

Long-term photometry of WX Arietis: evidence for eclipses and dips*

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Abstract. We present R-band photometry of the SW Sex-type cataclysmic variable WX Arietis made in October 1995 and August 1998–February 1999. Contrary to previous results, we find that WX Ari is an eclipsing system with an orbital inclination of $i \simeq 72^\circ$. The R-band light curves display highly variable, shallow eclipses ~ 0.15 -mag deep and $\simeq 40$ min long. The observed eclipse depth suggests a partial eclipse of the accretion disc. The light curves also show a wide dip in brightness centred at orbital phase $\varphi \sim 0.75$ and a hump close to the opposite phase at $\varphi \sim 0.2$. The observed dip may be explained by the probable vertical thickening of the outer rim of the accretion disc downstream from the bright spot. We also demonstrate that the disc brightness in all SW Sex systems is nearly the same. This implies that the orbital inclination of these systems is only a function of eclipse depth.

Key words: accretion, accretion disks – stars: binaries: eclipsing – stars: binaries: spectroscopic – stars: individual: WX Ari – stars: novae, cataclysmic variables

1. Introduction

The SW Sex phenomenon, a term coined by Thorstensen et al. (1991), is common to a set of nova-like cataclysmic variables (CVs) which share the same peculiar but consistent spectroscopic behaviour. This group of CVs originally comprised only eclipsing systems with orbital periods in the range 3–4 hr. All of these systems exhibit strong single-peaked Balmer, He I and He II emission lines which, with the exception of He II, remain largely unobscured during primary eclipse. In addition, the radial velocity curves of Balmer and He I lines show significant phase lags relative to the photometric ephemeris. Furthermore,

these emission lines display absorption components which show maximum depth at phases opposite primary eclipse (Szkody & Piché 1990).

Given that all of the original members of the SW Sex class are eclipsing CVs, a number of authors have speculated that the various peculiar phenomena exhibited by the SW Sex stars are a consequence of their high orbital inclinations. This assumption was thrown into doubt when a number of supposed low-inclination members of the class were discovered, including WX Ari (Beuermann et al. 1992; Hellier et al. 1994), V795 Her (Casares et al. 1996; Dickinson et al. 1997), S193 (Rodríguez-Gil et al. 1998; Martínez-Pais et al. 1999; Taylor et al. 1999) and V442 Oph (Hoard & Szkody 1999). Although these systems present the same spectroscopic properties as their high-inclination partners (with the exception of the occurrence of eclipses), there is still some controversy about whether they really are the low-inclination counterparts of SW Sex stars. In this paper we will show that the best example of a proposed low-inclination SW Sex star, WX Ari, exhibits eclipses and is actually a high-inclination SW Sex star.

WX Ari (also known as PG 0244+104) is one of a number of CVs discovered by the Palomar-Green (PG) survey for ultraviolet excess objects (Green et al. 1982). Beuermann et al. (1992) undertook the first spectroscopic study of this star, finding an orbital period of 0.13934 ± 0.00006 d. This work also showed that WX Ari displays many of the characteristic peculiarities of the SW Sex systems. After detecting the absence of eclipses, the authors suggested that WX Ari could be a low-inclination SW Sex star. Until then, the only photometric data available were those of Warner (1983), which did not cover the 3.34 hr orbital period of the system, so Hellier et al. (1994) decided to obtain new photometry to settle the issue of whether WX Ari eclipses. They concluded that WX Ari is a low-inclination SW Sex star not showing eclipses. Curiously, the V-band light curve presented in the upper panel of their Fig. 1 *does* show a shallow eclipse. This led Dhillon (1996) to propose that WX Ari is not a low-inclination system. Since Hellier's database only spanned two observing nights, we decided to undertake a new photometric study of WX Ari with the aim of giving a definite answer to the eclipsing nature of this SW Sex star. The results of this study are presented in this paper.

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* Based on observations made with the Optical Ground Station (OGS) and the IAC-80 telescopes, operated on the island of Tenerife by the European Space Agency (ESA) and the Instituto de Astrofísica de Canarias (IAC), respectively, at the Spanish Observatorio del Teide and with the Jacobus Kapteyn Telescope (JKT), operated on the island of La Palma by PPARC at the Spanish Observatorio del Roque de los Muchachos.

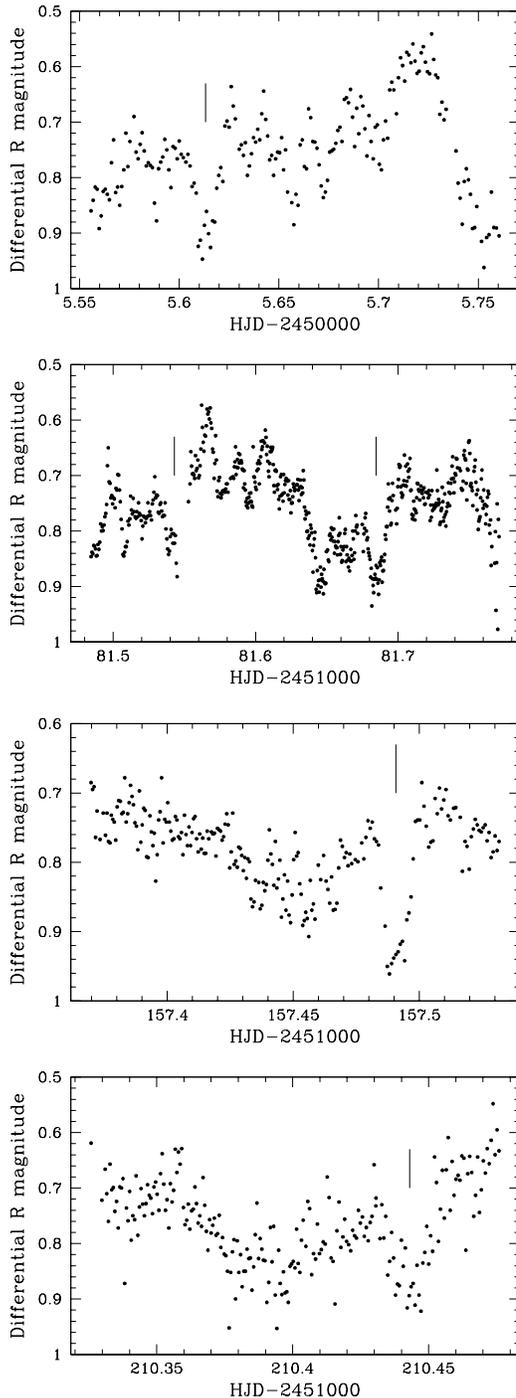


Fig. 1. Selected light curves of WX Ari in the R-band. Five eclipses are marked. Although flickering is very strong the eclipses are easily seen.

2. Observations and data reduction

The photometric data were obtained with the 1-m Optical Ground Station (OGS) and the 0.82-m IAC-80 telescopes at the Observatorio del Teide on Tenerife, and with the 1-m Jacobus Kapteyn Telescope (JKT) at the Observatorio del Roque de los Muchachos on La Palma. The system was observed on one night in October 1995 with the JKT and for a total of 17 nights

Table 1. Observing log

Night	Telescope	Filter	Exposure (s)	Coverage (h)
1995 Oct 15	JKT	R	30	4.91
1998 Aug 26	OGS	R	60	1.17
1998 Aug 27	OGS	R	60	2.51
1998 Sep 02	IAC 80	R	40	3.46
1998 Sep 03	IAC 80	R	50	4.78
1998 Sep 23	OGS	R	40	2.77
1998 Sep 24	OGS	R	25	6.88
1998 Oct 05	IAC 80	R	60	3.39
1998 Nov 24	IAC 80	R	40	3.60
1998 Dec 09	IAC 80	R	40	3.88
1999 Jan 30	IAC 80	R	40	3.70
1999 Jan 31	IAC 80	R	40	3.60
1999 Feb 01	IAC 80	R	50	3.42
1999 Feb 02	IAC 80	R	50	3.64
1999 Feb 05	IAC 80	R	70	3.42
1999 Feb 06	IAC 80	R	40	3.45
1999 Feb 07	IAC 80	R	40	1.51
1999 Feb 09	IAC 80	R	50	3.06

in the period August 1998–February 1999 with the OGS and the IAC-80 telescopes. The observations on both telescopes on Tenerife were made using CCD cameras equipped with Thomson 1024×1024 -pixel² chips, whilst the JKT data were obtained with a Tek 1024×1024 -pixel² chip. A detailed observing log is given in Table 1. All the data were acquired through a Kron-Cousins R-filter and the time resolution was always better than 90 s.

The individual images were bias-corrected and then flat-fielded in the standard way. All the data reduction was undertaken with the IRAF¹ package. The instrumental magnitudes were then found by performing aperture photometry on the individual images. The seeing during all the observing runs was estimated to be always better than $1.5''$, even reaching sub-arcsecond values on a couple of nights. From the scatter in the comparison star light curves we estimate that the differential photometry is accurate to ~ 1 per cent.

3. Results and discussion

3.1. Evidence of eclipses and ephemeris

In Fig. 1 we present four R-band light curves of WX Ari. From the light curves it is clear that WX Ari displays eclipses approximately 0.15-mag deep, in contrast with the previous results of Beuermann et al. (1992) and Hellier et al. (1994). Due to the shallowness of the observed eclipses, we consider that they are partial eclipses of the accretion disc (see below). The duration of the eclipses is $\simeq 40$ min.

We derived the first photometric ephemeris for WX Ari from 13 eclipses. The times of mid-eclipse were calculated by fitting

¹ IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

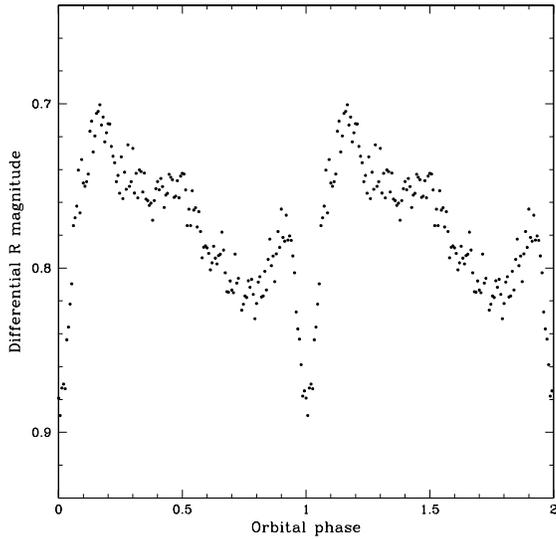


Fig. 2. The mean R-band light curve of WX Ari after binning the data into 150 phase bins. Note the well-defined eclipse at zero phase, the hump at phase ~ 0.2 and the dip at phase ~ 0.75 . Two orbital periods are plotted for clarity.

Table 2. Times of mid-eclipse for WX Ari

HJD (mid-eclipse) (2450000+)	Cycle Number (E)	$O - C$ (s)
5.61319	-7721	-28.37
1053.67288	-200	-81.39
1059.66493	-157	-85.81
1060.63953	-150	-159.97
1080.70952	-6	135.40
1081.54740	0	288.58
1081.68478	1	118.27
1142.44301	437	214.27
1142.57998	438	8.85
1157.49072	545	22.59
1209.46623	918	-192.02
1210.43840	925	-476.13
1215.46330	961	237.29

parabolas to the bottom of the eclipses. A least squares fit to these eclipse timings yields the following ephemeris:

$$T_0 = \text{HJD } 2451081.54406(2) + 0.13935119(3) E \quad (1)$$

The eclipse timings and the differences between the observed and calculated times of mid-eclipse ($O-C$) are given in Table 2. There is no evidence for any periodicity in the $O-C$ diagram.

3.2. Light curve morphology and eclipse profiles

The individual light curves are dominated by intense flickering, typically associated with emission from the bright spot and/or turbulent regions of the disc (see e.g. Horne & Stiening 1985).

WX Ari displays asymmetric eclipses with ingress steeper than egress. This asymmetry in eclipse shape is a common fea-

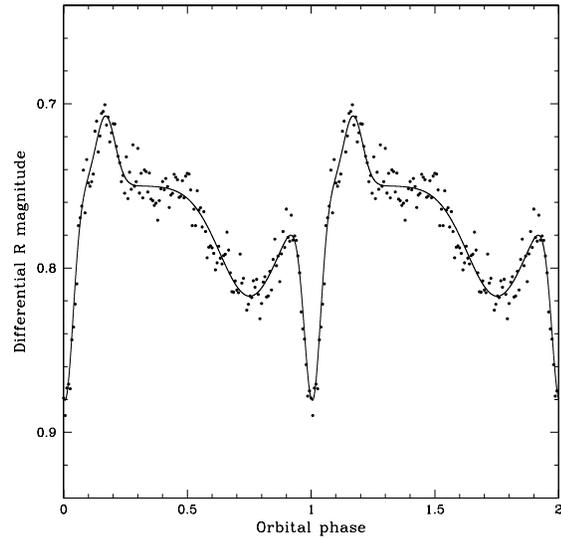


Fig. 3. Triple Gaussian fit to the mean R-band light curve of WX Ari (solid line).

ture to all SW Sex systems and is indicative of the bright spot (Penning et al. 1984). Only PX And exhibits a different behaviour in its continuum light curves, with eclipse egress steeper than ingress (Thorstensen et al. 1991). Eclipses in WX Ari are shallower (~ 0.15 mag) than in the lowest-inclination eclipsing SW Sex star, PX And (~ 0.5 mag, and variable). The eclipses are also variable in depth, a feature also observed in PX And (Thorstensen et al. 1991). The variable depth of the eclipse in CVs is still a puzzling matter. This variability may be related to local fluctuations in the disc –which is in a time-averaged steady state– caused for instance by a rotating accretion curtain (Thorstensen et al. 1991).

The mean R-band light curve of WX Ari is presented in Fig. 2 after phase-binning the data into 150 bins. The light curve shows an intricate behaviour: apart from the well-defined eclipse, it exhibits a large dip in brightness centred around phase 0.75 and a post-eclipse hump centred at phase ~ 0.2 . It also displays a flat region with differential R-magnitude ~ 0.75 , which extends from phase ~ 0.25 to ~ 0.5 . We will consider this flat region as the out-of-eclipse light level. In Fig. 3 we show a triple-Gaussian fit to the average light curve, assuming that the light curve can be decomposed into four components: a constant out-of-eclipse intensity, a hump, a wide dip and the eclipse. We want to stress that this triple-Gaussian fit is merely an aid to the eye, just included to clarify the light curve structure. The presence of the wide dip in brightness prior to eclipse added to the strong flickering present in the light curves may have prevented Hellier et al. (1994) from detecting the eclipse in one of their V-band light curves.

The intricate shape of the light curve makes an explanation of the nature of its components very difficult, but we will suggest some possibilities. Due to the lack of adequate spectroscopic observations (i.e. the spectral features of the secondary star are not detected in the optical), it could not be clear whether the eclipse center corresponds to inferior conjunction of the sec-

ondary star. The possibility of the eclipse being a partial eclipse of the bright spot can not be *a priori* ruled out, but there are evidences against it: (i) the eclipse is not flat-bottomed, as seen in e.g. U Gem (Zhang & Robinson 1987), although the observed V-shaped profile can arise from a grazing eclipse of the bright spot; (ii) if our zero phase corresponds to an eclipse of the bright spot, the brightening at $\varphi \sim 0.9$ should correspond to a pre-eclipse orbital hump. This requires an out-of-eclipse level located at the bottom of the dip at $\varphi \sim 0.75$. This intensity level should be observed during a more extended range of phases than the mean light curve shows (i.e. the bottom of the dip is narrow); (iii) the eclipse of the bright spot should occur after the pre-eclipse orbital hump, when the intensity is decreasing towards the out-of-eclipse level (see again Zhang & Robinson 1987). In WX Ari the eclipse is observed when the brightness is increasing. In the light of these facts, we consider that the eclipse is more likely a partial eclipse of the disc, and is centred at inferior conjunction of the secondary.

The light curve structure resembles that of other eclipsing CVs in the optical domain, like the nova-likes UX UMa and RW Tri (Mason et al. 1997) and is also similar to the X-ray light curves of some LMXBs, like X1822-371 (Hellier & Mason 1989). These similarities lead us to propose that the wide dip in brightness observed in WX Ari before eclipse may be caused by a raised disc rim downstream from the bright spot (Armitage & Livio 1998). When it is on the line of sight between the disc centre and the observer, it obscures a significant fraction of the disc causing the observed dip. A similar dip was observed in the dwarf nova Z Cha in the phase range 0.6–0.8 during superoutburst (Kuulkers et al. 1991) as well as in other high-inclination dwarf novae (e.g. OY Car, Naylor et al. 1987; U Gem, Mason et al. 1988) and other CVs like EX Hya (Córdova et al. 1985), BG CMi (McHardy et al. 1986). The observed dip extends nearly half of the orbital cycle, which implies that the structure causing it may extend almost halfway around the disc. The same extension is seen in RW Tri (Mason et al. 1997).

The nature of the post-eclipse hump is the most puzzling matter. It may be due to the fact that at phase ~ 0.2 we are viewing the inner side of the raised rim, which may be reprocessing energetic radiation coming from the inner parts of the disc into visible wavelengths. The problem is that the widths of the dip and the hump are very different and there is no strong reason to expect the reprocessed radiation to originate only in a small region of the inside extended rim. The small width of this feature suggests that it may be related to the emergence of the bright spot out of the secondary, but with the current data we can conclude nothing with respect to its origin.

3.3. Orbital inclination

From the geometry of a point eclipse by a spherical body, it is possible to determine the inclination, i , of a binary system through the relation

$$\left(\frac{R_2}{a}\right)^2 = \sin^2(\pi\Delta\varphi_{1/2}) + \cos^2(\pi\Delta\varphi_{1/2})\cos^2 i, \quad (2)$$

where R_2/a is the volume radius of the secondary star, which depends only on the mass ratio, $q = M_2/M_1$ (Eggleton 1983):

$$\frac{R_2}{a} = \frac{0.49 q^{2/3}}{0.6 q^{2/3} + \ln(1 + q^{1/3})}. \quad (3)$$

$\Delta\varphi_{1/2}$ is the mean phase full-width of the eclipse at half the out-of-eclipse intensity. In order to determine the orbital inclination of WX Ari, we calculated $\Delta\varphi_{1/2}$ from two different Gaussian fits: (i) the triple-Gaussian fit to the mean light curve described above and (ii) a single-Gaussian fit to the eclipse profile after masking the rest of the light curve, with the exception of the flat region extending from phase 0.25 to 0.5. The adopted $\Delta\varphi_{1/2}$ was the average value of those derived from the two different fits, which is

$$\Delta\varphi_{1/2} = 0.082 \pm 0.006$$

Eliminating R_2/a from Eqs. (2) and (3), we can obtain an estimate of the orbital inclination of the system assuming a value of the mass ratio, q . Using the mass-period relation recently derived by Smith & Dhillon (1998):

$$M_2(M_\odot) = 0.126 P_{orb}(\text{h}) - 0.11, \quad (4)$$

where $P_{orb}(\text{h})$ is the orbital period of the system expressed in hours, we obtain a value of $M_2 = 0.31 M_\odot$ for the secondary in WX Ari. Assuming a mass for the compact object of $M_1 = 0.8 M_\odot$ (the average mass of white dwarfs in CVs with orbital periods above the period gap; Smith & Dhillon 1998), we derive a value of the mass ratio for WX Ari of $q = 0.39$. This mass ratio corresponds to an orbital inclination of $i \simeq 80^\circ$. Taking into account the error in $\Delta\varphi_{1/2}$ the orbital inclination ranges between $\sim 79^\circ$ and $\sim 82^\circ$, *if the eclipsed light source is centred on the white dwarf*.

In (2) the parameter a is the distance from the eclipsed light source to the center of the secondary star, whereas in (3) it is the separation of the system. The shallowness of the eclipse in WX Ari suggests that we are actually observing a partial eclipse of the disc (i.e. the white dwarf is not eclipsed), so a is not the same quantity in both equations and we are in fact overestimating the inclination. Hence, the value derived above ($i \simeq 80^\circ$) can be considered as a (very pessimistic) upper limit to the orbital inclination.

3.3.1. The brightness of the discs in SW Sex stars

The absolute magnitude of an steady state accretion disc is a function of many variables (Warner 1987), $M_V = M_V(\dot{M}_d, M_1, R_1, R_d)$, where \dot{M}_d is the mass accretion rate through the disc, M_1 is the mass of the white dwarf, R_1 its radius and R_d is the radius of the disc. By adopting an $M - R$ relation for the primaries in CVs, the dependence on R_1 can be eliminated. We assume the mass of the white dwarfs in SW Sex systems, M_1 , as a constant. On the other hand, the radius of the discs in these systems does not differ very much from one object to the others (Harrop-Allin & Warner 1996) and can be taken as $R_d/a = 0.6 - 0.7 R_{L1}/a$, where R_{L1}/a is the

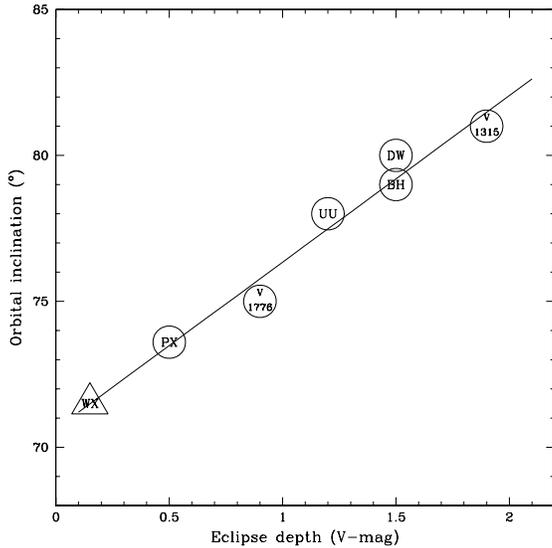


Fig. 4. Orbital inclination as a function of V-band eclipse depth for SW Sex stars. WX Ari is plotted with a triangle because the eclipse depth was measured in the R-band (see text for details).

distance (in units of the separation of the system) from the centre of the primary to the inner Lagrangian point. R_{L1}/a only depends on the mass ratio, q (see e.g. Warner 1995). From Kepler's Third Law we obtain that $R_d = R_d(M_1, P_{orb})$ and then we have $M_V = M_V(\dot{M}_d, P_{orb})$. The eclipsing SW Sex systems are confined in a short orbital period range of 3.24–3.95 hours. The result of entering this short period range in $\dot{M} - P_{orb}$ relations (e.g. Verbunt & Wade 1984) is a nearly equal \dot{M}_d in the eclipsing SW Sex stars, so we can assume that M_V is only function of P_{orb} . Thus, the M_V of the discs in SW Sex stars must be approximately the same. As a consequence, the eclipse depth must be a function of the orbital inclination.

We have searched for values of orbital inclination and eclipse depth for all the eclipsing SW Sex stars in the literature, with the aim of finding a correlation. In Fig. 4 we present a plot of the values found, which are summarized in Table 3.

The eclipse depth for all the systems was measured from V-band light curves. The systems SW Sex and LX Ser are not included in the plot due to the lack of reasonable estimates of the orbital inclination. We found a clear linear correlation between orbital inclination and eclipse depth. After fitting a straight line to the data we get:

$$i = 5.7 \Delta V + 70.6 \quad (5)$$

The fact that all the systems lie very well within a straight line, indicates that the statements derived above are valid, particularly, M_1 and M_V can be taken as constants. We do not have extensive V-band photometry to measure the eclipse depth, but due to the low inclination of WX Ari we can consider the eclipse depth in R-band not to be very different from that in V-band. Entering the eclipse depth measured in WX Ari (~ 0.15 mag) in (5), we obtain a value of the orbital inclination of $i \sim 72^\circ$. We have to note that the ordinate at the origin of the linear fit

Table 3. V-band eclipse depth and $\Delta\varphi_{1/2}$ of SW Sex systems

Object	ΔV	i ($^\circ$)	Reference
PX And	0.5	73.6	1
V1776 Cyg	0.9	75	2
UU Aqr	1.2	78	3
DW UMa	1.5	80	4
BH Lyn	1.5	79	5
V1315 Aql	1.9	81	6

References: 1 Thorstensen et al. (1991); 2 Garnavich et al. (1990); 3 Baptista et al. (1994); 4 Shafter et al. (1988); 5 Hoard & Szkody (1997); 6 Dhillon et al. (1991)

is 70 degrees, value below which eclipses are not expected to occur.

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