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Some conference participants during a coffee break in the Palais de la Méditerrannée.

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Variable stars in the Gaia era: Mira, RR Lyrae, δ and Type-II Cepheids

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Abstract. Classical variables like RR Lyrae, classical and Type-II Cepheids and Mira variables all follow period-luminosity relations that make them interesting as distance indicators. Especially the RR Lyrae and δ Cepheids are crucial in establishing the distance scale in the Universe, and all classes of variables can be used as tracers of galactic structure. I will present an overview of recent period-luminosity relations and review the work that has been done using the *Gaia* DR1 data so far, and discuss possibilities for the future.

Keywords. Cepheids, stars: variables: other, stars: distances, distance scale, stars: AGB and post-AGB, Magellanic Clouds

1. Introduction

Miras, RR Lyrae, classical and Type-II Cepheids belong to the oldest known variable stars, certainly in the literature of the west. The American Association of Variable Star Observers (AAVSO) website has interesting historical information about the prototypes o Ceti or Mira (discovered by Fabricius in 1596, see `www.aavso.org/vsots_mira`), RR Lyrae (discovered by Wilhelmina Fleming, and published in Pickering *et al.* 1901, see `www.aavso.org/vsots_rrlyr`), and δ Cephei (discovered by John Goodricke in 1784, see `www.aavso.org/vsots_delcep`).

Type-II Cepheids are subdivided in three classes, typically based on pulsation period: The BL Herculis variables (BLH; periods 1-4 days; discovery paper by Cuno Hoffmeister 1929), the W Virginis stars (WVir; periods 4-20 days; discovered by Eduard Schönfeld in 1866, see `www.aavso.org/vsots_wvir`), and the RV Tauri stars (RVT; periods 20-$\sim$70 days; discovered by Lidiya Tseraskaya (or Ceraski), published in Ceraski 1905, see `www.aavso.org/vsots_rvtau`).

In evolutionary terms, RR Lyrae (RRL) variables are evolved, metal poor, core He-burning stars at or slightly brighter than the zero-age horizontal branch (ZAHB). Marconi *et al.* (2015) provide recent nonlinear, time-dependent convective hydrodynamical models of RRL over a broad range in metal abundances (Z = 0.0001-0.02) and masses, ranging from 0.8 $M_{\odot}$ (for Z= 0.0001) to 0.54 $M_{\odot}$ (for Z= 0.02). They provide analytical relations for the edges of the instability strip (IS) as a function of Z. Period-radius-metallicity relations for fundamental and first-overtone pulsators are determined, as well as a large set of period-luminosity and period-Wesenheit relations.

Classical or δ Cepheids (CEPs) are evolved objects with initial masses in the range ~ 2 to ~ 15 $M_{\odot}$. Theoretical pulsation models have been calculated by Bono *et al.* (2000) and Anderson *et al.* (2014, 2016) who considered the effect of rotation on the evolution and pulsation. A Cepheid can cross the IS up to three times The, so-called, first crossing occurs when the star evolves from the main sequence to the red giant branch during a core contraction phase. This crossing is expected to be fast, and Cepheids in this phase should be rare. The majority of Cepheids are expected to be on the second and third crossings during the so-called "blue loops" experiencing core helium burning.

As mentioned above, the Type-II Cepheids (T2C) are subdivided in three classes, typically based on period, but they are thought to have different evolutionary origins. Evolutionary modelling of T2Cs has been pioneered by Gingold (1976, 1985) establishing the classical picture that T2Cs are low-mass stars, evolving from the blue HB through the IS to the asymptotic giant branch (AGB) for the short-period stars, blue loops off the AGB for the stars of intermediate period, and post-AGB (PAGB) evolution for the longest period, also see Wallerstein (2002) and Bono *et al.* (2016).

The anomalous Cepheids (ACs) are also pulsating stars which overlap in period range with RRL and the BLH stars. They form a separate PL relation clearly different from the RRL, classical Cepheids and T2Cs. They pulsate in the fundamental mode (FU) and first overtone (FO) mode (unlike T2C). Models have been calculated by Fiorentino & Monelli (2012). Their mean mass is around $1.2 \pm 0.2\ M_{\odot}$, and there is also discussion if ACs are the result of binary interaction.

Groenewegen & Jurkovic (2017a, b) recently studied the 335 T2C and ACs discovered by the OGLE-III survey in the Large and Small Magellanic Cloud. From fitting the spectral energy distribution (SED) they derived effective temperature and luminosity. In the 2017a paper the resulting Hertzsprung-Russell diagram was compared in a qualitative way to modern evolutionary tracks. In agreement with the findings cited above the BL Her can be explained by stars in the mass range $\sim 0.5 - 0.6\ M_{\odot}$ and the ACs by stars in the mass range $\sim 1.1 - 2.3\ M_{\odot}$. The origin of the (p)WVir is unclear however: tracks of $\sim 2.5 - 4\ M_{\odot}$ cross the IS at the correct luminosity, as well as (some) lower mass stars on the AGB that undergo a thermal pulse when the envelope mass is small, but the timescales make these unlikely scenarios to explain this class of objects as a whole. The peculiar W Vir have been suggested to be binaries, and in general, some of the phenomenon observed in T2C and ACs may well be linked to so called binary evolutionary pulsators (BEP; Karczmarek *et al.* 2016).

In the 2017b paper, pulsation models for RRL (Marconi *et al.* 2015) and Cepheids (Bono *et al.* 2000) were used to estimate the pulsation mass for all objects. Both estimates agreed best for the BLH ($M \sim 0.49\ M_{\odot}$) and the ACs ($M \sim 1.3\ M_{\odot}$). The masses of the W Vir appeared similar to the BL Her. The situation for the pWVir and RVT stars was less clear. For many RV Tau the masses are in conflict with the standard picture of (single-star) post-AGB evolution, the masses being either too large ($\gtrsim 1\ M_{\odot}$) or too small ($\lesssim 0.4\ M_{\odot}$).

Groenewegen & Jurkovic (2017a) found that $\sim 60\%$ of the RVT showed an infrared excess in their SEDs, not unsurprising if RVT have indeed evolved of the AGB. Surprisingly however, $\sim 10\%$ of the W Vir (including the pWVir) objects also showed an infrared excess, confirming the result of Kamath *et al.* (2016) that there exist stars with luminosities below that predicted from single-star evolution that show a clear infrared excess, and which they called dusty post-red giant branch stars, and suggested to have evolved off the RGB as a result of binary interaction.

AGB and super-AGB stars are intermediate mass stars (initial mass $\sim$0.8-12 $M_{\odot}$) in the last phase of active nuclear burning, that undergo double-shell burning, experience thermal pulses (or Helium shell flashes) that change the composition of the envelope, making it increasingly rich in carbon, so that S-stars (C/O ratio close to one, and that show increased abundances of s-process elements), and C-stars (Carbon stars with C/O>1) can form. They are cool giants, where dust can form close to the star that is driven outward in a slow stellar wind.

(S)AGB stars also pulsate, classically divided into irregular (Lb), semi-regular (SR) and Mira (M) variables. The SR and M are sometimes also called long-period variables (LPVs), as they are not so different. Miras are not necessarily less regular than the SR, and the definition that Miras should have an pulsation amplitude in the visual band larger than 2.5 magnitudes is arbitrary.

That Miras follow a PL relation is well known (Glass & Lloyd Evans 1981), and it should be noted that a 500 day Mira is $\sim$0.5 mag brighter than a 50 day Cepheid in the near and mid-IR. The revolution came with advent of the microlensing surveys, MACHO and OGLE. Wood *et al.* (1999) and Wood (2000) showed that red giants in the LMC follow several sequences, 3 that define pulsating stars, a sequence that consists of binary systems, and one that is formed by the long secondary period (LSP) that occurs in many red giants. Subsequent works expanded on this in various ways (Ita *et al.* 2004, Soszyński *et al.* 2004, 2005, Fraser *et al.* 2008, Riebel *et al.* 2012, Soszyński & Wood 2013, Soszyński *et al.* 2013) and revealed many more (sub-)sequences, including those for RGB stars.

2. Cosmological connection

The small dispersion in the PL relation of classical Cepheids makes them the primary calibrator in the distance ladder, and ultimately in determining the Hubble constant (Freedman *et al.* 2001). Riess *et al.* (2016) find $H_0 = 73.24 \pm 1.74$ km/s/Mpc by using locally calibrated Cepheids (15 Cepheids with parallaxes in our MW, 8 detached eclipsing binaries (dEBs) in the LMC, 2 dEBs in M31, and the megamaser in NGC 4258), to determine the brightness of Type-I SNe in 19 galaxies that host Cepheids and SNIa, and then measure the distance to $\sim$ 300 SNIa in the Hubble flow with $z < 0.15$. This value for H_0 differs by more than 3σ from the $H_0 = 66.93 \pm 0.62$ km/s/Mpc determined by the Planck mission (Planck Collaboration *et al.* 2016). Whether this discrepancy is real is of obvious importance and requires that all steps in the stellar distance ladder are investigated and improved, and this includes the Cepheid PL relation.

In this line, the Carnegie-Chicago Hubble Program (Beaton *et al.* 2016; this volume) aims at a 3% measurement of H_0 using alternative methods to the traditional Cepheid distance scale. They aim to establish a completely independent route to the Hubble constant using RRL variables, and the tip of the red giant branch (TRGB) method. This requires a reassessment of the RRL PL relation.

3. Period-luminosity relations

Mostly recent empirical PL and PLZ relations for RRL, Type-II, ACs and classical Cepheids in selected filters and Wesenheit relations are compiled in Table 1. If a slope was adopted it is listed between parentheses. Large the table is, it is certainly not complete and the numbers hide important details in their derivation. Period-luminosity relations exist in other infrared filters than K, and in other Wesenheit combinations than V and I, or V and K. The original references should be consulted about solutions for other filter combinations or pulsation modes, the details of the filter(s) used, the details in the definition of the Wesenheit function, any cuts in pulsation period that were applied, or, mostly for the LMC, whether the effect of the orientation of the disc was taken out or not.

Table 1 includes solutions based on *Gaia* (Gaia Collaboration *et al.* 2016b) data release one (GDR1; Gaia Collaboration *et al.* 2016a). Clementini *et al.* (2016) derived PL relations in the *Gaia G* band based on data in the south ecliptic pole in the outskirts of the LMC. Gaia collaboration *et al.* (2017) contains several PL relations based on known RRL, T2C and CEP in our Galaxy based on the TGAS solution. They present solutions

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based on three approaches. The first is based on a least-square fit of absolute magnitude versus $\log P$ where the absolute magnitude is calculated from

$$M = m_0 + 5 \log \pi - 10, \tag{3.1}$$

with m_o the dereddened magnitude and the parallax is in milli-as. A simple application of this method requires a selection in parallax space ($\pi > 0$) and is therefore subject to Lutz-Kelker bias (Lutz & Kelker 1973, Oudmaijer *et al.* 1998, Koen 1992), which Gaia collaboration *et al.* (2017) did not correct for. They also present two methods that work in parallax space. In this case Eq. 3.1 is rewritten (for a PL relation $\alpha + \beta \log P$, or similarly for a $M_{\rm V}-$[Fe/H] relation for RRL) as

$$10^{0.2\alpha} = \pi \cdot 10^{0.2(m_0 - \beta \log P - 10)}. \tag{3.2}$$

The first method is based on a Bayesian approach, and the other, on a weighted non-linear least squares solution of this equation, called the astrometric based luminosity (ABL), and these are the solutions listed in Table 1. They cite Arenou & Luri (1999), although the method was used in a classical paper by Feast & Catchpole (1997) to determine the zeropoint of the Cepheid PL relation based on *Hipparcos* data for 220 Cepheids. The method was shown to be free from bias by Koen & Laney (1998).

Table 1 also includes PL relations based on individual distances to Galactic and MC Cepheids based on the Baade-Wesselink method (Storm *et al.* 2011a,b, Groenewegen 2013). This method depends on the so-called projection factor, p, that translates the pulsational velocity to the radial velocity in the line-of-sight measured via spectroscopy. Both papers derive a p factor that depends quite strongly on period from the condition that the distance to the LMC should not depend on pulsation period (Storm *et al.* find $p = 1.550 - 0.186 \log P$; Groenewegen 2013 find $p = 1.50 - 0.24 \log P$). However, the most recent studies indicate that the data is consistent with a constant p factor of 1.29 $\pm$ 0.04 (Kervella, this volume; Kervella *et al.* 2017). The reason behind this discrepancy is currently unknown.

4. GCVS $\Longleftrightarrow$ GDR1

As a usefull exercise I cross correlated the latest edition of the General Catalog of Variable Stars (version 5.1; Samus *et al.* 2017, see `www.sai.msu.su/gcvs/gcvs/gcvs5/htm/`) with the GDR1 for several types of variables. The results are summarised in Table 2. The third column lists which identifiers were used in the search, the fourth column how many of those types are listed in the GCVS, the fifth column how many have a parallax listed in the GDR1 TGAS solution, and the last column how many of those have a relative parallax error less than 16%. The week after the conference, on May 1st, Gaia Collaboration *et al.* (2017) appeared that did a very similar search, to ultimately derive the PL relations listed in Table 1.

The RRL is the class with the largest number of (accurate) parallax data available. As they are intrinsically faint GDR1 is not hampered by the fact that many bright stars are not listed there. Table 3 lists the 18 RRL with $\sigma_\pi/\pi < 0.16$ plus SU Dra, sorted by relative parallax error. SU Dra is included as it is one of five RRLs which have the parallax determined using the *HST* by Benedict *et al.* (2011). For those five stars their is good agreement between the *HST* based parallaxes and GDR1. The last column gives the parallax listed by van Leeuwen (2007) based on the re-reduction of the *Hipparcos* data.

The next entries in Tables 2 and 3 are for the T2C, of the BLH & WVir, and RVT types. Only 2 have an accurate parallax determined in GDR1. κ Pav, one of two T2C with an HST based parallax in Benedict *et al.* (2011), is missing, probably because it is

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Table 1. PLZ relations for RRL and different classes of Cepheids ($\text{mag} = \alpha + \beta \log P + \gamma$ [Fe/H]).

Class	Band	α	β	γ	Sample	Reference
RRLab	V	19.385 ± 0.017	-	0.214 ± 0.047	LMC	Gratton *et al.* (2004)
RRLab	M_V	0.93 ± 0.12	-	0.23 ± 0.04	GCC	Chaboyer *et al.* (1999)
RRLab	M_V	0.82 ± 0.04	-	(0.214)	GAL	Gaia Collaboration *et al.* (2017)
RRLab	W(V,I)	17.172 ± 0.003	-2.933 ± 0.009	-	LMC	Jacyszyn-Dobrzeniecka *et al.* (2017)
RRLab	W(V,I)	17.492 ± 0.007	-3.001 ± 0.028	-	SMC	Jacyszyn-Dobrzeniecka *et al.* (2017)
RRLab	K	17.43 ± 0.01	-2.73 ± 0.25	0.03 ± 0.07	LMC	Murareva *et al.* (2015)
RRLab	K	13.28 ± 0.02	-2.33 ± 0.08	-	M5	Coppola *et al.* (2011)
RRLab	K	10.420 ± 0.024	-2.33 ± 0.07	-	M4	Braga *et al.* (2015)
RRLab	K	12.752 ± 0.054	-2.232 ± 0.044	0.141 ± 0.020	ω Cen	Navarrete *et al.* (2017)
RRLab	M_K	-1.16 ± 0.27	(-2.33)	-	GAL	Groenewegen & Salaris (1999)
RRLab	M_K	-1.05 ± 0.13	-2.38 ± 0.04	0.08 ± 0.11	GCC	Sollima *et al.* (2006)
RRLab	M_K	-0.95 ± 0.14	-2.53 ± 0.36	0.07 ± 0.04	GAL	Murareva *et al.* (2015)
RRLab	M_K	-1.17 ± 0.10	(-2.73)	0.07 ± 0.07	GAL	Gaia Collaboration *et al.* (2017)
RRLab	[3.6]	10.229 ± 0.010	-2.332 ± 0.106	-	M4	Neeley *et al.* (2015)
RRLab	[4.5]	10.192 ± 0.010	-2.336 ± 0.105	-	M4	Neeley *et al.* (2015)
RRLab	W1	-1.113 ± 0.013	-2.38 ± 0.20	-	GAL	Klein *et al.* (2014)
RRLab	W2	-1.111 ± 0.013	-2.39 ± 0.20	-	GAL	Klein *et al.* (2014)
T2C	G	18.640 ± 0.085	-1.650 ± 0.109	-	LMC	Clementini *et al.* (2016)
T2C	W(V,I)	17.365 ± 0.015	-2.521 ± 0.022	-	LMC	Matsunaga *et al.* (2009)
T2C	W(V,I)	17.554 ± 0.083	-2.304 ± 0.107	-	SMC	Matsunaga *et al.* (2011)
T2C	K	13.27 ± 0.10	-2.24 ± 0.14	-	GB	Groenewegen *et al.* (2008)
T2C	K	17.412 ± 0.029	-2.278 ± 0.047	-	LMC	Matsunaga *et al.* (2009)
T2C	K	17.600 ± 0.082	-2.113 ± 0.105	-	SMC	Matsunaga *et al.* (2011)
T2C	K	17.47 ± 0.02	-2.385 ± 0.030	-	LMC	Ripepi *et al.* (2015)
T2C	K	17.405 ± 0.038	-2.483 ± 0.089	-	LMC	Bhardwaj *et al.* (2017)
T2C	M_K	-1.58 ± 0.17	(-2.385)	-	GAL	Gaia Collaboration *et al.* (2017)
T2C	W(V,K)	17.33 ± 0.02	-2.49 ± 0.03	-	LMC	Ripepi *et al.* (2015)
T2C	W(V,K)	17.415 ± 0.012	-2.456 ± 0.025	-	LMC	Bhardwaj *et al.* (2017)
AC FU	G	18.00 ± 0.04	-2.95 ± 0.27	-	LMC	Clementini *et al.* (2016)
AC FU	K	16.74 ± 0.02	-3.54 ± 0.15	-	LMC	Ripepi *et al.* (2014)
AC FU	W(V,K)	16.58 ± 0.02	-3.58 ± 0.15	-	LMC	Ripepi *et al.* (2014)
CEP FU	G	17.361 ± 0.020	-2.818 ± 0.032	-	LMC	Clementini *et al.* (2016)
CEP FU	M_V	-1.43 ± 0.10	(-2.81)	-	GAL	Feast & Catchpole (1997)
CEP FU	M_V	-1.275 ± 0.023	-2.678 ± 0.076	-	GAL	Fouqué *et al.*(2007)
CEP FU	M_V	-1.54 ± 0.10	(-2.678)	-	GAL	Gaia Collaboration *et al.* (2017)
CEP FU	W(V,I)	16.375 ± 0.014	-3.314 ± 0.020	-	SMC	Ngeow *et al.* (2015a)
CEP FU	W(V,I)	15.897 ± 0.001	-3.327 ± 0.001	-	LMC	Inno *et al.* (2016)
CEP FU	W(V,I)	16.492 ± 0.002	-3.358 ± 0.005	-	SMC	Jacyszyn-Dobrzeniecka *et al.* (2017)
CEP FU	W(V,I)	15.888 ± 0.004	-3.313 ± 0.006	-	LMC	Jacyszyn-Dobrzeniecka *et al.* (2017)
CEP FU	$M_{W(V,I)}$	-2.60 ± 0.03	-3.32 ± 0.08	(0.0)	MC+G	Storm *et al.* (2011b)
CEP FU	$M_{W(V,I)}$	-2.414 ± 0.022	-3.477 ± 0.074	-	GAL	Fouqué *et al.* (2017)
CEP FU	$M_{W(V,I)}$	-2.82 ± 0.11	(-3.477)	-	GAL	Gaia Collaboration *et al.* (2017)
CEP FU	K	16.494 ± 0.026	-3.212 ± 0.033	-	SMC	Groenewegen (2000)
CEP FU	K	16.514 ± 0.025	-3.213 ± 0.032	-	SMC	Ngeow *et al.* (2015a)
CEP FO	K	15.941 ± 0.032	-3.132 ± 0.083	-	SMC	Bhardwaj *et al.* (2016b)
CEP FU	K	16.051 ± 0.050	-3.281 ± 0.040	-	LMC	Persson *et al.* (2004)
CEP FU	K	16.070 ± 0.017	-3.295 ± 0.018	-	LMC	Ripepi *et al.* (2012)
CEP FU	K	15.984 ± 0.017	-3.228 ± 0.004	-	LMC	Macri *et al.* (2015)
CEP FO	K	15.458 ± 0.014	-3.257 ± 0.023	-	LMC	Macri *et al.* (2015)
CEP FU	M_K	-2.282 ± 0.019	-3.365 ± 0.063	-	GAL	Fouqué *et al.* (2007)
CEP FU	M_K	-2.63 ± 0.10	(-3.365)	-	GAL	Gaia Collaboration *et al.* (2017)
CEP FU	M_K	-2.33 ± 0.03	-3.30 ± 0.06	(0.0)	MC+G	Storm *et al.* (2011b)
CEP FU	M_K	-2.49 ± 0.08	-3.07 ± 0.07	-0.05 ± 0.10	MC+G	Groenewegen (2013)
CEP FU	W(V,K)	15.870 ± 0.013	-3.325 ± 0.014	-	LMC	Ripepi *et al.* (2012)
CEP FU	W(V,K)	15.894 ± 0.002	-3.314 ± 0.002	-	LMC	Inno *et al.* (2016)
CEP FU	W(V,K)	15.837 ± 0.049	-3.287 ± 0.010	-	LMC	Bhardwaj *et al.* (2016a)
CEP FU	$M_{W(V,K)}$	-2.87 ± 0.10	(-3.32)	-	GAL	Gaia Collaboration *et al.* (2017)
CEP FU	$M_{W(V,K}$	-2.69 ± 0.08	-3.11 ± 0.07	$+0.04 \pm 0.10$	MC+G	Groenewegen (2013)
CEP FU	[3.6]	16.01 ± 0.02	-3.31 ± 0.05	-	LMC	Monson *et al.* (2012)
CEP FU	[4.5]	15.90 ± 0.02	-3.21 ± 0.06	-	LMC	Monson *et al.* (2012)
CEP FU	$M_{[24]}$	-2.46 ± 0.10	-3.18 ± 0.10	-	GAL	Ngeow *et al.* (2015b)

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Table 2. Link between GCVS classes and GDR1.

Class	Type	GCVS	Number in GCVS	Number in GDR1	Number with $(\sigma_\pi/\pi) < 0.16$
RRL		RRab, RRc	6631	331	18
T2C	BLH/WVir	CW, CW:, CWA, CWA:, CWB, CWB:	271	44	2
T2C	RVT	RV, RV:, RVA, RVA:, RVB, RVB+EA, RVB:	159	52	0
AC		BLBOO	1	0	0
CEP		DCEP	632	289	1
M/SR		M, SRA, SRB	10491	732	1

Table 3. Data on RR Lyrae and Type-II Cepheids.

Name	Hipparcos	Type	Period (d)	G (mag)	$\pi \pm \sigma_\pi$ (mas, GDR1)	$\pi \pm \sigma_\pi$ (mas, HST)	$\pi \pm \sigma_\pi$ (mas, Hipp)
RR Lyrae							
RR Lyr	95497	RRab	0.567	7.6	3.64 ± 0.23	3.77 ± 0.13	3.46 ± 0.64
FO CVn		RRc	0.284	10.8	3.15 ± 0.25		
RZ Cep	111839	RRc	0.309	9.2	2.65 ± 0.24	2.54 ± 0.19	0.59 ± 1.48
CS Eri	12199	RRc	0.311	8.9	2.16 ± 0.23		2.71 ± 1.10
X Ari	14601	RRab	0.651	9.5	2.02 ± 0.22		0.88 ± 1.32
UV Oct	80990	RRab	0.542	9.5	2.02 ± 0.23	1.71 ± 0.10	2.44 ± 0.81
AR Per	19993	RRab	0.425	10.3	1.99 ± 0.24		0.93 ± 1.45
DX Del	102593	RRab	0.472	9.9	1.66 ± 0.22		0.77 ± 1.38
EW Cam	36213	RRab	0.628	9.4	1.69 ± 0.23		2.13 ± 1.10
V1057 Cas		RRc	0.423	10.0	2.20 ± 0.31		
XZ Dra	94134	RRab	0.476	10.3	1.43 ± 0.21		2.26 ± 0.88
SW And	1878	RRab	0.442	9.6	1.77 ± 0.26		1.48 ± 1.21
XZ Cyg	96112	RRab	0.467	9.9	1.56 ± 0.23	1.67 ± 0.17	2.29 ± 0.84
AV Peg	107935	RRab	0.390	10.4	1.53 ± 0.23		2.28 ± 1.72
V4424 Sgr	97923	RRab	0.425	10.2	1.66 ± 0.25		0.92 ± 1.94
RX Eri	22442	RRab	0.587	9.7	1.83 ± 0.28		1.50 ± 1.12
BH Peg	112994	RRab	0.641	10.6	1.40 ± 0.22		0.31 ± 1.82
BN Vul	95702	RRab	0.594	10.7	1.45 ± 0.23		6.09 ± 2.24
SU Dra	56734	RRab	0.660	9.7	1.43 ± 0.28	1.42 ± 0.16	0.20 ± 1.13
Type-II Cepheids							
VY Pyx	43736	BL Her	1.239	7.0	3.85 ± 0.28	6.44 ± 0.23	5.01 ± 0.44
KT Com	66179	W Vir	4.070	8.0	4.16 ± 0.66		5.50 ± 0.73
κ Pav	93015	W Vir	9.078	(5.0)		5.57 ± 0.28	6.52 ± 0.77

so bright. Interestingly, the parallax measurement for VY Pyx differs quite a bit from the HST and the *Hipparcos* based value.

The ACs are listed under the identifier "BLBOO" in the GCVS. There is only one, BL Boo, which is not listed in GDR1.

There is only one classical Cepheid with an accurate parallax in GDR1, CK Cam. Table 4 lists that star and the 12 stars which have an *HST* based parallax from Benedict *et al.* (2007), Riess *et al.* (2014) and Casertano *et al.* (2016). Most are too bright to be included in GDR1. The two fainter stars suggest that the parallaxes derived using the new WFC3 scanning technique will be competitive beyond GDR2.

There is a very large number of Mira and SR variables listed in the GCVS, but since these stars are intrinsically bright only one has an accurate parallax, the anonymous SRb variable V375 And. Whitelock & Feast (2000) and Whitelock *et al.* (2008) studied Miras and Mira-like variables and derived the K band PL relation. Table 5 lists 8 stars with relative parallax error < 0.16 in *Hipparcos* data. I also added R Dor, the star with the largest angular diameter on the sky (see column 6). This is a relevant factor for these very large giants and supergiants, that have large convective cells. Chiavassa *et al.* (2011) show that in a star like Betelgeuse the photocentre shifts by a noise characterised by a standard deviation of the order of 0.1 AU. They find that in the worst situation, the

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Table 4. Data on classical Cepheids.

Name	V	$\pi \pm \sigma_\pi$ (mas, HST)	$\pi \pm \sigma_\pi$ (mas, Hipparcos)	$\pi \pm \sigma_\pi$ (mas, GDR1)
β Dor	3.5	3.14 ± 0.16	3.64 ± 0.28	
δ Cep	3.7	3.66 ± 0.15	3.81 ± 0.20	
FF Aql	4.7	2.81 ± 0.18	2.05 ± 0.34	1.64 ± 0.89
l Car	3.2	2.01 ± 0.20	2.06 ± 0.27	
RT Aur	5.3	2.40 ± 0.19	−0.23 ± 1.01	
T Vul	5.5	1.90 ± 0.23	2.31 ± 0.29	
Y Sgr	5.1	2.13 ± 0.29	3.73 ± 0.32	
X Sgr	4.0	3.00 ± 0.18	3.39 ± 0.21	
ζ Gem	3.8	2.78 ± 0.18	2.71 ± 0.17	
W Sgr	4.3	2.28 ± 0.20	2.59 ± 0.75	
SS CMa	9.9	0.348 ± 0.038		0.69 ± 0.23
SY Aur	9.1	0.428 ± 0.054		0.69 ± 0.25
CK Cam	7.6		−0.59 ± 1.13	1.56 ± 0.25

Table 5. Data on Mira and SR variables.

Name	Type	V (GCVS) (max - min)	$\pi \pm \sigma_\pi$ (mas, Hipparcos)	$\pi \pm \sigma_\pi$ (mas, GDR1)	θ (mas)	Reference for θ
V375 And	SRb	7.0 - 7.2	2.35 ± 0.54	2.91 ± 0.46		
o Cet	M	2.0 - 10.1	10.91 ± 1.22		33.6 ± 3.5	Whitelock & Feast (2000)
L_2 Pup	SRb	2.6 - 6.2	15.61 ± 0.99		17.9 ± 1.6	Kervella *et al.* (2014)
R Car	M	3.9 - 10.5	6.34 ± 0.81		∼ 20	Ireland *et al.* (2004)
R Leo	M	4.4 - 11.3	9.01 ± 1.42		37.4 ± 2.3	Whitelock & Feast (2000)
R Hya	M	3.5 - 10.9	8.24 ± 0.92		28.7 ± 3.3	Whitelock & Feast (2000)
W Hya	SRa	7.7 - 11.6	9.59 ± 1.12		45 ± 4	Whitelock & Feast (2000)
W Cyg	SRb	6.8 - 8.9	5.72 ± 0.38		11.5 ± 0.4	Dyck *et al.* (1996)
R Cas	M	4.4 - 13.5	7.95 ± 1.03		24.9 ± 2.9	Whitelock & Feast (2000)
R Dor	SRb	4.8 - 6.6	16.02 ± 0.69		57 ± 5	Whitelock & Feast (2000)

degradation of the astrometric fit caused by this photocentric noise will be noticeable up to about 5 kpc for the brightest supergiants.

The effect could possibly be present in Cepheids as well but should be almost an order of magnitude smaller. The largest Cepheid is l Car with a mean angular diameter of ~ 3 mas (Kervella *et al.* 2004) comparable to its parallax. Others are smaller; see Table 12 in Groenewegen (2013) for predicted angular diameters and references to measured ones.

5. GDR1

Several papers have used GDR1 data in order to study the classical variables. Two important ones have already been mentioned, (1) Gaia collaboration *et al.* (2017) that analysed the parallax data in TGAS for known RRL, T2C, CEP and derived the zeropoint of various PL relations (see Table 1), and (2) Clementini *et al.* (2016) that analysed classical variables in the south ecliptic pole data.

Casertano *et al.* (2017) used the 212 Cepheids from van Leeuwen *et al.* (2007) with $VIJH$ data to construct the $m_{\rm H} = m_{160} - 0.3861(m_{555} - m_{814})$ magnitude and compare the TGAS parallax to the photometric parallax calculated from their adopted absolute calibration $M_{\rm H} = -2.77 - 3.26 \log P$. They find that "the parallaxes are in remarkably good global agreement with the predictions, and there is an indication that the published errors may be conservatively overestimated by about 20%. Our analysis suggests that the parallaxes of 9 Cepheids brighter than G = 6 may be systematically underestimated".

Gould *et al.* (2016) use a similar approach and compare TGAS to photometrically determined parallaxes for 100 RRab stars using the K band PL relation, and find that the errors in TGAS are overestimated. The error in parallax quoted in GDR1 are inflated

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Figure 1. This contribution is dedicated to the memory of Jan Cuypers (1956-2017) who died unexpectedly on the last day of February. Not only was he the head of the outreach department of the Royal Observatory of Belgium, and head of the Astronomy and Astrophysics department, Jan was heavily involved in *Gaia* in the context of DPAC Coordination Unit 7 on period determination and variable star classification. The picture was taken in 2010. It shows Jan fourth from the left with his colleagues from the Royal Observatory involved in *Gaia*.

compared to the formal parallax uncertainty (Eq. 4 and Appendix B in Lindegren *et al.* 2016), $\sigma_{\rm tgas}(\pi) = \sqrt{(A\sigma_{\rm int})^2 + \sigma_0^2}$, where $(A, \sigma_0) = (1.4,\ 0.2)$ is used in GDR1. Gould *et al.* propose that (1.1, 0.12) is more appropriate.

6. Outlook

The first data release of *Gaia* has shown the potential impact that this data can have on the calibration of the distance scale, and that the community seems ready for GDR2! The number of classical variables that can be expected is huge. From Table 20 in Robin *et al.* (2012) "Gaia Universe model snapshot" one can deduce that in the full catalog ($G < 20$), or at the bright end ($G < 12$), where additional abundance and detailed RV monitoring data will be available, one may expect 80 000 (400) RRab, 6500 (2200) classical Cepheids, and 40 000 (18 000) Mira variables. Eyer & Cuypers (2000) quote similar numbers.

In GDR2 one may already expect significant better precision in the parallaxes, as well as time series of the G band, and of the integrated BP and RP bands, providing colour information. There already may be an all-sky release and characterisation of RRL with sufficient epochs.

As became clear from GDR1, an important issue is the bright limit, that is currently near $G = 6$ and that has a huge impact on the availability of parallax data for the best known classical Cepheids with accurate *HST* parallaxes. Efforts are ongoing to bring this limit to $G = 3$ (Sahlmann *et al.* 2016), or even slightly brighter (Sahlmann *et al.*, this volume). An alternative route where *Gaia* could also contribute is to study Cepheids in clusters (Anderson *et al.* 2013; Chen *et al.* 2015). The well known Cepheids δ Cep and ζ Gem are located in clusters (Majaess *et al.* 2012a,b) that can provide alternative distances via main-sequence fitting.

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References

Anderson, R. I., Ekström, S., Georgy, C., *et al.* 2014, *A&A*, 564, A100
Anderson, R. I., Eyer, L., & Mowlavi, N. 2013, *MNRAS*, 434, 2238
Anderson, R. I., Saio, H., Ekström, S., Georgy, C. & Meynet, G. 2016, *A&A*, 591, A8
Arenou, F. & Luri, X. 1999, *ASP-CS*, 167, 13
Beaton, R. L., Freedman, W. L., Madore, B. F., Bono, G., *et al.* 2016, *ApJ*, 832, 210
Benedict, G. F., McArthur, B. E., Feast, M. W., Barnes, T. G., *et al.* 2007, *AJ*, 133, 1810
Benedict, G. F., McArthur, B. E., Feast, M. W., Barnes, T. G., *et al.* 2011, *AJ*, 142, 187
Bhardwaj, A., Kanbur, S. M., Macri, L. M., *et al.* 2016a, *AJ*, 151, 88
Bhardwaj, A., Ngeow, C.-C., Kanbur, S. M., & Singh, H. P. 2016b, *MNRAS*, 458, 3705
Bhardwaj, A., Macri, L. M., Rejkuba, M., *et al.* 2017, *AJ*, 153, 154
Bono, G., Castellani, V., Marconi, M. 2000, *ApJ*, 529, 293
Bono, G., Pietrinferni, A., Marconi, M., *et al.* 2016, *Com. Konkoly*, 105, 149
Braga, V. F., Dall'Ora, M., Bono, G., *et al.* 2015, *ApJ*, 799, 165
Casertano, S., Riess, A. G., Anderson, J., Anderson, R. I., *et al.* 2016, *ApJ*, 825, 11
Casertano, S., Riess, A. G., Bucciarelli, B., Lattanzi, M. G., *et al.* 2017, *A&A*, 599, A67
Ceraski, W. 1905, *AN*, 168, 29
Chaboyer, B. 1999, in: A. Heck & F. Caputo (eds), *Post-Hipparcos Cosmic Candles* (Kluwer, Dordrecht), p. 111
Chen, X., de Grijs, R., & Deng, L. 2015, *MNRAS*, 446, 1268
Chiavassa, A., Pasquato, E., Jorissen, A., *et al.* 2011, *A&A*, 528, A120
Clementini, G., Ripepi, V., Leccia, S., *et al.* 2016, *A&A*, 595, A133
Coppola, G., Dall'Ora, M., Ripepi, V., *et al.* 2011, *MNRAS*, 416, 1056
Dyck, H. M., Benson, J. A., van Belle, G. T., & Ridgway, S. T. 1996, *AJ*, 111, 1705
Eyer, L. & Cuypers, J. 2000, *ASP-CS*, 203, 71
Feast, M. W. & Catchpole, R. M. 1997, *MNRAS*, 286, L1
Fiorentino, G. & Monelli, M. 2012, *A&A*, 540, A102
Fouqué, P., Arriagada, P., Storm, J., *et al.* 2007, *A&A*, 476, 73
Fraser, O. J., Hawley, S. L., & Cook, K. H. 2008, *AJ*, 136, 1242
Freedman, W. L., Madore, B. F., Gibson, B. K., Ferrarese, L., *et al.* 2001, *ApJ*, 553, 47
Gaia Collaboration, Brown, A. G. A., Vallenari, A., Prusti, T., *et al.* 2016a, *A&A*, 595, A2
Gaia Collaboration, Clementini, G. Eyer, L., *et al.* 2017, *A&A*, in press (arXiv: 1705.00688)
Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., Brown, A. G. A., *et al.*, 2016b, *A&A*, 595, A1
Gingold, R. A. 1976, *ApJ*, 204, 116
Gingold, R. A. 1985, *MemSAIt*, 56, 169
Glass, I. S. & Lloyd Evans, T. 1981, *Nature*, 291, 303
Gould, A., Kollmeier, J. A., & Sesar, B. 2016, *arXiv*, 1609.06315
Gratton, R. G., Bragaglia, A., Clementini, G., *et al.* 2015, *A&A*, 421, 937
Groenewegen, M. A. T., 2000, *A&A*, 363, 901
Groenewegen, M. A. T., 2013, *A&A*, 550, A70
Groenewegen, M. A. T. & Jurkovic, M. 2017a, *A&A*, in press (arXiv: 1705.00886)
Groenewegen, M. A. T. & Jurkovic, M. 2017b, *A&A*, in press (arXiv: 1705.04487)
Groenewegen, M. A. T. & Salaris, M. 1999, *A&A*, 348, L33
Groenewegen, M. A. T., Udalski, A., & Bono, G. 2008, *A&A*, 481, 441
Hoffmeister, C. 1929, *AN*, 236, 233
Inno, L., Bono, G., Matsunaga, N. *et al.*, 2016, *ApJ*, 832, 176

Ireland, M. J., Tuthill, P. G., Bedding, T. R., *et al.* 2004, *MNRAS*, 350, 365
Ita Y., Tanabé, T., Matsunaga, N., *et al.*, 2004, *MNRAS*, 347, 720
Jacyszyn-Dobrzeniecka, A. M., Skowron, D. M., Mróz, P., *et al.* 2016, *AcA*, 66, 149
Jacyszyn-Dobrzeniecka, A. M., Skowron, D. M., Mróz, P., *et al.* 2017, *AcA*, 67, 1
Kamath, D., Wood, P. R., Van Winckel, H., & Nie, J. D. 2016, *A&A*, 586, L5
Karczmarek, P., Wiktorowicz, G., Iłkiewicz, K., *et al.* 2017, *MNRAS*, 466, 2842
Kervella, P., Montargès, M., Ridgway, S. T., *et al.* 2014, *A&A*, 564, A88
Kervella, P., Trahin, B., Bond, H. E., *et al.* 2017, *A&A*, 600, A127
Klein, C. R., Richards, J. W., Butler, N. R., & Bloom, J. S. 2014, *MNRAS*, 440, L96
Koen, C. 1992, *MNRAS*, 256, 65
Koen, C. & Laney, D. 1998, *MNRAS*, 301, 582
Lindegren, L., Lammers, U., Bastian, U., *et al.* 2016, *A&A*, 595, A4
Lutz, T. E. & Kelker, D. H. 1973, *PASP*, 85, 573
Macri, L. M., Ngeow, C.-C., Kanbur, S. M., Mahzooni, S., & Smitka, M. T. 2015, *AJ*, 149, 117
Majaess, D., Turner, D., & Gieren, W. 2012a, *ApJ*, 747, 145
Majaess, D., Turner, D., Gieren, W., Balam, D., & Lane, D. 2012b, *ApJ*, 748, L8
Marconi, M., Coppola, G., Bono, G., Braga, V., *et al.* 2015, *ApJ*, 808, 50
Matsunaga, N., Feast, M. W., & Menzies, J. W. 2009, *MNRAS*, 397, 933
Matsunaga, N., Feast, M. W., & Soszyński, I. 2011, *MNRAS*, 413, 223
Monson, A. J., Freedman, W. L., Madore, B. F., *et al.* 2012, *ApJ*, 759, 146
Muraveva, T., Palmer, M., Clementini, G., *et al.* 2015, *ApJ*, 807, 127
Navarrete, C., Catelan, M., Contreras Ramos, R., *et al.* 2017, *arXiv*, 1704.03031
Neeley, J. R., Marengo, M., Bono, G., *et al.* 2015, *ApJ*, 808, 11
Ngeow, C.-C., Kanbur, S. M., Bhardwaj, A., & Singh, H. P. 2015a, *ApJ*, 808, 67
Ngeow, C.-C., Sarkar, S., Bhardwaj, A., Kanbur, S. M., & Singh, H. P. 2015b, *ApJ*, 813, 57
Oudmaijer, R. D., Groenewegen, M. A. T., & Schrijver, H. 1998, *MNRAS*, 294, L41
Persson, S. E., Madore, B. F., Krzemiński, W., *et al.* 2004, *AJ*, 128, 2239
Pickering, E. C., Colson, H. R., Fleming, W. P., & Wells, L. D. 1901, *ApJ*, 13, 226
Planck Collaboration, Ade, P. A. R., Aghanim, N., Arnaud, M., *et al.* 2016, *A&A*, 594, A13
Riebel, D., Margaret M., Fraser, O., *et al.* 2012, *ApJ*, 723, 1195
Riess, A. G., Casertano, S., Anderson, J., MacKenty, J. & Filippenko, A.V. 2014, *ApJ*, 785, 161
Riess, A. G., Macri, L. M., Hoffmann, S. L., Scolnic, D., *et al.* 2016, *ApJ*, 826, 56
Ripepi, V., Marconi, M., Moretti, M. I., *et al.* 2014, *MNRAS*, 437, 2307
Ripepi, V., Moretti, M. I., Marconi, M., *et al.* 2012, *MNRAS*, 424, 1807
Ripepi, V., Moretti, M. I., Marconi, M., *et al.* 2015, *MNRAS*, 446, 3034
Robin, A. C., Luri, X., Reylé, C., *et al.* 2012, *A&A*, 543, A100
Sahlmann, J., Martín-Fleitas, J., Mora, A., *et al.* 2016, *SPIE*, 9904, E2E
Samus N. N., Durlevich O. V., Kazarovets E V., Kireeva N. N., Pastukhova E. N. 2017, *Astron. Rep.*, 61, 80
Sollima, A., Cacciari, C., & Valenti, E. 2006, *MNRAS*, 372, 1675
Soszyński, I., Udalski, A., Kubiak, M., *et al.* 2004, *AcA*, 54, 129
Soszyński, I., Udalski, A., Kubiak, M., *et al.* 2005, *AcA*, 55, 331
Soszyński, I. & Wood, P. R. 2013, *ApJ*, 763, 103
Soszyński, I., Wood, P. R., & Udalski, A. 2013, *ApJ*, 779, 167
Storm, J., Gieren, W., Fouqué, P., Barnes, T. G., *et al.* 2011a, *A&A*, 534, A94
Storm, J., Gieren, W., Fouqué, P., Barnes, T. G., *et al.* 2011b, *A&A*, 534, A95
van Leeuwen, F. 2007, *A&A*, 474, 653
van Leeuwen, F., Feast, M. W., Whitelock, P. A., & Laney, C. D. 2007, *MNRAS*, 379, 723
Wallerstein, G. 2002, *ARAA*, 114, 689
Whitelock, P. A. & Feast, M. 2000, *MNRAS*, 319, 759
Whitelock, P. A., Feast, M., & van Leeuwen, F. 2008, *MNRAS*, 386, 313
Wood P. R., 2000, *PASA*, 17, 18
Wood P. R., Alcock, C., Allsman, R. A., *et al.* 1999, in: T. Le Bertre, A. Lebre A. & C. Waelkens (eds), *IAU Symp. 191, Asymptotic Giant Branch Stars* (Kluwer, Dordrecht), p. 151