1992A&A...261..203P

Astron. Astrophys. 261, 203–208 (1992)

ASTRONOMY
AND
ASTROPHYSICS

The light-time effect as the cause of period changes in β Cephei stars

II. σ Scorpii

A. Pigulski

Wrocław University Observatory, ul. Kopernika 11, PL-51-622 Wrocław, Poland

Received September 11, 1991; accepted January 31, 1992

Abstract. The $O-C$ diagram for the main pulsation period of the β Cephei-type star σ Scorpii indicates that the period increased in the first half of the century, decreased after 1960, and again increased about 1984. We show that these changes of the observed period can be explained by a superposition of two effects: an evolutionary increase of the intrinsic pulsation period and a variation due to the light-time effect in a binary system. The star responsible for the latter effect is the system's component detected by means of the lunar occultations and speckle interferometry. A companion at a similar separation was recently found to cause the observed period changes in β Cep, the prototype of this class of variables. In this way, σ Sco becomes the second β Cephei-type star in which the light-time effect in a binary system contributes to the observed changes of the pulsation period.

The rate of the secular period change found for σ Sco locates this star in the shell-hydrogen burning phase. Since a similar rate of period change is observed in BW Vul, we note the possible connection between evolutionary status and the pulsation amplitudes in β Cephei-type stars.

Key words: β Cep stars – spectroscopic binary stars – visual binary stars – individual stars: σ Sco

---

1. Introduction

σ Scorpii (HR 6084 = HD 147165, B1 III) belongs to a quadruple system. The system's primary is a β Cephei-type star and a brighter component in a spectroscopic binary with an orbital period of about 33 d. The fainter component has been recently detected spectroscopically by Mathias et al. (1991). A more distant tertiary component was discovered by lunar occultations (see Nather et al. 1974). The speckle interferometry made by Morgan et al. (1978) confirmed its presence. Its separation from the spectroscopic pair is now equal to about $0''.4$ and slowly increases. As was found by lunar occultations, the tertiary is about 2.2 mag fainter than the spectroscopic pair, orbiting it with a period in the range from one to several centuries (Evans et al. 1986). The last, fourth component of the system is the fainter star in the visual common proper motion pair ADS 10009 (sep. $20''.0$, $\Delta m = 5.6$ mag).

The light variability of the primary can be described as a superposition of four periodic terms (Jerzykiewicz & Sterken 1984), of which two, having the periods $P_2 = 0^{d}.24684$ and $P_1 = 0^{d}.23967$, are also observed in radial velocities. In this paper we follow the notation of the pulsation periods used by Jerzykiewicz & Sterken (1984). The main pulsation period, P_2, dominates the radial velocity as well as the light variations. Below we shall consider the changes of this period only.

An inspection of the $O-C$ diagram for P_2 shows that an increase and a decrease were both observed. Struve et al. (1955, 1961) found an increase of P_2 with a rate of 2.3 s cen^{-1} before 1950. van Hoof (1966) reported a decrease of the period after 1960. On the other hand, Sterken (1975) maintained that P_2 varied with a period of 23.2 yr, while Chapellier (1985) proposed that it had suffered two abrupt changes. The latter author found one increase (between 1924 and 1947) and one decrease (around 1960) of the period. Recent observations (Mathias et al. 1991; Heynderickx 1991) indicate that an increase of P_2 is observed again.

Another β Cephei-type variable, β Cep itself, is also a member of a multiple system rather similar to σ Sco, since in both cases the variable primaries have speckle companions at comparable separations. It was recently shown by Pigulski & Boratyn (1992; hereafter Paper I) that orbital motion of the variable primary in the β Cep binary system, consisting of the variable and its speckle companion, leads to the apparent changes of the pulsation period via the light-time effect. The $O-C$ diagram and the speckle interferometric observations of β Cep could therefore be used to derive the orbital elements of this system.

Similarity of both stellar systems opens the possibility that the observed changes of the main pulsation period of σ Sco are also caused by the light-time effect. In order to verify this idea, we carried out an analysis similar to that made previously for β Cep. In the present paper we give an account of the results we obtained.

2. Observational data

The history of the variability of σ Sco began in 1904, when Slipher (1904) discovered that the star's radial velocity varies. His discovery was followed by numerous spectrographic observations of Selga (1916) and Henroteau (1918, 1921, 1923, 1925). Unfortunately, after Henroteau's observations in the early 20-ties, the star was not observed spectroscopically until about 1950. The radial-velocity data published after 1950 include Levee (1952), Struve et al. (1955, 1961), Campos & Smith (1980), Burger et al. (1982), Kubiak & Seggewiss (1983), vander Linden & Butler (1988), and Mathias et al. (1991). All were used in our analysis.

Photometric variability of the star was detected in 1947 by Hogg et al. (1951). Below we make use of all available photometric data, namely those of Hogg (1957), van Hoof (1966), Watson (1971), Sterken (1975), Burger et al. (1982), Kubiak & Seggewiss (1983), Odell et al. (1983), Sterken (1984), vander Linden & Sterken (1987), and Heynderickx (1991).

3. The *O–C* diagram for the main pulsation period

As we mentioned in the Introduction, two pulsation periods (P_1 and P_2) are present in the radial-velocity variations of σ Sco. However, in the adopted procedure of the derivation of the times of maximum radial-velocity of P_2, the presence of the secondary period, P_1, can be neglected, because its amplitude is several times smaller than that of P_2 (Struve et al. 1955).

The radial-velocity curve of P_2 is not sinusoidal in shape. Its descending branch is much steeper than the ascending one and is characterized by a "stillstand", a short interval with almost constant radial velocity. The times of radial-velocity maximum were taken from a fit of a mean radial-velocity curve to the observations on individual nights. This mean radial-velocity curve had to be constructed first. For this purpose we used the observations of Struve et al. (1955), because they are numerous and of good quality. After freeing these radial velocities from the orbital contribution induced by the spectroscopic companion, we phased them with P_2 and averaged in equal phase intervals. Then, we interpolated the mean curve in the intermediate points by a cubic spline fit.

The $O-C$ values for the times of maximum radial velocity were calculated using the ephemeris:

$$\text{Max. radial} - \text{velocity} = \text{HJD } 2420644.8309 + 0^{\mathrm{d}}.246836\,E, \qquad (1)$$

where E is the number of pulsation cycles.

The situation is more complicated in the case of photometric data, where four periodic terms are observed. Since the semi-amplitudes of the two faintest pulsational terms (P_5 and P_6) are always smaller than 0.002 mag in all Strömgren filters (Jerzykiewicz & Sterken 1984), they can be neglected in the analysis. However, the ratio of the amplitudes of P_2 to P_1 varies from about two in the Strömgren y filter to almost five in u (Jerzykiewicz & Sterken 1984). Therefore, the shorter the wavelength of the filter, the smaller is the difference between the time of observed light maximum and the time of light maximum of P_2. Thus, when multi-colour observations were available, we adopted the epochs of maximum in the filter of shortest wavelength. In a few cases, when only times of light minimum were available from the literature, we calculated the times of maximum by adding the difference between the epochs of light maximum and minimum, equal to 0.1327 d. This is a mean value, calculated from the Strömgren u times of maximum and minimum, given by Sterken (1975) for the 1972–74 photometry. The photometric $O-C$ values were calculated assuming the same ephemeris, Eq. (1), as for the times of maximum radial velocity.

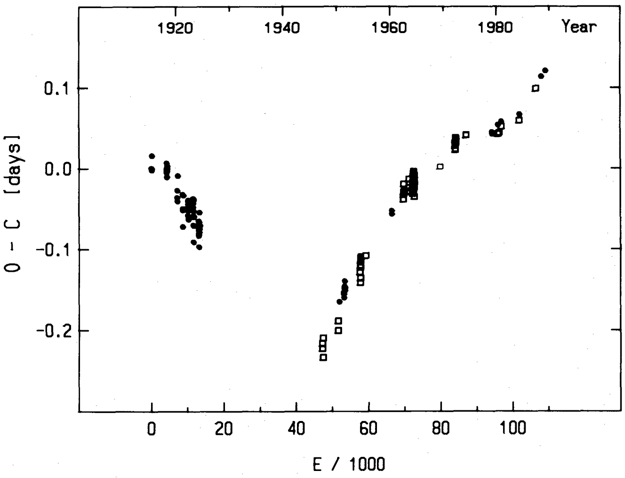

Fig. 1. The $O-C$ diagram for the main pulsation period, P_2, of σ Sco. Filled circles represent $O-C$ values based on the radial velocity observations, while open squares those based on the photometric data. Predicted times of maximum were calculated from Eq. (1). An average time difference between light and radial-velocity maximum, equal to $0^{\mathrm{d}}.0615$, was subtracted from all photometric $O-C$ values

Since for β Cephei-type stars the times of radial-velocity and light maximum do not coincide, we had to establish an average time difference, Δt, between these maxima. We obtained Δt by means of a least-squares fit of a third degree polynomial to the two kinds of $O-C$ values for the interval when they overlap in the $O-C$ diagram, i.e., after 1947. We found Δt to be equal to 0.0615 d. This value was subtracted from all photometric $O-C$ values in order to obtain the single $O-C$ diagram presented in Fig. 1. This diagram will be discussed in Sect. 5.

4. 33-day spectroscopic orbit

Three effects contribute to the observed changes of the radial velocity of σ Sco. The main one is the pulsation with two periods, P_1 and P_2, and amplitudes $2K = 15$ and 110 km s^{-1}, respectively (Struve et al. 1955). The other, with an amplitude of about 60 km s^{-1}, is the orbital motion induced by the 33-day spectroscopic companion. As we will show in Sect. 5, the third effect is the small change of the radial velocity caused by the tertiary. Fortunately, the three effects can be easily separated because of their different time-scales. In the previous section we freed radial velocities from the pulsational contribution by fitting a mean radial-velocity curve to the observations on a given night. The nightly values of the mean radial velocity so obtained will be used now for deriving the elements of the spectroscopic orbit.

The discovery of the night-to-night variations of the mean radial velocity of σ Sco was announced by Selga (1916). The period of these changes was first estimated by Henroteau (1918) to be equal to $34^{\mathrm{d}}.08$. Later, periods in the range between $32^{\mathrm{d}}.0$ and $34^{\mathrm{d}}.2$ were proposed. However, from the recent studies (Goossens et al. 1984; Mathias et al. 1991) it seems clear that only a period very close to 33 d can satisfactorily fit all observations.

We derived the spectroscopic parameters of the system from the nightly mean values of the radial velocity, obtained in the preceding section. To begin with, we performed frequency analysis of these nightly means. We found that the best value of the orbital period is equal to $33^{\mathrm{d}}.012$. Then we calculated the remaining orbital elements by means of the method of differential corrections, using the elements of Mathias et al. (1991) as the first approximation. The spectroscopic orbital elements we derived are listed in Table 1 and the radial-velocity curve is shown in Fig. 2. The orbital period of $33^{\mathrm{d}}.012$ is in good agreement with the recent determinations of Goossens et al. (1984) and Mathias et al. (1991). The large scatter (standard deviation = 7.0 km s^{-1}) around the spectroscopic radial-velocity curve seen in Fig. 5 is partially due to the changes of the radial velocity induced by the tertiary, which are discussed in the next section.

Table 1. The spectroscopic elements of the primary–secondary pair in σ Sco system

$P_{\mathrm{orb}} = 33.012$ d (obtained by means of Fourier analysis)
$\gamma = +3.9 \pm 0.8$ km s^{-1}
$K_1 = 29.2 \pm 1.5$ km s^{-1}
$e = 0.40 \pm 0.04$
$\omega = 287^\circ \pm 6^\circ$
$T_0 = 2418448.5 \pm 0.4$ JD
$a_1 \sin i = (1.22 \pm 0.06)\ 10^7$ km $= 0.081 \pm 0.004$ AU
$f(M_1) = 0.066 \pm 0.010 M_\odot$.

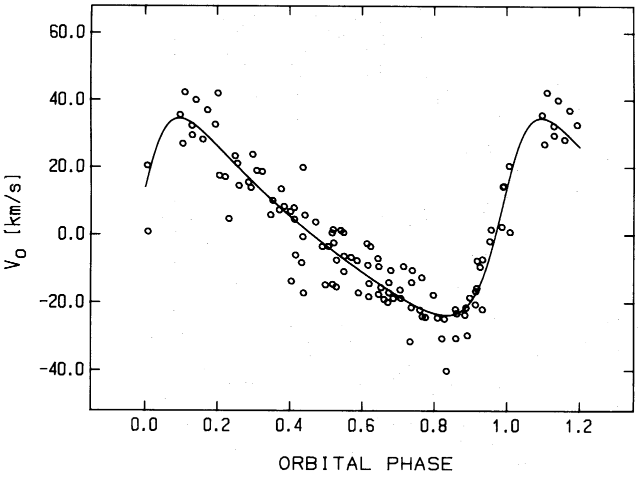

Fig. 2. The spectroscopic radial-velocity curve (continuous line) and the nightly mean values of the radial velocity (open circles) shown as a function of the phase of $33^{\mathrm{d}}.012$ period. Phase 0.0 corresponds to the time of periastron passage

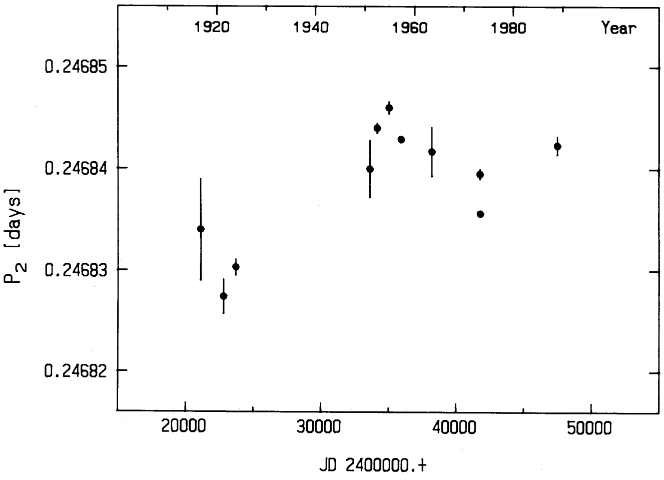

Fig. 3. The values of P_2, compiled from the literature, plotted as a function of Julian day

5. Interpretation of the period changes

The points in the $O-C$ diagram (Fig. 1) span about 75 yr. However, no observations were made between 1925 and 1947. Due to this gap, there is an ambiguity in the number of elapsed cycles between 1925 and 1947. During this interval, the large period increase found by Struve et al. (1955) took place. Later, a slow decrease of the period was observed, while observations made after 1984 indicate that the period increased again.

These quite complicated changes of the period are in good agreement with the values of P_2 obtained directly, without recourse to the $O-C$ diagram, shown in Fig. 3. We took these data from the compilation of Sterken (1975), except that two values based on van Hoof's (1966) photometry made in 1962–1963 and 1964 were replaced by $P_2 = 0.2468417 \pm 0.0000024$, derived by Goossens et al. (1984). Moreover, two values of the period were added: from the 1972–1974 photometry (Jerzykiewicz & Sterken 1984) and from spectroscopy made in 1987–1988 (Mathias et al. 1991).

The period changes seen in the $O-C$ diagram (Fig. 1) and in Fig. 3 cannot be explained in terms of an evolutionary effect alone, because an increase and a decrease of the period are both observed. The presence of the speckle tertiary at an angular separation of the order of a few tenths of arcsecond suggests that the light-time effect may contribute to the observed changes (see Paper I). As far as the 33-day spectroscopic orbit is concerned, the effect is always smaller than 2 min, much below the accuracy with which times of maximum light or radial-velocity could be determined. We can also neglect the presence of the most distant, visual companion, because it cannot cause any detectable changes of the radial velocity in the time interval under consideration.

The light-time effect in a binary system leads to the cyclic changes in the $O-C$ diagram. Independently of the configuration of the orbit, a single minimum and a single maximum of the pulsation period should be observed during one orbital revolution. Thus, if the period increase around 1984 has the same orbital phase as the episode of the period increase which took place between 1925 and 1947 when the star was not observed, the observed period for the observations made in 1918–1925 should be exactly the same as in the mid-sixties. From Fig. 3 it can be seen that this is clearly not the case. Moreover, the orbital period, which has to be adopted in this case (40–50 yr), is much smaller than expected from the speckle interferometric observations and lunar occultations. Thus, we conclude that also the light-time effect alone cannot explain the observed period changes. We shall show now that only when it is assumed that the evolutionary and the light-time effect act together, a satisfactory explanation of the observed period changes is possible.

Two major sets of radial velocity measurements were made for σ Sco. The first one (hereafter called set I) comprises the studies of Henroteau (1918, 1921, 1923, 1925) made in the years 1918–1924. The second (hereafter set II) consists of the observations of Levee (1952) and Struve et al. (1955), made between 1950 and 1954. Figure 4 shows the nightly values of the mean radial velocities, corrected for the velocity variation computed from the spectroscopic elements obtained in Sect. 3. Despite rather large scatter, it can be clearly seen that there is a small difference in the mean radial velocity between both sets of points. This difference can be explained as an orbital effect due to the tertiary. Calculations give the mean radial velocity for set I equal to -2.7 ± 1.0 km s^{-1}, and for set II, $+3.1 \pm 0.7$ km s^{-1}. The difference, $\Delta V_{\mathrm{rad}} = 5.8 \pm 1.2$ km s^{-1}, should lead to the change of period equal to $\Delta P_{\mathrm{light-time}} = \Delta V_{\mathrm{rad}} P_2 / c = 0^{\mathrm{d}}.0000047 \pm 0^{\mathrm{d}}.0000010$,

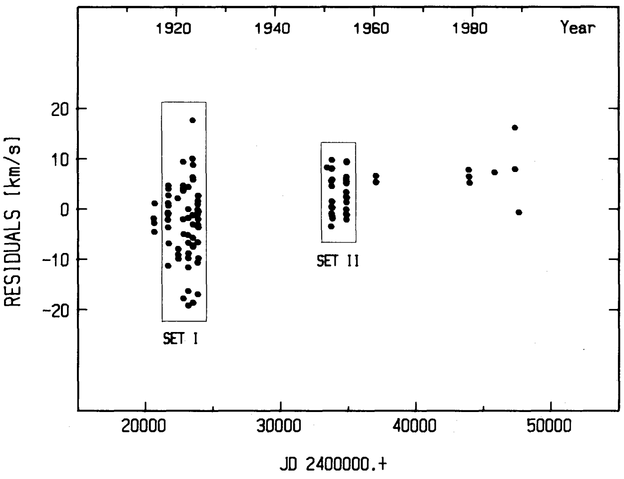

Fig. 4. Residuals from the spectroscopic solution shown in Fig. 2 plotted as a function of Julian day. Two main sets of the radial velocity measurements described in the text are indicated

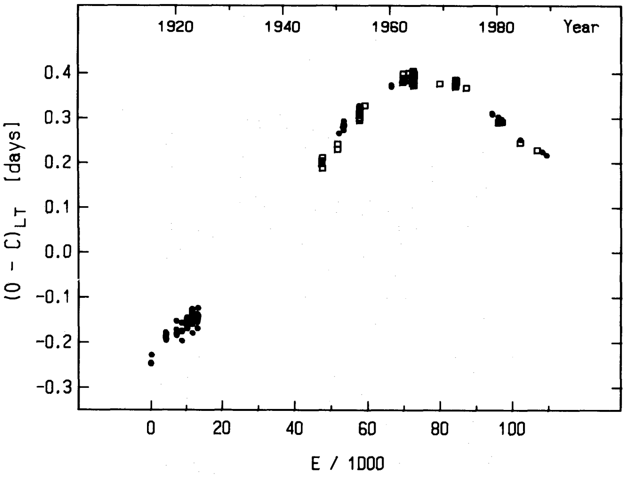

Fig. 5. The $(O-C)_{\rm LT}$ diagram for the main pulsation period of σ Sco. It was obtained by removing the evolutionary increase of period of 3.3 s cen^{-1}, according to Eq. (2). The symbols are the same as in Fig. 1. The observations made before 1925 were shifted downwards by one cycle relative to their position in Fig. 1

Table 2. A compilation of the speckle interferometric observations of σ Sco

Date (yr)	Binary separation (″)	Position angle (°)	Reference
1976.471	0.326	291.8	Morgan et al. (1978)
1977.4868	0.353 ± 0.002	285.4 ± 0.6	McAlister (1979)
1980.4792	0.367	277.4	McAlister et al. (1983)
1980.4819	0.367	277.9	McAlister et al. (1983)
1981.4567	0.372	275.2	McAlister et al. (1984)
1981.4704	0.369	277.1	McAlister et al. (1984)
1981.4730	0.369	275.6	McAlister et al. (1984)
1983.4254	0.377	272.9	McAlister et al. (1987)
1984.3783	0.384	272.3	McAlister et al. (1987)
1987.2726	0.407	264.5	McAlister et al. (1989)
1989.2275	0.416	261.4	McAlister et al. (1990)
1989.3038	0.414	261.4	McAlister et al. (1990)

where c is the velocity of light. But the average period calculated from the times of maximum radial-velocity is equal to $P_{\rm I}=0^{\rm d}.2468283\pm0^{\rm d}.0000005$ for set I, while for set II it is : $P_{\rm II}=0^{\rm d}.2468447\pm0^{\rm d}.0000003$. The difference, $P_{\rm I-II}=P_{\rm I}-P_{\rm II}=0^{\rm d}.0000164\pm0^{\rm d}.0000006$ is much larger than the value obtained above from the light-time effect. The additional increase, equal to $P_{\rm I-II}-P_{\rm light-time}=0^{\rm d}.0000117\pm0^{\rm d}.0000012$ must be intrinsic. The corresponding value of the rate of the period change is equal to $+3.3\pm0.3$ s cen^{-1}. This value is somewhat uncertain, because one cannot be sure that there are no systematic differences between the two sets of radial-velocity data.

We can say, therefore, that two effects contribute to the observed changes of the main pulsation period of σ Sco. The first one is an evolutionary increase with a rate of about 3 s cen^{-1}, and the second is a variation due to the light-time effect caused by the speckle tertiary.

Having determined the evolutionary effect we have removed it from the $O-C$ diagram according to the equation:

$$(O-C)_{\rm LT}=(O-C)+0^{\rm d}.000015\,E-1^{\rm d}.29\,10^{-10}\,E^2, \qquad (2)$$

where $(O-C)$ are the $O-C$ values shown in Fig. 1. The coefficient before the quadratic term in Eq. (2) corresponds to the rate of period increase equal to 3.3 s cen^{-1}. The values of $(O-C)_{\rm LT}$ are plotted in Fig. 5. The notation $(O-C)_{\rm LT}$ is used because the changes seen in this figure are due to the light-time effect only. In Fig. 5, the observations made before 1925 are shifted downwards by one cycle relative to their position in Fig. 1. It seems that now they are at the appropriate position, but the above-mentioned ambiguity in the number of elapsed cycles still exists. From the $(O-C)_{\rm LT}$ diagram it is clearly seen that the observations do not cover the whole orbital period of the tertiary. Nather et al. (1974) and Evans et al. (1986) analysed the lunar occultations of σ Sco since 1860 and suggested that this orbital period is of the order of 100–350 yr. The $(O-C)_{\rm LT}$ diagram is consistent with any value from this range, so that it cannot help to give a more accurate value of the orbital period. Thus, all we can do is to say that the changes seen in the $(O-C)_{\rm LT}$ diagram can be fully explained by the orbital motion. However, with the observations available now, we cannot derive the spectroscopic elements from the $(O-C)_{\rm LT}$ diagram, as was done in Paper I for β Cep.

All speckle observations of the star, compiled from the literature, are listed in Table 2 and plotted in Fig. 6. We added 180° to the values of the polar angles, presented in the papers referred to in Table 2, because the 180° ambiguity in polar angle, present in speckle observations has been removed by lunar occultations.

The speckle observations cover about 12 yr. During this time, the separation of the tertiary increased from about $0''.33$ in 1976 to $0''.42$ in 1989, while the polar angle decreased by about 30°. The observations shown in Fig. 6 are consistent with the $(O-C)_{\rm LT}$ diagram, but the elements of the visual orbit cannot be, of course, derived from these limited data.

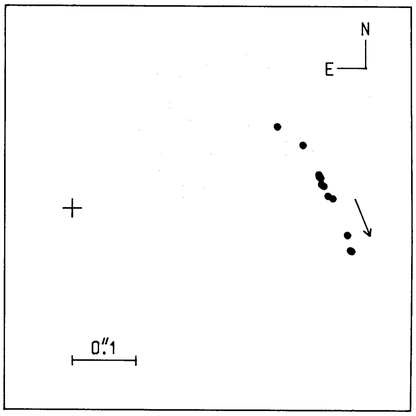

Fig. 6. Relative orbit of the speckle tertiary in the σ Scorpii system. The position of the spectroscopic pair is marked by plus sign, while the speckle observations are shown as filled circles. The direction of the motion of the tertiary is indicated by the arrow

6. Summary and conclusions

We showed that the observed variation of the main pulsation period of σ Sco can be explained by the light-time effect in a binary system and an evolutionary increase of the intrinsic pulsation period with a rate equal to about 3 s cen^{-1}. The detailed analysis of the radial-velocity data and the $O-C$ diagram allowed us to separate these effects. Unfortunately, unlike the case of β Cep (Paper I), the available observations are insufficient to derive the orbital elements of the spectroscopic pair – speckle tertiary system. Systematic photometric or spectrographic observations, as well as speckle interferometry of the star, covering the whole orbital revolution are required for this purpose. Thus, σ Sco becomes a very important target in the future studies of the period changes in β Cephei-type stars.

Our identification of the cause of the observed period changes in β Cep (Paper I) and σ Sco (this paper) has the following consequences as far as their evolutionary status is concerned. A photometric study of two open clusters, NGC 3293 and NGC 6231 by Balona and his co-workers (Balona 1977, 1983; Balona & Engelbrecht 1983, 1985; Balona & Shobbrook 1983, Shobbrook 1983) led to the discovery of a number of β Cephei-type variables. Their position in the colour–magnitude diagrams of the clusters indicates that they are undoubtedly core hydrogen-burning stars. On the other hand, from the position of the field β Cephei-type stars such as β Cep and σ Sco in the HR diagram it is impossible to decide whether they are in the core hydrogen-burning phase, the secondary contraction phase, or the shell hydrogen-burning phase. However, the predicted rates of the evolutionary period changes differ between these phases. According to Eggleton & Percy (1973) and Lesh & Aizenman (1974), a main-sequence β Cephei-type star increases its period with a rate always less than 1 s cen^{-1}. On the other hand, in the secondary contraction phase the period decreases, while in the shell-hydrogen burning phase it increases again. In the initial stages of the latter phase, the rate of period increase is of the order of a few s cen^{-1}.

In the case of β Cep (Paper I) the long-term period changes were fully explained by the light-time effect. This leads to the conclusion that β Cep is a main-sequence star. On the other hand, σ Sco has a positive rate of period change equal to about 3 s cen^{-1}, locating it in the shell-hydrogen burning phase. Another β Cephei-type star with a well documented, positive rate of the pulsation period change of similar size is BW Vul.

Observations indicate that most evolved δ Scuti stars have the largest pulsation amplitudes. Dziembowski (1988) suggested that this fact may be explained in terms of the mechanism of the resonant mode coupling. This mechanism limits the growth of pulsation amplitudes of δ Scuti stars, but is less effective for evolved objects. Dziembowski (1988) proposed that the same mechanism may work in β Cephei-type stars as well. Making use of this idea, Sterken & Jerzykiewicz (1990) pointed out that the large pulsation amplitude observed in BW Vul is an additional argument in favour of the shell-hydrogen burning phase for this star.

Two stars, σ Sco and BW Vul, have the rates of period change consistent with the shell-hydrogen burning phase. At the same time, these two stars have the largest pulsation amplitudes among β Cephei-type stars. It is then possible that evolved β Cephei-type stars have the largest pulsation amplitudes, as in the case of δ Scuti stars. Future investigation of the pulsation amplitudes of β Cephei-type stars in NGC 3293 should throw some light on this matter.

Acknowledgements. The author is grateful to Prof. M. Jerzykiewicz for valuable comments upon reading the manuscript and to Dr. M. Muciek for his help in collecting the speckle interferometric data. The suggestions of the referee, Dr. R. Foy are also acknowledged.

References

Balona L.A., 1977, Mem. R. Astron. Soc. 84, 101
Balona L.A., 1983, MNRAS 203, 1041
Balona L.A., Engelbrecht C.A., 1983, MNRAS 202, 293
Balona L.A., Engelbrecht C.A., 1985, MNRAS 212, 889
Balona L.A., Shobrook R.R., 1983, MNRAS 205, 309
Burger M., de Jager C., van den Oord G.H.J., 1982, A&A 109, 289
Campos A.J., Smith M.A., 1980, ApJ 238, 250
Chapellier E., 1985, A&A 147, 135
Dziembowski W., 1988, in: Kovács G., Szabados L., Szeidl B., (eds.) Multimode Stellar Pulsations. Konkoly Obs., Kultura, Budapest, p. 127
Eggleton P.P., Percy J.R., 1973, MNRAS 161, 421
Evans D.S., McWilliam A., Sandmann W.H., Frueh M., 1986, AJ 92, 1210
Goossens M., Lampens P., de Maerschalck D., Schrooten M., 1984, A&A 140, 223
Henroteau F., 1918, Lick Obs. Bull. 9, 173
Henroteau F., 1921, Publ. Dominion Obs., Ottawa 5, 303
Henroteau F., 1923, Publ. Dominion Obs., Ottawa 8, 45
Henroteau F., 1925, Publ. Dominion Obs., Ottawa 9, 91
Heynderickx D., 1991, Ph.D. Thesis, Katholieke Univ., Leuven
Hogg A.R., 1957, MNRAS 117, 95
Hogg A.R., Gottlieb K., Simonov G.V., Hall B., 1951, MNRAS 111, 339
Jerzykiewicz M., Sterken C., 1984, MNRAS 211, 297
Kubiak M., Seggewiss W., 1983, Acta Astron. 33, 243
Lesh J.R., Aizenman M.L., 1974, A&A 34, 203
Levee R.D., 1952, ApJ 115, 402

Mathias P., Gillet D., Crowe R., 1991, A&A 252, 245

McAlister H.A., 1979, ApJ 230, 497

McAlister H.A., Hendry E.M., Hartkopf W.I., Campbell B.G., Fekel F.C., 1983, ApJS 51, 309

McAlister H.A., Hartkopf W.I., Gaston B.J., Hendry E.M., Fekel F.C., 1984, ApJS 54, 251

McAlister H.A., Hartkopf W.I., Hutter D.J., Franz O.G., 1987, AJ 93, 688

McAlister H.A., Hartkopf W.I., Sowell J.R., Dombrowski E.G., Franz O.G., 1989, AJ 97, 510

McAlister H.A., Hartkopf W.I., Franz O.G., 1990, AJ 99, 965

Morgan B.L., Beddoes D.R., Scaddan R.J., Dainty J.C., 1978, MNRAS 183, 701

Nather R.E., Churms J., Wild P.A.T., 1974, PASP 86, 116

Odell A.P., Dorchak F., Rogalski K., Tapia S., Wisniewski W.Z., Smith D.H., 1983, IBVS No. 2453

Pigulski A., Boratyn D.A., 1992, A&A 253, 178 (Paper I)

Selga M., 1916, Revista de la Sociedad Astron. de Espana y America 48, 41

Shobbrook R.R., 1983, MNRAS 204, 47P

Slipher V.M., 1904, Lowell Obs. Bull. 1, 57

Sterken C., 1975, A&A 43, 321

Sterken C., 1984, A&AS 58, 657

Sterken C., Jerzykiewicz M., 1990, in: Cacciari, C., Clementini G. (eds.) Confrontation between stellar pulsation and evolution. Astr. Soc. Pacific, San Francisco, p. 236

Struve O., McNamara D.H., Zebergs V., 1955, ApJ 122, 122

Struve O., Sahade J., Zebergs V., 1961, ApJ 133, 509

vander Linden D., Butler K., 1988, A&A 189, 137

vander Linden D., Sterken C., 1987, A&AS 69, 157

van Hoof A., 1966, Z. Astrophys. 64, 165

Watson R.D., 1971, ApJ 170, 345