to the relatively larger BB temperatures. This is in qualitative agreement with all of them (except TU Gem) being classified as R stars (see Table 1). TU Gem which lies in the region of the bulk of Gigoyan et al.'s stars, is the only one of our stars which is classified as an N type carbon star. The four squares in the upper right part of the diagram represent Mira stars, corresponding to very low BB temperatures.

The JHK filters are constructed such that the continuum (i.e., H^-) absorption always will be smaller in the H filter than in the J and K filters. Beside the effect of H^- on the colours, CN and C_2 contribute with absorption in J and in H, whereas CO (second overtone) has its absorption concentrated in the region of the H filter. The resultant effect is that the H magnitude is relatively more sensitive to metallicity than either J or K. Hence, a decreasing metallicity implies decreasing $H-K$ and

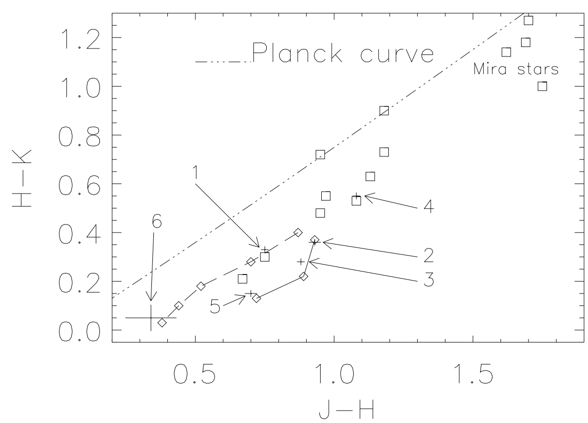

Fig. 1. $J-H$ vs. $H-K$ diagram for our data (cross symbols) in Table 3 (plus error bars and star numbers marked by arrows). Synthetic $J-H$ and $H-K$ are shown for two metallicities and various temperatures. For $Z = 10^{-4}Z_{\odot}$ three model values (4000, 3500 and 3000K) are connected by a solid line starting near star 5. For $Z = Z_{\odot}$ the models are, starting near star 6, 5300, 4800, 4300, 3700, and 3200K. All models are calculated for $log(g)$ = 0.0 and C/O = 1.07. For comparison, the theoretical BB line has been over-plotted together with the JHK data for the faint high latitude C stars in Gigoyan et al. (1994) (box symbols - errors unknown).

increasing $J-H$. This is shown qualitatively in Fig. 1 by comparing synthetic JHK colours of solar metallicity carbon giants of C/O=1.07 (a representative value for the solar neighbourhood carbon stars) and log(g)=0, with corresponding carbon star models for Z=$10^{-4}Z_{\odot}$. The colours have been computed for the present analysis by use of the MARCS code (Gustafsson et al. 1975, Jørgensen et al. 1992) by use of the filter functions due to Bessell & Brett (1988). We see that the observed colours of three of our stars are in good agreement with the stars being very metal deficient, whereas two of the stars (BD +34 4134 and V Ari) somewhat surprisingly fall closer to the region of the solar metallicity carbon stars model colours. We interpret the diagram as showing most of our program stars as being of lower metallicity and higher effective temperature than the bulk of the carbon stars.

We speculate that the reason for BD +34 4134 and V Ari looking more like solar metallicity stars in the $J-H$, $H-K$ diagram (in spite of their association with the halo and – for V Ari – low spectroscopically determined metallicity) can be caused by a much higher C/O ratio. However, for V Ari a K magnitude and $J-H$ and $H-K$ colours have been reported by Feast & Whitelock (1992). Their colours are slightly but significantly different from ours. This difference places V Ari close to the position of star 3 in our Fig. 1 and seems to indicate a variability so great that colours from models are of little quantitative use as V Ari's shift in position corresponds both to metallicities $Z_{\odot}$ and $10^{-4}Z_{\odot}$.

Given Noguchi et al. (1981) I and L values for V Ari and UV Cam, it should be concluded that no significant shell contribution is present for either object. However, again, to extract firm conclusions about the presence of shells around V Ari and UV Cam, based on their colours alone, is probably not possible. Kipper (unpublished), studying the IRAS fluxes of V Ari, deduced that a 500K dust shell around the object could be present, with a total mass of $10^{-8}M_{\odot}$ and a 500$R_{\odot}$ radius. He noted however the poor quality of the IRAS data employed, which rendered his result inconclusive.

It is worth noticing that V Ari and UV Cam were included in Bergeat & Lunel's (1980) study; V Ari was the only target outside the steep strip they describe in their $J-H$ vs. $H-K$ diagram. In his $J-H$ vs. $H-K$ diagram, UV Cam was the only object among 17 C stars found to deviate, by Bahng (1969). This effect can be clearly seen in his Fig. 1.

3.2. Distances and luminosities

M_{bol} values have been obtained (Zombeck 1990) from bolometric corrections (BC_K) as derived from Fig. 2 in Frogel et al. (1980), together with an average value of M_K=-8.1 (Gigoyan et al. 1994), for those cases where no distance values are available in Table 2. According to Chen et al. (1984) the BC_K values derived this way are accurate to within 0.1 mag. For UV Cam and TU Gem a distance of 800 pc, as derived by Peery (1975) was employed in the calculations.

Gigoyan et al. (1994) proposed an average value of -8.1 for M_K, but this was derived for N stars and R stars are usually about a magnitude fainter than N stars in K. It must therefore be stressed that the resulting M_{bol} is then also about 1 magnitude brighter than the value expected for R stars. The last two stars in our list are fainter in M_v and, according to $H-K$, hotter than the others –see Table 5. This may indicate that they could be early R type and therefore much fainter in K also. For that reason, they are excluded from the analysis. It should also be remembered that the average bolometric magnitude of –mostly N– carbon stars in LMC is -4.9. Given the considerations above, few R stars in the Galaxy may be expected to exceed this value.

Derived luminosities, together with distance computations, can be found in Table 4. These calculations are based on our K measurements together with literature values in Table 2 whenever possible. The M_K value obtained for TU Gem deserves attention: it may indicate that the distance of 800 pc to the object, as derived by Perry (1975), could be incorrect.

As the question of luminosities is a complicated one, often very different values can be found for the same target in the literature. In order to illustrate this, a compilation of such values for M_{bol} and luminosities is included in the last column of Table 4.

3.3. Temperature and gravity calculations

As our objects all have $J-K<2$, $T_{\rm eff}$ values can be calculated for them following the method described in Gigoyan et al. (1994), which makes use of the empirical relationship between $T_{\rm eff}$ and $J-K$ derived by Bessel et al. (1983). The obtained results are presented in Table 5 (3^{rd} column). Also, using Fig. 9 in Tsuji (1981) together with our $H-K$ values, effective temperature estimates have been derived and included in Table 5.

Table 4. Luminosity and distance calculations

No.	BC_K (1)	M_K (2)	A_K	BC	log(d) (pc)	M_{bol}	log($L_\star/L_\odot$)	Liter. M_{bol}	Liter. log($L_\star/L_\odot$)	ref.
1	2.8	-8.1	0.02	-2.7	3.41	-5.3	4.01	-3.5		e
2	3.0	-7.5	0.14	-2.1		-4.5	3.68	-4.9	3.83,3.98	p,c
3	2.9	-8.1	0.16	-2.9	3.26	-5.2	3.97			
4	3.3	-8.7	0.07	-3.7		-5.4	4.05	-5.56,-5.4	4.04,4.07	g,p,c
5	2.4		0.07							
6	1.7		0.11							

(1): Frogel et al. (1980). (2): M_K=-8.1 average value for those stars without known distance.
(e): Eggen (1972). (p): Peery (1975). (c): Claussen et al. (1987). (g): Gao et al. (1985).

Table 5. Temperature and log$g$ calculations. For comparison, temperatures from literature are also included –5^{th} column.

No.	$J-K$	T (1)	T(2)	T(3:Lit.)	log g (4)
1	1.08	3607.1	3190	3000, 3532 3550, 3500	-0.2
2	1.29	3258.1	3140 (3000)	2911	0.0
3	1.16	3465.7	3370	3096, 3580	-0.2
4	1.62	2828.0	2800 (2800)	2700/2390 2600, 2767	-0.6
5	0.85	4086.7	>4200		
6	0.39	5566.9	>4000 (4000)		

(1): Bessel et al. (1983). (2): Tsuji (1981). In parenthesis: values estimated by Kipper et al. (1996) using all available data.
(3): V Ari: Bouigue (1954), Baumert (1972), Tsuji et al. (1991), Kipper & Kipper (1990). UV Cam: Baumert (1972).
BD+34 911: Baumert (1972), Tsuji et al. (1991).
TU Gem: Gao et al. (1985), Bouigue (1954), Baumert (1972). These Baumert (1972) temperatures are de-reddened (Sleivytė 1986b).
(4): Kipper & Jørgensen (1994).

In parenthesis are given the values estimated by Kipper et al. (1996) using all the available data. For V Ari, where a R=4.18 mag measurement is provided by Sleivytė (1986a), the obtained results can be compared with a $T_{\rm eff}$ value of 3086K, derived if the method described by Johnson (1964) is employed. In doing so, our JHK values in Table 3 together with I=6.10 (Bergeat & Lunel 1980) have also been used.

For comparison, temperature determinations from literature have also been included in Table 5 (5^{th} column), together with their corresponding references. It should be here noted that Bouigue (1954) determines the vibrational temperatures of C_2 and CN molecules while Baumert (1972) provides IR temperatures, neither being exactly coincident with effective temperatures.

log(g) values in Table 5 for our targets have been obtained following the method described in Kipper & Jørgensen (1994), assuming as they do 1 $M_\odot$ for the mass of our targets. Our M_{bol} values in Table 4 were employed. Given the uncertainties carried out in the determination of M_{bol} itself, together with those for the various determinations of the $T_{\rm eff}$ values above described, only temperatures obtained through Bessel et al.'s method are used, as an example.

4. Summary

The primary goal of this paper is to present a uniform and high quality set of JHK observations of the peculiar C stars V Ari, UV Cam, BD+34 911,TU Gem, BD+57 2161 and BD+34 4134. Our observational results are given in Table 3. Star 6 (BD+34 4134) presents a problem in interpretation because of the faint JH and K fluxes observed compared to its V magnitude in Table 2. We call for re-observation of this object.

By assuming that the colour indices are simply related to temperature, a standard assumption in this field, we can conclude that our sample of stars is on average hotter than the sample of C stars in Gigoyan et al. (1994). No conclusive evidence has been found for circumstellar narrow-band emission, and therefore it is possible to assume that there is a simple relationship between colour indices and the temperature. The position of our stars in the $H-K$ versus $J-H$ diagram classify them with considerably lower metallicity and/or higher effective temperature than the bulk of carbon stars. Using that assumption, and the calibrated relationship between colour index and temperature, by Bessel et al. (1983) we derive effective temperatures for our stars, and present them in Table 5. Using what is known about distances and absolute magnitudes in the literature, we can furthermore derive tentative luminosities, gravities and distances. The derived low luminosities place them near (or below) the theoretical lower limit of the C-star luminosity distribution function.

Data suitable for a direct Luminosity determination will become available when the astrometric HIPPARCOS data is released as five of our six stars are in the HIPPARCOS input catalog. These will set improved limits on the luminosities we have only estimated here, and hence improve our understanding of the onset of the He shell flash in metal poor carbon stars.

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