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Hipparcos parallaxes and the nature of δ Scuti stars*

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Abstract. Hipparcos parallaxes give new tests of the nature of δ Sct variables. For many individual stars accurate distances are now available, i.e. directly determined luminosities and radii can be used to test theoretical models. Of particular interest are the at present very unclear relations between high–amplitude δ Sct stars and the much more abundant low–amplitude δ Sct variables, and the relations between field variables and the SX Phe stars in globular clusters.

Only a few high–amplitude variables have Hipparcos parallaxes sufficiently accurate to provide precise model tests. Here we give a discussion of this group, considering SX Phoenicis and AI Velorum, which have the best parallaxes among the high–amplitude stars, in some detail. It is shown that two new tests based on the improved parallaxes are in good agreement with the (generally accepted) assumption that the high–amplitude variables are normal stars following standard evolution. AD Canis Minoris may be an interesting exception with strongly deviating properties. We also briefly comment on the population II stars.

Key words: stars: δ Sct – stars: individual: SX Phe – stars: individual: AI Vel

1. Introduction

The relations between the high–amplitude δ Scuti stars and normal, low-amplitude δ Sct variables have been uncertain for a long time. After the review papers by Breger (1979, 1980) the generally accepted idea has been that all δ Sct stars are normal stars evolving according to standard stellar evolution theory. An important test of this assumption is an independent mass determination, since alternative (and more speculative) possibilities proposed in the literature all predict much lower masses than the 1.0–2.5 solar masses obtained in the standard scenario. Recently, interest in the low-mass possibility has increased due to the fact that high–amplitude δ Sct stars predominantly have negative period derivatives (e.g. Rodríguez et al. 1995), which can not be explained naturally in the standard evolution scenario. Furthermore, modern CCD–observations have shown the presence of many SX Phe stars (i.e. high–amplitude δ Sct variables) in globular clusters (see e.g. Mateo 1993). Belonging to the "blue stragglers", they can not be explained by the simple standard evolution scenario. They are probably created by mass transfer in binary systems or even by coalescense (see Sills et al. (1995) for recent models and references). At present, observational evidence that (i) high–amplitude and low–amplitude δ Sct stars are basically identical and (ii) that field and globular cluster variables have same physical characteristics, is needed.

Hipparcos parallaxes (ESA 1997) allow us to perform two new tests of the nature of δ Sct variables. First, we can directly use the much improved distances to compare observations and theoretical models in the HR diagram.

Second, the parallaxes can be used to derive a pulsation mass from the pulsation equation, using a theoretical Q–value, which is accurately known for δ Sct stars. This mass is independent of detailed stellar evolution theory, Q being determined by pulsation analysis of outer envelope models. Therefore, this mass provides an independent test of the nature of δ Sct stars, and can be used to distinguish between the standard scenario and the low–mass possibilities just mentioned. A serious problem for application of the pulsation equation is that a safe mode identification must be available. This requirement immediately excludes all low–amplitude stars from this test, and in the high–amplitude group only the double–mode variables are quite

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* Based on observations made with the ESA Hipparcos satellite

Table 1. Information on high–amplitude δ Sct stars. Parallax with standard error given in milliarcsec in Columns 3 and 4, and observed mean magnitude, V, and estimated amplitude, A_V, in Columns 7 and 8 are taken from the Hipparcos Catalogue. Columns 5 and 6 give effective temperature, $T_{\rm eff}$, and metal content [Fe/H] mainly from McNamara (1992). Column 9 gives absolute magnitude, M_V, and Columns 10 and 11 pulsation periods [notes – (1): oscillation in fundamental mode only, (2): oscillation in first and second overtones]. Colums 12 and 13 compare evolution mass, M_{ev}, and pulsation mass, M_Q (see text for details). Finally, Column 14 gives the uncertainty (1–σ error) in M_Q arising from the parallax

Star	Hipparcos			$T_{\rm eff}$	[Fe/H]	V	A_V	M_V	Π_0	Π_1	M_{ev}	M_Q	$\sigma_\pi(M_Q)$
	#	π	$\sigma(\pi)$	[K]	[dex]	[mag]	[mag]	[mag]	[d]	[d]	[$M_\odot$]	[$M_\odot$]	[%]
V474 Mon	28321	10.32	0.86	7400	0.0	6.15	0.43	1.22	0.1361	(1)	2.0	1.66	25
AD CMi	38473	8.40	1.73	7580	0.0	9.31	0.32	3.93	0.1230	(1)	1.2:	0.04	62
AI Vel	40330	9.99	0.53	7620	−0.2	6.56	0.61	1.56	0.1117	0.0863	1.6	1.29	16
VZ Cnc	42594	5.43	0.99	7100	0.2	7.73	0.73	1.40	(2)	0.1742	1.9	0.60	55
V703 Sco	86650	3.91	0.98	7000	0.0	7.85	0.46	0.81	0.1500	0.1152	2.1	3.38	75
RS Gru	107231	4.42	1.05	7600	−0.5	8.28	0.56	1.51	0.1469	(1)	1.4	0.82	71
SX Phe	117254	12.91	0.78	7850	−1.3	7.33	0.77	2.88	0.0550	0.0428	1.0	0.70	18

safe. By chance, the two high–amplitude stars with the largest and most accurately determined Hipparcos parallaxes, AI Vel and SX Phe, are double–mode variables. And by even better luck, SX Phe belongs to population II with [Fe/H] ≈ -1.3, $Z \approx 0.001$, although such objects are statistically very rare in the solar vicinity. SX Phe gives a possibility for direct comparison of a close field variable with globular cluster counterparts.

In the present paper we discuss these two tests for all high–amplitude δ Sct stars with sufficiently accurate Hipparcos parallaxes, and briefly comment on the relations between the normal low–amplitude stars and the high–amplitude variables.

2. HR diagram

Hipparcos parallaxes in combination with standard photometry allow a direct comparison in the HR diagram of observations and theoretical stellar evolution models. In Table 1 we collect observational data for the seven high–amplitude stars with the most accurate parallaxes. We choose to discuss SX Phe and AI Vel in some detail because they have the best data, and because their accurately known period ratio provides a further constraint on the theoretical models (Petersen & Christensen–Dalsgaard 1996). In the following comparisons we use these models.

In Fig. 1 we compare standard evolution tracks in the HR diagram with observed positions of SX Phe according to the Hipparcos Catalogue and the Hipparcos Input Catalogue (HIC). Among the stars of Table 1, only AI Vel and SX Phe had parallaxes determined before the Hipparcos mission. For SX Phe HIC gives $\pi = 0.023 \pm 0.008$ arcsec (significantly higher the the Hipparcos result), while AI Vel has $\pi = 0.028 \pm 0.011$ arcsec. M_V–values are calculated from the parallaxes, using the observed magnitude $V = 7.33$ and a bolometric correction of $BC = -0.05$ mag. In the literature many estimates of the effective temperature of SX Phe are available; we take $T_{\rm eff} = 7850 \pm 200$ K.

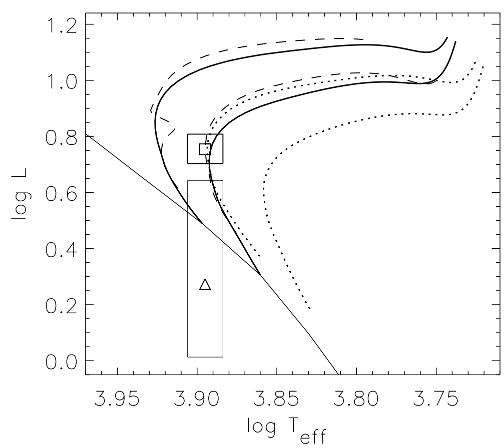

Fig. 1. Comparison of standard evolution tracks in the HR diagram with observed positions of SX Phe according to the Hipparcos parallax [□] and the best earlier data [△]. Error boxes correspond to catalogue data and to ± 200 K in effective temperature. Full curves give ZAMS and evolution tracks of mass 1.0 and 1.1 $M_\odot$ calculated for $(X, Z) = (0.70, 0.001)$. Dashed curves are for $(X, Z) = (0.70, 0.002)$ and mass 1.1 and 1.2 $M_\odot$, and dotted curves for $(X, Z) = (0.75, 0.001)$ and mass 1.0 and 1.1 $M_\odot$. On each of the three evolution tracks within the Hipparcos error box one model with the observed period of SX Phe is located

From Fig. 1 is seen that the Hipparcos data are in agreement with models with $Z = 0.001-0.002$ and masses $1.0 - 1.1$ $M_\odot$. According to Petersen & Christensen–Dalsgaard (1996) the period ratio requires Z close to 0.001, which is also in agreement with recent observational determinations (Table 1). From the models Petersen & Christensen–Dalsgaard *predicted* the parallax of SX Phe

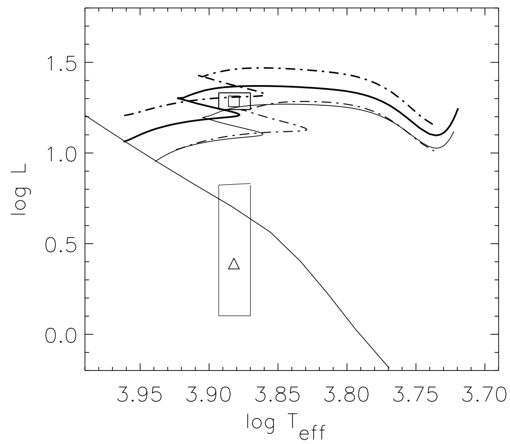

Fig. 2. AI Vel shown precisely as SX Phe in Fig. 1. Full curves give ZAMS and evolution tracks of mass 1.6 and 1.7 $M_\odot$ calculated for (X, Z) = (0.70, 0.01). Dash–dotted curves are for (X, Z) = (0.70, 0.02) and mass 1.8 and 2.0 $M_\odot$.

to be 0.012 ±0.002 arcsec, which is seen to be in good agreement with the Hipparcos result. We conclude that Hipparcos data strongly support the assumption of standard evolution for SX Phe. In particular, any doubt based on the old, too large parallax values has now been removed.

In Fig. 2 we compare standard evolution tracks in the HR diagram calculated for metal contents $Z = 0.01$ and 0.02 with observed positions of AI Vel in precisely the same way as we just showed for SX Phe. For AI Vel the result is even more striking, and we confirm our conclusion of agreement with standard evolution. With the preferred $Z = 0.01$ an evolution mass of 1.63 $M_\odot$ is determined in the post–main–sequence stage, and the model with the observed period is located within the Hipparcos error box.

3. Masses from the pulsation equation

A mass–determination, which uses stellar envelope models and pulsation theory, but does not depend on detailed stellar evolution theory, can be obtained from the pulsation equation

$$\Pi_i = Q_i \, M^{-1/2} \, R^{3/2} \quad (1)$$

where Π_i are the normal mode periods and Q_i the conventional "pulsation constants" with i = 0 referring to the fundamental mode, i = 1 to the first overtone, etc. Sufficiently accurate Q–values are available from simple pulsation models. In the present paper we use mass, M, and radius, R, in solar units. Rewriting Eq. (1)

$$M = \frac{Q_i^2}{\Pi_i^2} \, \pi^{-3} \, T_{eff}^{-6} \, 10^{22.40-0.6\,(V_0-BC)} \quad (2)$$

where standard notation is used, it is seen that the parallax, π, combined with information derived from standard photometry, allows calculation of this pulsation mass, which we call the Q–mass.

In order to illustrate the order of magnitude of the contributions to the total uncertainty of a derived Q–mass, we use the data for SX Phe as an example in the following.

The contribution from the parallax to the uncertainty of the mass becomes $\sigma_\pi(M)/M = 3\,\sigma(\pi)/\pi$. Using the data of Table 1, we obtain $\sigma_\pi(M)/M \approx 0.18$, i.e. an uncertainty of 18%.

Let us briefly discuss the contributions from the other terms of Eq. (2) to the total uncertainty in the derived mass. The observed period is always known very accurately and does not contribute to the error. Theoretical Q–values are known from pulsation models with an uncertainty smaller than ±1 %. According to Eq. (2) the corresponding uncertainty in M is about 2 %.

The effective temperature given for individual high–amplitude δ Sct stars in the literature scatter considerably. Using for SX Phe $\sigma(T_{eff}) = 200$ K and $T_{eff} = 7850$ K, we estimate a standard error in T_{eff} of 2.5 % , i.e. a contribution to the total error in M of ≈ 15 %. Uncertainties in $(V_0 - BC)$ include photometry, interstellar absorption and errors in BC due to uncertain chemical composition of the stars. Taking 0.10 mag as a representative value, we find that the last term in Eq. (2) gives a contribution of 14 % to the total uncertainty in the Q–mass. Thus we estimate that for SX Phe the contributions to the uncertainty in M added linearly can amount to 47 %. This illustrates the well–known high sensitivity of pulsation masses to uncertainties in observations.

In Table 1 we compare the derived Q–mass with the evolution mass, which is known within about 15 %. It is seen that these masses are generally in agreement within the expected uncertainties, except for AD CMi. We conclude that this test now gives an independent confirmation of the generally accepted scenario of standard evolution in all δ Scuti stars. In particular very low masses are excluded. This is in contrast to M_Q determined from the "old" parallaxes; here the same exercise results in derived M_Q of 0.048 and 0.13 $M_\odot$ for AI Vel and SX Phe, respectively. We note that AD CMi shows a large deviation (by a factor of about 30).

4. Discussion and conclusion

Period–luminosity relations for high–amplitude δ Sct stars have been studied by e.g. Nemec et al. (1994), McNamara & Powell (1990) and Fernie (1992). Now for the first time it is possible to compare these relations with absolute magnitudes directly derived from trigonometric parallaxes. Nemec et al. investigate period–luminosity–metal relations for population II variable stars. They give for SX Phe variables oscillating in the fundamental mode

$$M_V(SX) = 0.36 - 2.56(\pm 0.54)\,\log \Pi_0 + 0.32\,[\mathrm{Fe/H}]. \quad (3)$$

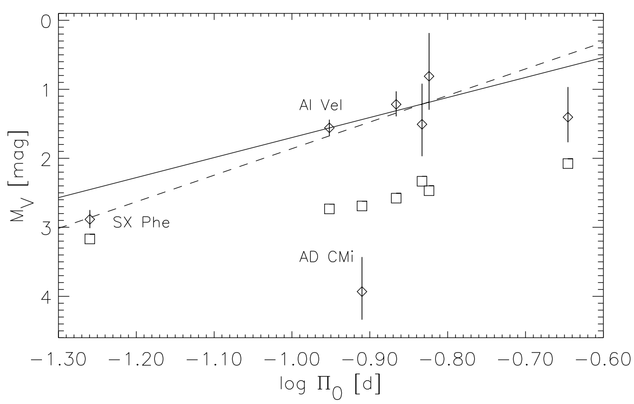

Fig. 3. Period–luminosity diagram for the nearest field high–amplitude δ Sct stars. Hipparcos data with 1–σ error bars are marked by diamonds. Squares give results from Eq. (3) using the data of Table 1, and the full and dashed lines are period–luminosity relations given by Fernie (1992) and McNamara & Powell (1990), respectively (see text for details). Except for the result based on the parallax of AD CMi, all data agree within their estimated uncertainties.

In Fig. 3 we compare M_V from Hipparcos parallaxes (with error bars indicated) with results from Eq. (3) shown as squares. It is seen that we find good agreement for SX Phe, which is the only population II variable with an accurate parallax. Nemec et al. give for SX Phe $M_V = 3.04$, using [Fe/H] $= -1.70$, and mention that Hipparcos will provide an improved zero–point. The fact that SX Phe agrees nicely with Eq. (3) derived from globular cluster variables, gives a strong indication that SX Phe — and therefore probably also (most) other field high–amplitude δ Sct stars — are basically identical with the variables in the blue straggler region in globular cluster HR diagrams. This is particularly important, because SX Phe seems to be the only population II δ Sct star, for which an accurate parallax can be expected, also for many years to come. It is not surprising that Eq. (3) gives a less accurate fit to the population I variables with much longer periods than the globular cluster stars. Clearly, formulae with a larger slope than Eq. (3) could improve the fit to parallax data (excluding AD CMi).

Fernie (1992) discusses δ Sct stars as small Cepheids, extending the Cepheid period–luminosity law to δ Sct periods. Fernie remarks that the population II star SX Phe also fits his relation: $M_V = -2.902 \log \Pi_0 - 1.203$ very well. McNamara & Powell (1990) give a similar relation: $M_V = -3.85 \log \Pi_0 - 1.99$. Fig. 3 shows these relations, and it is seen that with the exception of AD CMi there is a satisfactory agreement with Hipparcos data.

We conclude that the improved tests of basic properties of high–amplitude δ Sct stars based on Hipparcos parallaxes all show that these variables follow standard stellar evolution theory. Further, Hipparcos data for the unique population II field variable SX Phe show that this star is very similar to the variable blue stragglers in globular clusters.

It is remarkable that AD CMi seems to deviate drastically from the other stars, indicating perhaps a different evolution stage. Even with a $1-\sigma$ error in π the data of Table 1 give a position in HRD well below the zero–age main–sequence. The Hipparcos Catalogue contains several quantities for each star that may be used to judge the reliability of the observations. For the deviating star AD CMi it is interesting to note that none of these casts doubt on the given formal standard error $\sigma(\pi)$. In particular, the parallax is based on few observations only, since the number of photometric observations is given as 37 observations (field crossings), a number about 30 percent of average, but none was rejected. The goodness-of-fit is quite normal, $F2 = -0.95$; and no duplicity was found. Lindegren (1996, priv. comm.) checked the NDAC observation equations for this star: the parallax factors have a good distribution in spite of the small number, and the residuals are all quite small (< 3 milliarcsec), which supports the above conclusion.

It is worth noting that many Hipparcos parallaxes are actually more accurate than the original expectation for the mission which was $\sigma(\pi) \approx 0.002$ arcsec, e.g. for SX Phe and AI Vel by a factor of 2.6 and 3.8, respectively. Clearly, the present tests had been less convincing, if this remarkable performance had not been obtained.

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References

Breger, M. 1979, PASP, 91, 5
Breger, M. 1980, ApJ, 235, 153
ESA 1997, The Hipparcos Catalogue, ESA SP–1200
Fernie, J.D. 1992, AJ 103, 1647
Mateo, M. 1993, in "Blue stragglers", ed. R.A. Saffer, ASP Conf. Ser., 53, 74
McNamara, D.H. 1992, "Stars, Cepheid Variable, Dwarf", in "The Astronomy and Astrophysics Encyclopedia", ed. S.P. Maran, Cambridge Univ. Press, Cambridge, p. 720
McNamara, D.H., Powell, M. 1990, in "Confrontation between stellar pulsation and evolution", eds C. Cacciari, G. Clementini, ASP Conf. Ser., 11, 316
Nemec, J., Nemec, A.F.L, Lutz, T.E. 1994, AJ, 108, 222
Petersen, J.O., Christensen–Dalsgaard, J. 1996, A&A, 312, 463
Rodríguez, E., Lopez de Coca, P., Costa, V., Martin, S. 1995, A&A, 299, 108
Sills, A.P., Bailyn, C.D., Demarque, P. 1995, ApJ, 455, L163

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