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THE EFFECTIVE TEMPERATURE OF WOLF 485A AND THE STATISTICS OF ZZ CETI STARS

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ABSTRACT

High-speed photometry shows that the bright DA white dwarf Wolf 485A is not a variable star, with an upper limit on the semi-amplitudes of luminosity variations of 0.0005 mag in the period range characteristic of the ZZ Ceti stars. However, its time-averaged multichannel color index $(G-R)$ places it in the instability strip. If confirmed, this result would make Wolf 485A an important object, the lone counterexample to the assertion that *all* DA white dwarfs evolve to become nonradial pulsators as they enter the ZZ Ceti instability strip. New photometric and spectrophotometric observations conclusively show, however, that the effective temperature of Wolf 485A is around 15,000 K, substantially above the blue edge of the instability strip ($T_e \approx 13{,}000$ K). The source of this discrepancy most probably lies in erroneous multichannel colors for that object.

Subject headings: stars: individual — stars: pulsation — stars: variable — stars: white dwarfs

I. INTRODUCTION

The use of multichannel scanner (MCSP) data has proved a powerful tool in the search for new variable DA white dwarfs (ZZ Ceti stars). In recent surveys, the temperature-sensitive $(G-R)$ index, which measures the slope of the Paschen continuum, has been successfully used to delineate the boundaries of the ZZ Ceti instability strip. As reported by Fontaine *et al.* (1982), all the variable DA white dwarfs have $-0.45 \le (G-R)_{69} \le -0.38$, where the colors are on the older AB69 scale. On the recently revised AB79 absolute calibration, the instability strip is shifted to the range $-0.41 \le (G-R)_{79} \le -0.29$ (Greenstein 1982).

A detailed knowledge of the probability that a star entering the instability region (13,000 K $\gtrsim T_e \gtrsim$ 11,000 K) becomes pulsationally unstable bears directly on our understanding of the envelope structure of DA stars (e.g., Winget and Fontaine 1982). The evidence available at this stage suggests that *most, if not all, DA stars within the ZZ Ceti instability strip are indeed variable* (Fontaine *et al.* 1982; Greenstein 1982). Of course, the validity of this result, and of its implications for the structure of the envelopes of DA white dwarfs, rests on its withstanding the test of time. Continued photometric observations with narrow-band filter systems and the pursuit of fast photometry on recently identified prospective candidates for variability should help improve the statistics of ZZ Ceti stars and further our understanding of the pulsational properties of these objects.

As part of an ongoing survey for additional pulsating DA white dwarfs, light curves of Wolf 485A (BD −7°3632, EG 99, G14−58, LFT 1014, LHS 354, WD 1327−083) have been obtained in the 1978 and 1980 observing seasons. This star was selected on the basis of its $(G-R)$ color index [$(G-R)_{69} = -0.40$; Greenstein 1976], which places it in the ZZ Ceti instability strip. Because no obvious periodicities were detected in the light curves of Wolf 485A, this star had become an important object in terms of the statistics of ZZ Ceti stars. Indeed, the confirmed presence of a truly constant star in the instability strip would have important consequences for our current understanding of the compositional structure of DA white dwarfs. Although we note that various selection effects—e.g., particular geometrical orientations—could be responsible for the presence of an apparently nonvariable star in the instability strip, it was our feeling that Wolf 485A deserved further study. Pending such additional observations, this object was consequently not included in the statistical analysis of Fontaine *et al.* (1982).

Wolf 485A was also singled out as an interesting object by Greenstein (1982) who provided a list of 17 prospective candidates deserving pulsation studies. His selected objects all have multichannel colors in or near the ZZ Ceti instability strip. At $V = 12.2$, Wolf 485A is the brightest of the six highest priority targets in Greenstein's list.

In § II of this paper, we report on our high-speed photometric observations (including new data) which show that Wolf 485A does *not* vary by more than 0.0005 mag over time scales characteristic of DA white dwarf pulsations. It is most likely a constant star. The potentially critical implication of this result for the statistics of ZZ Ceti stars has prompted us to review the evidence suggesting that this star should be in the instability strip in the first place. To this end, we present in § III new Strömgren photometry and digital spectrophotometry of Wolf 485A. These data suggest very strongly that this star is hotter than indicated by its $(G-R)$ color index; this result relocates Wolf 485A *outside* of the ZZ Ceti instability strip and, in turn, alleviates the apparent conflict between the outcome of the statistical study of ZZ Ceti stars of Fontaine *et al.* (1982) and the fast-photometry results obtained on Wolf 485A.

II. HIGH-SPEED PHOTOMETRIC OBSERVATIONS OF WOLF 485A

A total of five independent light curves were obtained for Wolf 485A, one of the brightest white dwarf stars. Of those, four were secured with single-channel photometers attached to the 1.5 m reflectors on Mount Wilson and on Palomar Mountain. These observations were obtained as described in Fontaine *et al.* (1980) and McGraw *et al.* (1981). In addition, additional observations were recently obtained with the new Mount Wilson dual-channel photometer attached to the 2.5 m Hooker telescope. The observing procedure has been described in Fontaine *et al.* (1984*b*). In all cases, no filters were used to

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TABLE 1

HIGH-SPEED PHOTOMETRIC OBSERVATIONS OF WOLF 485A

Run Number	Date (UT)	Telescope[a] (m)	Integration Time (s)	Total Number of Data Points	Period Range (s)	Maximum Semi-Amplitude (mag)
1...........	1978 May 29	MW, 1.5	10	400	20–1333	0.0020
2...........	1978 Jun 2	MW, 1.5	20	196	40–1307	0.0020
3...........	1980 May 18	MP, 1.5	20	268	40–1787	0.0023
4...........	1980 May 19	MP, 1.5	20	184	40–1227	0.0017
5...........	1983 Apr 7	MW, 2.5	20	304	40–2027	0.0006

[a] MW = Mount Wilson; MP = Mount Palomar.

maximize the photon detection rate. The details of the runs are summarized in Table 1.

None of the light curves showed any obvious periodicities. This was confirmed by the individual Fourier analysis of each light curve. No significant frequency peaks were found in any of the Fourier spectra. As an example, Figure 1 shows the complete (i.e., up to the Nyquist frequency) power spectrum of Wolf 485A for run 5. After verifying that there was no significant power at 10 mHz, we have inserted an artificial signal with an amplitude equal to 0.1% of the mean intensity of the star at that particular frequency. As can be seen in Figure 1, the tracer (with a normalized power equal to 1) dominates the power spectrum. The power of the largest peaks is less than 0.3, meaning that the maximum semi-amplitudes of possible periodicities are less than 0.0006 mag. At that level, Wolf 485A is definitely constant; the shape of the power spectrum is also totally consistent with noise. From run 5 alone, we obtain upper limits on the semi-amplitudes of luminosity variations of Wolf 485A that are amongst the most stringent that we know of for white dwarf stars.

Because of variable extinction, low-frequency variations are always present in the light curves of ZZ Ceti stars. An extinction law has been applied to remove these variations in our data. However, we cannot exclude the presence of variations over time scales of several thousand seconds, i.e., over periods longer than our individual runs. To reliably *measure* the frequency of a given periodic signal in a data string, there exists a "rule of thumb" which requires that the total length of the string be about 10 times the period of the signal. To *detect* a possible low-frequency component, we may relax this requirement to a total length equal to 3 times the period. Using this, we give in Table 1, the relevant period range and the upper limit on the semi-amplitudes of luminosity variations for each run. We note that the upper limits for the first four runs are considerably larger than for run 5, reflecting, in part, the smaller signal-to-noise (S/N) ratios obtained at the smaller telescopes. To search for a possible low-amplitude periodic signal, we have also added the five power spectra. The result is entirely consistent with pure noise while providing more stringent limits on the semi-amplitudes of luminosity variations. From our analysis, a minimal statement is certainly that, at the time of the observations, Wolf 485A did not vary with semi-amplitudes larger than 0.0005 mag in the observed period range of ZZ Ceti stars (110–1200 s). It is most likely a constant star.

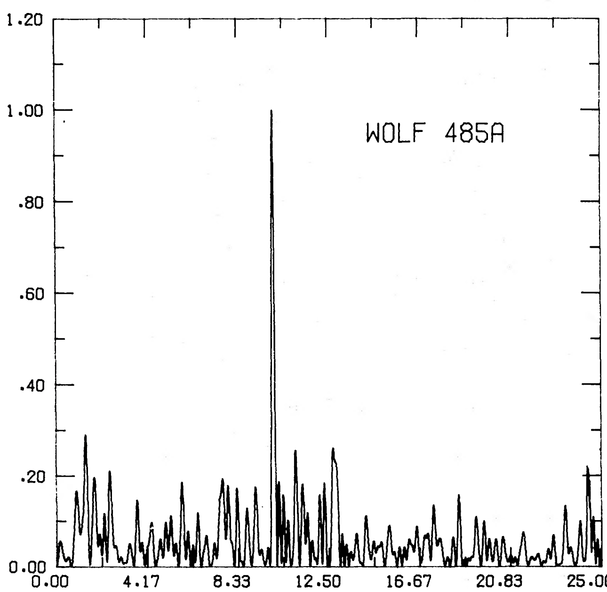

FIG. 1.—Power spectrum of Wolf 485A for run 5. The peak at 10 mHz with a normalized power equal to 1 is an artificial tracer with an amplitude of 0.1% of the mean intensity of the star. The spectrum is consistent with noise.

III. WOLF 485A: HOTTER THAN THE ZZ CETI VARIABLES?

a) Evidence Based on Multichannel Scanner Colors

At $V = 12.2$, Wolf 485A has multichannel-scanner data of good quality, at a resolution of 80 Å for $\lambda \leq 5880$ Å and 160 Å for $\lambda \geq 6040$ Å.[3] Its colors, on the AB79 scale, are $(U-V)_{79} = +0.27$, $(U-G)_{79} = +0.33$, $(B-V)_{79} = -0.02$, and $(G-R)_{79} = -0.33$ (Greenstein 1984*a*). In Greenstein's (1982) various two-color diagrams, Wolf 485A falls consistently above the white dwarf sequence, defined either empirically by the observed hydrogen-rich degenerates, or theoretically by model atmosphere loci for gravities between $\log g = 7.5$ and 8.5. The direction of this discrepancy is that the $(U-V)$ or $(U-G)$ color index appears too blue for the assigned $(G-R)$ (Greenstein 1982, Fig. 3). This errant position was already noted by Shipman and Sass (1980), who assigned, on the basis of the location in the multichannel two-color diagram, $T_e = 12{,}800$ K and an improbable $\log g = 9.0$, a result based on the earlier estimates of the multichannel colors of Wolf 485A (Greenstein 1976) using a slightly modified absolute calibration. A similarly high gravity would be obtained with the revised multichannel data which incorporate the updated AB79 calibration. There are thus, at this stage, two possibilities to explain the odd position of Wolf 485A in the multichannel

[3] Dr. J. L. Greenstein has kindly informed us that the data presented in his analyses (Greenstein 1982, 1984*a*) are those of Oke (1974). No subsequent multichannel observations have been made for this star. We note, however, that the spectral resolution of the MCSP data of Wolf 485A is denoted $Q = A$ in Greenstein (1982); this corresponds to a 40/80 Å resolution, in apparent conflict with the Oke (1974) assignment.

two-color diagrams: (*i*) Wolf 485A is a truly unusual DA star with, possibly, an abnormally large gravity (log $g > 8.5$); or (*ii*) the multichannel scanner colors, in particular $(G-R)$, of this bright star are in error.

b) Evidence Based on Strömgren Photometry

Wolf 485A has been observed in the Strömgren system by Graham (1972) and Wegner (1979, 1983). Their observations yield $(u-b) = +0.489$, $(b-y) = -0.031$ (Graham 1972; average of 4); $(u-b) = +0.513$, $(b-y) = -0.030$ (Wegner 1979; average of 2); $(u-b) = +0.453$, $(b-y) = -0.017$ (Wegner 1983; average of 2). In order to obtain a fourth, completely independent measurement of that object, Wolf 485A was reobserved by us at the Mount Wilson 2.5 m telescope on 1981 May 29, in the course of a statistical study of ZZ Ceti stars on the Strömgren system (Fontaine *et al.* 1984*a*). Our observations, based on a single measurement, yield $(u-b) = +0.468$, $(b-y) = -0.030$. These results are in excellent agreement with those of Graham (1972) and Wegner (1979, 1983). Assuming equal weights for the four independent measurements, we find a probable value of the temperature-sensitive index $(b-y)$ equal to -0.027 ± 0.007. This suggests an effective temperature clearly *above* the blue edge of the ZZ Ceti instability strip ($[b-y] \approx +0.032$; McGraw 1977 and Fontaine *et al.* 1984*a*).

Graham's (1972) Strömgren photometry was analyzed by Shipman and Sass (1980) in the course of their study of the two-color diagrams of DA stars. In contrast to its errant position in the multichannel two-color diagrams, Wolf 485A appears to be a normal DA star in the Strömgren diagram; its assigned effective temperature is $T_e = 15{,}400$ K, 2800 K hotter than that based on the multichannel scanner colors.[4] Furthermore, its gravity, from its position in Wegner's (1983) Strömgren two-color diagrams, appears normal. If anything, we would assign it a gravity slightly below log $g = 8.0$ on that basis. This result suggests very strongly that, from the two solutions offered to the problem posed by the peculiar location of Wolf 485A in the multichannel two-color diagrams, the second one is the more likely, namely that this star has erroneous multichannel colors. This result concurs with Greenstein's (1984*b*) assessment of the origin of the deviation shown by Wolf 485A from the mean DA $(b-y)$ versus $(G-R)$ relation as being due to "photometric errors." It is also interesting to note that if a value of log $g = 8.0$ is adopted, both the MCSP color indices $(U-V)$ and $(U-G)$ imply an effective temperature above 14,500 K (cf. Greenstein's 1982 Fig. 3). This would indicate that the R magnitude is the source of the error.

c) Evidence Based on Optical Spectroscopy

We have observed Wolf 485A on 1984 April 11 with the IIDS system behind the Gold Spectrograph attached to the Kitt Peak National Observatory 2.1 m reflector. The 600 lines mm^{-1} grating (no. 35) was used in second order, and provided coverage of the 4050–5000 Å region. An entrance aperture of 6″ was adopted, and the resulting spectral resolution was better than 4.25 Å. The usable portion of the integrated spectrum of Wolf 485A (total exposure: 50 minutes) is displayed in Figure 2.

Theoretical profiles of the Hβ and Hγ transitions were calculated to permit detailed comparisons with the high S/N ratio spectroscopic observations. These calculations make use of LTE continuum model atmospheres similar to those of Wesemael *et al.* (1980), and of additional models from Lacombe (1984). All models are of pure hydrogen composition and have log $g = 8.0$. The validity of this last assumption, already known to be quite satisfactory from the work of Koester, Schulz, and Weidemann (1979) and Shipman (1979), has been further strengthened by the recent detailed analysis of DA stars in the 8000–16,000 K temperature range of Weidemann and Koester (1984).

An unambiguous effective temperature determination for stars in the ZZ Ceti region is not possible with spectroscopic information alone. This is because the hydrogen lines reach

[4] We are aware of two other effective temperature determinations of Wolf 485A in the literature: $T_e = 13{,}920$ K (Koester, Schulz, and Weidemann 1979) and $T_e = 15{,}100$ K (Oke and Shipman 1971). The former estimate is based, in part, on the abnormally red $(G-R)$ color and is consequently most likely too low. The latter value is based on a model atmosphere fit to the *complete* multichannel scanner energy distribution (3300–10,000 Å), a procedure which smooths over irregularities in the data (see Oke and Shipman 1971, Fig. 4).

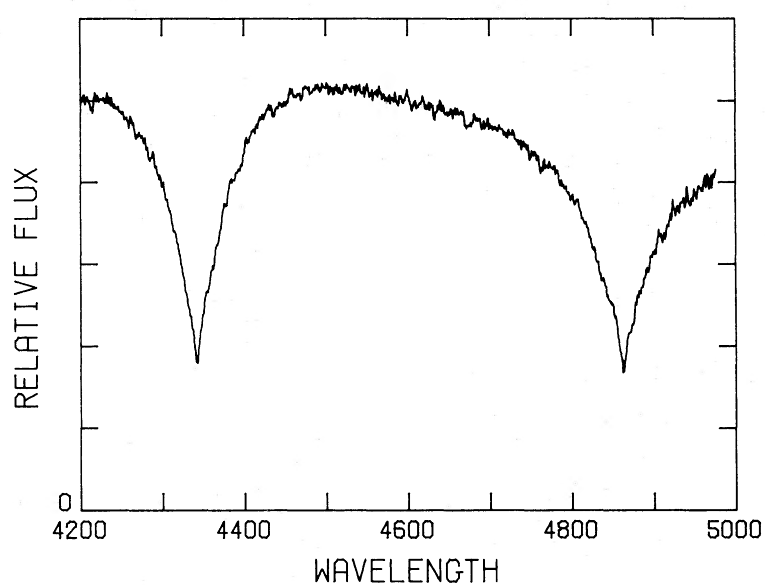

FIG. 2.—IIDS spectrum of Wolf 485A obtained with the KPNO 2.1 m telescope. The spectral resolution is $\lesssim 4.25$ Å.

their peak strength around $T_e \approx 13{,}000$ K for log $g = 8.0$ (e.g., Weidemann 1963; Greenstein and Vauclair 1979; Schulz and Wegner 1981); a star on the cool side of this peak has Balmer lines virtually indistinguishable from those of a star on the hot side of the maximum. This is true not only when line equivalent widths but also when line profiles are used. The ambiguity in the fit can be resolved, if some—even crude—colorimetric information is available. In the present case, we shall make use of the evidence presented in § III*b* which suggests very strongly that Wolf 485A is indeed on the hot side of the peak in hydrogen line strength.

Hydrogen line profiles were calculated with the broadening theory of Vidal, Cooper, Smith (1973), and were folded with a Gaussian of appropriate FWHM. The Hβ and Hγ lines were fitted individually, with the continuum set 120 Å (Hβ) and 110 Å (Hγ) from the line center, respectively. The best fitting effective temperatures obtained are $T_e = 14{,}600$ K for Hβ and $T_e = 15{,}500$ K for Hγ. Figure 3 displays the fits achieved with our nominal best fitting effective temperature of $T_e = 15{,}000 \pm 700$ K. Allowing for a two-dimensional fit in both gravity and effective temperature space may help decrease the difference between the individual best fitting values to each line.

Because of the need for a crude colorimetric temperature indicator, our spectroscopic effective temperature determination does not represent a fully independent estimate. It is reassuring, however, that—once the appropriate side of the temperature peak has been chosen—the spectroscopic temperature estimate is entirely consistent with the Shipman and Sass (1980) Strömgren-based determination and with the Oke and Shipman (1971) overall energy distribution fit.

IV. CONCLUDING REMARKS

The recent studies of Winget (1981), Winget *et al.* (1982), and Michaud and Fontaine (1984) have provided a self-consistent theoretical picture of the ZZ Ceti phenomenon. Briefly, our current understanding is that the majority of the DA white dwarfs evolve to become ZZ Ceti pulsators when they enter the instability strip. To account for the location and sharpness of the blue edge of the strip, most DA white dwarfs must have hydrogen layers with masses in the range $10^{-12} \lesssim \Delta M(\mathrm{H})/M \lesssim 10^{-8}$ by the time they have cooled to characteristic ZZ Ceti effective temperatures. Although standard evolution theory predicts that a hydrogen layer mass $\Delta M(\mathrm{H})/M \approx 10^{-4}$ should be left on a hot DA white dwarf (Iben and Tutukov 1984), diffusion-induced hydrogen burning (Michaud and Fontaine 1984) provides a natural mechanism to explain the relatively low hydrogen content of the ZZ Ceti stars.

Within that framework, the fraction of DA white dwarfs entering the instability region with, for example, hydrogen layer masses much larger than $\Delta M(\mathrm{H})/M \approx 10^{-8}$, must be very small. If not, the blue edge of the instability strip would be blurred, in contrast to the observations obtained so far. For instance, a 0.6 $M_\odot$ DA white dwarf model with $\Delta M(\mathrm{H})/M = 10^{-6}$ becomes pulsationally unstable only after the star has cooled down to an effective temperature lower than 10,000 K, i.e., *cooler* than the actual, observed red edge of the strip. The presence of a truly constant star in the instability strip must therefore be regarded as a rare event if our current understanding of the ZZ Ceti stars is at all correct. In addition, the existence of a star in the strip with a hydrogen layer mass sufficiently large to damp the oscillations may be embarassing, since it would then be difficult to explain how diffusion-induced hydrogen burning could be turned off in DA white dwarfs (see Michaud and Fontaine 1984).

Based on its $(G-R)$ color index, Wolf 485A belongs within the instability strip. Excluding possible geometrical effects, Wolf 485A was shown to be constant and would therefore provide the first example of the existence of such stars. However, the photometric and spectrophotometric evidence presented in this paper leave little doubt that Wolf 485A has an effective temperature of $\sim 15{,}000$ K, significantly larger than

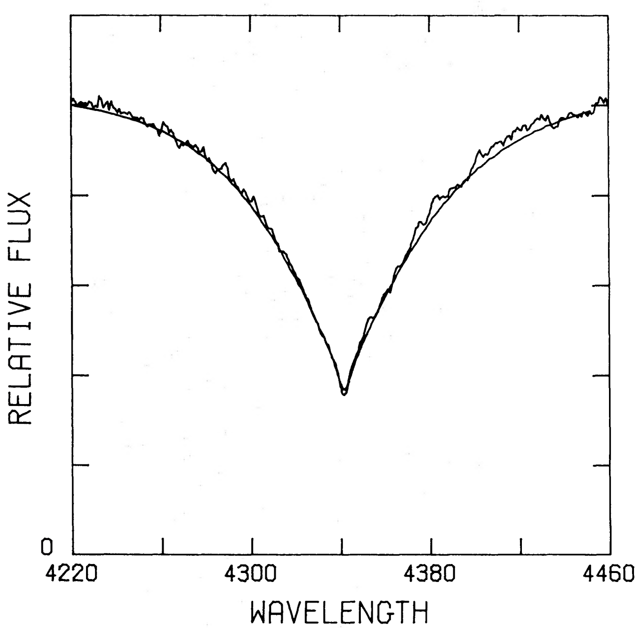

FIG. 3*a*

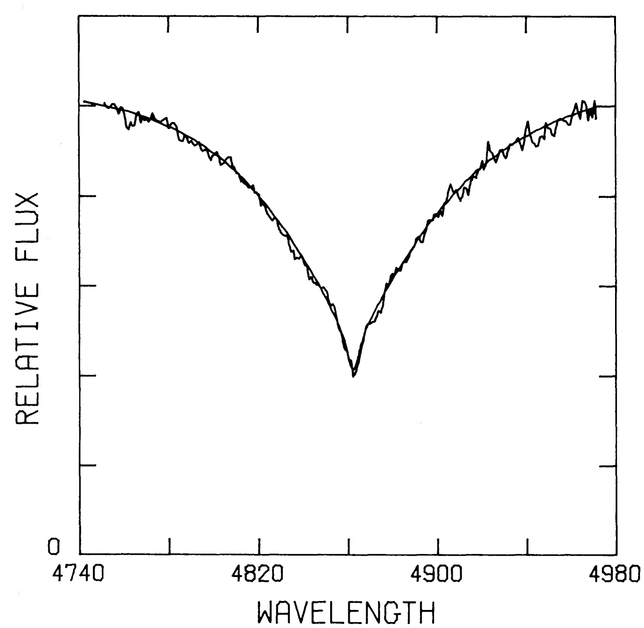

FIG. 3*b*

FIG. 3.—(*a*) The Hγ profile in Wolf 485A, together with the theoretical fit for our nominal best fitting temperature of $T_e = 15{,}000$ K. The model assumes log $g = 8.0$ and a pure hydrogen composition. The theoretical spectrum has been convolved with a Gaussian of FWHM = 4.25 Å. (*b*) Same as Fig. 3*a*, but for Hβ.

the blue edge of the ZZ Ceti instability strip ($T_e \approx 13{,}000$ K). The multichannel colors—particularly the R magnitude—must be incorrect. With the relocation of Wolf 485A outside the instability strip, *all* of the DA white dwarfs so far studied in the range $-0.45 \leq (G-R)_{69} \leq -0.38$ are variable.

After this paper was accepted for publication, we received a preprint of a paper by Digel and Shipman (1984), who reach conclusions similar to ours concerning the effective temperature of Wolf 485A.

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