Chemical Composition of Cepheids in the Milky Way and in the Magellanic Clouds

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Cepheids are excellent tracers of young stellar populations. Here we present some assets of Cepheids and describe the specifics of their chemical analysis, before presenting several recent results obtained for Cepheids in the Milky Way disk and in the Magellanic Clouds.

1 Context and Methods

Abundance gradients provide sound constraints for the chemo-dynamical evolutionary models of the Milky Way, in particular to quantify the radial flows of gas and the radial migration of stars. Historical tracers (HII regions, B stars, Cepheids, open clusters, planetary nebulae) have been favoured for a long time, because they are bright and/or because their ages and distances could be derived with good/excellent accuracy. The availability of *Gaia*-based distances, asteroseismology, and survey-dedicated instruments, will clear the way for Red Giant Branch (RGB) stars (e.g., Anders et al., 2017), but the historical tracers remain useful because they adequately complete the age range, especially towards very young ages.

When studying chemical abundance gradients, two quantities must be determined with the best achievable accuracy: the (detailed) chemical composition of the tracer and its Galactocentric distance. In this perspective, Cepheids are excellent targets as their spectra contain a large number of well-defined absorption lines that allow us to derive reliable abundances for many α, iron-peak, and neutron-capture elements. Moreover, Cepheids are famous for being excellent cosmological distances indicators via their period-luminosity relations. This is an indisputable advantage as their distance can be obtained with a great accuracy, mostly limited by uncertainties on the determination of the extinction.

Cepheids have several other assets: they are very luminous, and therefore, allow us to probe the thin disk over large distances. Only in the inner disk, where extinction becomes too severe, is it required to trade spectroscopy in the optical bands for near-infrared studies (see Sect. 2). Moreover, classical Cepheids are in a homogeneous evolutionary stage (core helium burning) and their individual ages can be computed via period-age relations. Whether period-age relations, including rotation or not, are adopted, ages of Cepheids vary from $\sim 10 - \sim 300$ Myr (Bono et al., 2005, no rotation) to $\sim 15 - \sim 500$ Myr (Anderson et al., 2016, average rotation). At such ages, Cepheids only trace the present-day abundance gradients, and are the perfect complement for large-scale surveys that mostly target RGB/red clump stars.

Because they are pulsating stars, the spectroscopic analysis of Cepheids is more complicated than in the case of non-variable stars. In particular, no simultaneous photometry is available in general, and the temperature must be derived from the spectrum only, using the line depths ratios method: T_{eff} is obtained using relations for depth ratios of carefully selected pairs of lines calibrated by Kovtyukh & Gorlova (2000, 32 relations) and Kovtyukh (2007, 131 relations). This method has the advantage to be independent of the interstellar reddening. Once T_{eff} has been calculated, a canonical spectroscopic analysis can be conducted. Because some usual absorption lines are too wide in cool supergiants, and because the pulsations lead to an excursion up to ~ 1000 K in T_{eff} (and up to ~ 0.9 dex in $\log g$) over the period, great care must be taken when selecting the linelist (e.g., Lemasle et al., 2013).

No atmosphere models are available for pulsating stars, and the current use of hydrostatic models for variable stars can be questioned. In the case of Cepheids embedded in stellar clusters, several authors report similar chemical compositions for the Cepheids and main sequence (Fry & Carney, 1997) or RGB (Lemasle et al., 2017) cluster members. In a series of papers, (Luck & Andrievsky, 2004; Kovtyukh et al., 2005; Andrievsky et al., 2005; Luck et al., 2008), the chemical composition has been found to be consistent over the pulsation cycle despite the variation of the atmospheric parameters. However, the recent theoretical studies of Vasilyev et al. (2017a,b) indicate that convective inhomogeneities may bias current results and that phases $\phi_{\mathrm{ph}} \approx 0.3 \ldots 0.65$ are preferred to minimize this bias (see also Vasilyev et al. 2018, these Proceedings).

2 Cepheid Abundances in the Inner Disk of the Milky Way

The early papers by Harris (1981) and Harris & Pilachowski (1984) already reported a value of -0.07 dex/kpc for the [Fe/H] gradient across the disk, close to the current value of -0.06 dex/kpc. With time, studies have extended towards the inner and outer disk and now include light, α, iron-peak, and neutron-capture elements (e.g., Andrievsky et al., 2004; Lemasle et al., 2007, 2008; Luck et al., 2011; Luck & Lambert, 2011; Genovali et al., 2015; da Silva et al., 2016).

Cepheid metallicities reach $+0.4, +0.5$ dex in the inner disk (Andrievsky et al., 2002; Pedicelli et al., 2010; Genovali et al., 2013). Comparing these high values to the solar or even sub-solar metallicities of young clusters of similar ages located at the edge of the bar or in the nuclear bulge (see Fig. 1) indicates that a mechanism where the bar drags gas from the inner thin disk into the nuclear bulge is too simple, and that some dilution with more metal-poor gas is required (Genovali et al., 2014).

The possible steepening of the gradient in the inner disk (Andrievsky et al., 2002; Genovali et al., 2014) remains an open question as it is not seen in very young clusters (e.g., Spina et al., 2017). From Cepheids, it seems in addition that after reaching a plateau at $\approx +0.4, +0.5$ dex, metallicity flattens or even decreases again towards the bulge (Martin et al., 2015; Andrievsky et al., 2016), possibly because a drop in the gas density would reflect in the star formation rate and hence in chemical enrichment. The quoted investigations on the inner disk rely only on a few stars (9 Cepheids inside the first 6 kpc from the Galactic center). A larger, un-biased sample of Cepheids is required to obtain more stringent conclusions and will require the analysis of NIR spectra of Cepheids (Inno et al., in prep.).

3 First Metallicity Estimate for a Star Located in the Far Side of the Disk

Kovtyukh et al. (2016) have studied the chemical composition of the almost complete (18 out of 24) sample of Galactic double-mode Cepheids (Cepheids that pulsate in two modes simultaneously). Taking advantage of the metallicity dependence of their period ratio P_1/P_0, a linear relation between [Fe/H] and P_1/P_0 was calibrated, allowing us, for instance, to determine the metallicity distribution function of the double-mode Cepheids in the Magellanic Clouds. This also provided the opportunity to estimate the metallicity of two double-mode Cepheids discovered by OGLE (Soszyński et al., 2011) towards the Galactic bulge. It turned out that one of them was identified by Feast et al. (2014) as a Cepheid located at a large Galactocentric distance in the far side of the disk. The star is located high above the Galactic plane, which Feast et al. (2014) attribute to a flared outer disk. This is the first metallicity estimate for a star located in the far side of the disk.

4 Cepheid Abundances in the Magellanic Clouds

4.1 Cepheids in the LMC populous cluster NGC 1866

NGC 1866 is a young ($\approx 100 - 200$ Myr) massive cluster in the outskirts of the LMC that harbors a large number (23) of Cepheids (Welch & Stetson, 1993). In Lemasle et al. (2017) we analyzed the chemical composition of six Cepheids in NGC 1866. We found a very homogeneous chemical composition among the Cepheids, as the dispersion remains below 0.1 dex for elements for which numerous lines could be measured, and below 0.2 dex otherwise. Our results are also very consistent with abundances in RGB stars (Mucciarelli et al. (2011): 14 stars, Colucci & Bernstein (2012): 3 stars). This very small internal scatter not only confirms that all the Cepheids in our sample are indeed cluster members, but it also indicates that there is no abundance spread (at least for the elements considered) within NGC 1866.

Ages can be computed for individual Cepheids using period-age relations that are derived from pulsation models. We computed ages for the 23 Cepheids in NGC 1866 both with the period-age relation of Bono et al. (2005) (no rotation) and with the relations of Anderson et al. (2016) computed with models that include an average rotation ($\omega = 0.5\omega_c$). As stated by Anderson et al. (2016), their relations lead to ages that are 1.5−2 times older (and ranging from $\sim$ 185 to $\sim$ 250 Myr) than those derived using the Bono et al. (2005) relations, which range from $\sim$ 95 to $\sim$ 115 Myr. In both cases, the age spread is very limited, which reinforces previous studies reporting no age variation within NGC 1866, and at least, ensures that Cepheids all belong to the same sub-population. Both the lack of an abundance spread and of an age spread suggest the absence of multiple stellar populations in NGC 1866.

4.2 No evidence of a metallicity gradient in the SMC from Cepheids

Combining the metallicity of 4 Cepheids in Lemasle et al. (2017) with the results of Romaniello et al. (2008, 14 stars), we could investigate the metallicity distribution in the SMC. The Cepheids' near-infrared JHK_s magnitudes were derived using the NIR light-curve templates of Inno et al. (2015). Distances were then computed using period-Wesenheit relations calibrated on the entire SMC sample of fundamental-mode Cepheids. Wesenheit indices are reddening-free quantities by construction (Madore, 1982). We used the W_{HJK} index as defined by Inno et al. (2016) which is minimally affected by the uncertainty in the reddening law. The metallicity spread barely reaches 0.3 dex, and there is no evidence of a metallicity gradient along the main axis of the SMC, as shown in Fig. 2. Using instead the PL-relation at [3.6] μm and the mid-infrared mean-light magnitudes of Scowcroft et al. (2016) to compute distances led to the same conclusion. It should be noted, however, that our sample is very small and does not contain Cepheids in the inner few degrees of the SMC in an on-sky projection, but on the other hand, it samples adequately the SMC over $\approx$ 20 pc in the depth direction.

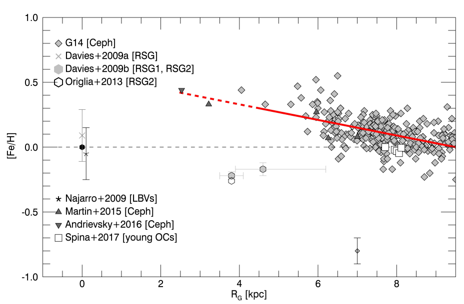

Fig. 1: Metallicities of Cepheids compared to other inner disk tracers: RSGs (Davies et al., 2009b,a; Origlia et al., 2013), LBVs (Najarro et al., 2009) or young open clusters (Spina et al., 2017).

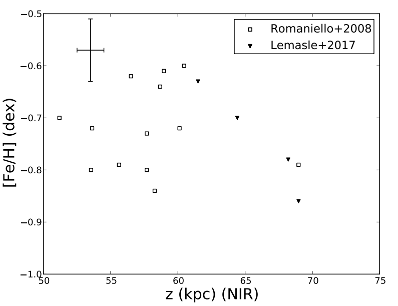

Fig. 2: SMC metallicity distribution from Cepheids in the z (depth) direction. Distances are derived from NIR photometry. Typical error bars are shown in the top left corner.

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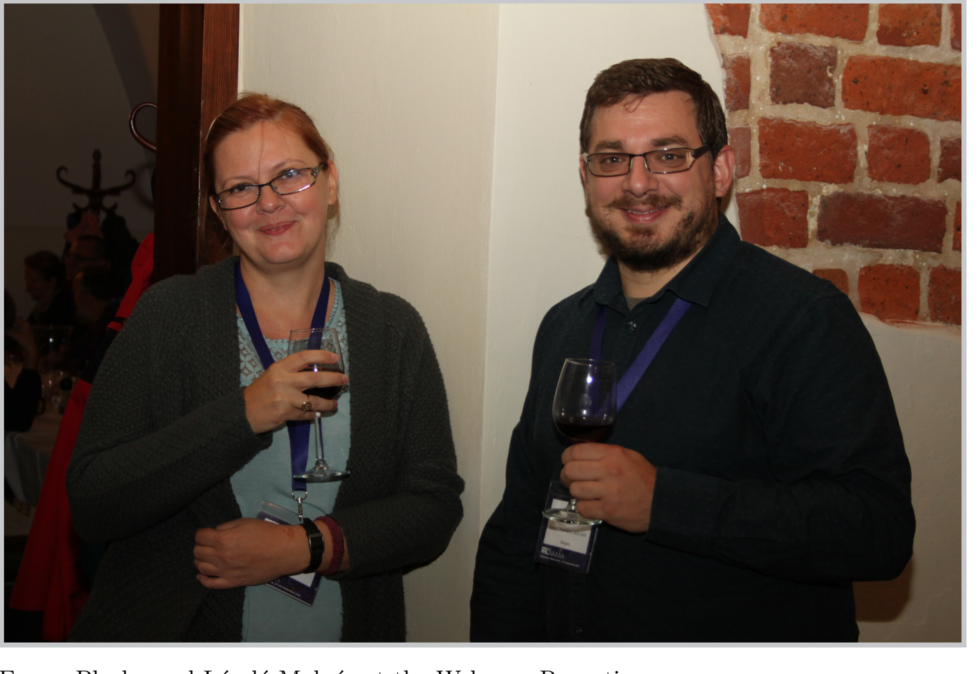

Emese Plachy and László Molnár at the Welcome Reception.