Astron. Astrophys. 319, 881–885 (1997)

ASTRONOMY AND ASTROPHYSICS

Absolute magnitudes and kinematics of barium stars*

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Received 15 May 1996 / Accepted 29 July 1996

Abstract. The absolute magnitude of barium stars has been obtained from kinematical data using a new algorithm based on the maximum-likelihood principle. The method allows to separate a sample into groups characterized by different mean absolute magnitudes, kinematics and z-scale heights. It also takes into account, simultaneously, the censorship in the sample and the errors on the observables. The method has been applied to a sample of 318 barium stars. Four groups have been detected. Three of them show a kinematical behaviour corresponding to disk population stars. The fourth group contains stars with halo kinematics.

The luminosities of the disk population groups spread a large range. The intrinsically brightest one ($M_v = -1^m.5$, $\sigma_M = 0^m.5$) seems to be an inhomogeneous group containing barium binaries as well as AGB single stars. The most numerous group (about 150 stars) has a mean absolute magnitude corresponding to stars in the red giant branch ($M_v = 0^m.9$, $\sigma_M = 0^m.8$). The third group contains barium dwarfs, the obtained mean absolute magnitude is characteristic of stars on the main sequence or on the subgiant branch ($M_v = 3^m.3$, $\sigma_M = 0^m.5$). The obtained mean luminosities as well as the kinematical results are compatible with an evolutionary link between barium dwarfs and classical barium giants. The highly luminous group is not linked with these last two groups. More high-resolution spectroscopic data will be necessary in order to better discriminate between barium and non-barium stars.

Key words: stars: absolute magnitude – barium stars – kinematics

1. Introduction

Barium stars were defined as a group by Bidelman & Keenan (1951) based upon 80 Å/mm spectrograms. They are G and K post-main-sequence stars which show enhancements of many s-process elements, particularly BaII and SrII, as well as CH, CN and C_2. The BaII λ4554 line strength is used to characterize the abundance peculiarity, on a scale from 1 (mild barium stars) to 5 (strong barium stars). Barium stars likely all belong to binary systems (McClure et al. 1980; McClure 1983; Jorissen & Mayor 1988; McClure & Woodsworth 1990). Orbital elements determinations show long periods ranging from 1 to about 18 years and suggest an average mass of 1.5 $M_\odot$ with a probable mass range of 1 to 4 $M_\odot$ (Culver & Ianna 1976, 1980; Culver et al. 1977). Abundance anomalies are explained via the mass transfer, either through Roche lobe overflow (Webbink 1986) or wind accretion in a detached system (Boffin & Jorissen 1988; Jorissen & Boffin 1992), the companion being a white dwarf star (Böhm-Vitense 1980; Böhm-Vitense et al. 1984).

Due to the lack of precise trigonometric parallaxes of barium stars, the most critical point is the determination of their absolute magnitudes. A summary of previous determinations using different methods is given in Jaschek et al. (1985). The absolute visual magnitudes range between $-3^m.7 \leq M_v \leq +5^m$ (from luminosity class Ib to luminosity class IV, with the majority of stars having luminosities of normal giants). Jaschek et al. (1985) obtained a mean value $M_v = 0^m.0$ for "certain" barium stars and $M_v = -1^m.3$ for "mild" barium stars. The absolute magnitude dispersion (σ_M) is very large ($1^m.2$), a fact well known from previous works. More recently Hakkila (1990), using the methods of secular and statistical parallaxes, obtained for "certain" barium stars a mean value $M_v = 1^m.4$ and a dispersion $\sigma_M = 1^m.3$. Hakkila (1990) made statistical corrections in order to take into account several selection effects present in the dataset. There are, however, some drawbacks in this study. The main ones are that the method assumes a spherical velocity distribution for the whole sample and, as quoted by the author, that the final result is strongly dependent upon the applied statistical corrections which were estimated under the assumption of a single gaussian distribution in luminosity.

Barium stars appear to have young to old disk kinematics (Lü 1991). The intermediate age is of about 2 10^9 yrs, but the formal errors indicate a possible larger range between 5 10^8 and 4 10^9 yrs (Hakkila 1989).

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* Table 2 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

Luri et al. (1996a) have developed a new method, based on the maximum-likelihood principle, to obtain luminosity calibrations from kinematical data. The algorithm allows to separate a sample in physically homogeneous groups and to estimate the mean absolute magnitude and the velocity ellipsoid of each group. The method takes into account, in a natural way, the sample selection effects and the errors in the observables. It is well suited to determine the absolute magnitude calibration of barium stars, specially to seek for sub-groups which will conciliate the large range of absolute magnitudes and kinematical behaviours obtained in previous works.

In this study, the algorithm has been applied to a sample of barium stars. The main goal is to analyse kinematical properties and luminosities in terms of evolutionary status.

2. Material

The barium star sample has been selected from the Lü catalogue (1991). In order to apply the maximum likelihood (ML) method for luminosity calibration summarized in the next section, the following data and their corresponding errors are necessary: positions, apparent magnitudes, proper motion components and radial velocities. Astrometric and photometric data have been taken from the INCA database (Gómez et al. 1989; Turon et al. 1991) which contains all the data compiled for the preparation of the Hipparcos Input Catalogue (Turon et al. 1992). Radial velocity data come from different sources: McClure & Woodsworth (1990) and Griffin R. (1983, 1991) for stars with orbit determination (about 20 stars), Coravel data obtained by one of us (L. Prévot) or kindly communicated by M. Mayor for about 250 stars. The precision of the radial velocities in the cited sources is better than 1 km s^{-1}. For the remaining stars, the radial velocities have been taken from the catalogues of Wilson (1953), Evans (1978), Barbier-Brossat (1989), Barbier-Brossat et al. (1994) and Lü (locally cited). In these last sources the precision of the radial velocities varies between 1.5 and 5.5 km s^{-1}. The final sample contains 318 stars.

3. A new maximum likelihood method

The maximum likelihood method has been extensively used to calibrate the absolute magnitude of a group of stars from kinematical data (Rigal 1958; Jung 1970; Heck 1975). The correct use of these algorithms requires the sample to be homogeneous, which means that all the stars in the sample should be represented by the same probability density function (pdf). Otherwise, the presence of stars belonging to a different statistical population can bias the ML estimation. Moreover, these algorithms do not take into account the observational selection effect on the sample (e.g. the Malmquist bias) and the obtained results need a bias correction which is not always simple to evaluate.

The newly developed method (Luri 1995; Luri et al. 1996a) allows to consider the case of a non homogeneous sample and takes into account the effects due to the sample selection, the interstellar absorption, the galactic differential rotation and the errors in the observables. The sample is assumed to be a mixture of stars coming from several groups, each of them being characterized by the following pdfs: a gaussian law for the absolute magnitude (M_0, σ_M), a Schwarzschild ellipsoid velocity distribution $(U_0, V_0, W_0, \sigma_U, \sigma_V, \sigma_W)$ and an exponential-disk spatial distribution (Z_0 being the scale height in the direction perpendicular to the galactic plane). The number of different groups composing the sample (N) is not usually known. In order to obtain it, a Wilk's test is applied: ML estimations are performed assuming $N = 1, 2, 3, ...$ and the maximum likelihood values obtained for N and $N + 1$ are compared using the test. The algorithm also provides a statistical discrimination of the sample stars into the different groups (for details see Luri et al. 1996a and Luri 1995).

As mentioned before, the input observational data for each star are: galactic coordinates, apparent magnitude, proper motion components, radial velocity and their corresponding errors. The effect of the interstellar absorption on the apparent magnitude has been taken into account using the Arenou et al. (1992) model. The galactic differential rotation effect on the kinematical data has been included using the Oort-Lindblad model at first order. Finally, the sample selection in apparent magnitude has been described by a selection function which is uniform up to a certain magnitude m_c and then linearly decreases up to the limiting magnitude of the sample (see Luri et al. 1996b for details). The quantity m_c is treated as a parameter and is determined by the ML algorithm.

As shown in the Introduction, barium stars spread a very large range in luminosities. The new ML method outlined above is well suited to be applied to barium stars: it allows to separate the sample into groups characterized by different mean absolute magnitudes, kinematics and z-scale heights.

Table 1. Mean visual absolute magnitudes and kinematics of disk population barium stars

	Group 1		Group 2		Group 3	
	mean	σ	mean	σ	mean	σ
M_v	-1.5	0.2	0.9	0.4	3.3	0.7
σ_M	0.3*	0.3	0.8	0.2	0.1*	0.4
U_0	-5	2	-10	6	8	10
σ_U	17	2	36	3	25	10
V_0	-6	2	-13	4	-7	7
σ_V	13	2	20	2	15	6
W	-7	2	-7	2	-2	6
σ_W	8	2	16	2	13	5
Z_0	101	16	308	100	$--$	$--$
%	41	4	50	6	9	5

4. Results

The method has been first applied to the total sample (318 stars) and two groups with different kinematical behaviour were separated. The first one, containing 93% of the sample stars, has velocity dispersions characteristic of disk population: σ_U, σ_V and

σ_W = 28, 17 and 13 km s^{-1}, respectively. The second group contains only 18 stars and presents kinematical characteristics of halo stars: σ_U, σ_V and σ_W = 86, 141 and 66 km s^{-1}, respectively. These stars have been eliminated from the sample and the method has been newly applied using the remaining 300 stars.

Our results show the presence of three disk population groups, their characteristics are given in Table 1. The entries are self-explanatory. M_v and σ_M correspond to the visual range and are expressed in magnitudes. The kinematical parameters ($U_0, V_0, W_0, \sigma_U, \sigma_V$ and σ_W) are given in km s^{-1}. Z_0 is expressed in pc. The last row gives the percentage of the sample belonging to each group. The σ values represent the error of the fitting procedure, estimated using Monte-Carlo simulations (Luri 1995). The asterisks indicate that the given σ_M values are not well determined. The comparison of these values with the associated errors suggests that they are underestimated. A reasonable lower value for σ_M in both cases is $0^m.5$.

The first group is intrinsically very bright. Their mean luminosity is characteristic of bright G and K giants (MK type II) (Schmidt-Kaler 1982). The kinematics σ_U, σ_V and σ_W = 17±2, 13±2 and 8±2 km s^{-1}, respectively, corresponds to stars of about 8 10^8 yrs (Gómez et al. 1990). The obtained scale height perpendicular to the galactic plane is compatible with the kinematical results. The group contains 41% of the total sample stars.

The second group, the most numerous one (50% of the stars), shows a mean absolute magnitude of normal G and K giants (MK type III) (Schmidt-Kaler 1982). The velocity ellipsoid (σ_U = 36±3 km s^{-1}, σ_V = 20±2 km s^{-1} and σ_W = 16±2 km s^{-1}) and Z_0 = 308±100 pc are characteristic of normal G and K disk giants (Mihalas & Binney 1981).

The third group is very small (9% of the sample stars). The mean absolute magnitude as well as the kinematical behaviour agree with those of G-type subgiants (Schmidt-Kaler 1982). The value of Z_0 could not be determined due to the small size of the group.

Table 2 gives for each star the probability of belonging to each of the three obtained groups. Each star has been assigned to the group for which it has the highest probability. Notice that in any statistical discrimination procedure, a certain percentage of misclassification occurs. Table 2 also gives the spectral type taken from the INCA database and the strength of the BaII line (I_{Ba}) taken from Lü catalogue (1991).

Finally, the 18 stars presenting kinematical behaviour of halo stars are the following: HD 26, 10613, 15589, 50264, 55496, 88927, 104340, 107541, 115277, 119185, 150862, 197481, 206983, 207585, 219116, 222349 and BD -01 302 and -10 4311. For this sample it has not been possible to calibrate the absolute magnitude due in part to the small number of stars in the sample.

5. Discussion

As mentioned in the Introduction, almost all barium stars appear to be binaries and the abundance anomalies are explained as a consequence of the transfer, either through Roche lobe overflow or wind accretion onto the present Ba II star, of carbon and s-process elements produced in asymptotic giant branch evolution of the original primary. On the other hand, the statistical analysis of the available orbits imply that the mass of the companion lies in a narrow range ($0.5 - 0.7\,M_\odot$), characteristic of white dwarfs stars, provided that the barium star has a mass in the range $1.3 - 2.2\,M_\odot$, typical for stars on the red giant branch (Jorissen et al. 1996).

The obtained groups, given in Table 1, are characterized by different absolute magnitudes and kinematics. These results are analysed in order to assess a possible evolutionary link between the groups.

We have used the kinematical results in order to estimate an average sample age for each group from the age-dispersion relationship given by Lacey (1992). The total velocity dispersions have been evaluated from the data of Table 1. The estimated average sample ages are: 7 $10^8 \pm 10^8$ yrs for group 1, 2 $10^9 \pm 10^9$ yrs for group 3 and 5 $10^9 \pm 10^9$ yrs for group 2. The young age of group 1 is incompatible with a possible evolutionary link between this group and the other two. Moreover, the precursors of barium stars in group 1 should be more massive than those of other groups. Stars in groups 1 and 2 have left the main sequence. If all stars in each of these groups evolve from stars of the same mass (disregarding the fact that the mass of the barium star correlates with the mass of its companion (Boffin & Jorissen 1988)), a rough average mass value of the precursors can be set using the estimated averaged sample ages combined with stellar evolution models (Lebreton 1996). We have obtained averaged masses of about 2.2 $M_\odot$ for goup 1 and $1.2 - 1.3\,M_\odot$ for group 2. In fact, the precursors spread a wide range of masses and we can consider that the obtained values show only that the precursors of barium stars in group 1 are more massive than those in group 2.

Group 1 seems to be a separate group. It is the brightest one and contains a high percentage of stars. If we take into account the formal error on M_0 and the associated σ_M of the gaussian law for the absolute magnitude, the group spreads (at 1 sigma level) an absolute magnitude range between −0.7 and −2.3 magnitudes. These luminosities are compatible with the luminosities of stars with masses between 2 and 4 $M_\odot$ in the asymptotic giant branch which is a powerful source of s-elements (Lattanzio 1986). On the bases of the mean absolute magnitude and kinematical age results, it can not be ruled out that some of the stars may be bright giants in the AGB phase. Catchpole et al. (1977) suggested that when the stars are divided into groups according to their observed strength of the Ba II line, the barium-weak group is young and of high luminosity while the barium-strong group is old and of low luminosity. At this point, we can ask whether group 1 compared to group 2 contains principally mild barium stars. Using the data on the strength of the BaII line given in Table 2, we have calculated the number of stars belonging to different bins in I_{Ba}. We have considered as mild stars those stars that have Ba II line intensity less than 1. Our statistics show that in group 1 about 78% of the stars have I_{Ba} values less or equal to 1 and in group 2 we find a smaller although still high percentage of 53%. It is a well known fact that strong barium stars are found among short period systems (Jorissen & Boffin 1992) and that the orbital period is related to the orbital separation. It may be possible that mild barium stars have wider separations between components, making more difficult the detection of their binary nature. If we consider the stars with known orbits or with variable radial-velocity, there is no substantial difference between both groups. On the other hand, McWilliam (1990) analysed several stars from the Lü list (1991) and found no heavy-element overabundances, suggesting that the Lü compilation could be "contaminated" with non-barium stars (Jorissen et al. 1996). In the light of these considerations, the possibility that our group 1 contains barium binaries as well as single barium and non-barium giants in the AGB can not be disregarded. High-resolution spectra will be necessary in order to better discriminate the stars.

Group 2 is the oldest one and the most numerous. Its mean absolute magnitude and average age correspond to stars in the red giant branch, as is commonly assumed for barium stars. Nevertheless, we have also identified a third group with a mean absolute magnitude and kinematics corresponding to stars on the main sequence or on the subgiant branch. Several authors have argued the existence of barium dwarfs as the main sequence counterparts of the barium giants (North & Duquennoy 1992; North et al. 1994). The binary scenario proposed to explain barium stars also predicts the existence of barium dwarfs (Boffin & Jorissen 1988; Jorissen & Mayor 1992). Only a few number of barium dwarfs has been identified. In a spectroscopic study, North et al. (1994) quoted ten barium dwarfs (the sample includes also CH subgiants), among which seven are in our original sample. The classification obtained with our algorithm is in excellent agreement with the results of North et al.: the stars HD 89948, 123585, 188985 and 202400 belong to group 3 and the stars HD 150862, 222349 and BD -10 4311 are in the group presenting kinematical characteristics of halo stars. North et al. (1994) showed that the evolutionary state within the main sequence of the barium dwarfs remains unclear in the sense that the spectroscopic surface gravity for several objects suggests that they have left the main sequence. Moreover, the results of North et al. support the idea that dwarf barium stars may be the possible progenitors of barium giants. We identify the group 3 as the group containing these types of objects and our results are compatible with an evolutionary link between groups 2 and 3.

Finally, the algorithm also identified a small group of stars with kinematics corresponding to the halo population. The mean absolute magnitude could not be estimated basically due to the small size of the sample. This could also mean that the sample spreads a large range in absolute magnitude, probably explained by metallicity and evolutionary effects.

6. Conclusions

Using a new algorithm based on the M-L principle, four groups of barium stars have been detected. Mean luminosities and kinematical behaviours have been obtained for three groups belonging to the disk population. The fourth group contains stars with halo kinematics. Our results confirm that barium stars constitute an inhomogeneous sample and agree with previous works in the sense that their luminosities spread a large range: from luminosity class Ib to luminosity class IV-V, with most of the stars having luminosity of normal giants. Contrary to previous works, we have identified several groups and obtained their visual absolute magnitudes and kinematics. In addition to the group of normal giants, two other groups have been discriminated: a young and high luminosity one and a second one corresponding to main sequence and/or subgiants stars. Within the framework of the binary scenario proposed to explain barium stars, our results are compatible with an evolutionary link between the barium dwarf group and the group of classical red giants. The highly luminous group is not linked with the other two. It seems to be an inhomogeneous group containing binaries as well as single stars in the AGB. High-resolution spectra will be necessary in order to determine CNO and s-process abundances and better discriminate between barium and non-barium stars.

Acknowledgements. We thank M. Mayor for communicating us unpublished data. Part of this work was supported by the PICASSO program-AI 93135 and by the CICYT under contract ESP95-0180.

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