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# Barium in Cepheids: new data on the abundance distribution in the Galactic disc

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## ABSTRACT

Using an Non-Local Thermodynamic Equilibrium (NLTE) analysis and a homogenous spectral data base, we have determined Ba abundances in a sample of 210 Galactic Cepheids and related objects. We confirm the previous result reported in Andrievsky et al. that the barium distribution in the range of Galactocentric distances from 5 to 18 kpc shows very small gradient value. The value determined here –  $d[\text{Ba}/\text{H}]/dR \approx -0.01 \text{ dex kpc}^{-1}$  – is smaller than that for other s-process elements, such as La, Pr, Nd and Sm (Luck & Lambert), that typically show gradients of  $-0.03 \text{ dex kpc}^{-1}$ .

**Key words:** stars: abundances – stars: variables: Cepheids – Galaxy: disc – Galaxy: evolution.

## 1 INTRODUCTION

Barium is an element whose primary source is the main s-process in asymptotic giant branch (AGB) stars. This contrasts with  $\alpha$ - and iron peak elements that derive from supernovae. Thus, barium and its kindred s/r-process elements provide information on a different environment of element production in the evolving galaxy than one finds in lighter species and provides another vital piece of information for Galactic chemical evolution.

In Andrievsky et al. (2013), we determined Non-Local Thermodynamic Equilibrium (NLTE) barium abundances in a sample of 270 Cepheids distributed at Galactocentric distances from 4 to 15 kpc. We found the rather unexpected result that the barium abundance distribution does not show any significant slope; that is, the barium radial Galactocentric abundance gradient is about zero. This result contrasts with the previous finding for other s/r-process elements, which shows the gradient for those elements is small, but non-zero (Luck & Lambert 2011). We combined the previous gradient results with the data of Simmerer et al. (2004) on relative s- and r-process contributions to overall abundances for Ba, La, Pr, Nd, Sm and Eu and estimated that the gradient value for Ba should be about  $-0.03 \text{ dex kpc}^{-1}$ . The estimated gradient for Ba is comparable to other observed values for s/r-process elements, and is smaller than the gradient value for  $\alpha$ -elements and iron, but is several times larger than the gradient found by us, which is less than  $0.01 \text{ dex kpc}^{-1}$  in absolute value. Therefore, it is important to check our previous finding with an extended sample of stars, and this is the main aim of our present study.

## 2 STAR SAMPLE

Our present star sample includes 303 high-resolution spectra of 210 classical Cepheids and other related objects. The related objects are primarily type II Cepheids. The spectra are part of the data base previously used for abundance analysis by Luck & Lambert (2011). These spectra were obtained with Hobby-Eberly Telescope and its High-Resolution Spectrograph. The spectra span a wavelength range 400–785 nm with a nominal resolution of 30 000 and a per pixel signal-to-noise ratio of 100 or greater. The list of our programme stars, their atmosphere parameters and iron abundances as well as Galactocentric distances, all taken from Luck & Lambert, are given in Table 1. Note that not all of the stars and/or spectra of Luck & Lambert are included in this study. For this analysis, we deemed a number of the Ba II profiles too asymmetric for proper analysis and thus did not include those stars/spectra.

In Fig. 1, we show a comparison of barium abundance determination in 33 stars, which are common for our previous and present studies. As one can see, agreement is rather good. At the same time for nine stars (not showed in this figure), we did not achieve reasonable agreement. Among them: BN Per (present barium abundance value is 2.03, previous value was 2.64), CV Mon (2.39, 2.00), DX Gem (2.29, 2.69), EK Mon (2.48, 2.10), FM Aql (2.17, 2.54), RZ Gem (2.22, 2.55), TX Mon (2.47, 2.05), V508 Mon (2.47, 2.05) and V527 Mon (2.27, 2.52).

Since in Andrievsky et al. (2013) we used spectroscopic data obtained with various telescopes and various spectrograph facilities, and the present sample of stars is entirely based on observations carried out with Hobby-Eberly 9.2-m Telescope (in that sense this material is more homogeneous), we consider our present barium abundance determinations in the common stars are being more robust.

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**Table 1.** Parameters and abundances for programme Cepheids.

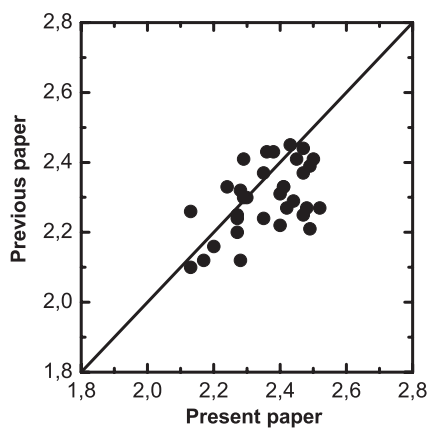
Object	Phase	$T$ (K)	$\log(g)$	$V_t$ ( $\text{km s}^{-1}$ )	$\varepsilon(\text{Fe})$	$\varepsilon(\text{Ba})$	$R_G$ (kpc)
AA Gem	0.422	5141	1.23	3.92	7.34	2.01	11.55
AA Gem	0.658	5190	1.45	5.85	7.38	2.05	11.55
AA Mon	0.841	5797	2.26	4.90	7.41	2.12	11.36
AA Ser	0.342	5045	1.26	3.52	7.91	2.64	5.99

*Notes.* (1) Phases, effective temperatures, gravities, microturbulent velocities, iron abundances and galactocentric distances from Luck & Lambert (2011).

(2) AU Peg, BC Aql, DR Cep, QQ Per, EK Del, GP Per and RW Cam are also from Luck & Lambert (2011) but are W Vir stars and hence not included in the gradient calculations.

(3) The Guide Star Catalog (GSC) objects are also from Luck & Lambert (2011). They are Cepheids from Wils & Greaves (2004) but have insufficient data to compute a distance. There are a few Cepheids in the named variables that also lack distances due to missing data.

The full version of this table is available in the electronic form.



**Figure 1.** Comparison of the results of the barium abundance determination in common stars.

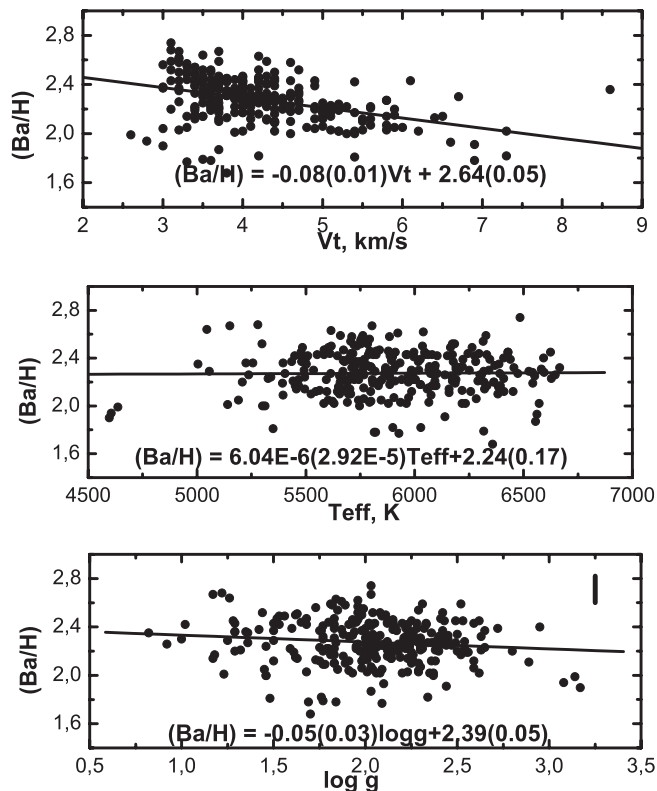
### 3 ABUNDANCE ANALYSIS

Andrievsky et al. (2009) give a detailed description of the barium atomic model used in this NLTE analysis. The model was discussed briefly in Andrievsky et al. (2013), where a discussion of the derivation of NLTE barium abundances can also be found. We have extended the number of barium lines in this study relative to our previous work by adding the line at 455.4 nm. To treat this line, it is necessary to take into account the isotopic shift between line components. Specifically, we used the even-to-odd barium isotope ratio for the present day metallicity; i.e. 82:18 (Cameron 1982). Since this line is strongest in comparison to the other Ba II lines, it was used as an additional line in abundance determination. We incorporated this line into analysis, because in the present sample it appears in the observed spectral domain. This line was used in statistics for almost all the stars. Exceptions were made for the stars with the rather high metal content (Cepheids, which are closer to the Galactic centre). In the spectra of those stars, this line (and many others) is strong and situated in the very crowded region of spectra, where correct continuum placement is problematic, and therefore, an analysis of this line can produce unreliable results. So, in such cases, we used three other lines for statistics, and this fourth line served as a ‘reference’ one. If abundance derived from it deviated too much from the other line results, it was discarded. Results of the barium abundance determination are given in Table 1.

As a rule, barium lines are rather strong in cool supergiant spectra, and this leads to abundances based on an equivalent width analysis or a synthetic spectra technique that are often not especially reliable. The difficulty can be that the great line strength found in Ba II lines leads in the calculations to line optical depths at or near unity closer to the upper levels of the model atmospheres. The un-convolved line core itself can be ‘black’ to several thousandths of a nanometre from line centre; this can be true, in particular, for the strongest 455.4 nm line. This means that the abundances are very sensitive to the properties of the line outside the line core; i.e. the line is dominated by damping in the wings and velocity fields that allow greater absorption far from line centre. One way to try to attempt to ameliorate this problem is to use model atmospheres that are extended to very shallow optical depths. The model used here are ATLAS9 (Kurucz 1992) models that extend out to reference optical depths of  $\log \tau \approx -7$ . The problem with this approach is that such shallow optical depth could be non-physical. Cepheids exhibit time-dependent chromospheric activity (Schmidt & Parsons 1984) which indicates that it is not unlikely that their atmospheres show an extended structure somewhat like the Sun. That is, the photospheric temperatures decline to a minimum and then rise into the chromosphere with the inversion occurring at about  $\log \tau \approx -5$ .

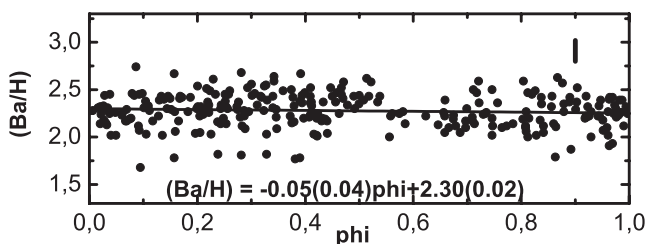
These difficulties plague our NLTE barium abundances. While the NLTE calculations should yield realistic level population estimates, we cannot overcome the saturation problem, as it is the line strength, not the populations, that set the overall uncertainty in the abundances. As shown in Fig. 2 (top panel), the problem manifests itself as a slight dependence of the barium abundance on the adopted microturbulent velocity and a significant scatter at any particular value of the microturbulent velocity. This dependence on microturbulence was also evident in the analysis of Andrievsky et al. (2013). The microturbulent velocity is determined from Fe II lines (see description of the modified method in Kovtyukh & Andrievsky 1999) of lesser strength than Ba II lines, but there is no guarantee that this velocity applies to the portion of the atmosphere nearer the upper boundary, where the Ba II lines are formed.

The internal uncertainty in the microturbulent velocity is of the order of  $\pm 0.2$ – $0.3 \text{ km s}^{-1}$ . Such an uncertainty leads to a possible error in the barium abundance of about  $\pm 0.12$  dex at  $T_{\text{eff}} = 6300 \text{ K}$ ,  $\log g = 2.5$  and  $\pm 0.14$  dex at  $T_{\text{eff}} = 5000 \text{ K}$ ,  $\log g = 1.5$  for lines of the strength observed in these Cepheids. Fig. 2 indicates that such a small error margin cannot rectify the trend in abundance,



**Figure 2.** NLTE barium abundance versus microturbulent velocity (upper panel), effective temperature (middle panel) and surface gravity (bottom panel). While there is a weak dependence of barium upon microturbulent velocity –  $d\text{Ba}/dV_t \approx -0.1 \text{ dex}/(\text{km s}^{-1})$ , there is no obvious trend relative to effective temperature or gravity. All panels include a linear fit to the barium abundance versus the corresponding atmosphere parameter. All of the data shown in these panels are per phase values; that is, they are not averages. Sigma value is indicated in this and other plots by a thick vertical line.

it is very likely that a more systematic and pervasive problem affects this data. Such a problem could be systematic effects relative to the effective temperature or the gravity. However, no significant dependence of the NLTE barium abundance upon the effective temperature and surface gravity is found in the data – see Fig. 2 middle and bottom panel. One could also expect that some observational selection connected to the preference of certain pulsation phases can introduce a possible error (or, more correctly, some bias in the resulting barium abundances appears that might influence derived gradient). To check this, we constructed the barium abundance distribution depending on the phase. As one can see from Fig. 3, there is no significant dependence of  $(\text{Ba}/\text{H})$  on phase. In the next section, the barium abundance uncertainty is discussed in more details.



**Figure 3.** Barium abundance versus individual pulsational phase.

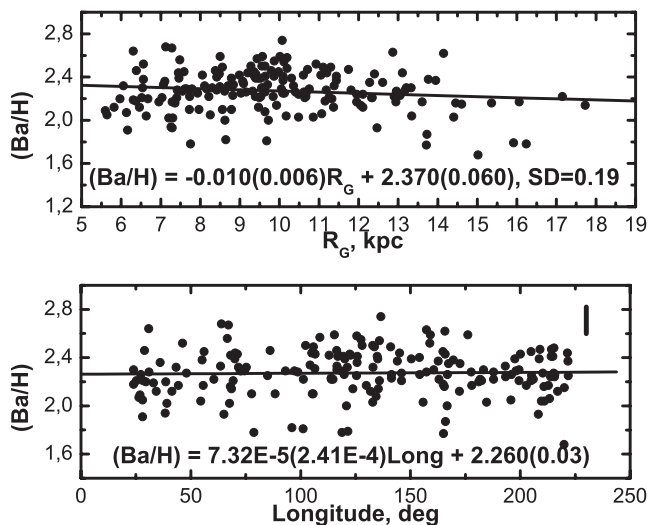
#### 4 UNCERTAINTIES OF THE BARIUM ABUNDANCE DETERMINATION

We detected the rather high scatter of the barium abundance distribution, and therefore, we have to investigate all the possible contributors that could be responsible for such scatter. The main contributors to the barium abundance errors are the effective temperature, surface gravity and microturbulent velocity uncertainties. According to our data, the typical uncertainty of the effective temperature determinations is about 100 K, or less. Nevertheless, we varied the effective temperature by 150 K, and found the response in the barium abundance of about  $\pm 0.09 \text{ dex}$  (for the basic model  $T_{\text{eff}} = 6000 \text{ K}$ ,  $\log g = 2.0$  and  $V_t = 3.5 \text{ km s}^{-1}$ , and solar barium abundance, i.e. 2.17. The behaviour of the line  $5853.7 \text{ \AA}$  was studied). From our experience, we know that the typical uncertainty in the  $\log g$  determination is about  $\pm 0.2 \text{ dex}$ . Such an error can produce error in the barium abundance (for the same basic model as above) of about  $\pm 0.06 \text{ dex}$ . The microturbulent velocity is determined with a precision of about  $\pm 0.25 \text{ km s}^{-1}$ , and this produces the variation of abundance of about  $\pm 0.12 \text{ dex}$ . Finally, The standard error of the barium abundance determination from the four lines is about 0.15 dex (varies for different stars from 0.07 to 0.22 dex). Therefore, the total standard error is  $\pm 0.22 \text{ dex}$ . This value is indicated in some plots by a thick vertical line.

We also checked an influence of the truncated atmosphere model on resulting abundance. We generated model with  $T_{\text{eff}} = 6000 \text{ K}$ ,  $\log g = 2.0$  and  $V_t = 3.5 \text{ km s}^{-1}$  starting it not from  $\log \tau = -6.875$ , but from  $\log \tau = -5$  (see the discussion above). We found that this change does not affect resulting barium abundance.

#### 5 THE BARIUM ABUNDANCE DISTRIBUTION IN GALACTIC DISC

While accepting the limitations of our data, we are curious about how this data play out in terms of the radial and azimuthal barium abundance distribution in the Galactic disc. The radial distribution is presented in top panel of Fig. 4. From this figure, one can see that barium abundance data show a wide spread at each Galactocentric distance. For the region from 7 to 9 kpc in Galactocentric radius,

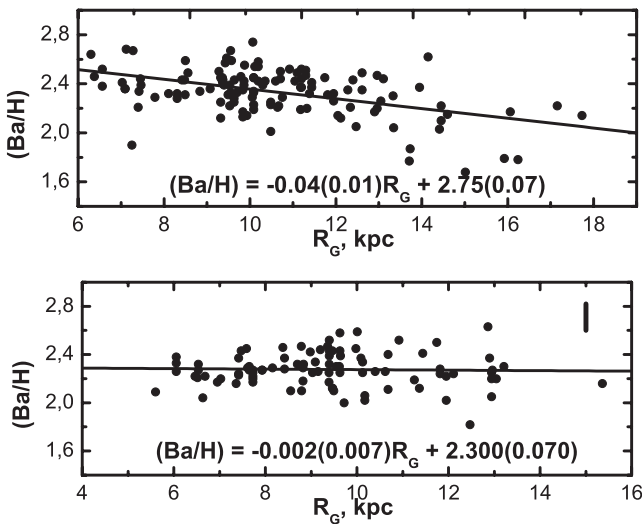


**Figure 4.** The NLTE barium abundances plotted versus Galactocentric distance (upper panel) and Galactic longitude (bottom panel). There is little to no evidence for a relation between barium and either spatial variable. The barium abundance data in these plots are average values for the Cepheids.

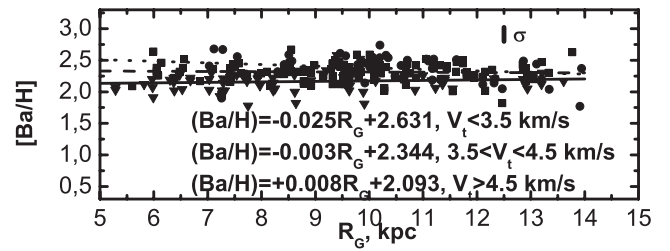
the barium abundances have a range of 0.9 dex with a standard deviation of 0.2 dex about the mean. For comparison, the iron data of Luck & Lambert in this Galactocentric radius range exhibit a standard deviation about the mean of 0.09 dex with a range of about 0.4 dex. There is a hint that at the distances larger than about 14 kpc, the barium abundance may have a tendency to decrease, but our statistics are not sufficient for a definitive conclusion. An equal-weight fit to all the stars gives a gradient  $d[\text{Ba}]/dR_G$  of approximately  $-0.01$  dex  $\text{kpc}^{-1}$ . If we restrict our sample to the maximum limiting Galactocentric distance achieved in our previous study, i.e. 15 kpc, then we obtain a gradient of  $-0.0002$  dex  $\text{kpc}^{-1}$  in agreement with our previous finding. The mean  $(\text{Ba}/\text{H})$  value for our present sample is  $2.27 \pm 0.19$  dex, also in excellent agreement with our previous result  $\langle (\text{Ba}/\text{H}) \rangle = 2.25 \pm 0.13$  dex (Andrievsky et al. 2013).

There is no evidence for longitudinal variations in abundance at any Galactic radius (Luck & Lambert 2011). This implies that the Galaxy is well mixed at common radii. Since the barium data show little to no radial distribution, we do not bin it by radius but only look at the longitude, where we find no evidence for a trend – see Fig. 4 (bottom panel). This is as expected, based upon the Luck & Lambert result.

The bulk of the stars have microturbulent velocities in the range  $3\text{--}5$   $\text{km s}^{-1}$ . While Fig. 1 (top panel) indicates significant scatter in the abundances in this velocity range, there is little evidence for any systematic behaviour within the range. If we limit the microturbulent range to a small interval, it is possible that the systematic effects in the abundances would be comparable object-to-object, allowing recovery of relative abundances more accurately. In Fig. 5, we show the barium abundances versus Galactocentric radius relation for phases where the microturbulent velocity is  $3\text{--}4$   $\text{km s}^{-1}$  in the top panel and  $4\text{--}5$   $\text{km s}^{-1}$  in the bottom panel. It is possible for stars with multiple abundance determinations to be present in both panels as the microturbulent velocities differ from phase to phase. To our great surprise, the data for determinations based on microturbulent velocities of  $3\text{--}4$   $\text{km s}^{-1}$  show a clear trend with Galactocentric radius. The slope of the relation is  $d\text{Ba}/dR_G = -0.037$  dex  $\text{kpc}^{-1}$ .



**Figure 5.** The NLTE abundances of barium versus Galactocentric distance. The abundances here are per phase values – not averages – as they are selected based on the microturbulent velocity. The top panel is for determinations with  $3 < V_t < 4$   $\text{km s}^{-1}$ . The range for the bottom panel is  $4 < V_t < 5$   $\text{km s}^{-1}$ . The top panel shows a relation between abundance and distance while the bottom one does not.



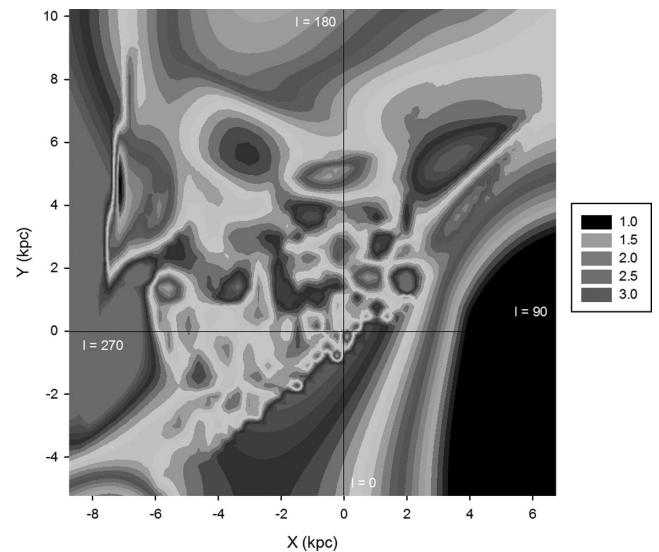
**Figure 6.** The same as Fig. 5 but for three ranges of microturbulence value. Dots are for  $V_t < 3.5$   $\text{km s}^{-1}$  (interpolating line is dotted line), squares are for  $3.5 < V_t < 4.5$   $\text{km s}^{-1}$  (dashed line) and triangles are for  $4.5 < V_t < 15$   $\text{km s}^{-1}$  (solid line).

This value is commensurate with that found for other  $s/r$ -process elements (Luck & Lambert 2011). Unfortunately, the  $4\text{--}5$   $\text{km s}^{-1}$  subset of the data deflates our hopes. It shows no trend with Galactocentric radius. If we use more detailed splitting of the total sample on microturbulence value (see Fig. 6), then the following conclusion can be made: different data sets (with different characteristic  $V_t$  values) simply contribute to an increase of the barium abundance scatter at all distances with a little evidence of a significant gradient. In this figure, we restricted ourselves with a maximum distance of 14 kpc. The number of stars with the large distances is small to make any reliable statistical conclusions.

In Fig. 7, we show 2D barium abundance distribution in Galactic disc. It does not show any structure.

We are left disconsolate; the bulk of the barium evidence currently indicates at best a very small gradient, but there is a glimmer that a gradient might still be there. We now briefly turn to a discussion of how an abundance gradient could be flattened or destroyed.

Barium nuclei are produced in lower mass AGB stars along with even heavier  $s$ -process elements, as well as some  $Y$ . This branch of the  $s$ -process is the main  $s$ -process. The gross yield of the  $s$ -process depends on the mass of the producer. For instance, 1.5 solar mass AGB star produces about 10 times more barium than a



**Figure 7.** 2D barium abundance distribution in Galactic disc. Different intensities of the contours correspond to the different absolute barium abundances. Two lines intersection indicates position of the Sun. For the four main directions the Galactic longitudes are showed. Our data do not extend past 4 kpc towards the Galactic centre, therefore it falls off the plot at  $(0, -7.9)$ .

3 solar mass AGB star does (Husti et al. 2009). If for some reason, the elemental abundance production ratios were also a function of mass, it is conceivable that certain gradients could be enhanced or suppressed in the Galactic disc. A possible scenario first discussed in Andrievsky et al. (2002) for this is as follows.

The homogenization of material ejected by AGB stars by a large-scale mixing mechanism that operates on a characteristic time-scale smaller than the lifetime of the primary barium producers will lead to a flattening of the barium abundance distribution in Galactic disc. In such a process, the gradient expected from standard Galactic chemical evolution models will be erased. Such a large-scale mixing mechanism may be associated with the gas streams in the Galactic disc. According to Brand & Blitz (1993), there are the random and systematic gas flows in the disc with velocities ranging from about 4 to 17 km s<sup>-1</sup>. Assuming a velocity of 10 km s<sup>-1</sup>, the characteristic time of a gas flow mixing process over a baseline of 10 kpc should be about 1 Gyr. This time-scale corresponds to the lifetime of a star with mass of about 3 solar masses. Thus, this mechanism is capable of flattening the abundance gradient value to about zero, since its characteristic time is shorter than the lifetime of the 1–2 solar mass stars that are efficient producers of barium (of course, their progenitors could be slightly more massive). This means that only those elements that are produced by more massive AGB stars and/or SNe, which have shorter lifetimes, should display (negative) gradient values. The obvious caveat is that if 1–2 solar mass stars are efficient producers of Ba, they will also be primary producers of other main s-process elements and those elements (primarily Y, La and Ce along with Pr and Nd to a lesser extent, see Arlandini et al. 1999; Pignatari et al. 2010) should also show flattened gradients. These elements do show gradients significantly smaller than the gradients from  $\alpha$ - and iron group elements (Luck & Lambert 2011), and this could provide additional support to this hypothesis independent of the barium abundance gradient found in this study.

## 6 CONCLUSION

The current evidence is not conclusive relative to the existence of a radial gradient in Galactic barium abundances. Distinct problems in the analysis complicate the interpretation. Andrievsky et al. (2002) found near-to-zero gradient values for the s-process elements La, Ce, Nd and Gd. However, Luck & Lambert (2011), for a larger sample of Cepheids obtained small, but distinctly non-zero, gradients for Y, La, Ce, Pr, Nd, Sm and Eu. The current data taken uncritically imply no gradient. How these findings can be rectified at this time is unclear leaving the question of s-process gradients in the current Galactic disc open. We have to note that our present barium abundance was derived from the rather strong Ba II lines (the weak lines of this ion are not available) using the NLTE approximation, while literature La, Ce, Nd, etc., abundances are from the weak lines. They were derived with the help of a simple LTE approximation. Until NLTE data for these elements are not available, no definite conclusion about consistency of the Ba and La, Ce, Ne, etc., gradients can be made.

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## SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

**Table 1.** Parameters and abundances for programme Cepheids (<http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stt1992/-/DC1>).

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