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# HD 160529: a new galactic luminous blue variable*

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**Abstract.** The galactic early-type A hypergiant HD 160529 has been photometrically monitored in the Strömgren system during the past 18 years. HD 160529 has become fainter in the optical range by 0.5 mag during the past eight years. In addition, pulsation-like variations with a quasi-period of 57 days and with a peak-to-peak amplitude of about 0.1 mag in $b$ and $y$ were found. The fading was not completely monotonous; a fall of at least 0.2 mag in $b$ and $y$ within about 40 days around JD2446500 is particularly remarkable. This jump is accompanied by a change in the temperature-sensitive $c_1$ index of about −0.14 mag. HD 160529 has become visually fainter and hotter during the past eight years, thus becoming a new case of a galactic Luminous Blue Variable (LBV). Model calculations on the basis of the photometry and previously published as well as new spectroscopic observations have shown HD 160529 to be a close counterpart of R 110, a recently discovered LBV in the LMC. From this comparison an absolute magnitude of $M_V = -8.9$ and a distance of 2.5 kpc is derived. The stellar parameters characterising the maximum state are estimated to be $T_{\rm eff} \approx 8000$ K, $\log g \approx 0.55$, $R \approx 330\ R_{\odot}$, from which the mass is estimated to be only $M \approx 13\ M_{\odot}$. From the H$\alpha$ profile a lower limit of the mass-loss rate of HD 160529 was calculated, which is about 10 times higher than that of R 110; this could be a consequence of the higher metallicity of the galactic LBV. The low mass of HD 160529 makes this luminous blue star a good candidate for a post-RSG (red supergiant phase) object, providing some evidence that (as sometimes argued) low metallicity is not a necessary prerequisite for evolution of massive stars backward to higher temperatures.

**Key words:** HD 160529 – variable stars – luminous blue variables

## 1. Introduction

The early A hypergiant HD 160529 located in the direction to the galactic center has been considered for a long time as one of the most luminous stars of the Galaxy. It was classified by various authors (e.g. Merrill & Burwell 1943; Beals 1951; Bidelman 1954; Hiltner 1954; Buscombe 1959; Wallerstein 1970) as an extremely luminous A2 to A4 star. Feast et al. (1960) considered this star as being perhaps comparable in absolute magnitude with HD 33579 (the brightest A hypergiant in the LMC), which has an absolute luminosity of $M_V = -9.7$. A coordinated observing campaign over a time span of about two years (1972 and 1973) revealed quite considerable variability of HD 160529, both spectroscopically and photometrically (Wolf et al. 1974). Dramatic radial velocity variations ($\Delta v \approx 30$ to 40 km sec$^{-1}$) and line profile variations with occasional line splitting (cf. e.g. Fig. 7 in Wolf et al. 1974) were found, evidencing the existence of strong hydrodynamic mass fluxes and mass loss. In addition, strong P Cygni-type profiles of H$\alpha$ and H$\beta$ were observed and, at one occasion, even an inverse P Cygni profile in H$\beta$ was seen. The spectroscopic variations were correlated with photometric variations of at least 0.15 mag in the visual. For these brightness variations a typical timescale of a couple of months was derived by Sterken (1977, 1981). Another interesting finding of the spectroscopic analysis of Wolf et al. was the rather low excitation temperature of $T_{\rm exc} = 7800$ K, which is definitely too low for an A2 to A4 star. Interestingly, this low value fits quite well the classification A9Ia given by Houk (1982) which is based on a spectrum taken two months earlier than were obtained the coudé spectra of Wolf et al. In addition, HD 160529 was significantly brighter ($V = 6.5$) during that coordinated campaign than the value of $V = 6.67$ quoted in the literature (Hiltner 1954). Obviously the star has become visually brighter and cooler in the seventies.

Sterken (1981) considered this enigmatic hypergiant as a test case for a long-term photometric monitoring campaign, and in fact it is HD 160529 that provided the main impact for initiating the "Long-term Photometry of Variables" (LTPV) program at ESO (Sterken 1983). Within this campaign HD 160529 was now found to have decreased again in brightness by about 0.5 mag during the past 8 years, establishing HD 160529 as a new case of a galactic LBV. The photometric data collected during almost twenty years of observation and which have provided this result on HD 160529's nature are discussed below. In addition, some spectroscopic observations obtained at an intermediate brightness phase of HD 160529 and during its present fainter phase are presented.

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*Based on observations collected at the European Southern Observatory at La Silla, Chile.

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## 2. Observations

The observations of HD 160529 were carried out at the European Southern Observatory (ESO La Silla, Chile) during several observing runs.

### 2.1. *uvby photometry*

The bulk of the data consists of differential Strömgren photometry essentially acquired at the Danish 50cm and ESO 50cm telescopes. The two comparison stars were C1≡HD 160461 (A1V) and C2≡HD 160575 (B1/B2II), and were the same comparison stars as used by Sterken (1977). The differential magnitudes of the star (≡HD 160529) are defined as V = HD 160529 – (C1+C2)/2. The differential magnitudes of the comparisons are defined as C = C1 – C2. The mean magnitudes and colours of the comparison stars are $y$ = 7.520(9), $b-y$ = 0.105(5), $m_1$ = 0.118(7), $c_1$ = 1.175(9) for C1 and $y$ = 7.617(11), $b-y$ = 0.332(5), $m_1$ = –0.026(6), $c_1$ = 0.100(7) for C2. The numbers in parentheses are standard deviations expressed in millimagnitudes.

A large number of observing runs is involved in the present analysis and we will not give details about individual observations. We will only outline the partition of the data following the different natural groups corresponding to (more or less) homogeneous instrumental systems and reduction techniques. This partition is given in Table 1. A most important part of the data has been acquired in the framework of the LTPV project.

The four entries (BCDE) associated with the ESO 50cm telescope in the framework of the LTPV are justified because different sets of filters and/or different photometers have been used, and this led to somewhat different instrumental systems.

It is clear that the precision of the photometry as derived from the differences between the two comparison stars is good within a single dataset, but somewhat decreases when some datasets are being combined. For example, dataset F consists of older measurements and is not perfectly compatible with other datasets. The data from the LTPV project, on the other side, are more coherent.

The $u$ and $v$ magnitudes, however, are considerably inhomogeneous even among the datasets ABCDE (LTPV) and they have been omitted from the first parts of the analysis of the variability of HD 160529.

Only dataset F has been previously discussed in the literature (Sterken 1981 and references therein).

### 2.2. *Near-infrared photometry*

In May 1982, three independent *JHKLM* observations of HD 160529 were made, yielding $J = 3.55$, $H = 3.14$, $K = 2.84$, $L = 2.57$ and $M = 2.48$ (epoch JD2445090). Mean errors are 0.01 mag, except for $M$, where the mean error amounts to 0.02 mag. The infrared data are discussed in section 5.

### 2.3. *Spectroscopy*

Spectra of HD 160529 have been obtained between June 11 and June 17, 1986 (JD2446593 - JD2446599) with the ESO Coudé Auxiliary Telescope and with the Coudé Echelle Spectrograph. The spectra have been recorded with a high-density RCA CCD (15 $\mu$ pixel) giving a spectral resolution of 60,000. A ThAr and a high-temperature incandescent lamp have been used for wavelength calibration and flat-fielding. In the red spectral region about 50 Å are covered in one exposure. We observed the wavelength ranges 5860–5910 Å (HeI$\lambda$5876 and NaD), 6330–6380 Å (SiII lines), and 6535–6585 Å (H$\alpha$). The H$\alpha$ emission is, unfortunately, partly saturated. Additional observations of H$\beta$ and H$\alpha$ were respectively obtained on June 14, 1990 (JD2448056) and on October 30, 1990 (JD2448194) with the same equipment, at resolution 50,000. On November 6, 1990 (JD 2448201) an ECHELEC spectrum of HD 160529 was secured. All spectrographic data have been reduced with the ESO MIDAS image processing system.

## 3. The variability of the star

### 3.1. *The very long-term photometric variations*

The time basis covering all the datasets (ABCDEFGH) extends over more than 6000 days, and permits the investigation of the very long-term variations. The global precision of the photometry, estimated from the differences between the two comparison stars, is $\sigma_b^{(C)}$ = 0.013 and $\sigma_y^{(C)}$ = 0.011 ($b^{(C)}$ = –0.313 and $y^{(C)}$ = –0.094). The noise is not perfectly white and some excess of power for $\nu$ < 0.015-0.020 d$^{-1}$ is observed in the corresponding power spectra. This is mostly due to the above-mentioned lack of homogeneity of the photometry.

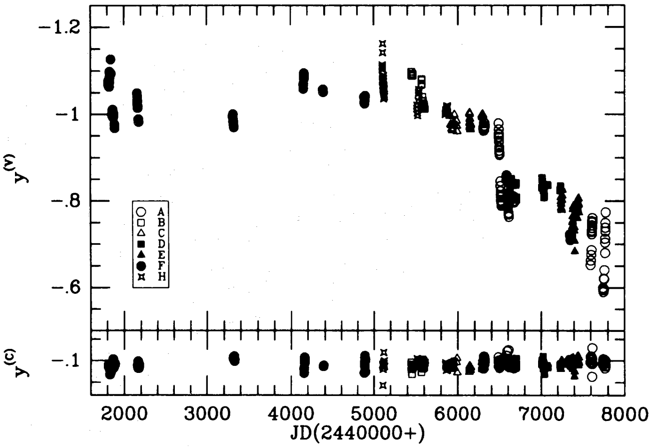

**Fig. 1.** Differential magnitudes $y$ used in this paper (ABCDEFH), for both the variable (V) and the comparison (C). Both panels (V and C) have the same scale. The symbols refer to different datasets as explained in the legend. More information about the different datasets is given in Table 1.

The differential magnitudes of HD 160529 in the $y$ filter are given in Fig. 1. It is immediately clear that the behaviour of the star can be separated into two distinct intervals. The first spans from JD2441800 to JD2445000 (dataset F alone) and is characterized by the absence of a marked trend in the variable brightness of the star. The dispersion of the magnitudes of the variable are $\sigma_b^{(V)}$ = 0.042 and $\sigma_y^{(V)}$ = 0.040 around a rather constant mean value of $b^{(V)}$ = –0.271, and $y^{(V)}$ = –1.033, which corresponds to $V$ = 6.54. This result can be further extended in the past by making reference to the photometry acquired between JD2441440 and JD2441490, and published by Wolf et al. (1974). In this latter case, though, the dispersion is some 30 to 40 % larger because those data are non-differential measurements occasionally collected during a photometric monitoring of $\sigma$ Sco (Sterken 1984). Hiltner (1954) measured a somewhat lower brightness value of $V$ = 6.67 for HD 160529.

The whole dataset F has been analyzed by Sterken (1981) who suggested the presence of a possible (quasi-)period of $P$=

**Table 1.** Journal of observations. All the datasets have been obtained in the *uvby* system. The numbers for the filtersets refer to the filtersets given by Manfroid et al. (1991); GOS refers to the paper by Grønbech et al. (1976). For dataset G solely the *b*-filter was used. $N_{\rm mes}$ denotes the number of measurements.

| Dataset | JD(244–) | $N_{\rm mes}$ | Telescope | Observer | Filterset |
|---|---|---|---|---|---|
| A | 6304-7771 | 94 | Danish | LTPV | 7 |
| B | 5442-5606 | 22 | ESO | LTPV | 4 |
| C | 5904-6297 | 28 | ESO | LTPV | 5 |
| D | 6612-7234 | 41 | ESO | LTPV | 6 |
| E | 7237-7459 | 46 | ESO | LTPV | 6 |
| F | 1812-4896 | 65 | Danish, ESO, Bochum | C.Sterken | GOS, 4, 4 |
| G | 6603-6606 | 15 | ESO | C.Sterken | - |
| H | 5101-5870 | 53 | Danish | C.Sterken | GOS |

101.3 days with an amplitude of about 0.1 mag. However, the sampling in dataset F is such that the power spectrum shows a lot of aliases of the above-mentioned possible frequency below 0.02 d$^{-1}$, and some of these aliases are powerful enough to question the existence of a single time-scale. An analysis of the power spectrum (following the method of Scargle 1982) shows that several independent peaks are significant against the null-hypothesis of white-noise. Consequently, the possibility that we deal with correlated random variations cannot be rejected. Although $P$ = 101.3 days could be selected as a good period, it is clear that we have no evidence for the existence of a strict periodicity and still less evidence to decide its value. The sampling is so scant that no single run is long enough to cover a complete cycle. Therefore, we remain sceptical about the presence of a quasi-periodicity in dataset F.

The second interval spans from JD2445000 to almost JD2447800 (datasets ABCDEGH) and is characterized by a marked fading of the star. This fading is on average quite linear in the $b$ filter and amounts to $\Delta b = 0.153\ 10^{-3}$ mag d$^{-1}$, i.e. about half a magnitude over 8 years. The corresponding value for the y filter is $\Delta y = 0.151\ 10^{-3}$ mag d$^{-1}$, i.e. a similar gradient (though the downward trend is not perfectly linear). Once this first trend is removed, the residual dispersion of the magnitudes can be expressed through the standard deviations $\sigma_b^{(V)} = 0.045$ and $\sigma_y^{(V)} = 0.045$ which are in rather good agreement with the corresponding dispersions present before the fading. Therefore, the star also varies on shorter timescales. The event around JD2446500 will be separately described in the next section (see also Figs. 1 and 2).

### 3.2. *The long- and intermediate-term photometric variations*

Figure 2 shows a high time-resolution view of the unique event around JD2446500. After JD2446481 a strong decrease in brightness takes place up to at least JD2446518. The real minimum has probably not been observed. After the jump, which exceeds 0.2 mag, the star seems to be somewhat more stable and has a tendency to conserve its mean fading rate by keeping a rather constant mean value between JD2446581 and JD2447008.

After having removed the trend established by the mean rate of fading, we performed a frequency analysis using Deeming's method (Deeming 1975). The power spectrum of the ABCDEGH data (of which the long-term fading has been removed) is dominated by a peak at $\nu$ = 0.011 d$^{-1}$, both in $b$ and in $y$. This peak is completely caused by the event at JD2446500. In order to prove that the frequency $\nu$ = 0.011 d$^{-1}$ is exclusively due to the event, we have analyzed several datasets from which the measurements between JD2446481 and JD2446497 either have been simply suppressed or have been shifted to the same overall mean, and those between JD2446505 and JD2446702 have been shifted to the same value. The resulting effect of these manipulations is a net removal of the event of JD2446500. In addition, we removed the very long-term variations by subtracting a fitted polynomial of order 1 ($b$ filter) or of order 2 ($y$ filter). Effectively, the peaks around $\nu$ = 0.011 - 0.013 d$^{-1}$ disappeared from the power spectra of all the modified data, confirming their relation to the event.

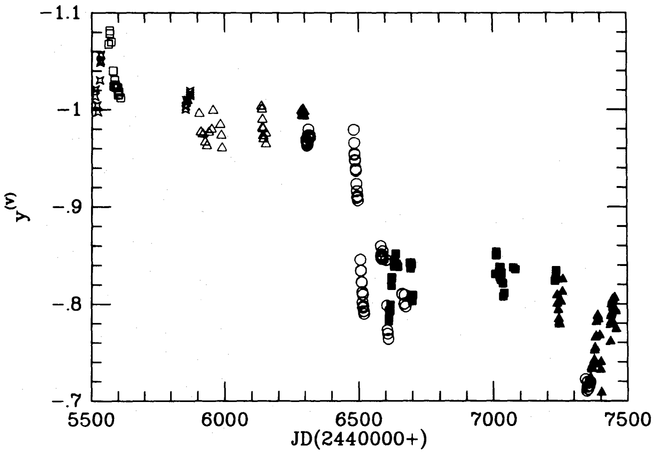

**Fig. 2.** Plot as a function of time of the differential magnitudes $y^{(V)}$. Only an enlarged portion of the lightcurve around the JD2446500 event is shown. The symbols used are the same as in Fig. 1.

Figure 3 gives the power spectrum of the $y$ magnitudes of datasets ABCDE treated in such a way. The advantage of limiting ourselves to the LTPV data is that the error is smaller ($\sigma_b^{(C)}$ = 0.008 and $\sigma_y^{(C)}$ = 0.009). The spectrum of Fig. 3 exhibits two peaks at $\nu \sim 0.017$ d$^{-1}$ and at $\nu \sim 0.018$ d$^{-1}$, which correspond to a semi-amplitude of $a_y = 0.026$ ($\sigma_a = 0.003$). For the $b$ filter we obtain the same frequencies and $a_b = 0.028$ ($\sigma_a = 0.003$). Besides these two peaks, the power spectra essentially exhibit an excess of power at low frequencies indicative of the presence of a slightly correlated random process.

We performed a statistical analysis of the power spectrum of Fig. 3 and of its $b$-filter counterpart using the method of Scargle (1982), as well as simulations in order to obtain a better estimate for the number of independent frequencies in the power spectrum

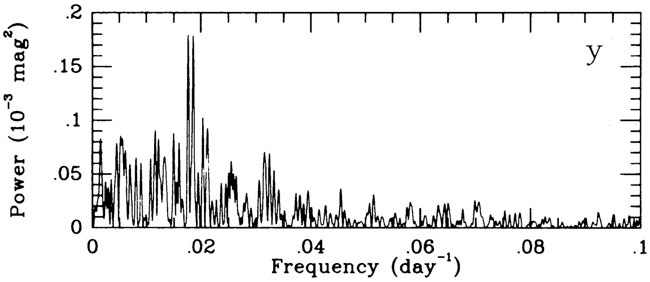

**Fig. 3.** Power spectrum (Deeming's method) of the modified $y$ differential magnitudes (see section 3.2 for more details). Double peaks at $\nu = 0.017$ - $0.018$ d$^{-1}$ are clearly visible. The part of the power spectrum between 0.1 and 0.5 d$^{-1}$ looks similar to the part between 0.08 and 0.1 d$^{-1}$.

(the method is used and explained in e.g. Gosset et al. 1990). It turns out that the above-mentioned peaks are significant and hence the frequencies $\nu \sim 0.017 - 0.018$d$^{-1}$ ($P \sim 57$ days) have to be adopted. The oscillations corresponding to these frequencies are clearly visible in some parts of the light curve (see Fig. 4).

The fact that the peak is effectively double does not necessarily imply that the frequency is physically double: such an effect could be induced by a time-dependent amplitude of the variation, by a time-dependent frequency (i.e. a quasi-periodicity), or by another more complicated effect. After prewhitening for $\nu = 0.0176$ d$^{-1}$ the resulting data have their power spectra dominated by an excess of power at low frequencies ($\nu < 0.03$ d$^{-1}$), which is the footprint of a slightly correlated random process. Both peaks disappeared simultaneously. The random process cannot be easily further studied because one does not know whether e.g. the fading of the star and/or the unique event of JD2446500 are to be included or not. In addition, part of the power may originate in the inhomogeneity of the photometric data. It is interesting to note that no outstanding peak is present around 0.017-0.018 d$^{-1}$ in the power spectra of the differential magnitudes of the comparison stars. Therefore, we can conclude that besides very long-term variations and occasional events like the one observed around JD2446500, the star exhibits light variations with a period or a quasi-period $P \sim 57$ days, a value we prefer to adopt instead of the previously accepted $P = 101.3$ days. The variations are very similar to what is observed in other luminous stars (see e.g. Sterken 1977, 1988; van Genderen 1989). The new value for the quasi-period renders HD 160529 even more similar to HD 168607 (which has recently been suggested to be an LBV; Chentsov and Luud 1989), and to HD 168625 (see Fig. 4 of Sterken 1977). It should however be kept in mind that the mean brightness of HD 160529 varied by more than 0.4 mag during the time interval spanned by our study. This could have some influence on the exact value for the quasi-period.

In addition to this 57 days quasi-periodic variation, HD 160529 exhibits short time-scale light variability (Sterken 1976, 1977, 1981). The typical time-scales are roughly from a few minutes to half an hour. The present sample does not permit to analyze in detail such a phenomenon, but the deviations from the mean curve of some individual measurements may indicate that the characteristic is present in our data, too.

### *3.3. The colour variations*

From the preceding paragraphs, one can conclude that the variability of the star in the $b$ and $y$ bands is very similar. For all the datasets considered here, the $\sigma^{(V)}_{b-y}$ of the star is never larger than 1.8 times the $\sigma^{(C)}_{b-y}$ of the comparison stars. An investigation of the behaviour in $u$ and $v$ would also be useful but, as quoted above, our photometry is not homogeneous enough to allow this. In spite of this, we tried to outline the largest possible dataset corrected for the inhomogeneity by studying the measurements close in time but belonging to different datasets. Dataset F is readily excluded and also no measurements of dataset H are close enough to measurements of dataset B. A general investigation of the latter seems to indicate that dataset B is in a photometric system markedly different from the datasets C, D and E which, in turn, seem rather homogeneous with respect to each other. Dataset A is different but, on the basis of measurements close in time, we have deduced the following transformations

$$u_{DAN} = u_{ESO} + 0.19 \tag{1}$$

$$v_{DAN} = v_{ESO} + 0.09 \tag{2}$$

where DAN $\equiv$ A and ESO $\equiv$ CDE. The data have been transformed to the DAN system and are plotted in Fig. 4. The precision estimated from the comparison stars is now $\sigma_{v,b,y} = 0.008$ and $\sigma_u = 0.010$. One readily sees that the variability of the star in $u$ and $v$ has roughly the same characteristics as in $b$ or in $y$, although a few differences are present: the variations have a tendency to be larger in the $v$ filter by about 5 to 10 %; the same effect is still more marked in the $u$ filter where the variations are larger by some 50 to 80 % (see also Sterken 1977). In addition, the long-term behaviour of the star in the $u$ filter is slightly different, in particular in the range JD2446000 - JD2446500. In Fig. 5, we plotted the differential Strömgren index $c_1$; a jump of about 0.14 mag occurs around JD2446400 (i.e. just during the first part of the JD2446500 event). The jump in $c_1$ is entirely due to a brightening of the star in the $u$ band.

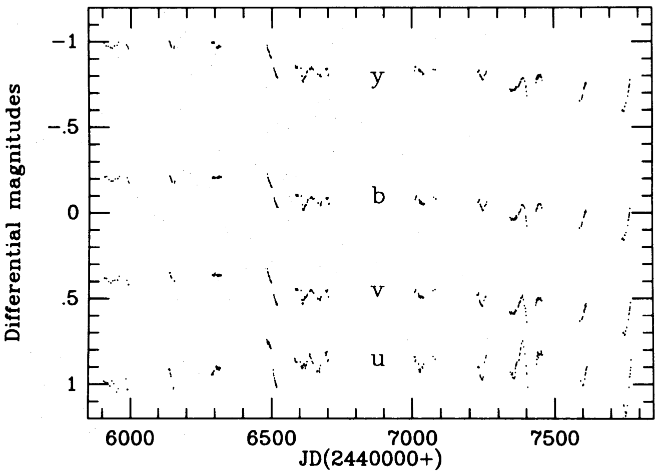

**Fig. 4.** The lightcurve of HD 160529 in the four Strömgren filters. This is the largest homogeneous dataset we have.

In order to investigate the intermediate-term variations in more detail and in all four filters, we defined a new dataset consisting of the measurements acquired between JD2446581 and JD2447800. This part of the lightcurve has the advantage that variations at large time-scales can be easily cleaned out and that the above-mentioned (quasi-)periodicity is well covered. A second-order polynomial trend has been removed from the data corresponding to each filter and they have been submitted to a Fourier analysis. In each filter, the dominant frequency is $\nu = 0.018$ d$^{-1}$, in good agreement with the previous results. We report in Table 2 the semi-amplitudes of the fitted sine curves as well as the global standard deviations of the present subsets (after removal of the polynomial). Our previous conclusions on the dependence of the amplitude of the variations on the different filters is confirmed; the variability in $v$ is slightly stronger and the one in $u$ is markedly larger.

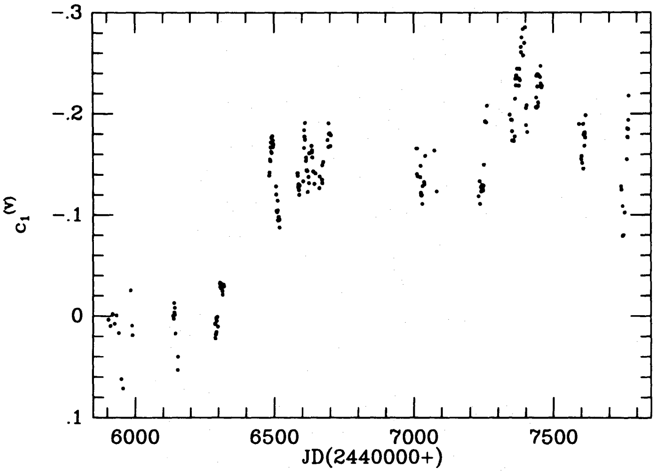

**Fig. 5.** The differential Strömgren index $c_1$ as a function of time. Note the strong jump around JD2446400.

**Table 2.** Estimated semi-amplitudes ($a$) for $\nu = 0.018$ d$^{-1}$ and standard deviations ($\sigma_{tot}$) of the modified data comprised between JD2446581 and JD2447800 (see section 3.3). $\sigma_a$ is the standard deviation of the value ($a$) deduced from the fit. The last two lines are $a$ and $\sigma_{tot}$, normalized to the $b$ filter.

| | $u$ | $v$ | $b$ | $y$ |
|---|---|---|---|---|
| $a$ | 0.056 | 0.038 | 0.036 | 0.036 |
| $(\sigma_a)$ | (0.007) | (0.003) | (0.003) | (0.003) |
| $\sigma_{tot}$ | 0.066 | 0.039 | 0.037 | 0.038 |
| $a/a(b)$ | 1.56 | 1.06 | 1.00 | 1.03 |
| $\sigma_{tot}$ / $\sigma_{tot}(b)$ | 1.78 | 1.05 | 1.00 | 1.03 |

### *3.4. The spectra*

The spectra which have been obtained in June 1986 are shown in Fig. 6. They have been obtained right after the event near JD2446500, at $y = 6.7$. H$\alpha$ has a P Cygni profile with a strong emission component. The emission peak is overexposed, and so we can only give a lower limit of about 5 × the continuum level for the strength of the emission line. In addition, we observed emission in the NaD lines and emission in FeII$\lambda$6369. The NaD lines have at least three absorption components at $-10$, $-62$ and $-114$ km sec$^{-1}$. The lines of the SiII multiplet 2 and the HeI$\lambda$5876 line are in absorption only.

We compared these spectra with the spectra published by Wolf et al. (1974), which have been obtained at a visual magnitude of 6.4-6.5. As principal differences, we find that the HeI$\lambda$5876 line

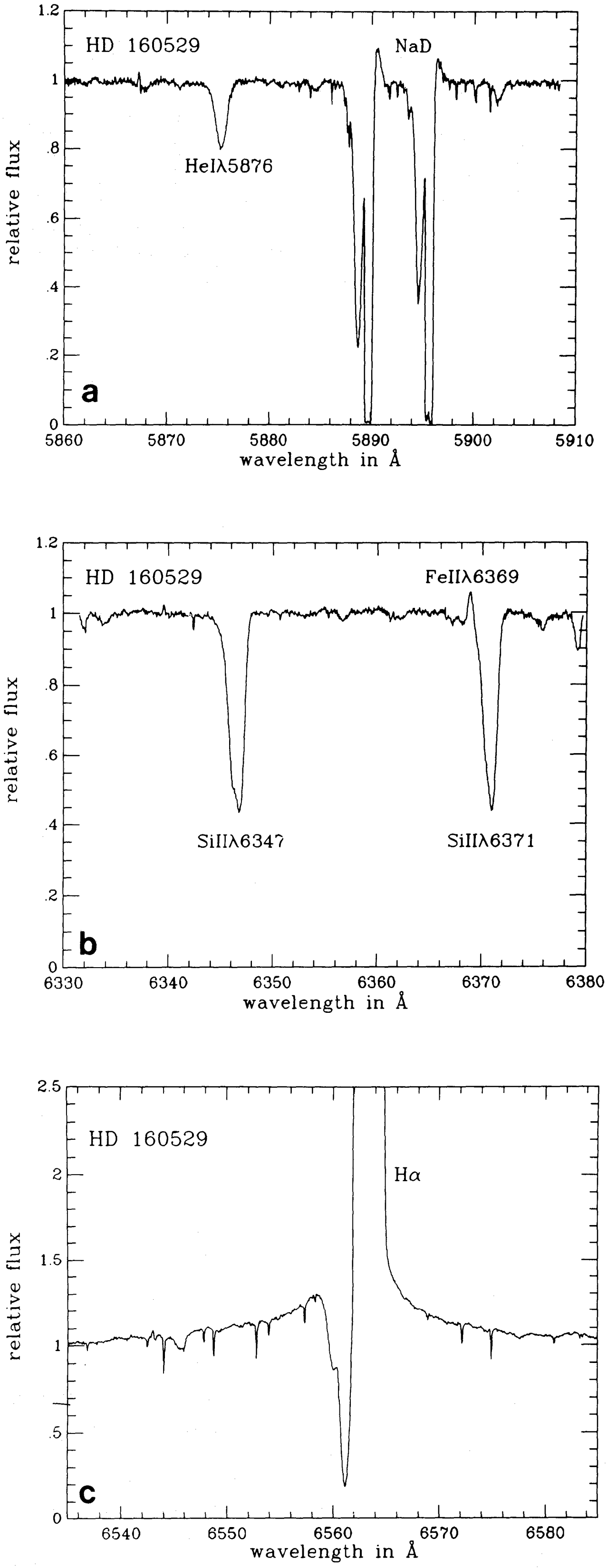

**Fig. 6.** The CES spectra of HD 160529 observed in June 1986. For details see section 3.4

is stronger on our spectra and that the emission at NaD has not been seen earlier. The velocities measured from the absorption lines are very similar to those reported by Wolf et al. (1974). The H$\beta$ profile, obtained on JD2448056 and the H$\alpha$ profile of JD2448194 are shown in Fig. 7. As can be seen, the H$\beta$ spectrum shows several CrII lines, each having two absorption components with mean heliocentric velocities of $-16$ and $-58$ km sec$^{-1}$. The H$\beta$ absorption has a mean velocity of $-139$ km sec$^{-1}$ and an edge velocity of $-180$ km sec$^{-1}$. The velocity of the emission peak is $-2$ km sec$^{-1}$. The H$\alpha$ spectrum shows similar values for the velocity ($-124$, $-189$ and $+9$ km sec$^{-1}$).

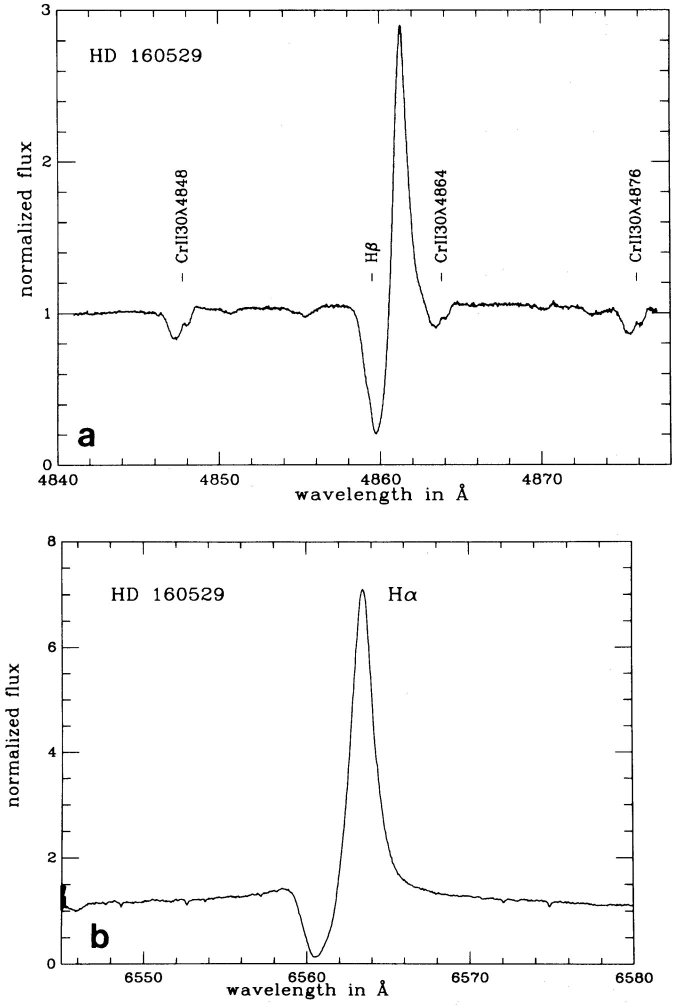

**Fig. 7.** H$\beta$ and H$\alpha$ profiles of HD 160529 respectively obtained on JD2448056 and - 8194

The ECHELEC spectrum of HD 160529 is underexposed and noisy, yet some useful information can be extracted for a comparison with the typical spectrum of the star characterizing its bright phase during the seventies. The spectrum is dominated by singly ionized metals. Measured equivalent widths of MgII$\lambda$4481 and some of the strongest TiII- and FeII-lines are presented in Table 3, along with the equivalent widths of the 1972 spectra of HD 160529 given by Campusano (1973) and of $\eta$ Leo (A0Ib) listed by Wolf (1971). Although the scatter of our equivalent width measurements is high, it can be readily seen that the ratio of the line strengths of the TiII/FeII lines has decreased by a factor of two for the spectrum of November 1990. Due to higher excitation potential of the FeII-lines this indicates a corresponding increase of the atmospheric temperature of HD 160529. The TiII/FeII line-ratio is now in good agreement with the ratio for $\eta$ Leo (for which an effective temperature of 10,400 K was derived by Wolf (1971) and it agrees well with the temperature derived from the $c_1$ index of HD 160529 in its present phase (see below). This higher temperature of about 10,000 K (which, according to Humphreys (1978) corresponds to a B8-supergiant) could also explain the presence of HeI$\lambda$4387 for which an equivalent width of $W_\lambda$ = 230 mÅ was measured. Note that HeI$\lambda$4471 is in a range of crowded ionized metallic lines and cannot reliably be identified due to strong blending effects.

**Table 3.** Equivalent widths $W_\lambda$ in mÅ of some prominent lines of HD 160529 derived from the ECHELEC spectrum of November 1990. For comparison we give the equivalent widths of the same lines from a 1972 spectrum (Campusano 1973) and for $\eta$ Leo, an A0Ib supergiant (measured by Wolf 1971).

| Ion | $\lambda$ | $\chi_{r,s}$ | HD160529 $W_\lambda$(1972) | HD160529 $W_\lambda$(1990) | $\eta$ Leo $W_\lambda$ |
|---|---|---|---|---|---|
| MgII 4 | 4481.3 | 8.83 | 913 | 740 | 502 |
| TiII 19 | 4443.8 | 1.08 | 615 | 114 | 91 |
| | 4450.5 | | 285 | 75 | 39 |
| 31 | 4468.5 | 1.13 | 512 | 221 | 151 |
| | 4501.3 | | 562 | 254 | 93 |
| 41 | 4308.1 | 1.16 | 495 | 184 | 95 |
| 50 | 4563.8 | 1.22 | 545 | 245 | 91 |
| FeII 27 | 4351.8 | 2.69 | 747 | 443 | 240 |
| 37 | 4491.4 | 2.84 | 458 | 182 | 151 |
| | 4520.2 | 2.79 | 578 | 488 | 182 |
| | 4555.9 | 2.79 | 673 | 478 | 204 |
| 38 | 4508.3 | 2.79 | 650 | 288 | 204 |
| | 4522.6 | 2.79 | 700 | 615 | 234 |
| | 4541.5 | | 440 | 384 | 132 |

## 4. The Eddington Limit in Model Atmospheres

Since we expect HD 160529 to lie close to the Eddington limit, we calculated the lowest gravity solar composition models possible with the ATLAS6 model atmosphere code (Kurucz 1979). In Table 4 we list the log g limits found. Lower gravity models at these tabulated effective temperatures could not be calculated because the surface point in the calculations ($\tau_{\rm Ross} = 10^{-3.5}$) becomes unstable to radiation pressure, and a static solution is not possible.

For this uppermost region of the Hertzsprung-Russell diagram (HRD) no theoretical *uvby* indices are available in the literature, so we computed synthetic *uvby* indices in the region close to the Eddington limit. The *uvby* colours are obtained in the following way. We compute the integrals

$$m_i = -2.5 \log \left[ \int F_\lambda S_{\rm i}(\lambda) A(\lambda) d\lambda \right] \tag{3}$$

$S_{\rm i}(\lambda)$ is the response function (filter transmission function plus photocathode spectral response) for the passband $i$ and A($\lambda$) is

**Table 4.** The Eddington limit in plane-parallel, line-blanketed, LTE model atmospheres.

| $T_{\mathrm{eff}}$ (K) | $\log g$ |
|---|---|
| 7500 | 0.38 |
| 8000 | 0.54 |
| 8500 | 0.72 |
| 9000 | 0.84 |
| 9500 | 0.93 |
| 10000 | 1.01 |
| 11000 | 1.15 |
| 12000 | 1.27 |
| 14000 | 1.52 |

the atmospheric transmission (Lamla 1982). By spline interpolating $F_\lambda$, $S_i(\lambda)$ and $A(\lambda)$ and integration using the trapezium formula, we obtained *uvby* magnitudes for 1 and 2 air-masses and determined zero air-mass magnitudes by reducing the 1 and 2 air-mass magnitudes to the zenith in a way analogous to the manner by which real observations are being reduced. The indices have been placed on the standard system using the same five secondary spectrophotometric standard stars as were used by Lester et al. (1986), and the transformation to the standard system was made in the same way as is described by them. If the computed indices are viewed as a natural system, in the sense used by photometrists, Crawford & Barnes (1970) have shown that it is generally necessary to use a relation of the form

$$\mathrm{index}_{\mathrm{std}} = A + B \times \mathrm{index}_{\mathrm{nat}} \tag{4}$$

to convert the indices to the standard system. They also showed that it is necessary to include a colour term for indices other than $(b-y)$ in order to adjust for the presence of H$\delta$ in the $v$ filter.

$$\mathrm{index}_{\mathrm{std}} = A + B \times \mathrm{index}_{\mathrm{nat}} + C \times (b-y) \tag{5}$$

The differences between the standard and the transformed indices for the standard stars have almost the same values as those described by Lester et al. (1986).

Using the coefficients derived in the above-mentioned way, we transformed the *uvby* indices computed from the Eddington-limit model-atmospheres to the standard system. The calculations were repeated using all combinations of filter transmission curves and photocathode response curves for the filter-photomultiplier combinations with which we obtained our photometric data. Table 5 gives the mean results (which are accurate to 0.01 mag), and also the reddening-free index

$$[c_1] \equiv c_1 - 0.2(b-y) \tag{6}$$

Comparing the range of variability in $c_1$ (i.e. $0.30 < [c_1]_{obs} < 0.44$) with the grid of theoretical $[c_1]$ values of Table 5, we find that the star evolves from maximum to minimum light along a path parallel to the Eddington limit (see Fig. 8). On the basis of the spectrographic arguments, the limits of this path are set to the range of values between 8,000 K to 10,000 K, which corresponds to a variation in spectral type from about A9Ia to B8Ia.

## 5. Discussion

The quasi-periodic photometric micro-variations of HD 160529 are very similar to those discussed by van Genderen (1989) for

**Table 5.** Synthetic theoretical Strömgren indices

| $T_{\mathrm{eff}}$ (K) | $\log g$ | $(b-y)$ | $c_1$ | $m_1$ | $[c_1]$ |
|---|---|---|---|---|---|
| 7500 | 0.45 | 0.12 | 1.56 | 0.09 | 1.54 |
| 7500 | 0.55 | 0.10 | 1.65 | 0.09 | 1.63 |
| 7500 | 0.65 | 0.09 | 1.69 | 0.09 | 1.67 |
| 8000 | 0.55 | 0.17 | 0.80 | 0.01 | 0.77 |
| 8000 | 0.65 | 0.14 | 1.13 | 0.04 | 1.11 |
| 8000 | 0.75 | 0.12 | 1.32 | 0.05 | 1.29 |
| 8500 | 0.75 | 0.13 | 0.67 | 0.02 | 0.65 |
| 8500 | 0.85 | 0.12 | 0.91 | 0.03 | 0.89 |
| 8500 | 0.95 | 0.10 | 1.08 | 0.04 | 1.06 |
| 9000 | 0.85 | 0.11 | 0.49 | 0.02 | 0.47 |
| 9000 | 0.95 | 0.10 | 0.67 | 0.03 | 0.65 |
| 9000 | 1.05 | 0.09 | 0.83 | 0.03 | 0.81 |
| 9500 | 0.95 | 0.10 | 0.39 | 0.02 | 0.37 |
| 9500 | 1.05 | 0.09 | 0.55 | 0.03 | 0.53 |
| 9500 | 1.15 | 0.07 | 0.68 | 0.03 | 0.66 |
| 10000 | 1.05 | 0.08 | 0.33 | 0.02 | 0.31 |
| 10000 | 1.15 | 0.07 | 0.47 | 0.03 | 0.45 |
| 10000 | 1.25 | 0.06 | 0.58 | 0.03 | 0.57 |
| 11000 | 1.15 | 0.07 | 0.13 | 0.03 | 0.12 |
| 11000 | 1.25 | 0.05 | 0.27 | 0.03 | 0.26 |
| 11000 | 1.35 | 0.04 | 0.37 | 0.03 | 0.37 |
| 12000 | 1.30 | 0.05 | 0.01 | 0.03 | 0.04 |
| 12000 | 1.40 | 0.03 | 0.18 | 0.03 | 0.18 |
| 12000 | 1.50 | 0.02 | 0.28 | 0.04 | 0.28 |

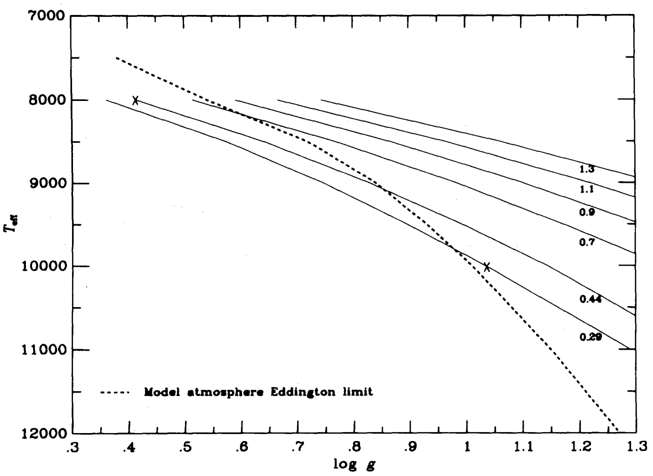

**Fig. 8.** $\log g - T_{\mathrm{eff}}$ diagram in the region around the Eddington limit. The solid lines are lines of equal $[c_1]$-values taken from Table 5. The two lower parts of the $[c_1]$ curves going beyond the Eddington limit are extrapolations. The two $[c_1]$-values representing the maximum and minimum phase are indicated by crosses.

LBV's and comparable to light variations of normal luminous stars. The very long-term variations of about 0.5 mag are more unusual. From its luminosity, its spectral type and from the amplitude of the variations, HD 160529 can be classified as a LBV. Stars belonging to that class are distinguished by slowly expanding envelopes. This is confirmed by radial velocity measurements from spectra obtained during the bright phase which occurred in the seventies. Although the system velocity of HD 160529 is hard to determine because of the presence of the expanding envelope, we argue that it is close to the velocity of the slower component of the split absorption lines found in the spectra, namely −10 km sec$^{-1}$. The position of the H$\alpha$ P Cyg emission is in reasonable agreement with this value. The average envelope velocity as determined from the fast component is −40 km sec$^{-1}$ and the maximum velocity as determined from the blue edge is −90 km sec$^{-1}$.

The history of the light variations is well documented from 1972 on; it shows that the star was slightly variable around a mean value of about $V = 6.5$ from 1972 to 1982 and is decreasing in brightness since then, attaining $V = 6.9$ in August 1989. Before 1972, the only photometry available is from Hiltner (1954), who measured $V = 6.67$. He classified the star as A2Ia$^{+}$. According to several authors, the spectral type did not change much between 1954 and 1970. However, Houk (1982) classified the star as A9Ia from data obtained in 1973. This suggests that the star has a later spectral type when it is brighter, which is a typical characteristic of LBV's (Stahl 1990; Wolf 1990).

In order to further study the relation between colours and brightness, we computed the *uvby* colours of stars near the upper limit of the HRD from the Kurucz (1979) models. We assumed the effective temperature of HD 160529, when it is close to maximum light, to be 8,000 K. This value is close to the excitation temperature ($T_{\rm exc} = 7{,}800$ K) derived by Wolf et al. (1974) from a curve-of-growth analysis. $\log g$ has been derived from the assumption that the star has the minimum surface gravity necessary for hydrostatic models. This gives $\log g = 0.55$. As a check we computed the H$\delta$ profile from an ATLAS6 model atmosphere and compared it with the observations of Campusano (1973). The model and the observations are shown in Fig. 9. The VCS theory (Vidal et al. 1973) for the Balmer line broadening was used. The agreement is not perfect, but quite good for a model which is so close to the instability limit.

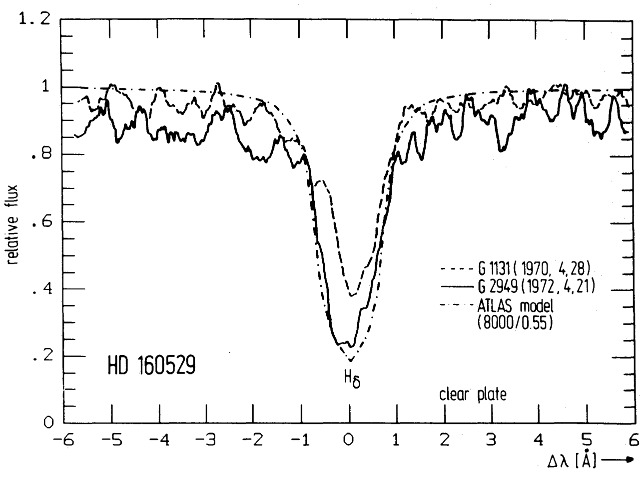

**Fig. 9.** Observed and computed H$\delta$ profile in the spectrum of HD 160529.

A particular source of uncertainty has been the absolute visual magnitude $M_{\rm V}$ of HD 160529. Hiltner (1954) and Wallerstein (1970) estimated −8.4 and −8.5, respectively, for this highly reddened star. With this luminosity HD 160529 would be at the lower limit of the known LBV's (Wolf 1989). However, the atmospheric parameters 8000/0.55 derived for the maximum state of HD 160529 are similar to those of the recently discovered LBV R 110 (7600/0.5) in the LMC (Stahl et al. 1990) which represents with $M_{\rm V} = -8.9$ the lower limit of the well-investigated LBV's. The amplitude of R 110's visual brightness variations is 0.5 mag and is of the same order as the – still ongoing – decrease of HD 160529 from its maximum brightness. Also the envelope expansion velocities of both stars are very similar. Since there is strong evidence for a correlation of the amplitude with the luminosity of the LBV's (see Wolf 1989), we ascribe to HD 160529 the same luminosity as to R 110. With $M_{\rm V} = -8.9$, $V = 6.5$ and $E_{\rm B-V} = 1.10$ (see below), we get (using $A_{\rm V} = 3.1\ E_{\rm B-V}$) a distance of 2.5 kpc for HD 160529. Accordingly, HD 160529 would be located beyond the Sagittarius arm in the inner arm of the Galaxy.

With $M_{\rm V} = -8.9$ and with the fluxes from the Kurucz model (8000/0.55) we derive $R/R_{\odot} \approx 330$ and $M/M_{\odot} \approx 13$ (the flux calibration of Bessell (1979) was assumed for the $V$ filter). This value for the mass of HD 160529 is surprisingly low for its high luminosity but is consistent with the earlier suggestion that the LBV instability-strip is occupied by highly evolved stars which have shed off a large amount of their mass due to mass loss (cf. e.g. Wolf 1990).

We estimated the mass-loss rate of HD 160529 from the H$\alpha$ line. Since the emission peak is overexposed, only a lower limit to the mass-loss rate can be determined. For this purpose we used the multi-level radiative transfer programs described by Bastian (1982) and Stahl et al. (1983) to compute the level populations of hydrogen in the wind, and the resulting line profiles. We used a velocity law of the form

$$v(r) = v_0 + (v_\infty - v_0)(1 - R_*/r) \qquad (7)$$

The velocity at the photosphere ($v_0$) was fixed to 10 km sec$^{-1}$. The electron temperature in the wind was set equal to $T_{\rm eff}$. Using $T_{\rm eff} = 9000$ K (note that the spectrum discussed here was taken when HD 160529 was fainter by about 0.2 mag than at maximum brightness; it is now widely accepted that the variability of LBV's in the visual occurs under the condition $M_{\rm bol} \approx$ const by adjustment of the bolometric correction, so we get this higher temperature), $R_* = 250$ R$_{\odot}$, $v_\infty = 120$ km sec$^{-1}$, we obtain a lower limit of $10^{-5}$ M$_{\odot}$ yr$^{-1}$ for the mass-loss rate of HD 160529. The same procedure has been used to determine the mass-loss rate from the H$\beta$ and the H$\alpha$ spectrum taken in 1990 June and October, respectively. In this case, however, we adopt a temperature of 10,000 K and a radius of 200 R$_{\odot}$ because of the lower brightness and thus presumably higher temperature of the star. For the terminal velocity we adopt 180 km sec$^{-1}$. We obtain an estimate for the mass-loss rate of $10^{-5}$ M$_{\odot}$ yr$^{-1}$ from these lines. As a comparison we also computed models for the H$\beta$ data published by Wolf et al. (1974). In this case we used a temperature of 8,000 K, a radius of 330 R$_{\odot}$ and an expansion velocity of 90 km sec$^{-1}$ to represent the maximum phase. Also in this case we obtain an estimate of $10^{-5}$ M$_{\odot}$ yr$^{-1}$ for the mass-loss of the star.

We also used the infrared photometry obtained in 1982 to estimate the mass-loss rate during maximum phase. First we determined the reddening of the star from these data. Assuming that the star has no IR excess in the near-infrared region ($JHK$), we find that a reddening value of $E_{\rm B-V} = 1.10$ is required. The reddening of $E_{\rm B-V} = 1.22$ from the literature gives too little flux in the near-IR if compared to Kurucz' models of 8,000 K. Only with much higher temperatures of about 9,500 K we could explain the observations with this high reddening. Since we have no spectroscopic evidence for such a high temperature, we prefer to use a reddening of $E_{\rm B-V} = 1.1$ in what follows. With this reddening we get a slight IR excess in $K$ and a larger excess in $L$ and $M$. We used the code described by Bertout et al. (1985) to determine the mass-loss rate. The same velocity law as above with a terminal velocity of 90 km sec$^{-1}$ has been used. This lower value for $v_\infty$ has been derived for the maximum phase (cf. Wolf et al. 1974). We find that a mass-loss rate of 2-3 $10^{-5}$ $M_\odot$ yr$^{-1}$ gives a good fit to the IR excess in the $K, L$ and $M$ bands.

To conclude, we find a mass-loss rate of 1-3 $10^{-5}$ $M_\odot$ yr$^{-1}$ for HD 160529, with no convincing evidence for a dependency on the brightness of the star. Such a mass-loss rate is typical for LBV's but is an order of magnitude larger than the mass-loss rate for R 110 estimated by Stahl et al. (1990). A possible interpretation could be the difference in chemical composition of these two stars. According to a previous suggestion by Appenzeller (1986) and Lamers (1986) the high mass-loss rate of LBV's is due to a line-opacity driving mechanism and is generated by the presence of a large amount of singly-ionized metallic lines. Due to the higher metallicity of the galactic star HD 160529, a higher radiation pressure is exerted on the envelope and thence an enhanced mass-loss rate is to be expected.

By comparison with the calculations of Maeder and Meynet (1988) the initial mass of HD 160529 was 25 $M_\odot$. Like R 110, HD 160529 most likely represents an object in the post Red-SuperGiant (RSG) evolutionary phase. HD 160529 is in fact the first galactic LBV observed of this kind.

Evolutionary models of luminous stars in the mass range around that of HD 160529 have been calculated by several groups in connection with SN1987A (cf. e.g. Woosley (1988) and literature quoted therein). As one of the most likely reasons for producing a blue supergiant progenitor of a supernova, low metallicity was often considered. HD 160529 perhaps provides evidence that low metallicity is not a necessary pre-requisite for the evolution of massive stars back to higher temperatures.

## 6. Conclusions

HD 160529 has previously been classified as an early A-type hypergiant. During the past eight years the star's visual brightness has decreased by about 0.5 mag and its spectral type has become B9 to B8. From these variations it has to be concluded that HD 160529 is a new case of a galactic LBV.

This finding suggests that some "normal" A hypergiants may be B stars in some extended phase of outburst. The A-star characteristics during the bright phase can be explained by an opaque quasi-stationary pseudo-photosphere. HD 160529 resembles in several respects (similar amplitude between maximum and minimum phase and similar stellar wind velocities) the recently discovered LBV R 110 of the LMC. Accordingly, HD 160529 is located at the lower limit of the LBV instability strip and is a good candidate for a luminous blue galactic star in the post-RSG evolutionary phase.

Deviating from these similarities to R 110, HD 160529 is distinguished by a ten times higher mass-loss rate. It is conjectured that this is a consequence of a stronger line-opacity driving force due to the higher metallicity of this galactic object.

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