The Galactic Bulge exploration I.: The period-absolute magnitude-metallicity relations for RR Lyrae stars for G_{BP}, V, G, G_{RP}, I, J, H, and K_{s} passbands using *Gaia* DR3 parallaxes

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Introduction

RR Lyrae stars are old, helium-burning, mostly radially pulsating horizontal branch giants. They are divided into three main groups based on their pulsation mode; fundamental mode (RRab), first-overtone (RRc), and double-mode pulsators (RRd) pulsating both in fundamental and first-overtone mode. The fundamental mode RR Lyrae pulsators often serve as distance and metallicity indicators toward old stellar systems within our Galaxy. The connection between pulsation periods, absolute magnitudes, and metallicities (PMZ relations) of RR Lyrae stars allows us to infer their distances from photometric time series, and it has been one of their most practical features.

This paper aims to empirically calibrate the PMZ relations of RR Lyrae in dense stellar regions in the Milky Way by using the data from the Optical Gravitational Lensing Experiment(OGLE), the Vista Variables in the Vía Láctea survey(VVV), and Gaia astrometric mission, etc. The precise calibration of PMZ relations will allow for accurate distance determination and enable us to probe the structure of the Galactic bulge from the point of view of old population pulsators.

Dataset for calibration of the PMZ relations

Metallicity mainly sourced from Crestani et al.（2021a) and Dékány et al.(2021). The pulsation periods were mainly from the International Variable StarIndex (VSX, Watson et al. 2006).

Often pulsation periods are quoted without their appropriate errors; thus, to account for possible minor uncertainties in P they used the following equation to approximate the uncertainties of pulsation periods σ_{P} :

$$\sigma_P = 1.001 \cdot P - 0.999 \cdot P$$

According to Iben & Huchra (1971) and Braga et al. (2016)， we can convert pulsation periods of the first-overtone (FO) pulsators into fundamental mode：

$$\log_{10}(P) = \log_{10}(P_{FO}) + 0.127$$

The parallaxes ϖ and their uncertainties σ_{ϖ} were obtained from the Gaia DR3 and considering the zero point offset from Lindegren et al.(2021) .

They also used 2D extinction maps from Schlegel et al.(1998) to obtain E(B-V) color excesses and its uncertainties and re-calibrated reddening laws from Schlafly＆Finkbeiner(2011).

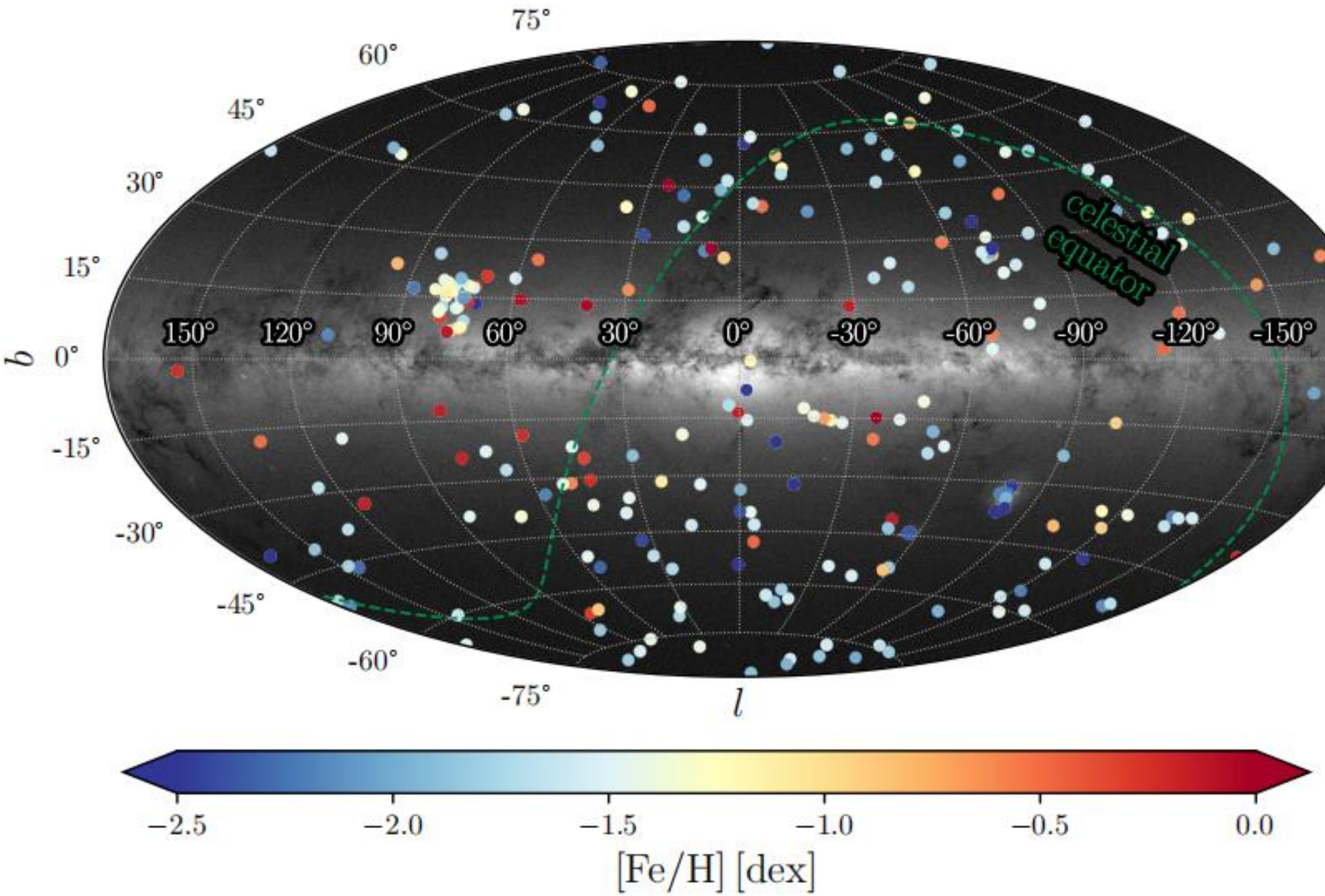

Fig. 1. Spatial distribution in the Galactic coordinates of our RR Lyrae calibration dataset with color-coding representing objects metallicity. *Gaia*'s all-sky star density map is underpinned in the background. The overdensity at $l \approx 80$ deg and $b \approx 10$ deg is due to RR Lyrae stars observed by the *Kepler* space telescope and followed up spectroscopically by Nemec et al. (2013). *Image credit: Gaia Data Processing and Analysis Consortium (DPAC); A. Moitinho / A. F. Silva / M. Barros / C. Barata, University of Lisbon, Portugal; H. Savietto, Fork Research, Portugal.*

The intensity magnitudes were obtained from various sources and subsequently transformed into the OGLE and VVV passbands.

In the case of the GBP, G and GRP-bands, they utilized the *Gaia* RR Lyrae catalog with their associated photometric and pulsation properties(Clementini et al.(2022)) to get the mean intensity magnitudes, m_{GBP} , m_G and $m_{G\mathrm{RP}}$. In total, they used 240 (201 RRab and 39 RRc stars) RR Lyrae variables for GBP, G and GRP-bands, respectively.

For the V-passband, their obtained photometry for RR Lyrae stars and subsequently their mean intensity magnitudes, m_V , from the All-Sky Automated Survey for Supernovae(ASAS-SN, Shappee et al.， 2014； Jayasinghe et al.， 2018). This sample contained 166 RR Lyrae stars (136 RRab and 30 RRc pulsators).

The same match was conducted for the I-band photometry from Dékány et al.(2021) which yielded 128 RR Lyrae stars in total (104 RRab and 24 RRc pulsators) with mean intensity magnitudes m_I.

The mean intensity magnitudes for V and I-passbands were obtained through Fourier decomposition of photometric light curves using an approach described in Petersen (1986).

$$m(t) = m + \sum_{k=1}^{n} A_k \cdot \cos(2\pi k \vartheta + \varphi_k)$$

The ϑ represents the phase function defined as:

$$\vartheta = (\mathrm{HJD} - M_0)\,/P$$

According to Udalski et al. 2015, The V and I-passbands from the ASAS-SN and ASAS surveys can be directly transformed into the OGLE photometric system：

$$m_V^{\mathrm{OGLE}} = 1.003 \cdot m_V + 0.006$$
$$m_I^{\mathrm{OGLE}} = 0.992 \cdot m_I + 0.107$$

In the case of the J and H-bands, we used the photometry provided by the 2MASS and estimated mean intensity magnitudes, m_J and m_H , from Braga et al.(2019). Since 2MASS provides, in most cases, single epoch observations at different pulsation phases, we needed to correct for the luminosity variation during the pulsation cycle to obtain mean intensity magnitudes. For this purpose, they utilized near-infrared photometric templates derived by Braga et al.(2019). In the end they had 115 RR Lyrae stars (97 RRab and 18 RRc variables) with mean intensity magnitudes m_J and 111 RR Lyrae stars (94 Rrab and 17 RRc variables) with mean intensity magnitudes m_H.

The mean intensity magnitudes in Ks-band were acquired from several sources, particularly from studies by Layden et al.(2019) and Braga et al.(2019) . They also used the 2MASS survey, where the same approach as in the J and H-passbands was used to correct for the luminosity variations as a function of the pulsation cycle. A combination of the studies and surveys mentioned earlier resulted in 155 RR Lyrae stars (129 RRab and 26 RRc variables) with mean intensity magnitudes m_{Ks}.

They used the equations from the CASU website and color terms $J - K$s for individual stars to convert their m_J , m_H , and m_{Ks} magnitudes into the VVV photometric system.

Calibration of the PMZ

The main goal is to improve the following PMZ relationship equations：

$$M = \alpha \log_{10}(P) + \beta\,[\mathrm{Fe/H}] + \gamma$$

For each passband **D** consists of vectors $\mathbf{d}^k$ that contain the following information for individual stars:

$$\mathbf{d}^k = \left\{\log_{10}(P), [\mathrm{Fe/H}], \varpi, m, E(B-V)\right\}^k$$

They employed the following approach utilizing the Bayesian framework where the posterior probability is:

$$p(\boldsymbol{\theta} \mid \mathbf{D}) \propto p(\mathbf{D} \mid \boldsymbol{\theta})\, p(\boldsymbol{\theta})$$

$$\boldsymbol{\theta}_i = \{\alpha_i, \beta_i, \gamma_i, \varepsilon_{M_i}\}$$

Jaynes (1968):

$$p(\varepsilon_{M_i}) = 1/\varepsilon_{M_i}$$

For the optical $G_{\rm BP}$, V, G, and $G_{\rm RP}$ bands:

$$p(\alpha_i, \beta_i, \gamma_i) = \mathcal{U}(-2.5 < \alpha < 0.5)$$
$$\mathcal{U}(0.0 < \beta < 0.5)$$
$$\mathcal{U}(-1.5 < \gamma < 1.5)$$

The marginalized likelihood $p(\mathrm{D} \mid \boldsymbol{\theta})$ for k number of stars can be written as such:

$$p(\mathbf{D} \mid \boldsymbol{\theta}_i) = \prod_{k=1}^{K} p(\mathbf{d} \mid \boldsymbol{\theta}) = \prod_{k=1}^{K} \mathcal{N}(M_{\rm data} \mid M_{\rm model}, \sigma_{M_{\rm tot}})$$

For I, J, H, and Ks bands, Marconi et al. (2015):

Table 6. Coefficients of the predicted metal-dependent optical and NIR (*RIJHK*) PLZ relations for FU, FO and FU+FO pulsators. They take account of the entire metallicity range (Z=0.0001–0.02). The global (FU+FO) relations were derived by fundamentalizing the FO periods using the canonical relation.

Type[a]	Band[b]	a[c]	b[d]	c[e]	σ_a[f]	σ_b[f]	σ_c[f]	*rms*[g]
FU	R	0.24	-1.39	0.17	0.02	0.07	0.01	0.10
FO	R	-0.34	-2.00	0.14	0.07	0.10	0.01	0.07
Glob	R	0.25	-1.22	0.17	0.02	0.06	0.01	0.10
FU	I	-0.07	-1.66	0.17	0.02	0.06	0.01	0.09
FO	I	-0.65	-2.20	0.14	0.06	0.10	0.01	0.05
Glob	I	-0.07	-1.53	0.17	0.02	0.04	0.01	0.09
FU	J	-0.51	-1.98	0.17	0.01	0.04	0.01	0.06
FO	J	-1.07	-2.46	0.15	0.04	0.08	0.01	0.04
Glob	J	-0.50	-1.90	0.18	0.01	0.03	0.01	0.06
FU	H	-0.76	-2.24	0.19	0.01	0.02	0.01	0.04
FO	H	-1.31	-2.70	0.16	0.02	0.04	0.01	0.02
Glob	H	-0.76	-2.22	0.18	0.01	0.02	0.01	0.04
FU	K	-0.82	-2.27	0.18	0.01	0.02	0.01	0.03
FO	K	-1.37	-2.72	0.15	0.02	0.04	0.01	0.02
Glob	K	-0.82	-2.25	0.18	0.01	0.02	0.01	0.04

They employed the Markov Chain Monte Carlo Ensemble sampler implemented in the emcee package Foreman-Mackey et al. (2013) to maximize the posterior probability. The result is:

$$M_{K_s} = -2.342 \log_{10}(P) + 0.138\,[\mathrm{Fe/H}] - 0.801,\ N = 97$$

$$M_H = -2.250 \log_{10}(P) + 0.157\,[\mathrm{Fe/H}] - 0.665,\ N = 72$$

$$M_J = -1.799 \log_{10}(P) + 0.160\,[\mathrm{Fe/H}] - 0.378,\ N = 64$$

$$M_I = -1.292 \log_{10}(P) + 0.196\,[\mathrm{Fe/H}] + 0.197,\ N = 79$$

$$M_{G_{\mathrm{RP}}} = -1.464 \log_{10}(P) + 0.167\,[\mathrm{Fe/H}] + 0.113,\ N = 110$$

$$M_G = -0.950 \log_{10}(P) + 0.202\,[\mathrm{Fe/H}] + 0.614,\ N = 110$$

$$M_V = -0.582 \log_{10}(P) + 0.224\,[\mathrm{Fe/H}] + 0.890,\ N = 112$$

$$M_{G_{\mathrm{BP}}} = -0.593 \log_{10}(P) + 0.228\,[\mathrm{Fe/H}] + 0.913,\ N = 107$$

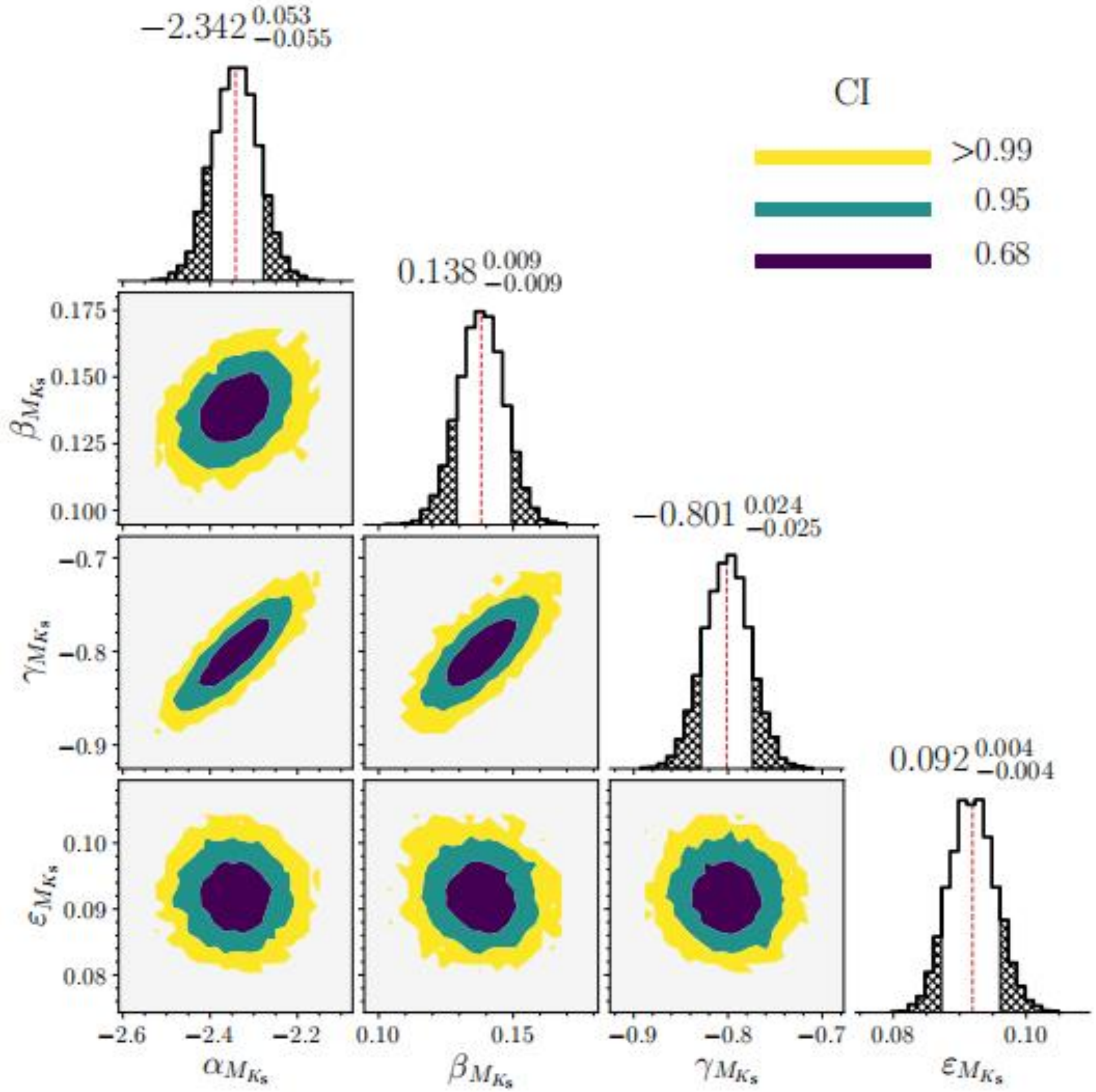

Fig. 2. Posterior probability distributions of the parameters of the PMZ relation for the $K_{\rm S}$-passband.

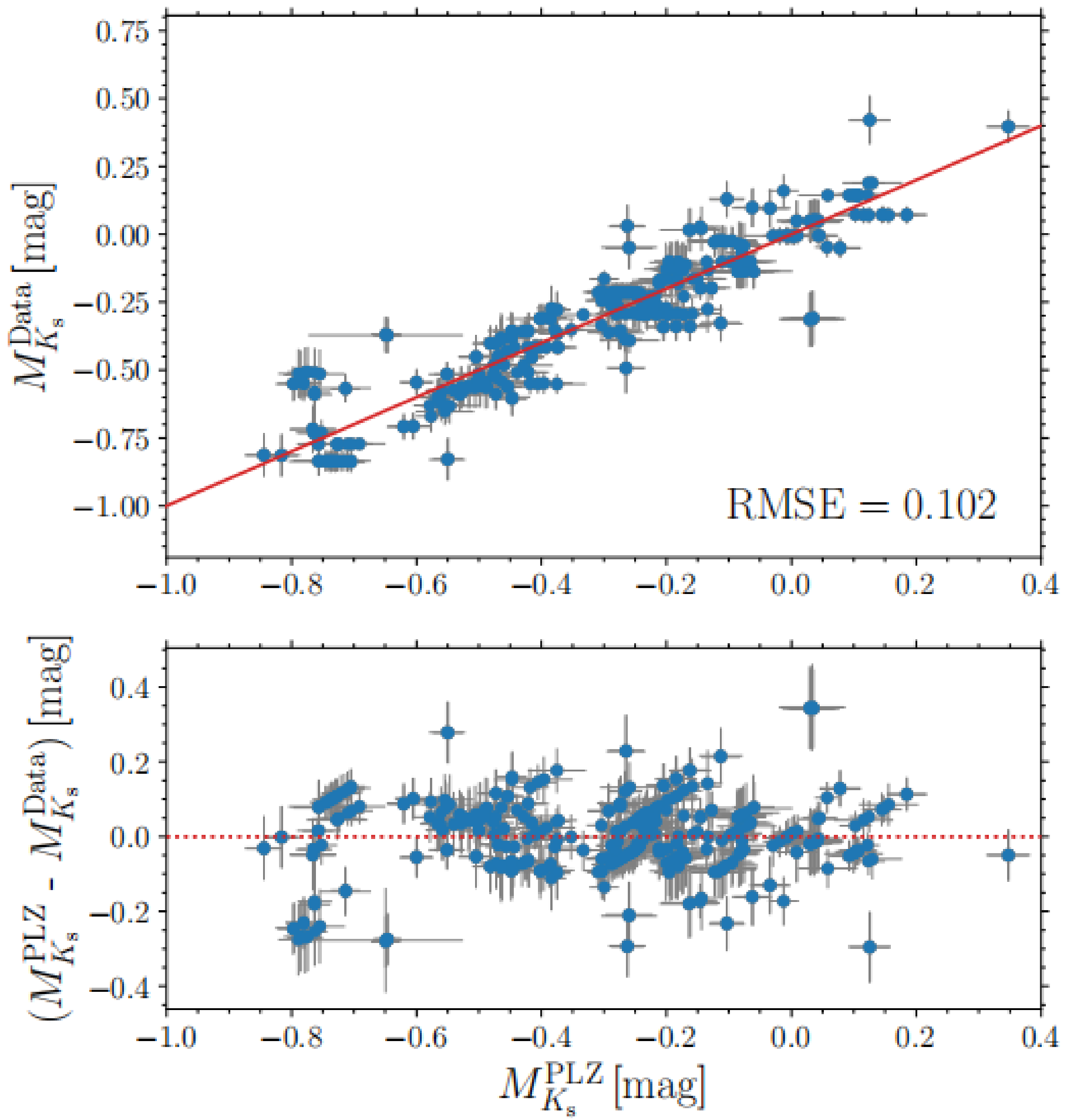

Fig. 3. Comparison of the absolute magnitudes predicted by our $K_{\rm S}$-band PMZ relation with absolute magnitudes calculated based on *Gaia* data.

Testing predicted absolute magnitudes and comparison of PMZ relations

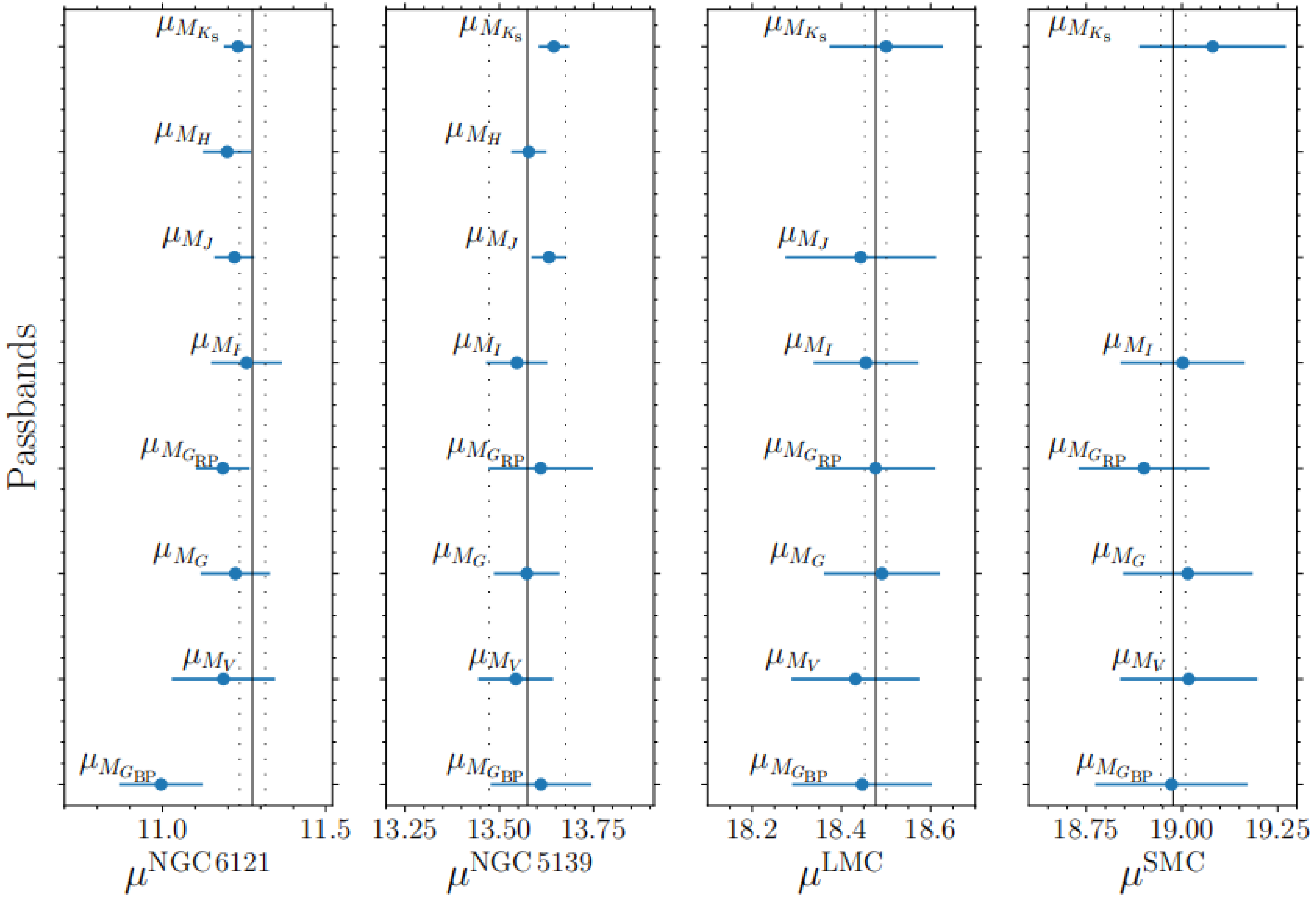

Fig. 4. Comparison of distance moduli for four systems (NGC 6121, NGC 5139, LMC, and SMC) with precise distances and uncertainties derived using different methods (other than RR Lyrae PMZ relations, Pietrzyński et al. 2019; Graczyk et al. 2020; Vasiliev & Baumgardt 2021) . From the left, the plots show a comparison for globular clusters NGC 6121, NGC 5139, LMC, and SMC, using distances and their uncertainties depicted with solid and dotted black lines in all three plots.

Table 1. List of distance moduli for tested stellar systems using derived PMZ relations. The first column contains the source for calculated distance moduli (passbands and literature value). The second and third columns represent the distance moduli of two globular clusters, NGC 6121 and NGC 5139. The last two columns list distance moduli for Magellanic Clouds.

Band	$\mu^{\mathrm{NGC\,6121}}$ [mag]	$\mu^{\mathrm{NGC\,5139}}$ [mag]	μ^{LMC} [mag]	μ^{SMC} [mag]
G_{BP}	11.00 ± 0.13	13.61 ± 0.13	18.45 ± 0.16	18.97 ± 0.20
V	11.25 ± 0.16	13.54 ± 0.10	18.43 ± 0.14	19.02 ± 0.18
G	11.12 ± 0.11	13.57 ± 0.09	18.49 ± 0.13	19.02 ± 0.17
G_{RP}	11.17 ± 0.08	13.61 ± 0.14	18.48 ± 0.13	18.90 ± 0.17
I	11.26 ± 0.11	13.55 ± 0.08	18.45 ± 0.12	18.91 ± 0.16
J	11.24 ± 0.06	13.63 ± 0.05	18.44 ± 0.17	–
H	11.16 ± 0.07	13.58 ± 0.05	–	–
K_{s}	11.27 ± 0.04	13.65 ± 0.04	18.50 ± 0.13	19.08 ± 0.19
Lit.	11.28 ± 0.04	13.58 ± 0.10	18.48 ± 0.02	18.98 ± 0.03

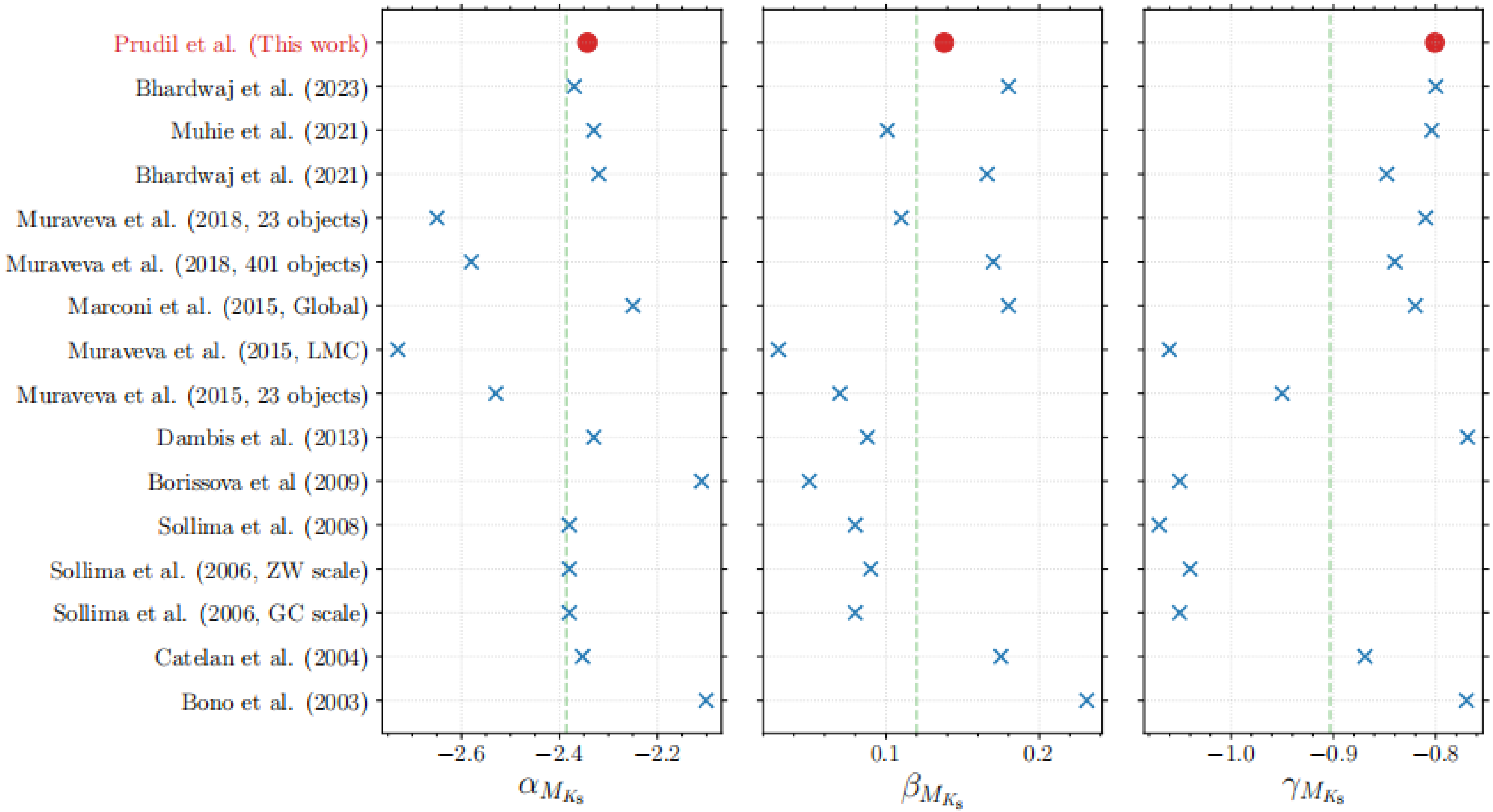

Fig. 5. Comparison of coefficients for K_s-passband PMZ relation across different studies (marked with blue crosses, e.g., Bono et al. 2003; Sollima et al. 2006, 2008; Borissova et al. 2009; Dambis et al. 2013; Muraveva et al. 2015; Bhardwaj et al. 2021; Muhie et al. 2021; Bhardwaj et al. 2023). Coefficients derived in this work are marked with red points. The Green dashed line represents the average of coefficients from previous studies.

Table 2. List of distances for the RR Lyrae star derived using various PMZ relations from the literature. The first column lists references for used PMZ relations. The second column represents the difference between the geometrical distance from *Gaia* parallax and the distance from the PMZ relation denoted in the third column.

PMZ source	*Gaia* – PMZ [pc]	distance [pc]
Bono et al. (2003)	–25.6	275.5
Catelan et al. (2004)	–19.2	269.1
Sollima et al. (2006, GC scale)	–22.5	272.4
Sollima et al. (2006, ZW scale)	–21.1	271.0
Sollima et al. (2008)	–25.0	274.9
Borissova et al. (2009)	–25.0	274.9
Dambis et al. (2013)	9.7	240.2
Muraveva et al. (2015, 23 objects)	–4.0	253.9
Muraveva et al. (2015, LMC)	–3.8	253.7
Marconi et al. (2015, Global)	–17.3	267.2
Muraveva et al. (2018a, 400 objects)	–4.2	254.1
Muraveva et al. (2018a, 23 objects)	10.5	239.4
Bhardwaj et al. (2021)	–15.9	265.8
Muhie et al. (2021)	3.8	246.1
Bhardwaj et al. (2023)	–11.3	261.2
This work	–4.4	254.3

Conclusions

This paper aims to improve the relation between the pulsation period, absolute magnitude, and metallicity (PMZ relation) of RR Lyrae. They select RR Lyrae with fundamental mode pulsation and first overtone mode pulsation to accurately derive the PMZ relation of RR Lyrae in dense stellar regions in the Milky Way.

The calibration process utilized Gaia parallax and high-resolution metal abundance introduced by Crestani et al. (2021b). Photometric data mainly uses relevant items with precise distance and publicly available photometric measurement data, including OGLE, VVV, ASAS-SN, and 2MASS. The Bayesian method was used to estimate the relevant parameters and their uncertainties. Finally, they got a improved PMZ relation.

They also tested their derived PMZ relations. For optical G_{BP}, near-infrared I, J, and Ks passbands, the PMZ relations accurately estimate distance moduli to NGC 6121, NGC 5139, LMC, and SMC. In the case of the optical G_{BP} and G-bands for the globular cluster NGC 6121, they detect a significant offset in the derived distance modulus. The offset is mainly caused by the projected reddening and mostly disappears when using 3D extinction maps toward NGC 6121.

In addition, they compared their Ks-band PMZ relation with previously study. Their period and metallicity parameters match well with the overall distribution of literature values. The zero-point parameter, on the other hand, matches with PMZ relations based on the Gaia parallaxes. Moreover, they tested assembled PMZ relation to estimate the distance toward the prototype of RR Lyrae class, the RR Lyr. We found a good agreement between our derived distance value and distance from Gaia. They believe that their derived PMZ relations will be used in the forthcoming papers to examine the structure and kinematics of the Galactic bulge.

Thank you