



Publication Year	2022
Acceptance in OA	2025-01-21T16:41:22Z
Title	The MAGIC project - III. Radial and azimuthal Galactic abundance gradients using classical Cepheids
Authors	Kovtyukh, V., Lemasle, B., Bono, G., Usenko, I. A., OLIVEIRA DA SILVA, Ronaldo, Kniazev, A., Grebel, E. K., Andronov, I. L., Shakun, L., Chinarova, L.
Publisher's version (DOI)	10.1093/mnras/stab3530
Handle	http://hdl.handle.net/20.500.12386/35698
Journal	MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY
Volume	510

The MAGIC project – III. Radial and azimuthal Galactic abundance gradients using classical Cepheids

V. Kovtyukh,¹★ B. Lemasle,² G. Bono,^{3,4} I. A. Usenko,⁵ R. da Silva,^{4,6} A. Kniazev^{7,8,9}, E. K. Grebel,² I. L. Andronov,¹⁰ L. Shakun¹ and L. Chinarova¹⁰

¹*Astronomical Observatory, Odessa National University, Shevchenko Park, UA-65014 Odessa, Ukraine*

²*Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Mönchhofstr. 12-14, D-69120 Heidelberg, Germany*

³*Dipartimento di Fisica, Università di Roma Tor Vergata, via della Ricerca Scientifica 1, I-00133 Rome, Italy*

⁴*INAF – Osservatorio Astronomico di Roma, via Frascati 33, Monte Porzio Catone, I-00078 Rome, Italy*

⁵*Laboratory of Positional Astronomy, Mykolaiv Astronomical Observatory Research Institute, Obsevatorna 1, UA-Mykolaiv 54030, Ukraine*

⁶*Agenzia Spaziale Italiana, Space Science Data Center, via del Politecnico snc, I-00133 Rome, Italy*

⁷*South African Astronomical Observatory, PO Box 9, 7935 Observatory, Cape Town, South Africa*

⁸*Southern African Large Telescope Foundation, PO Box 9, 7935 Observatory, Cape Town, South Africa*

⁹*Sternberg Astronomical Institute, Lomonosov Moscow State University, Universitetskij Pr. 13, Moscow 119992, Russia*

¹⁰*Dpt of Mathematics, Physics and Astronomy, Odessa National Maritime University, Mechnikova St. 34, Odessa UA-65029, Ukraine*

Accepted 2021 November 29. Received 2021 November 24; in original form 2021 September 16

ABSTRACT

Radial abundance gradients provide sound constraints for chemo-dynamical models of galaxies. Azimuthal variations of abundance ratios are solid diagnostics to understand their chemical enrichment. In this paper, we investigate azimuthal variations of abundances in the Milky Way using Cepheids. We provide the detailed chemical composition (25 elements) of 105 Classical Cepheids from high-resolution SALT spectra observed by the MAGIC project. Negative abundance gradients, with abundances decreasing from the inner to the outer disc, have been reported both in the Milky Way and in external galaxies, and our results are in full agreement with literature results. We find azimuthal variations of the oxygen abundance [O/H]. While a large number of external spirals show negligible azimuthal variations, the Milky Way seems to be one of the few galaxies with noticeable [O/H] azimuthal asymmetries. They reach ≈ 0.2 dex in the inner Galaxy and in the outer disc, where they are the largest, thus supporting similar findings for nearby spiral galaxies, as well as recent 2D chemo-dynamical models.

Key words: stars: abundances – stars: variables: Cepheids.

1 INTRODUCTION

Radial abundance gradients provide sound constraints to galaxy formation scenarios. Indeed, the star formation history, the accretion history, the radial migration of stars, and the radial flows of gas and their variations with the Galactocentric distance, simultaneously determine the shape of abundance gradients. Chemo-dynamical models of the Milky Way must therefore reproduce the observed gradients and their evolution with time.

The advent of Integral Field Spectrographs (IFS) has provided the opportunity to explore a large number of nearby spiral galaxies (for a review, see Sánchez 2020), most of them showing negative abundance gradients from the inner to the outer disc and a flattening of the gradient in the outermost regions (Sánchez-Menguiano et al. 2018). Spectroscopic investigations covering the outermost regions of large spiral galaxies also show a well-defined negative age gradient (e.g. Li et al. 2015), thus supporting the ‘inside-out’ scenario (e.g. Matteucci & Francois 1989; Spitoni & Matteucci 2011).

In the Milky Way, the task is more complicated:

(i) only recently, Gaia (Gaia Collaboration 2018) provided accurate parallax-based distances for a large number of tracers [in particular, red giant branch (RGB) stars], but they are limited to the extended (≈ 5 kpc) Solar neighbourhood, and RGB ages could be determined only for a smaller, nearby sample;

(ii) tracers with both accurate distances (even far from the Sun) and ages, such as Cepheids and open clusters, do not cover the entire age range, they are rarer than RGBs, and samples are not yet complete, especially in the outer disc;

(iii) extinction hampers the detection and the spectroscopic analysis in the optical regime of (all) distant tracers.

As a result, the radial distribution of oxygen and iron abundances (among others) in the Galactic disc is still not clear. Using Cepheids, linear [Fe/H] gradients with a slope of roughly -0.05 dex kpc⁻¹ describe well the data over distances in the (5–15) kpc range (e.g. Kovtyukh, Wallerstein & Andrievsky 2005; Genovali et al. 2014; Luck 2018), but more complicated features including a flattening in the outer disc and a sharp variation of ≈ 0.2 dex in the slope have also been suggested (e.g. Luck et al. 2003). Similar radial gradients and a flattening for Galactocentric distances larger than 14/16 kpc have also been found by Donor, Frinchaboy & Cunha (2020) and by Magrini et al. (2017) using open clusters covering a moderate

★ E-mail: vkovtyukh@ukr.net

Table 1. Information on the spectra and atmospheric parameters for the investigated Cepheids. The modified Julian date (MJD) of the observations and the exposure times are given in columns (2) and (3). The following columns display T_{eff} , its uncertainty (σ), the number N of line depth ratios used to derive T_{eff} , and the quantity $\sigma/\sqrt{N}$. Then the values of $\log g$ and V_t are provided, followed by $[\text{Fe}/\text{H}]$, its uncertainty and the number of Fe I lines used. Additional remarks are provided when necessary. Only the first 10 lines of the table are shown. The full table is available in electronic form as table 1.

Object	MJD 2450000+	Exp. time (s)	T_{eff} (K)	σ (K)	N	$\sigma/\sqrt{N}$ (K)	$\log g$	V_t km s^{-1}	$[\text{Fe}/\text{H}]$ (dex)	Sigma	N	Remarks
RW CMa	7733.40182	1597	6019	158	69	19.1	1.60	2.90	0.07	0.07	149	
RW CMa	7733.41557	1597	5992	81	57	10.7	1.60	3.20	0.03	0.06	137	
RW CMa	7755.34911	1597	5993	104	60	13.4	1.70	2.90	0.05	0.10	99	
V384 CMa	7763.31139	3000	5554	146	59	18.9	1.65	2.30	0.02	0.06	114	
CC Car	7530.33756	3000	5726	91	78	10.3	1.70	2.90	0.18	0.10	196	
CR Car	7736.51354	2248	5859	87	71	10.4	1.50	2.80	0.14	0.07	194	
CT Car	7531.30744	3340	5298	97	67	11.8	1.00	3.20	0.07	0.06	195	
FN Car	7737.55065	2212	5784	69	72	8.2	1.70	2.60	0.15	0.07	198	
FQ Car	7736.54721	2672	5210	57	69	6.9	1.30	3.10	0.17	0.08	183	
FZ Car	7548.29140	2943	5970	87	76	10.0	1.90	2.60	0.13	0.12	197	
...	...	...	...	...	...	...	...	...	...	...	...	

range in ages. A sharp variation in the slope of the radial gradient across the solar circle was also suggested by Twarog, Ashman & Anthony-Twarog (1997) by using a sizable sample of open clusters. Pure 1D chemical evolution models (e.g. Cescutti et al. 2007), as well as hybrid models, which include in addition 3D kinematics from numerical simulations (e.g. Minchev, Chiappini & Martig 2014; Kubryk, Prantzos & Athanassoula 2015), reproduce quite well the Cepheid and open cluster observations. We note in passing that, given their very young age (<300 Myr), Cepheids are presumably only marginally affected by radial migration.

Significant azimuthal variations in $[\text{O}/\text{H}]$ have for now been reported in only a few galaxies (Li, Bresolin & Kennicutt 2013; Sánchez et al. 2015; Sánchez-Menguiano et al. 2016; Zinchenko et al. 2016; Ho et al. 2017; Vogt et al. 2017; Ho et al. 2018). However, we still lack solid empirical/theoretical evidence to assess whether they are either local anomalies or the aftermath of secular evolutions. In the Milky Way, various authors have reported large-scale inhomogeneities in the azimuthal gradient, for instance Davies et al. (2009) using open clusters, Luck, Kovtyukh & Andrievsky (2006); Lemasle et al. (2008); Genovali et al. (2014) using Cepheids, Balser et al. (2011, 2015) using H II regions. The latter studies found azimuthal abundance variations for $[\text{O}/\text{H}]$, leading to different slopes (by a factor about two) for the $[\text{O}/\text{H}]$ Galactocentric radial gradient, depending on the Galactic azimuth range sampled, and those results were confirmed by Wenger et al. (2019). By using a 2D chemodynamical model taking account for the Milky Way spiral pattern Spitoni et al. (2019) found a scatter in the azimuthal variations of the oxygen abundance gradient and suggested that it is the consequence of the multiple spiral modes moving at different rotational velocities.

In this paper, we present new results of the **Milky Way Galaxy with SALT spectroscopy** project (MAGIC; Kniazev et al. 2019), a large spectroscopic survey that uses spectral instrumentation of the *Southern African Large Telescope* (SALT; Buckley, Swart & Meiring 2006; O'Donoghue et al. 2006). MAGIC targets pulsating variable stars, in particular, Cepheids in order to study the Milky Way chemical evolution. We provide the stellar parameters of 105 Classical Cepheids and the abundances of 25 elements, based on 122 high-resolution SALT spectra. Our spectroscopic analysis is described in Section 2, and the results in terms of radial gradients and azimuthal inhomogeneities are presented in Section 3

2 SPECTROSCOPIC ANALYSIS

2.1 Data

We have used the SALT HRS high-resolution spectrograph operated in the medium-resolution mode (MR: $R \sim 37\,000$ – $39\,000$). It provides two spectra in the blue and red arms over a spectral range of ≈ 3900 – 8900 Å. Both the blue and red CCDs were read out in the standard 1×1 binning mode. Three spectral flats and one spectrum of ThAr+Ar lamps were obtained in that mode from a 1-week series of HRS calibrations, which yield an accuracy of the velocity measurements of about 150 m s^{-1} in the MR mode.¹ The HRS primary data reduction, including overscan and gain corrections, as well as bias subtractions, was done through the SALT science pipeline (Crawford et al. 2010). The spectroscopic reduction of the HRS data was performed using our own HRS pipeline, described in detail in Kniazev, Gvaramadze & Berdnikov (2016) and Kniazev et al. (2019). Relevant information about the spectra is given in Table 1, and the main parameters of Cepheids are given in Table 2.

2.2 Determination of abundances

The effective temperature, T_{eff} , was derived from line-depth ratios (Kovtyukh 2007), a technique commonly employed in studies of Cepheid variables (e.g. Andrievsky et al. 2002a; Lemasle et al. 2007; Kovtyukh et al. 2016; Luck 2018; Proxauf et al. 2018). Once T_{eff} determined, the surface gravity $\log g$ was computed by imposing the iron ionization balance. The microturbulent velocity, V_t , was derived assuming that there is no correlation between the iron abundance $A(\text{Fe})$, obtained from Fe I lines, and the equivalent widths (EW) of the same lines. The adopted value for $[\text{Fe}/\text{H}]$ is the one derived from the Fe I lines, since we imposed the ionization balance and because they outnumber Fe II lines. The atmospheric parameters T_{eff} , $\log g$ and V_t are listed in Table 1.

The abundances of different elements were derived in the LTE approximation using atmosphere models interpolated for the specific atmospheric parameters of each individual star within the grid of models by Castelli & Kurucz (2004). We discarded strong lines (with EWs $> 150 \text{ mÅ}$) due to noticeable damping effects. The list of the lines measured is given in Lemasle et al. (2015). The oscillator

¹See this link for more details

Table 2. Spatial distribution of the Cepheids. The table lists the Galactic coordinates, the heliocentric distance, the pulsation period and pulsation mode, the azimuthal angle ϕ , and the Galactocentric distance R_G . The metallicity [Fe/H] is recalled in the last column. (Only the first 10 lines of the table are shown. The full table is available in electronic form).

Star	l (deg)	b (deg)	Distance (pc)	Period, pulsation mode (day)	ϕ (deg)	R_G (kpc)	[Fe/H] dex
RW CMa	232.04	−3.81	3051	5.7297117 F	−13.47	10.31	0.05
V384 CMa	230.28	−5.38	4679	4.2059423 F	−17.85	11.69	0.02
CC Car	289.37	−1.59	4515	4.7598281 F	−32.62	7.90	0.18
CR Car	285.66	−0.37	4740	9.7588957 F	−33.60	8.25	0.14
CT Car	287.63	−2.77	10 083	18.0608858 F	−62.02	10.87	0.07
FN Car	289.60	−0.12	3811	4.5856135 F	−27.59	7.75	0.13
FQ Car	290.91	−0.35	4261	10.2739900 F	−30.98	7.73	0.17
FZ Car	288.39	0.31	3962	3.5780713 IO	−28.58	7.86	0.13
GI Car	290.26	2.54	1912	4.4307267 IO	−13.46	7.70	0.03
V690 Car	280.59	−3.31	3368	4.1505759 F	−23.69	8.22	0.20
...	...	...	...	...	...	...	...

strengths, log gf, are adopted from the Vienna Atomic Line Database (Kupka et al. 1999, version 2018). The solar abundances are taken from Asplund et al. (2009). Abundances from C to Mn are listed in Table 3 and abundances from Fe to Gd are listed in Table 4.

To estimate the error budget on the abundances derived, we proceeded as follows:

We computed the abundances with deliberately over- or underestimated values for a given atmospheric parameter and computed the total uncertainty as the sum in quadrature of the uncertainties relative to a single parameter. Such a procedure overestimates the uncertainties in the final abundances due to uncertainties in the atmospheric parameters, as the latter are correlated. We repeated the exercise for two representative Cepheids and the uncertainties on the abundances are reported in Table 5.

3 THE GALACTIC RADIAL ABUNDANCE GRADIENTS

In this section, we study the radial abundance gradient for different groups of elements. As is customary for gradient studies, we display our measurements in the [Fe/H] versus Galactocentric distance (R_G) plane. The possible azimuthal dependence of the gradients are discussed in the next section. We complement our new chemical abundances (105 Cepheids) by literature values compiled by Luck (2018), who conducted a similar spectroscopic analysis.

3.1 Distances

For our new sample, as well as for the Cepheids from the literature, we have computed the Galactocentric distances by adopting a distance to the Galactic centre of $R_{G,\odot} = 8.15$ kpc (Gravity Collaboration 2019; Reid et al. 2019) and heliocentric distances to Cepheids from Skowron et al. (2019). Skowron et al. (2019) used mid-infrared Spitzer (Churchwell et al. 2009) and WISE (Mainzer et al. 2011) photometry together with the mid-infrared period–luminosity relations derived by Wang et al. (2018) and the extinction maps of Bovy et al. (2016).

Our sample includes ~ 10 Cepheids with $R_G \lesssim 6$ kpc (25 with $R_G < 7$ kpc), improving the sampling of the inner Galactic region. It also includes 14 Cepheids with $R_G > 11$ kpc. Such stars are important as the outer disc remains poorly sampled compared to the Solar neighbourhood. Moreover, these new distant Cepheids are mostly

located in the fourth Galactic quadrant (see Fig. 1), which has been only partially explored from the Cepheids point of view. The relevant information regarding the spatial location of the Cepheids is gathered in Table 2.

3.2 Radial abundance gradients

The radial iron gradient is shown in Fig. 2. Our new measurements overlap perfectly previous results in the [7–10] kpc range. They confirm a steeper slope in the inner disc as already proposed by Andrievsky et al. (2002b) and Pedicelli et al. (2010). [Fe/H] caps at $\approx +0.4 \pm 0.5$ dex, and there are hints that there is a plateau around those values towards the inner disc, as already suggested by Martin et al. (2015); Inno et al. (2019). The few Cepheids known to be located in the vicinity of the Galactic centre have been spectroscopically analysed by Kovtyukh et al. (2019).

Since oxygen is predominantly released in type II supernovae (SNe II), it is important to trace the radial abundance gradient of oxygen in order to investigate the impact of the spiral arms on the Galactic chemical enrichment. Indeed, the progenitors of SNe II are young massive stars, and most of them explode before having left the spiral arm in which they are born (Acharova, Lépine & Mishurov 2005). However, oxygen is difficult to measure in Cepheids because the few oxygen lines available in Cepheids’ atmospheres are blended or strongly affected by NLTE effects (Korotin et al. 2014; Vasilyev et al. 2019). The oxygen radial gradient, displayed in Fig. 3, nevertheless follows the iron gradient, albeit with a much larger scatter.

The same holds for the α -elements gradients, for which we show the radial distribution of the average abundances of the elements Si, Mg, and Ca (with equal weights) in Fig. 4. As expected, the oxygen and α -element radial abundance gradients are within the errors quite similar. Similarly to oxygen, sulphur abundances show a large scatter at a given R_G due to the small number (and weakness) of S lines available in the spectral range covered by our spectra.

It is no surprise that iron-peak elements follow the radial distribution of [Fe/H], as exemplified by the [Ni/H] gradient shown in Fig. 5

The large scatter in the distribution of neutron-capture elements as a function of R_G prevents us from drawing a stronger conclusion than an overall decrease from the inner to the outer disc, as already found by e.g. Lemasle et al. (2013); da Silva et al. (2016). We note that

Table 3. Abundances of Cepheids (C – Mn). (Only the first 10 lines of the table are shown. The full table is available in electronic form).

	C	N	O	Na	Mg	Al	Si	S	Ca	Sc	Ti	V	Cr	Mn
RW CMa	−0.46	0.46	−0.04	0.31	0.02	0.19	0.11	0.09	0.03	0.09	0.09	−0.12	−0.04	−0.17
V384 CMa	−0.51	0.46	−0.28	0.12	–	0.06	−0.02	−0.02	−0.05	0.07	−0.01	−0.22	−0.10	−0.29
CC Car	−0.17	0.47	−0.11	0.30	0.02	0.33	0.22	0.36	0.14	–	0.08	−0.10	0.00	−0.07
CR Car	−0.31	0.46	0.12	0.26	−0.14	0.19	0.19	0.13	0.15	0.22	0.18	0.03	−0.01	−0.11
CT Car	−0.32	0.40	−0.01	0.25	0.10	0.15	0.15	0.13	−0.07	–	−0.07	−0.09	−0.10	−0.11
FN Car	−0.33	0.37	0.09	0.31	0.07	0.22	0.20	0.18	0.15	0.07	0.13	−0.08	−0.03	−0.08
FQ Car	−0.18	0.53	0.15	0.39	0.07	0.27	0.26	0.32	0.08	–	0.09	−0.03	0.03	−0.03
FZ Car	−0.21	0.51	−0.11	0.29	0.09	0.21	0.18	0.23	0.14	0.17	0.15	−0.13	0.00	−0.09
GI Car	−0.33	0.34	−0.14	0.18	−0.01	0.13	0.12	0.30	0.06	0.28	0.10	−0.02	−0.09	−0.21
V690 Car	−0.18	0.46	0.13	0.38	0.12	0.32	0.23	0.26	0.11	0.23	0.10	−0.07	0.01	−0.09
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

Table 4. Abundances of Cepheids (Fe – Gd). (Only the first 10 lines of the table are shown. The full table is available in electronic form).

Star	Fe	Co	Ni	Y	Zr	La	Ce	Pr	Nd	Sm	Eu	Gd
RW CMa	0.05	0.10	−0.09	0.07	−0.09	0.03	0.05	−0.15	−0.03	−0.13	0.03	–
V384 CMa	−0.01	−0.14	−0.16	0.08	−0.07	0.05	0.07	−0.19	0.12	0.00	0.03	–
CC Car	0.18	−0.11	0.00	0.22	0.17	0.10	0.02	−0.18	0.02	0.00	0.18	–
CR Car	0.14	0.08	0.01	0.17	0.22	0.13	0.09	−0.06	0.07	−0.02	0.16	0.15
CT Car	0.07	−0.14	−0.09	0.20	−0.08	0.28	0.00	0.01	0.09	−0.02	0.11	−0.15
FN Car	0.13	−0.08	−0.01	0.16	0.17	0.08	0.05	−0.13	0.06	−0.06	0.11	–
FQ Car	0.17	−0.02	0.04	0.20	0.03	0.22	0.10	−0.05	0.15	0.13	0.25	–
FZ Car	0.13	0.02	−0.01	0.28	−0.05	0.14	0.01	−0.16	0.07	0.05	0.16	–
GI Car	0.03	−0.06	−0.12	0.25	0.14	0.14	0.08	−0.20	0.06	0.02	0.16	–
V690 Car	0.20	−0.08	−0.02	0.28	−0.04	0.21	0.11	−0.05	0.15	0.05	0.27	–
...	...	...	...	...	...	...	...	...	...	...	...	...

the only two europium lines in the optical spectra of Cepheids are usually weak, and they are affected by hyperfine structure splitting (hfs). However hfs corrections were found to be negligible by da Silva et al. (2016) and therefore cannot account for the observed scatter. The same authors also reported negligible corrections for the three Y lines for which hfs data were available from McWilliam, Wallerstein & Mottini (2013). The [Y/H] radial gradient is shown in Fig. 6. Similarly, the laboratory transition probabilities provided by Den Hartog et al. (2003) indicate no evident HFS structure for Nd II. Fig. 7 displays the [Nd/H] radial gradient.

3.3 The azimuthal abundance gradient

Fig. 8 illustrates the azimuthal variations in the abundance ratios at different Galactocentric distances. The azimuth, ϕ , is defined as the angle between the Galactocentric radius containing a given Cepheid and the reference radius ($\phi=0$) containing both the Sun and the Galactic centre. ϕ increases with the Galactocentric longitude. The azimuthal variations have been smoothed using a Locally weighted scatterplot smoothing algorithm (LOWESS; Cleveland 1979) using a first-degree polynomial and a bandwidth of 0.30. This means that 30 per cent of the sample is used for each local fit, with the weight of any considered data point strongly decreasing with its distance to the point on the curve being fitted. The total number of Cepheids in each annulus, ranging from a few tens to a few hundreds, is indicated in the figure. Given the difficulties to measure oxygen (see Section 3.2), the numbers are slightly larger for [Fe/H] than for [O/H]. The azimuthal variations of [Fe/H] remain within 0.2 dex at all radii. They are larger for the inner (5–7 kpc) and outer (13–15 kpc) annuli, and minimal (≈ 0.1 dex) for the 9–11 and 11–13 kpc annuli. A similar pattern

can be observed for the azimuthal variations of [O/H], with large fluctuations (≈ 0.2 dex) in the inner and outer Galactic disc, and minimal variations (≈ 0.05 dex) within 7–9 and 9–11 kpc.

Since our azimuthal variations are measured over a single annulus encompassing a fixed range of Galactocentric distances, a given annulus might overlap more than one spiral arm. We speculate that the azimuthal inhomogeneities could occur in regions where an annulus transitions from one spiral arm to another, for instance from the Norma to the Scutum–Centaurus arm in the inner disc, or from the Local to the Sagittarius–Carina arm, when comparing to the model by Hou (2021). Under this hypothesis, the limited variations in the 9–11 kpc ring could be explained by the fact that the corresponding annulus follows the Perseus arm. If this hypothesis turns out to be correct, it could imply that the chemical composition of Cepheids remains similar within a given spiral arm, but varies when compared to Cepheids from another arm. Unfortunately, it is for now impossible to attribute with certainty a given Cepheid to a specific spiral arm.

Davies et al. (2009) and Origlia et al. (2013) already reported large-scale azimuthal variations in the inner galaxy using red supergiants (RSG) in the Scutum clusters, located at the end of the bar. Genovali et al. (2013) noted that although the age difference between both tracers is minimal (a few Myr to a few tens of Myrs), Cepheids attain supersolar iron abundances in the inner disc (0.4–0.5 dex), while the Scutum RSGs have subsolar metallicities (−0.20 to −0.3 dex), hence a difference larger than 0.5 dex. These variations are usually attributed to the Galactic bar, they were later supported by Inno et al. (2019).

A number of recent studies using IFS updated the study of azimuthal variations in the properties of nearby galaxies, which

Table 5. Uncertainties in the final abundances due to uncertainties in the atmospheric parameters. Columns 2, 3, and 4 indicate respectively how the abundances are modified (mean values) when they are computed with over- or underestimated values of $T_{\text{eff}}(\pm 100 \text{ K})$, $\log g(\pm 0.2 \text{ dex})$, or $Vt(\pm 0.3 \text{ dex})$. The sum in quadrature of the differences is adopted as the uncertainty in the abundances due to the uncertainties in the atmospheric parameters.

Ion	Error budget for BB Sgr, P=6.63308 d				Error budget for V5567 Sgr, P=9.76316			
	ΔT_{eff} ($\pm 100 \text{ K}$)	$\Delta \log g$ ($\pm 0.2 \text{ dex}$)	ΔVt ($\pm 0.3 \text{ km s}^{-1}$)	Total dex	ΔT_{eff} ($\pm 100 \text{ K}$)	$\Delta \log g$ ($\pm 0.2 \text{ dex}$)	ΔVt ($\pm 0.3 \text{ km s}^{-1}$)	Total dex
C I	-0.07	0.04	-0.01	0.08	-0.05	0.09	-0.02	0.10
N I	-0.11	0.03	-0.02	0.12	-0.09	0.12	-0.02	0.15
O I	0.03	0.08	-0.01	0.09	0.00	0.08	-0.01	0.08
Na I	0.06	-0.01	-0.03	0.07	0.05	-0.01	-0.03	0.06
Mg I	-0.07	0.01	0.08	0.11	0.04	0.00	-0.04	0.06
Al I	0.05	-0.01	-0.03	0.06	0.04	0.00	-0.02	0.04
Si I	0.05	0.00	-0.02	0.05	0.06	0.02	-0.03	0.07
S I	-0.06	0.04	-0.02	0.07	-0.03	0.08	-0.02	0.09
Ca I	0.07	-0.01	-0.03	0.08	0.06	-0.01	-0.06	0.09
Sc II	0.01	0.08	-0.04	0.09	0.03	0.09	-0.05	0.11
Ti I	0.11	0.00	-0.02	0.11	0.09	-0.02	-0.01	0.09
Ti II	0.00	0.08	-0.04	0.09	0.01	0.08	-0.04	0.09
V I	0.12	0.01	-0.01	0.12	0.10	-0.02	-0.01	0.10
V II	0.00	0.08	-0.01	0.08	0.02	0.08	-0.01	0.08
Cr I	0.07	0.00	-0.02	0.07	0.06	-0.01	-0.02	0.06
Cr II	-0.03	0.07	-0.05	0.09	0.00	0.10	-0.06	0.12
Mn I	0.07	0.00	-0.03	0.08	0.07	-0.01	-0.03	0.08
Fe I	0.08	0.00	-0.02	0.08	0.07	-0.01	-0.03	0.08
Fe II	-0.03	0.07	-0.02	0.08	0.00	0.10	-0.03	0.10
Co I	0.11	0.01	-0.01	0.11	0.08	-0.02	-0.01	0.08
Ni I	0.09	0.01	-0.02	0.09	0.08	-0.01	-0.03	0.09
Y II	0.00	0.07	-0.04	0.08	0.03	0.08	-0.04	0.09
Zr II	0.00	0.07	-0.04	0.08	0.03	0.10	-0.04	0.11
La II	0.03	0.08	-0.03	0.09	0.05	0.08	-0.02	0.10
Ce II	0.02	0.07	-0.01	0.07	0.03	0.07	-0.03	0.08
Pr II	0.03	0.08	-0.01	0.09	0.05	0.07	-0.01	0.09
Nd II	0.02	0.07	-0.02	0.08	0.05	0.08	-0.03	0.10
Sm II	0.03	0.08	-0.01	0.09	0.05	0.08	-0.01	0.09
Eu II	0.01	0.07	-0.02	0.07	0.03	0.08	-0.02	0.09
Gd II	0.02	0.08	0.00	0.08	0.03	0.07	-0.01	0.08

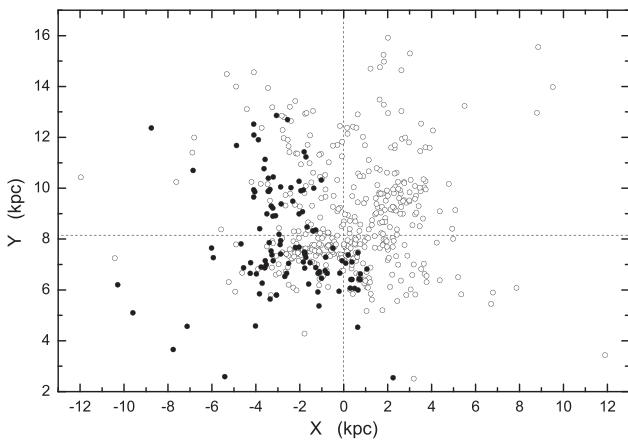


Figure 1. Locations of target Cepheids in the Galactic plane as viewed from the North Galactic Pole. The position of the Sun is at the intersection of the dashed lines. The Galactic centre is at $(X,Y) = (0,0)$. Open and filled circles are used to mark the Cepheids adopted from Luck (2018) and our new SALT observations, respectively.

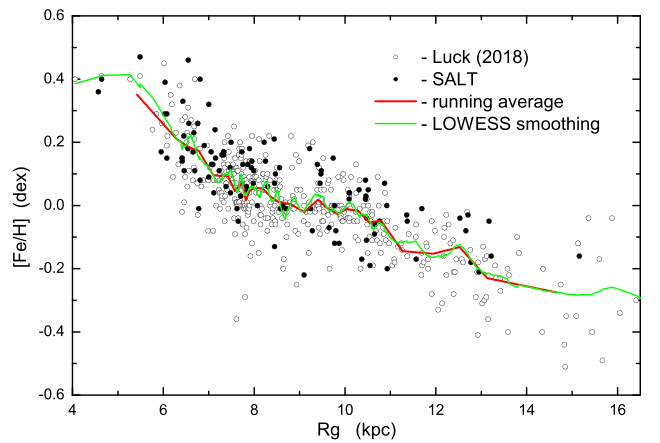


Figure 2. The radial distribution of the iron abundance. The filled circles indicate the Cepheids reported in this paper. The Cepheid variables from Luck (2018) are marked with open circles, their Galactocentric distances were recomputed for $R_{G,\odot} = 8.15 \text{ kpc}$. The solid red line represents a running average while the green line results from a LOWESS smoothing (the degree of polynomial = 2; bandwidth = 0.07).

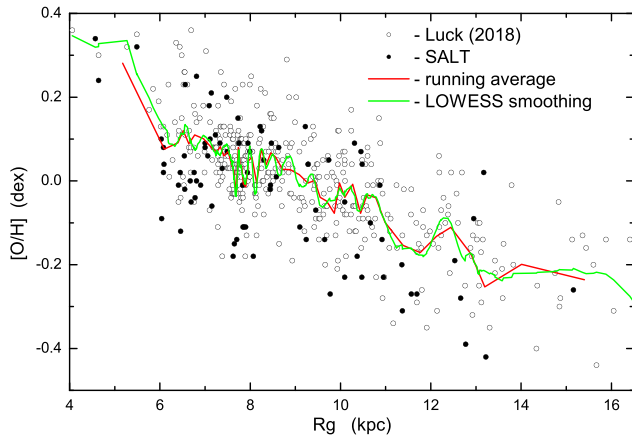


Figure 3. The same as in Fig. 2 but for [O/H].

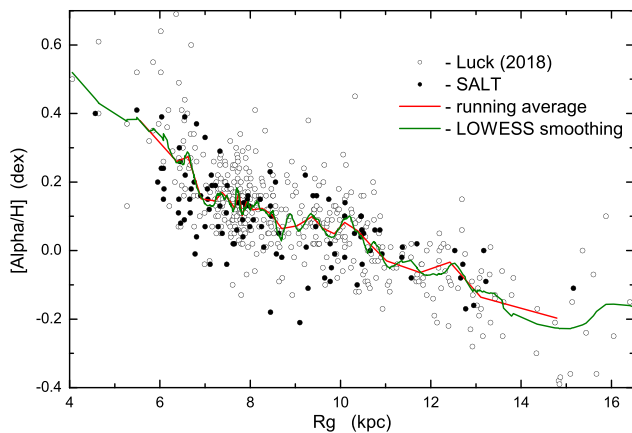


Figure 4. The same as in Fig. 2 but for α -elements (that is, the average abundances of Si + Mg + Ca) in Cepheids, normalized to the solar value.

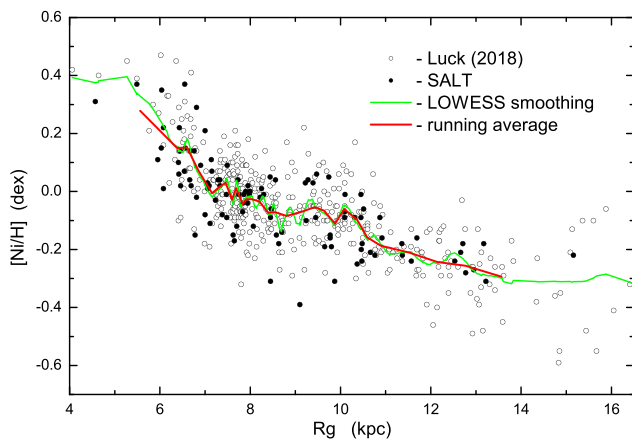


Figure 5. The same as in Fig. 2 but for [Ni/H].

was previously achieved via long-slit spectroscopy: Li et al. (2013) detected azimuthal variations in the oxygen abundance in the spiral galaxy M 101 (NGC 5457). Both Sánchez et al. (2015) and Sánchez-Menguiano et al. (2016) reported azimuthal variations in [O/H] in NGC 6754. They found larger inhomogeneities in the outer regions of this galaxy. Ho et al. (2017) found azimuthal variations (with respect

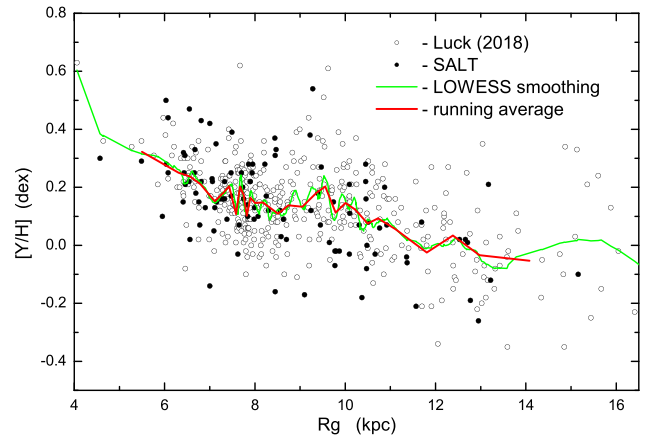


Figure 6. The same as in Fig. 2 but for [Y/H].

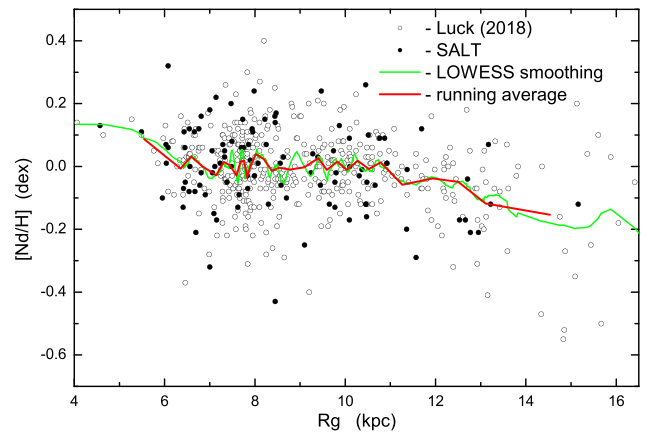


Figure 7. The same as in Fig. 2 but for [Nd/H].

to the oxygen radial gradient) of the order of ≈ 0.2 dex associated with the two spiral arms of NGC 1365 and Ho et al. (2018) reported similar variations of 0.06 dex in NGC 2997.

It is expected that the spiral arm structure plays an important role in homogenizing the interstellar medium (ISM; e.g. Kreckel et al. 2019). Ho et al. (2017) suggested that chemical enrichment takes place in tiny gas pockets in the interarm region, and that the ISM gets homogenized when crossing the spiral arm. In their analysis of the galaxy HCG 91c, Vogt et al. (2017) found both localized variations associated with individual H II regions, and extended structures at the boundaries of the spiral arms. They concluded that the enrichment of the ISM preferentially takes place along the spiral structure rather than in the interarm regions.

It should be noted that galaxies with large azimuthal variations represent a very small sample with respect to the overall population (e.g. Sánchez-Menguiano et al. 2018), and the inhomogeneities detected are usually of small amplitude. For instance, Zinchenko et al. (2016) reported typical asymmetries < 0.05 dex in 88 galaxies of the Calar Alto Legacy Integral Field Area survey Data Release 2. This raises the question of the origin of the larger ones and might indicate that they are related to localized events rather than to the secular evolution of the galaxy considered.

Spitoni et al. (2019) presented a 2D chemical evolution model of the Milky Way that is capable of tracing azimuthal variations of chemical abundances in the Galactic disc. Density fluctuations

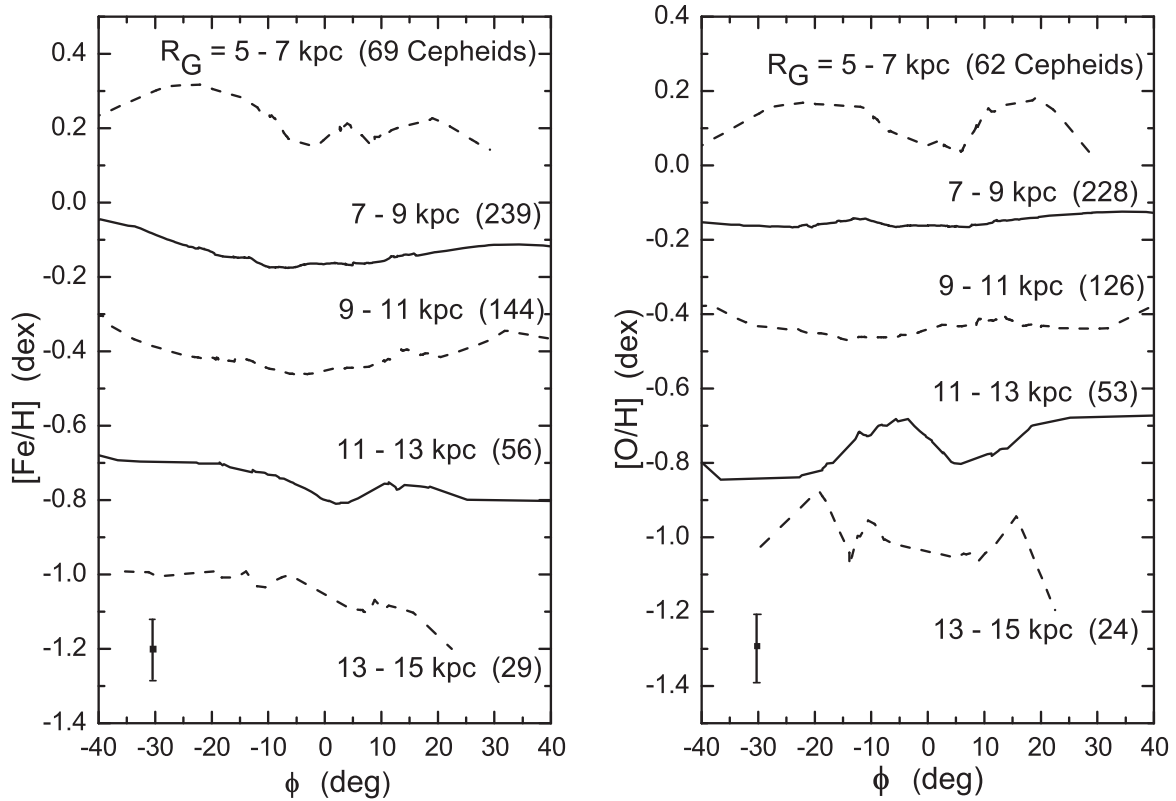


Figure 8. LOWESS smoothing of $[\text{Fe}/\text{H}]$ and $[\text{O}/\text{H}]$ for the azimuthal coordinate ϕ at different R_G . The $[\text{E}/\text{H}]$ ratios have been arbitrarily shifted for the sake of clarity. The total number of Cepheids in each annulus is indicated. Representative uncertainties on the *individual* Cepheids abundances are shown at the bottom left of each panel.

produce significant azimuthal variations in $[\text{O}/\text{H}]$, of the order of 0.1 dex around the mean. Such variations are more obvious in the outer disc. Our results support qualitatively the findings of Spitoni et al. (2019). Similar conclusions were reached by Spitoni et al. (2019) when comparing the outcome of their models to the Cepheids data of Genovali et al. (2014). Our results are also in agreement with the model predictions by Mollá et al. (2019). However, the variations in $[\text{O}/\text{H}]$ are slightly larger in our observational data than in the Spitoni et al. (2019), and especially, the Mollá et al. (2019) model, which we attribute to the (significant) uncertainties in the $[\text{O}/\text{H}]$ abundances of Cepheids. Using a simple analytical spiral arm model, Mollá et al. (2019) mention that the azimuthal variations in their models are smaller than the typical uncertainties associated with oxygen abundance tracers, and that they reach detectable values ≈ 0.1 dex, (peak to peak) only in the outer regions of the disc. Spitoni et al. (2019) specify that the largest fluctuations in azimuthal abundance gradients occur near the corotation radius of the spiral pattern, where chemical enrichment becomes more efficient because of the absence of relative motion between the gas and the spiral arm. Solar, Tissera & Hernandez-Jimenez (2020) analysed oxygen gradients in 106 resolved spiral galaxies selected from the high-resolution Evolution and Assembly of GaLaxies and their Environments simulations (Schaye et al. 2015). In this sample, they found a large scatter for the $[\text{O}/\text{H}]$ gradient measured at a random azimuthal direction when compared to its global average over the disc, which they interpret as an evidence significant azimuthal variations.

4 CONCLUSION

We report the chemical composition (25 elements) of 105 classical Cepheids. Abundances have been derived from 122 high-resolution SALT spectra observed in the context of the MAGIC project. The Galactocentric distances of the Cepheids are taken from the literature, they are based on mid-infrared photometry. Our new sample contains 25 Cepheids with $R_G < 7$ kpc (14 with $R_G < 6.5$ kpc), and 14 Cepheids with $R_G > 11$ kpc, thus significantly improving the sampling in the inner and outer disc. Our results are in line with Cepheids literature studies concerning radial abundance gradients of iron, α , or neutron-capture elements. We focus on the azimuthal variations of the oxygen abundance $[\text{O}/\text{H}]$. Since such variations are found to be negligible (typically < 0.05 dex) in external spirals, the Milky Way seems to be one of the few galaxies with noticeable $[\text{O}/\text{H}]$ azimuthal inhomogeneities. We find that they are the largest in the inner Galaxy, where they are usually attributed to perturbations induced by the rotating bar, and in the outer disc. In these outer regions, our results support similar results obtained in a few nearby spiral galaxies, as well as the outcome of chemo-dynamical evolution models by e.g. Spitoni et al. (2019) and Mollá et al. (2019).

SUPPORTING INFORMATION

Supplementary data are available at [MNRAS](https://academic.oup.com/mnras/article/510/2/1894/6449376) online.

Table S1. Spectra of the examined Cepheids.

Table S2. Atmospheric parameters of Cepheids.

Table S3. Abundance of Cepheids (C – Mn).

Table S4. Abundance of Cepheids (Fe – Gd).

Please note: Oxford University Press is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

ACKNOWLEDGEMENTS

The authors thank the anonymous referee for her/his careful reading of the paper and for her/his comments, which improved the clarity of our manuscript. This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Project-ID 138713538 – SFB 881 (‘The Milky Way System’, subproject A05). AK acknowledges the National Research Foundation of South Africa. Based on observations obtained with the SALT, programme 2016-1-MLT-002 (PI: Kniazev). Tables 1–4 are only available in electronic form at the CDS via the anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via [http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/MNRAS/\(vol\)/\(page\)](http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/MNRAS/(vol)/(page)).

5 DATA AVAILABILITY

The SALT data are available in the SALT Archive at <https://astronomers.salt.ac.za> after the proprietary period.

REFERENCES

- Acharova I. A., Lépine J. R. D., Mishurov Yu. N., 2005, *MNRAS*, 359, 819
 Andrievsky S. M. et al., 2002a, *A&A*, 381, 32
 Andrievsky S. M., Bersier D., Kovtyukh V. V., Luck R. E., Maciel W. J., Lépine J. R. D., Beletsky Y. V., 2002b, *A&A*, 384, 140
 Asplund M., Grevesse N., Sauval A. J., Scott P., 2009, *ARA&A*, 47, 481
 Balser D. S., Rood R. T., Bania T. M., Anderson L. D., 2011, *ApJ*, 738, 27
 Balser D. S., Wenger T. V., Anderson L. D., Bania T. M., 2015, *ApJ*, 806, 199
 Bovy J., Rix H.-W., Green G. M., Schlafly E. F., Finkbeiner D. P., 2016, *ApJ*, 818, 130
 Buckley D. A. H., Swart G. P., Meiring J. G., 2006, *SPIE*, 6267
 Castelli F., Kurucz R. L., 2004, preprint ([arXiv:astro-ph/0405087](https://arxiv.org/abs/astro-ph/0405087))
 Cescutti G., Matteucci F., François P., Chiappini C., 2007, *A&A*, 462, 943
 Churchwell E. et al., 2009, *PASP*, 121, 213
 Cleveland W., 1979, *J. Am. Stat. Assoc.*, 74, 829
 Crawford S. M. et al., 2010, *SPIE*, 7737, 773725
 da Silva R. et al., 2016, *A&A*, 586, A125
 Davies B., Origlia L., Kudritzki R.-P., Figuer D. F., Rich R. M., Najarro F., Negueruela I., Clark J. S., 2009, *ApJ*, 696, 2014
 Den Hartog E. A., Lawler J. E., Sneden C., Cowan J. J., 2003, *ApJS*, 148, 543
 Donor J., Frinchaboy P. M., Cunha K., 2020, *AJ*, 159, 199
 Gaia Collaboration, 2018, *A&A*, 616, A1
 Genovali K. et al., 2013, *A&A*, 554, A132
 Genovali K. et al., 2014, *A&A*, 566A, 37G
 Gravity Collaboration, 2019, *A&A*, 625, L10
 Ho I.-T. et al., 2017, *ApJ*, 846, 39
 Ho I.-T. et al., 2018, *A&A*, 618, A64
 Hou L. G., 2021, *Frontiers Astron. Space Sci.*, 8, 103
 Inno L. et al., 2019, *MNRAS*, 482, 83
 Kniazev A. Yu., Usenko I. A., Kovtyukh V. V., Berdnikov L. N., 2019, *Astrophys. Bull.*, 74, 208
 Kniazev A., Gvaramadze V., Berdnikov L., 2016, *MNRAS*, 459, 3068
 Korotin S. A., Andrievsky S. M., Luck R. E., Lépine J. R. D., Maciel W. J., Kovtyukh V. V., 2014, *MNRAS*, 444, 3301
 Kovtyukh V. V., 2007, *MNRAS*, 378, 617
 Kovtyukh V. V., Wallerstein G., Andrievsky S. M., 2005, *PASP*, 117, 1173
 Kovtyukh V. et al., 2016, *MNRAS*, 460, 2077
 Kovtyukh V. V., Andrievsky S. M., Martin R. P., Korotin S. A., Lépine J. R. D., Maciel W. J., Keir L. E., Panko E. A., 2019, *MNRAS*, 489, 2254
 Kreckel K. et al., 2019, *ApJ*, 887, 80
 Kubryk M., Prantzos N., Athanassoula E., 2015, *A&A*, 580, A127
 Kupka F., Piskunov N. E., Ryabchikova T. A., Stempels H. C., Weiss W. W., 1999, *A&AS*, 138, 119
 Lemasle B., François P., Bono G., Mottini M., Primas F., Romaniello M., 2007, *A&A*, 467, 283
 Lemasle B., François P., Piersimoni A., Pedicelli S., Bono G., Laney C. D., Primas F., Romaniello M., 2008, *A&A*, 490, 613
 Lemasle B. et al., 2013, *A&A*, 558, 31
 Lemasle B. et al., 2015, *A&A*, 579, A47
 Li Y., Bresolin F., Kennicutt R. C. Jr, 2013, *ApJ*, 766, 17
 Li C. et al., 2015, *ApJ*, 804, 125
 Luck R. E., 2018, *AJ*, 156, 171
 Luck R. E., Gieren W. P., Andrievsky S. M., Kovtyukh V. V., Fouqué P., Pont F., Kienzie F., 2003, *A&A*, 401, 939
 Luck R. E., Kovtyukh V. V., Andrievsky S. M., 2006, *AJ*, 132, 902
 Magrini L. et al., 2017, *A&A*, 603, A2
 Mainzer A. et al., 2011, *ApJ*, 731, 53
 Martin R. P., Andrievsky S. M., Kovtyukh V. V., Korotin S. A., Yegorova I. A., Saviane I., 2015, *MNRAS*, 449, 4071
 Matteucci F., François P., 1989, *MNRAS*, 239, 885
 McWilliam A., Wallerstein G., Mottini M., 2013, *ApJ*, 778, 149
 Minchev I., Chiappini C., Martig M., 2014, *A&A*, 572, A92
 Mollá M. et al., 2019, *MNRAS*, 490, 665
 O’Donoghue D. et al., 2006, *MNRAS*, 372, 151
 Origlia L. et al., 2013, *A&A*, 560, A46
 Pedicelli S. et al., 2010, *A&A*, 518, A11
 Proxauf B. et al., 2018, *A&A*, 616, A82
 Reid M. J. et al., 2019, *ApJ*, 885, 131
 Sánchez S. F., 2020, *ARA&A*, 58, 99
 Sánchez S. F. et al., 2015, *A&A*, 573, A105
 Sánchez-Menguiano L. et al., 2016, *ApJ*, 830, L40
 Sánchez-Menguiano L. et al., 2018, *A&A*, 609, A119
 Schaye J. et al., 2015, *MNRAS*, 446, 521
 Skowron D. M. et al., 2019, *AcA*, 69, 305
 Solar M., Tissera P. B., Hernandez-Jimenez J. A., 2020, *MNRAS*, 491, 4894
 Spitoni E., Matteucci F., 2011, *A&A*, 531, A72
 Spitoni E., Cescutti G., Minchev I., Matteucci F., Silva Aguirre V., Martig M., Bono G., Chiappini C., 2019, *A&A*, 628A, 38
 Twarog B. A., Ashman K. M., Anthony-Twarog B. J., 1997, *AJ*, 114, 2556
 Vasilyev V., Amarsi A. M., Ludwig H.-G., Lemasle B., 2019, *A&A*, 624, A85
 Vogt F. P. A., Pérez E., Dopita M. A., Verdes-Montenegro L., Borthakur S., 2017, *A&A*, 601, A61
 Wang S., Chen X., de Grijs R., Deng L., 2018, *ApJ*, 852, 78
 Wenger T. V., Balser D. S., Anderson L. D., Bania T. M., 2019, *ApJ*, 887, 114
 Zinchenko I. A., Pilyugin L. S., Grebel E. K., Sánchez S. F., Vílchez J. M., 2016, *MNRAS*, 462, 2715

This paper has been typeset from a $\text{\LaTeX}$ file prepared by the author.