Astron. Astrophys. 323, 827–830 (1997)

ASTRONOMY
AND
ASTROPHYSICS

Hipparcos parallaxes and the nature of δ Scuti stars*

E. Høg[1] **and J.O. Petersen**[1,2]

[1] Copenhagen University Observatory, NBIfAFG, Juliane Mariesvej 30, DK-2100 Copenhagen Ø, Denmark (erik@astro.ku.dk)
[2] Theoretical Astrophysics Center, Juliane Mariesvej 30, DK-2100 Copenhagen Ø, Denmark (oz@astro.ku.dk)

Received 10 October 1996 / Accepted 13 January 1997

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 briefly comment on globular cluster variables and period–luminosity relations.

Key words: stars: δ Sct – stars: individual: SX Phe; AI Vel; AD CMi – stars: evolution – stars: distances

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. We here define "standard stellar evolution" as evolution calculations that do not include complicating physics such as rotation, mixing outside convection zones or element diffusion, etc. While the hypothesis of standard evolution has been confirmed for many low–amplitude stars, available empirical evidence for high–amplitude variables is inconclusive.

An important test 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 fully 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). We remark that *after* a mass transfer event the newly formed blue straggler star, with a mass considerably larger than the cluster turn–off mass, may be observationally indistinguishable from a "normal" star of same mass (and composition) evolving according to standard evolution. In this sense blue stragglers can be described as standard stars.

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

Send offprint requests to: E. Høg

* 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 #	π	$\sigma(\pi)$	$T_{\rm eff}$ [K]	[Fe/H] [dex]	V [mag]	A_V [mag]	M_V [mag]	Π_0 [d]	Π_1 [d]	M_{ev} [$M_\odot$]	M_Q [$M_\odot$]	$\sigma_\pi(M_Q)$ [%]
V474 Mon	28321	10.32	0.86	7300	0.0	6.15	0.43	1.22	0.1361	(1)	2.0	1.85	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	1.33	16
VZ Cnc	42594	5.43	0.99	7100	0.2	7.73	0.73	1.40	(2)	0.1742	1.9	0.61	55
V703 Sco	86650	3.91	0.98	7300	0.0	7.85	0.46	0.81	0.1500	0.1152	2.1	2.68	75
RS Gru	107231	4.42	1.05	7600	–0.5	8.28	0.56	1.51	0.1469	(1)	1.4	0.84	71
SX Phe	117254	12.91	0.78	7850	–1.3	7.33	0.77	2.88	0.0550	0.0428	1.0	0.73	18

variables are quite 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.

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 Figs. 1 and 2 we compare standard evolution tracks in the HR diagram with observed positions of SX Phe and AI Vel 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 π = 0.023 $\pm$ 0.008 arcsec (significantly higher the the Hipparcos result), while AI Vel has π = 0.028 $\pm$ 0.011 arcsec.

M_V–values are calculated from the parallaxes, using the observed magnitudes from Table 1 and a bolometric correction of BC = -0.05 mag. In the literature many determinations of the effective temperature of SX Phe and AI Vel are available. We adopt the $T_{\rm eff}$–values given in Table 1 from McNamara (1992), and estimate an uncertainty of $\pm$200 K by comparisons with data given by Garrido et al. (1990), Nemec & Mateo (1990) and

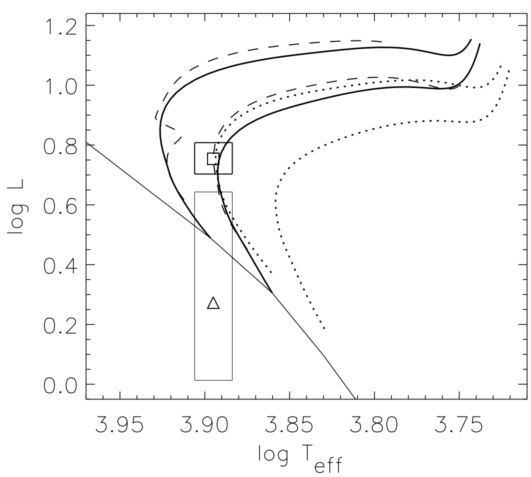

Fig. 1. Comparison of standard evolution tracks in the HR diagram with observed positions of SX Phe according to the Hipparcos parallax [□] and the best earlier parallax data [△]. Error boxes correspond to catalogue data and to $\pm$ 200 K in effective temperature. Full curves give ZAMS and evolution 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 three evolution tracks one model with the observed period of SX Phe is located within or close to the Hipparcos error box

Rolland et. al. (1991) for SX Phe, and by Fernley et al. (1987) and Rodríguez et al. (1990) for AI Vel.

From Fig. 1 for SX Phe 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 to be 0.012 $\pm$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

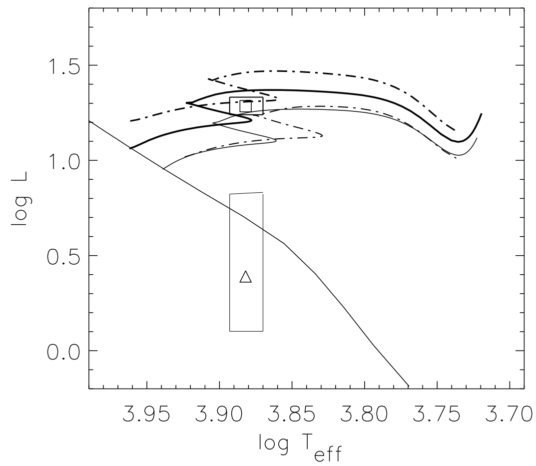

Fig. 2. AI Vel shown precisely as SX Phe in Fig. 1. Full curves give ZAMS and evolution tracks of mass 1.6 and 1.7 $M_\odot$ calculated for $(X,\, Z)$ = (0.70, 0.01). Dash–dotted curves are for $(X,\, Z)$ = (0.70, 0.02) and mass 1.8 and 2.0 $M_\odot$

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. For AI Vel Petersen & Christensen–Dalsgaard (1996) predicted the parallax to be 0.009$\pm$0.002 arcsec, which is also in agreement with the Hipparcos data in Table 1.

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

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

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. Rewriting Eq. (1)

$$M_Q = \frac{Q_i^2}{\Pi_i^2}\, \pi^{-3}\, T_{eff}^{-6}\, 10^{22.406-0.6\,(V_0+BC)} \qquad (2)$$

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, M_Q.

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 π 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 $\pm$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 again 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 $\approx$ 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 M_Q of SX Phe is 27 % smaller than M_{ev} — within the estimated error, and for AI Vel the corresponding difference is 17 %. For these two stars with the best parallaxes we now find M_Q in agreement with the standard evolution mass. This is in contrast to M_Q determined from the “old” parallaxes; here the same exercise results in derived M_Q of 0.060 and 0.13 $M_\odot$ for AI Vel and SX Phe, respectively. For the other stars of Table 1 the uncertainty contribution from the parallax to M_Q is uncomfortably large. We note that except for AD CMi (with a deviation of a factor of about 30) we do not find large disagreements between M_Q and M_{ev}. We conclude that with certain reservations this test now gives an independent confirmation of the generally accepted scenario of standard evolution also in high–amplitude δ Scuti stars.

4. Discussion

Hipparcos data (Table 1) give for SX Phe, which is the only population II δ Sct star with an accurate trigonometric parallax, M_V = 2.88 $\pm$ 0.13 mag. This is in satisfactory agreement with both standard stellar evolution models as explained in Sect. 2 and with the value M_V = 3.04 (with an estimated uncertainty of about 0.15 mag) given by Nemec et al. (1994). Nemec et al. investigate period–luminosity–metal relations for population II variable stars in globular clusters. They study both RR Lyrae stars, population II Cepheids, anomalous Cepheids and SX Phe variables in many globular clusters, and obtain simultaneous lsq–solutions for $P-L-$[Fe/H] relations for all four types of variables. Therefore their results for the relatively few SX Phe stars (both field variables and globular cluster stars) in their sample can be expected to be safely fixed to the M_V–scale in globular clusters.

The fact that the Hipparcos value of M_V for SX Phe agrees nicely with the value derived by means of globular cluster relations, gives an 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. Since we have seen that SX Phe can be precisely described by standard stellar evolution models, we can expect that standard evolution will also give a good approximation for SX Phe variables in globular clusters, although as blue stragglers they can not be described in full detail by standard evolution (see e.g. Sills et al. (1995) for modern modelling). The data available today indicate no difference between SX Phe variables and standard evolution models, and the more speculative non–standard low–mass possibilities mentioned in the introduction seem to be excluded.

Now for the first time it is possible to derive a period–luminosity relation for high–amplitude δ Sct stars directly from trigonometric parallaxes, not using photometric calibrations for M_V at all. Excluding AD CMi, we find from the data of Table 1 a lsq–solution (with weights given by $W = [\sigma(M_V)]^{-2}$)

$$M_V = -3.74 \log \Pi_0 - 1.91. \quad (3)$$

The deviation of AD CMi (2.44 mag) from the mean relation is very large. This confirms the exceptional position of AD CMi.

We here note that in the period interval where δ Sct stars are observed this period–luminosity relation agrees within estimated uncertainties with the relations published by e.g. McNamara & Powell (1990), Fernie (1992) and McNamara (1995). We defer a more detailed discussion of period–luminosity relations to a subsequent paper.

5. Conclusion

We conclude that the improved tests of basic properties of high–amplitude δ Sct stars based on Hipparcos parallaxes all strongly indicate that these variables follow standard stellar evolution theory, as the low–amplitude stars. Further, Hipparcos data for the unique population II field variable SX Phe indicate 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.

Acknowledgements. We thank J. Christensen–Dalsgaard for use of his model sequences. This work is based on data from the Hipparcos astrometry satellite and was supported in part by the Danish Space Board and by the Danish National Research Foundation through its establishment of the Theoretical Astrophysics Center.

References

Breger, M. 1979, PASP, 91, 5
Breger, M. 1980, ApJ, 235, 153
ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP–1200
Fernie, J.D. 1992, AJ 103, 1647
Fernley, J.A., Jameson, R.F., Sherrington, M.R., Skillen, I. 1987, MNRAS, 225, 451
Garrido, R., García–Lobo, E., Rodríguez, E. 1990, A&A, 234, 262
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. 1995, AJ, 109, 1751
McNamara, D.H., Powell, J.M. 1990, in "Confrontation between stellar pulsation and evolution", eds C. Cacciari, G. Clementini, ASP Conf. Ser., 11, 316
Nemec, J.M., Mateo, M. 1990, in "Confrontation between stellar pulsation and evolution", eds C. Cacciari, G. Clementini, ASP Conf. Ser., 11, 64
Nemec, J.M., Nemec, A.F.L., Lutz, T.E. 1994, AJ, 108, 222
Petersen, J.O., Christensen–Dalsgaard, J. 1996, A&A, 312, 463
Rodríguez, E., López de Coca, P., Costa, V., Martin, S. 1995, A&A, 299, 108
Rodríguez, E., Rolland, A., López de Coca, P. 1990, Ap&SS, 169, 113
Rolland, A., Rodríguez, E., López de Coca, P., García–Pelayo, J.M. 1991, A&AS, 91, 347
Sills, A.P., Bailyn, C.D., Demarque, P. 1995, ApJ, 455, L163