Spectroscopic analysis of the candidate \( \beta \) Cephei star \( \sigma \) Cas: Atmospheric characterization and line-profile variability

G. Catanzaro\(^a\)*, R. Ventura \(^a\), F. Ferrara \(^b\), L. Paternò \(^b\)

\(^a\)INAF – Osservatorio Astrofisico di Catania, Via S. Sofia, 78, 95123 Catania, Italy
\(^b\)Dipartimento di Fisica e Astronomia, Sezione Astrofisica, Università degli Studi di Catania, Via S. Sofia, 78, 95123 Catania, Italy

ARTICLE INFO

Article history:
Received 27 April 2009
Accepted 4 May 2009
Available online 12 May 2009
Communicated by P.S. Conti

PACS:
97.10.Tk
97.30.Dg
97.10.Sj
97.10.Ri

Keywords:
Stars: individual: \( \sigma \) Cas
Stars: abundances
Stars: fundamental parameters
Stars: oscillations

ABSTRACT

This study is an exploratory search to ascertain for the first time the detailed properties of \( \sigma \) Cas as a candidate pulsator of \( \beta \) Cephei type in view of future observing campaigns. This search is devoted to a precise characterization of the parameters of the star for verifying its location with respect to the \( \beta \) Cephei instability region and to a preliminary analysis of a possible spectral line-profile variability.

The characterization of the parameters of the star was based both on spectroscopic observations carried out by us on October 2007 and literature data used to build its spectral energy distribution. The suspected pulsational variability of the star have been studied by analyzing the line-profile variability of the two spectral lines HeI \( \lambda 5875 \) Å and SiIII \( \lambda 4552.6 \) Å. The search for periodicity was performed by adopting the pixel-by-pixel method.

From the analysis of the composite spectrum of \( \sigma \) Cas we derived the effective temperature and surface gravity. From literature values of distance, visual magnitude, bolometric correction and extinction we determined the luminosity and radius. By means of evolutionary tracks and isochrones we derived also mass and age. The values obtained pose \( \sigma \) Cas with a good certainty inside the \( \beta \) Cephei instability region. The line-profile variability analysis indicate a clear excess of oscillation power in the range 2–8 cycles d\(^{-1}\), with two prominent peaks at 3.00 and 5.32 cycles d\(^{-1}\), in the expected typical range of frequency of \( \beta \) Cephei pulsations. In this framework, it emerged that, besides the use of the canonical SiIII \( \lambda 4552.6 \) Å line for \( \beta \) Cephei pulsation studies, the HeI \( \lambda 5875.6 \) Å line might be an additional suitable candidate for period and mode analysis in \( \beta \) Cephei stars.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

\( \beta \) Cephei stars are early-B type, near main-sequence objects which exhibit variations in brightness, radial velocity, and line profiles on time scales of several hours, due to radial and non-radial p- and g-mode pulsations. They are located on the HR diagram in a narrow region where the classic k-mechanism is effective in the partial ionization zone of the iron group elements. They are in the late stages of core hydrogen-burning phase, just preceding the secondary gravitational contraction (Balona and Engelbrecht, 1981). For a clear look of their location inside the instability region, we address the reader to the HR diagram of the confirmed and candidate \( \beta \) Cephei stars recently published by Stankov and Handler (2005). Simultaneously excited radial and non-radial pulsation modes, the evidence of line-profile variability (LPV) on rotationally broadened spectral lines that allows the detection of much higher harmonic degrees \( \ell \) than those generally detected by photometric and radial velocity studies, and the relatively simple structure of their pulsation spectra make these stars of great interest from an asteroseismic point of view.

\( \sigma \) Cas (+HD 224572 = HR 9071) is a bright \((V = 4.88)\), rapidly rotating, near main-sequence star at a parallax of \( \pi = 2.14 \pm 0.75 \) mas, in a visual binary system (Muller, 1952), whose companion is a B3 V star about 2.1 mag fainter. It is classified as a B1 V star in Hoffleit and Jaschek (1982). Abt et al. (2002) estimated a value of the projected rotational velocity of 150 km s\(^{-1}\), averaged between the values obtained from HeI \( \lambda 4471 \) Å and MgII \( \lambda 4481 \) Å.

Line-profile variations in the SiIII \( \lambda 4560 \) Å triplet were detected in the spectra of this star for the first time by Telting et al. (2006) in the framework of a high resolution spectroscopic survey of \( \beta \) Cephei pulsations in early-B type, near main-sequence stars in the solar neighborhood. This discovery was based only on a visual inspection of spectra of the star collected at the Nordic Optical Telescope (La Palma, Canary Islands), William Herschel Telescope (La Palma, Canary Islands) and Coudé Auxiliary telescope (ESO, La Silla). The authors pointed out the likely pulsation origin of the observed LPVs and ascribed them to high degree pulsation modes.
identifying the star as a suspected β Cephei star. However, the lack of observed spectra, 7 in total, did not allow any attempt to perform a search for periodicities.

Spurred by this preliminary work, this study presents the results of spectroscopic observations of σ Cas, performed on a baseline of eight nights at the INAF – Catania Astrophysical Observatory, whose aim was to provide estimates of atmospheric parameters and chemical abundances for an essential characterization of the star for future asteroseismic investigations. We also derived power spectra of the LPV observed in the SiIII λ4552 Å and HeI λ5875 Å lines. In Section 2 we describe the data acquisition and reduction techniques. In Section 3 we report the procedures adopted for determining the atmospheric parameters and chemical abundances of the star. In Section 4 we report the results of a preliminary analysis of LPV and in Section 5 we draw some conclusions.

2. Observation and data analysis

Spectroscopic observations of σ Cas, in the spectral range from 4800 Å to 6500 Å, were carried out during the period October 8–19, 2007, at the 91 cm telescope of the INAF – Catania Astrophysical Observatory. The telescope is fiber linked with a REOSC spectrograph with a resolving power of about R = 21,000. A total amount of 62 spectra, covering about 32 h of observation distributed over eight almost consecutive nights (see Table 1), were collected. The integration time per exposure was 30 min with a resulting signal-to-noise ratio (S/N) at least 200.

The stellar spectra, calibrated in wavelength and with the continuum normalized to a unity level, were obtained by using standard data reduction procedures for spectroscopic observations within the NOAO/IRAF package.

3. Astrophysical characterization of the star

Since it has been proved that the position and extension of the β Cephei instability domain are strongly affected by metallicity (Pamyatnykh, 1999) – the instability strip shrinking down with the decreasing value of Z (see Fig. 11 of Pamyatnykh (1999)) – we needed to derive first the effective temperature and surface gravity, then the atmospheric chemical abundances and fundamental stellar parameter of our target in order to check the compatibility of the position of σ Cas with the locus of the β Cephei instability region. For the former quantities we undertook a spectroscopic analysis by using the highest SNR spectrum among those acquired and for the latter we used literature values of photometry and dispersion spectrum (SWP20971RL) that covers the 1150–2000 Å interval; UV fluxes taken from TD1 satellite (Thompson et al., 1978) that cover the 1565–2740 Å range; spectrophotometry in the range 3500–7800 Å taken from Khaitonov et al. (1988); UBV magnitudes from Morel and Magnenat (1978); and JHK magnitudes from 2MASS survey (Skrutskie et al., 2006).

The resulting spectrum was de-reddened following the procedure by Cardelli et al. (1989) and then compared with a grid of theoretical fluxes computed by means of the ATLAS9 code (Kurucz, 1993). The colour excess, E(B–V) = 0.14, needed by the reddening procedure and reported in Table 2, was obtained from Megier et al. (2005). The starting values of T_{eff} and log g were obtained from the Strömgren photometry according to the grid of Moon and Dworetzky (1985). The photometric colours were de-reddened with the Moon (1985) algorithm. The source of the Strömgren photometric data was the one of Hauck and Mermilliod (1998).

We then compared the observed profile of the Hα line with the synthetic one by minimizing the differences between them, using the χ^2-criterium for evaluating the goodness-of-fit:

\[ \chi^2 = \frac{1}{N} \sum \frac{(I_{\text{obs}} - I_{\text{th}})^2}{\delta I_{\text{obs}}} \]

where N is the total number of points, I_{obs} and I_{th} are the intensities of the observed and computed profiles, respectively, and \( \delta I_{\text{obs}} \) is the photon noise. Errors were estimated as the variation in the parameters that increase the χ^2 by a unity.

In order to calculate the atmospheric chemical abundances of σ Cas we computed the synthetic spectrum of the star in the whole observed spectral region using the above determined values of T_{eff}, log g, and v sin i. We used the ATLAS9 (Kurucz, 1993) code in order to compute the LTE atmospheric model with solar ODF and SYNTH code (Kurucz and Avrett, 1981) for computing the synthetic Hα profile.

The projected rotational velocity was estimated by means of a non-linear least-squares fit of a rotationally broadened Gaussian profile to the line-profile of the Mg i λ4481 Å. The derived value of 170 ± 5 km s^{-1} is in agreement with those previously determined in literature and reported in Table 2. The calculated values of T_{eff}, log g, and v sin i are listed in Table 3.

In Fig. 1 we show both the SED and Hα modelled by using the same set of atmospheric parameters that represent an acceptable compromise for reproducing the observed spectra.

In order to calculate the atmospheric chemical abundances of σ Cas we computed the synthetic spectrum of the star in the whole observed spectral region using the above determined values of T_{eff}, log g, and v sin i. We used the ATLAS9 (Kurucz, 1993) code in order to compute the LTE atmospheric model with solar ODF and SYNTH code (Kurucz and Avrett, 1981) to identify the observed spectral lines and derive chemical abundances. The values of the oscillator strengths, log gf, for each spectral line are those published by Kurucz and Bell (1995) with the subsequent improvement by Castelli and Hubrig (2004).

<table>
<thead>
<tr>
<th>HJD (2454300+)</th>
<th>ΔT (h)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>82.3069</td>
<td>6.00</td>
<td>11</td>
</tr>
<tr>
<td>83.3453</td>
<td>3.90</td>
<td>8</td>
</tr>
<tr>
<td>84.3932</td>
<td>5.27</td>
<td>9</td>
</tr>
<tr>
<td>85.3784</td>
<td>5.00</td>
<td>10</td>
</tr>
<tr>
<td>86.2912</td>
<td>7.04</td>
<td>13</td>
</tr>
<tr>
<td>88.5508</td>
<td>1.52</td>
<td>4</td>
</tr>
<tr>
<td>90.4624</td>
<td>3.20</td>
<td>7</td>
</tr>
</tbody>
</table>
In order to reproduce the spectrum recorded by IUE, we computed the photospheric spectrum by adopting the same atmospheric parameters deduced from the optical spectrum, after having broadened it by rotational velocity and instrumental resolution.

Fig. 1. Top: Observed spectral energy distribution (SED) constructed with the help of the various literature sources described in the text. Thick line represents theoretical SED computed by ATLAS9 code for $T_{\text{eff}} = 21,000$ K and $\log g = 3.6$. Bottom: Observed H$_\beta$ profile with over-imposed the synthetic line computed for the same parameters we used for the SED.
power of $R_{7500}$, corresponding to the nominal resolution of $D_k/C_{25}$ at 1500 Å. As an example, in Fig. 2 we show the comparison between the synthetic and observed spectra in two wavelength intervals, where it is clear that most of the spectral lines are quite well reproduced. Further, in the UV range we were able to identify, among the others, the two prominent lines of SiIV $\lambda 1394$ and $\lambda 1402$ Å and the line of SiIII $\lambda 1418$ Å. Since these lines are reproduced with the same abundance adopted for the optical silicon lines, the ionization equilibrium could be considered fulfilled, with the consequence that the adopted $T_{\text{eff}}$ and $\log g$ are correct.

The derived abundances in terms of solar abundances $\log(N_X/N_H)_{\odot}$, assuming the solar values given by Asplund et al. (2005), are reported in Table 4. The deduced uncertainties are typically of the order of 0.2 dex.

From our analysis it appears that $\sigma$ Cas shows normal abundances as deduced from all the spectral lines we have identified. This result agrees with the typical abundance pattern observed in $\beta$ Cephei stars as recently reported by Morel et al. (2006).

### 3.2. Fundamental parameters

We determined the luminosity of $\sigma$ Cas on the basis of the Sun’s bolometric magnitude determination by Drilling and Landolt (1999), $M_{bol} = 4.74$, the determination of the $\sigma$ Cas visual magnitude by Morel and Magnenet (1978), $V = 4.88$, the distance derived from Hipparcos main catalogue parallax (Perryman et al., 1997), $d = 467 \pm 164$ pc, the bolometric correction by Drilling and Landolt (1999), $B-C = 2.35$, and the extinction coefficient estimated by Megier et al. (2005), $A_V = 3.1E(B-V)$ where $E(B-V) = 0.14$. With these data we obtained:

$$\log L/L_\odot = 4.4 \pm 0.3 \quad (1)$$

with the consequence that the estimated radius of $\sigma$ Cas on the basis of our estimate of $T_{\text{eff}}(21,000 \pm 1000 \text{ K})$ is $R = 11.3 \pm 1.2 R_\odot$.

With our values of $T_{\text{eff}}$ and $L$, we constructed the HR diagram showed in Fig. 3. Comparison with evolutionary tracks of Bressan et al. (1993), computed for $Z = 0.02$ (solar metallicity), and with

![Fig. 2. Comparison between theoretical and observed spectra in two IUE wavelength ranges.](image-url)
isochrones computed by Bertelli et al. (1994) indicates for \( r \) Cas a mass of \( 12.5^{+3}_{-2} M_{\odot} \) and an age of \( 15.8 \pm 3.6 \) Myrs. These parameters indicate that the star is placed inside the \( \beta \) Cephei instability region.

4. Analysis of line-profile variations

Fig. 4 shows some examples of the HeI \( \lambda 5875.6 \) Å line-profile variations where a pattern of bumps moving across the line-profiles during the observing night (HJD = 2454386.291 to HJD = 2454386.584) is evident.

The search for periodicities in the line-profile variability was performed by adopting the so-called pixel-by-pixel method, based on the fact that the flux measured at each pixel (i.e. at each wavelength) across a line-profile fluctuates with the same period as a wave propagating in the photosphere of the star. A detailed description of this approach can be found in Mantegazza and Poretti (1999) and Mantegazza (2000).

Owing to the relatively high velocity of the star, the only spectral lines completely free from line-blend contamination, and therefore suitable for a study of line-profile variability were the Si\( iii \) \( \lambda 4552.6 \) Å (the most intense line of the Si\( iii \) triplet) and the HeI \( \lambda 5875.6 \) Å. Residuals were generated for both lines by subtracting the mean profile from the individual ones. Therefore from the whole set of residuals we extracted respectively, 67 and 69 time series (as many as the number of pixels sampling each line-profile), consisting of the measured fluxes at each wavelength across the line-profiles as a function of time.

The Fourier transform of the resulting time strings was performed by adopting the generalized version of the least-squares multiple sinusoid fit with known constituents (Mantegazza and Poretti (1995), originally developed by Vanicek (1971)). A "global" least-squares spectrum that contains the contribution to the variability coming – on the whole – from all the set of the time series (i.e. from the whole line-profile), is computed and a power spectrum is generated in terms of the so-called global reduction factor:

\[
RF_i = 1 - \frac{\sigma_{fin}^2}{\sigma_{in}^2}
\]

where \( \sigma_{in}^2 \) and \( \sigma_{fin}^2 \) are the global residual variances of the data before and after the fit of the line-profile variations with a sinusoidal function of trial frequency \( v_i \), respectively. We scanned all the frequency range from 0 up to the Nyquist frequency which is of about 24 cycles d\(^{-1}\). However the power spectra reported here have been truncated at 20 cycles d\(^{-1}\) since all the significant power appears at frequency well below 12 cycles d\(^{-1}\). The total length of data set is such that the HWHM of the main power peak in the window function is 0.060 cycles d\(^{-1}\).

The power spectra referring to the line-profile variability of HeI and Si\( iii \) lines are reported in Figs. 5 and 6, respectively.

The least-squares pixel-by-pixel power spectra describing the evolution of the variability across the line-profile, and the corre-
A significant concentration of power in the frequency range from about 2 cycles d$^{-1}$ to about 8 cycles d$^{-1}$, with two prominent peaks at 3.00 cycles d$^{-1}$ and 5.32 cycles d$^{-1}$, is evident; this is the expected typical range of frequency for $\beta$ Cephei pulsations. Each periodicity is distributed in discontinuous patches of power along most part of the corresponding global spectrum are shown for both lines.
the line-profiles and is characterized by a central peak flanked by quite strong sidelobes at small multiples of \(\pm 1\) cycles d\(^{-1}\), produced by the limited single-site temporal sampling, spread over eight quite consecutive nights (see the spectral window in the inset of Fig. 5). It is interesting to note that in the case of the most intense Hei \(\lambda 5875.6\) Å line (about 2 times more intense than the Si\(\text{III}\) one) the pulsation signal emerges much more clearly from the noise.

5. Discussion and conclusions

In this research note we presented for the first time a detailed astrophysical characterization of the suspected \(\beta\) Cephei star \(\sigma\) Cas. We combined UV IUE data with our optical spectra obtained with the 91 cm telescope of the INAF-Catania Astrophysical Observatory.

Effective temperature and surface gravity were determined by matching the UV and visible flux distributions, and, by means of spectral synthesis, we derived an almost standard atmospheric composition (see Section 3.1 and Table 4 for details). We also derived the luminosity of our target and constructed the correspondent HR diagram, confirming that our target lies in the \(\beta\) Cephei instability region as computed by Pamyatnykh (1999) for solar metallicity \((Z = 0.02)\). The inferred luminosity, mass, radius, and age are reported in Table 3.

The new set of spectroscopic observations has allowed to confirm the previous detection of line-profile variability (Teling et al., 2006) in \(\sigma\) Cas over a much larger dataset and provided pieces of information on the possible presence of pulsation periods, confined in the domain of \(\beta\) Cephei variability. It is interesting to note that the two spectral lines, the Si\(\text{III}\) \(\lambda 4552.6\) Å and Hei \(\lambda 5875.6\) Å, adopted in the analysis of the LPV of \(\sigma\) Cas, provided mutually consistent results, but with the He line producing a less noisy power spectra. The Si\(\text{III}\) triplet lines in the spectrum of \(\beta\) Cephei stars are the most popular and usually recommended spectral lines for studies of their pulsations. They are in general (i) strong enough and then much less subject to noise, (ii) not affected very much by blending, and (iii) almost insensitive to temperature variations (De Ridder et al., 2002). Further, the contribution functions, computed by using XLINOP (Kurucz and Avrett, 1981) for the cores of the two lines here considered, show that their formation regions are almost coincident. Then, the results obtained in the present work indicate that the Hei \(\lambda 5875.6\) Å spectral line might well be an additional suitable candidate line for period and mode analysis in \(\beta\) Cephei stars.

The limited temporal sampling of our spectroscopic data-set, the moderate spectroscopic resolution and signal-to-noise ratio of our spectra did not allow a precise determination of the pulsation frequencies and any attempt of mode identification. Anyway the promising results obtained strongly encourage the planning of new observations with a higher performance spectrophotograph, over a much larger data base, even in the framework of multisite simultaneous photometric and spectroscopic campaigns.

Acknowledgements

This work made use of the following facilities: (i) INES data from the IUE satellite; (ii) data from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation; and (iii) SIMBAD data-base, operated at CDS, Strasbourg, France.

References

Moon, T.T., 1985. Comm. from the Univ. of London Obs. 78.