JAGB stars as distance indicator

Martin Groenewegen

Else Magnus, L Girardi, G. Pastorelli, P. Marigo, M.L. Boyer

Royal Observatory of Belgium/Koninklijke Sterrenwacht van België, Brussels

(martin.groenewegen@oma.be)

200 year history

1826 - 2026
2026
200 jaar KSB - 200 ans ORB

Overview Talk

- Introduction
- Literature overview
- Work on SMC, LMC, and MW
- Conclusions and Prospects

Introduction

H_0 tension

classical path: Cepheid - SNIa

CMB: 67.4 ± 0.5 km/s/Mpc
Cepheid/SNIa: 73.2 ± 0.9 km/s/Mpc (Breuval et al 2024)

42 SNe in 37 galaxies

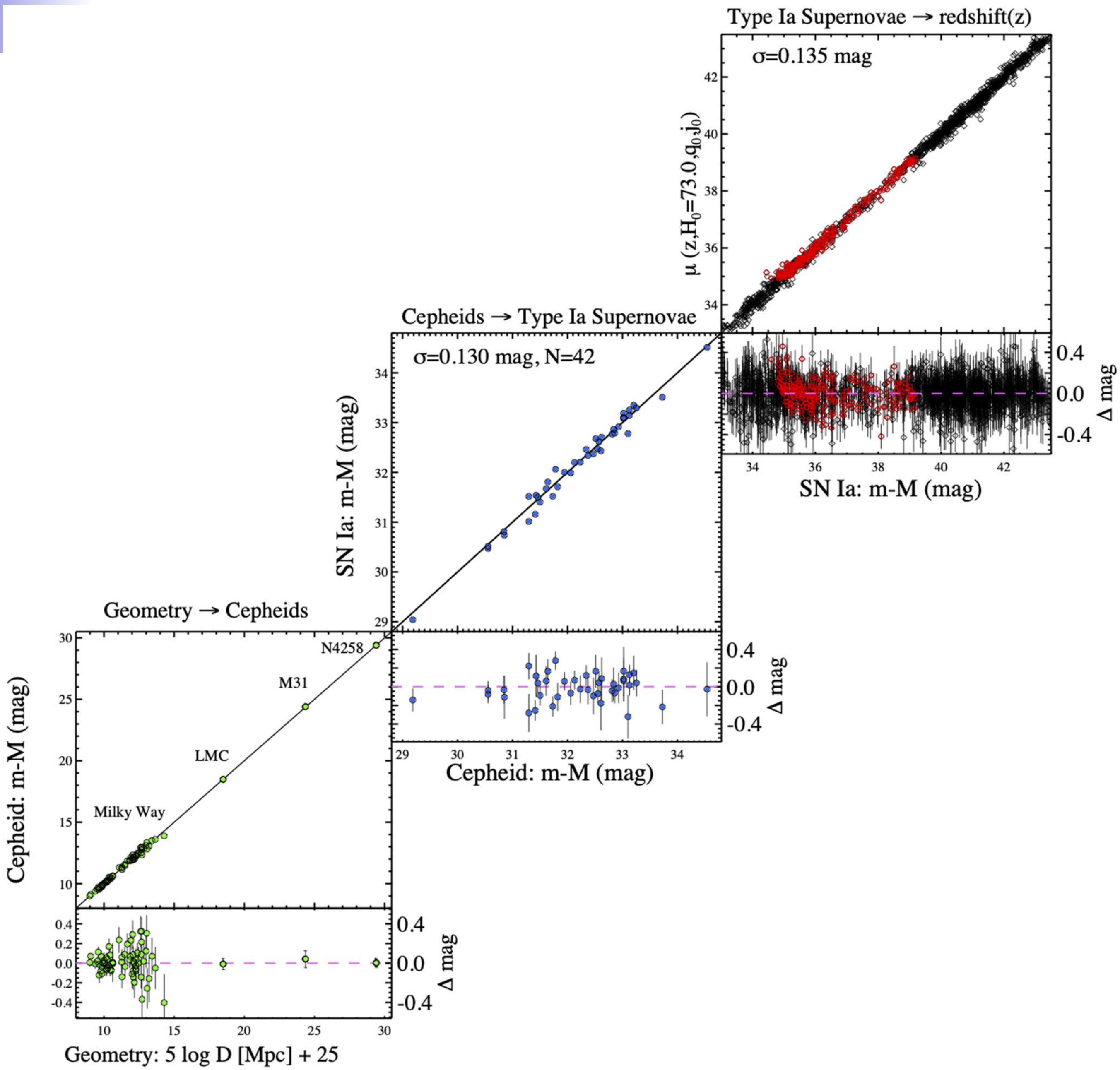
Four anchors:
MW (*Gaia* parallaxes),
SMC, LMC (dEBs),
NGC 4258 (megamaser)

Cross-checks:

Mira PL-relation (Caroline Huang 2401.09581)

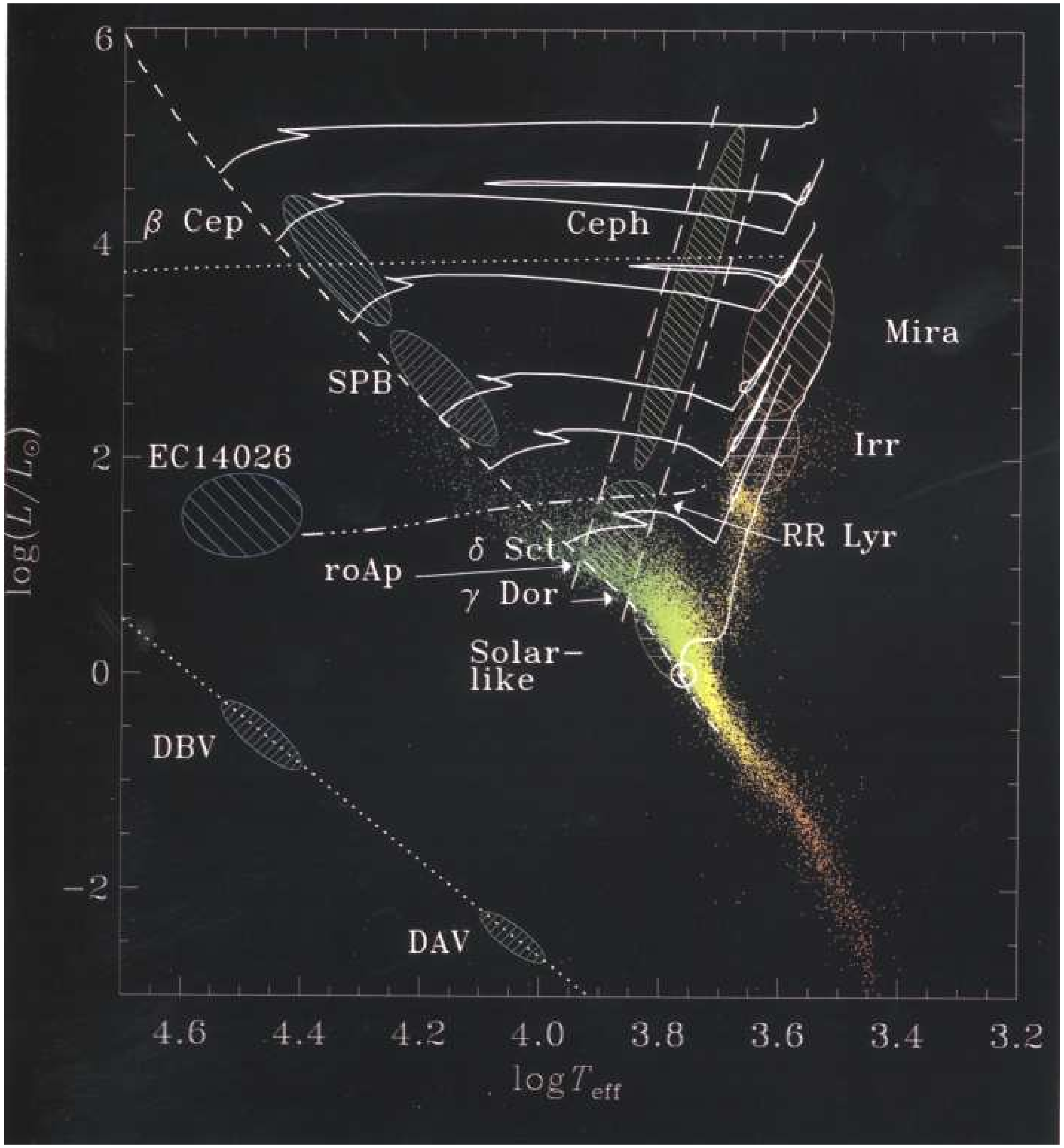
JAGB method

Introduction



Riess et al. (2022)

AGB stars



6
4
2
0
−2
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
log(L/L⊙)
log T_eff
β Cep
Ceph
Mira
SPB
Irr
EC14026
RR Lyr
δ Sct
roAp
γ Dor
Solar–
like
DBV
DAV

Late-type stars

- All stars $\lesssim$7-8 $M_\odot$ go through the AGB phase
- Alternate H and He shell-burning
- Dredge-up of Carbon (and s-process elements) into atmosphere
- Exact M $\rightarrow$ S $\rightarrow$ C sequence is uncertain

  Depends on:
  -initial mass
  -metallicity
  -mass loss
  -dredge-up
  -Hot Bottom Burning

  C-star formation:
  $M_{\rm initial} \gtrsim$1.5 $M_\odot$ (solar), $\gtrsim$1.3 $M_\odot$ (LMC)

Plus and Minus

(dis)advantages J-AGB (and TRGB) versus Cepheids:

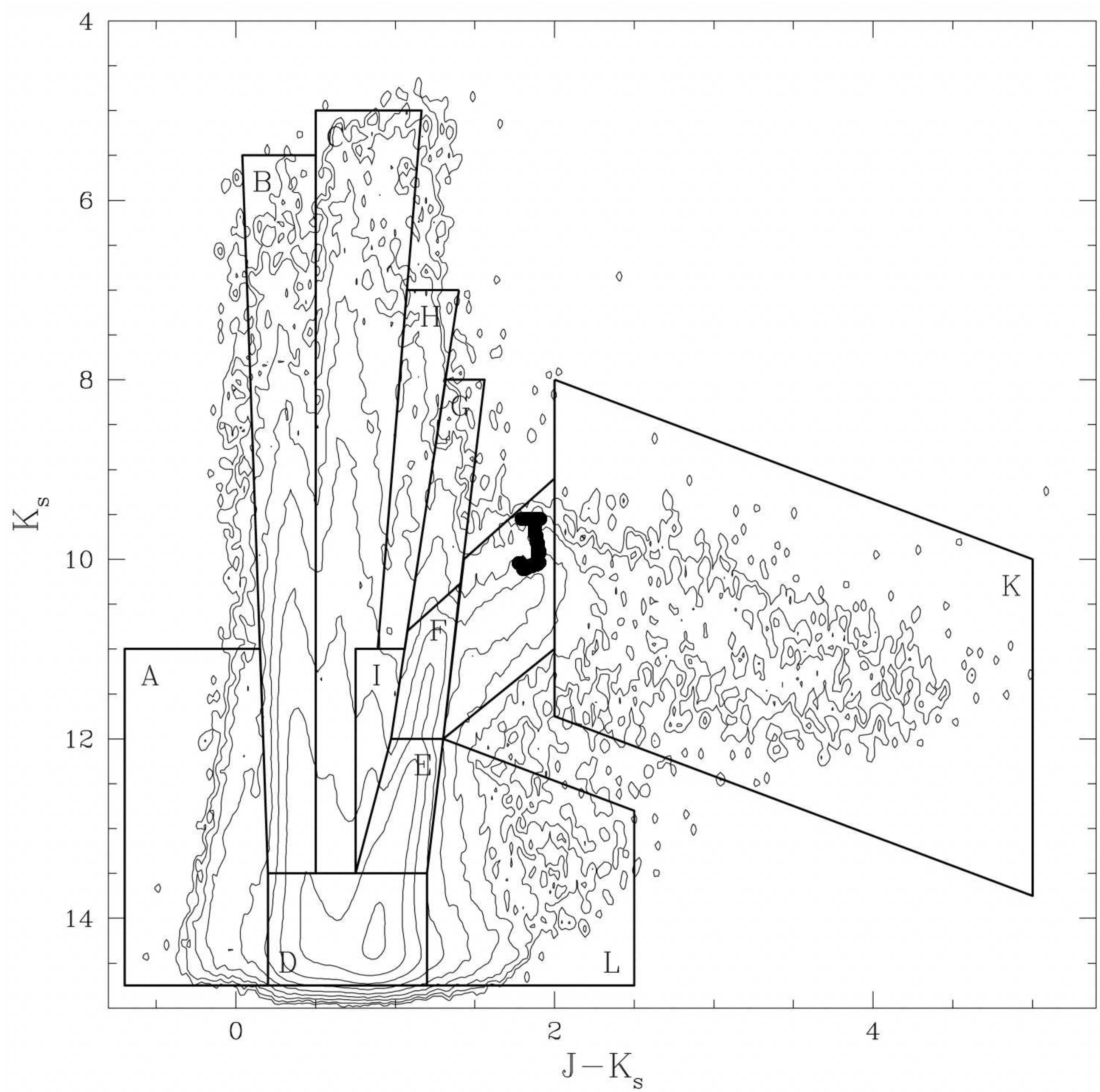
single epoch versus multi-epoch
(CEP more easily discovered in optical, but then requires IR follow-up [template fitting])

JAGB are 1 mag brighter than TRGB, and about brightness of 25d CEP

CEP are found only in young populations, typically in the inner parts [crowding/blending]
JAGB/TRGB are found in intermedeate-age populations, still good statistics in the outer parts of galaxies

but, theoretical understanding and absolute calibration in its infancy

History of JAGB



Nikolaev & Weinberg (2000)

History

N&W (2000), W&N (2001)

Based on 14 C-Miras with $1.4 < (J - K_\mathrm{s}) < 1.9$ in region J:

$$K_\mathrm{s} = -(0.99 \pm 0.80)\,(J - K_\mathrm{s}) + (12.36 \pm 1.33)$$

From this it actually follows that

$$K_\mathrm{s} + 0.99\,(J - K_\mathrm{s}) \approx J = 12.36$$

with DM of 18.5 one finds that $M_\mathrm{J} \approx -6.14$ mag

Astrophysical Journal, 899:66 (7pp), 2020 August 10 https://doi.org/10.3847/1538-4357/aba(

CrossM

Astrophysical Distance Scale: The AGB *J*-band Method. I. Calibration and a First Application

Barry F. Madore[1,2] and Wendy L. Freedman[2]
[1] The Observatories, Carnegie Institution for Science, 813 Santa Barbara Street, Pasadena, CA 91101, USA
[2] Dept. of Astronomy & Astrophysics, University of Chicago, 5640 S. Ellis Avenue, Chicago, IL 60637, USA; barry.f.madore@gmail.com, wfreedman@uchicago.edu
Received 2020 April 1; revised 2020 June 21; accepted 2020 June 24; published 2020 August 13

Abstract

A near-infrared, color-selected subset of carbon-rich asymptotic giant branch (C-AGB) stars is found to have tightly constrained luminosities in the near-infrared *J* band. Based on *JK* photometry of some 3300 C-AGB stars in the bar of the Large Magellanic Cloud (LMC) we find that these stars have a constant absolute magnitude of $\langle M_J \rangle = -6.22$ mag, adopting the detached eclipsing binary (DEB) distance to the LMC of 18.477 ± 0.004

History - Methodology

Reference	Gal.	$(J-K)$	$M_{\rm J}$	method
Madore & Freedman (2020)	LMC	1.3- 2.0	$-6.22\pm$ 0.04	mean
	SMC	1.3- 2.0	$-6.18\pm$ 0.05	mean
Freedman & Madore (2020)	MCs	1.3- 2.0	$-6.20\pm$ 0.04	mean; applied to 14 galaxies
Lee et al. (2022)	MW	1.4-2.0	$-6.14\pm$ 0.12	mean; 2 catalogs of C-stars
Madore et al. (2022)	MW/OC	(1.2)-2.0	$-6.40\pm$ 0.40	mean, 17 stars
			$-6.20\pm$ 0.02	average of MCs & MW
Ripoche et al. (2020)	LMC	1.4-2.0	-6.284 ± 0.004	median
	SMC	1.4-2.0	-6.16 ± 0.02	median
	MW	1.4-2.0	-5.60 ± 0.03	median
Zgirski et al. (2021)	LMC	1.3-2.0	$-6.21\pm$ 0.01	Gaussian
	SMC	1.3-2.0	$-6.20\pm$ 0.01	Gaussian
Parada et al. (2023)	LMC	1.4-2.0	$-6.33\pm$ 0.01	Lorentzian, mode $s=-0.47$
	SMC	1.4-2.0	$-6.18\pm$ 0.01	Lorentzian, mode $s=+0.02$

Ripoche et al. (2020), Parada et al. (2021), Parada et al. (2023): Lorentzian

(Adopt a selection box of 2.5 mag height in J)

External galaxies:

1) fit LF, determine s, 'SMC' or 'LMC'-like,

2) apply respective calibration

Our work - Data

1) Lebzelter+ 2022 LPV catalogue (1.7M objects).
Contains an C-star classifier based on *Gaia* Rp-spectra

2) Correlate with 2MASS, only retaining objects with 'AAA' [difference with Lee et al. 2022]

3) Get *Gaia* data

4a) SMC, LMC selected according to positional and proper motion cuts (4900, 39000 sources)
Distances from dEB (Pietrzynski+2019, Graczyk+2020)
Reddening Skowron+2021 maps
4b) MW
$R_{\rm plx} \equiv (\pi + 0.1)/\sigma_\pi >= 5$ (258 000 sources all-sky)
Distance from Bailer-Jones+2021
Sources in MCs, Sgr dSph, M31, M33 are removed
Reddening from STILISM-maps (Lallement+ 2018)

Our work - classification

Additional M/C-star classification from Lebzelter+2018, Mowlawi+2019

K versus ΔW_{G2M}

$$\Delta W_{\mathrm{G2M}} = W_{\mathrm{Bp,Rp}} - W_{\mathrm{K,J-K_s}},$$

where

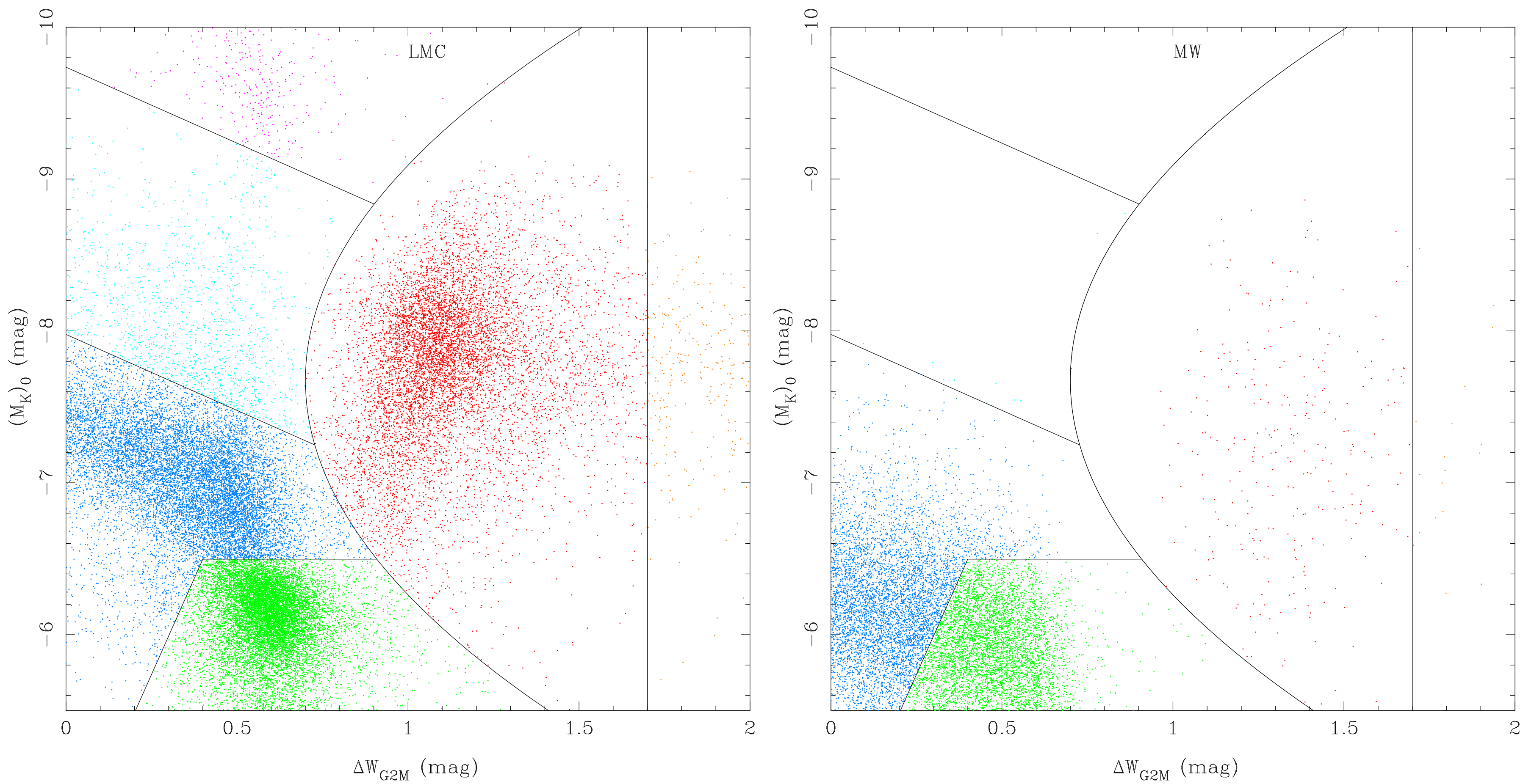
$$W_{\mathrm{Bp,Rp}} = Rp - 1.3 \cdot (Bp - Rp)$$

and

$$W_{\mathrm{K,J-K_s}} = K_{\mathrm{s}} - 0.686 \cdot (J - K_{\mathrm{s}})$$

are reddening-free Wesenheit indices.

Gaia - 2MASS diagram



Our work - Quantities

1) select range in $J - K$
2) select range in J
3) other selection in the data (photometric errors, *Gaia* parameters)

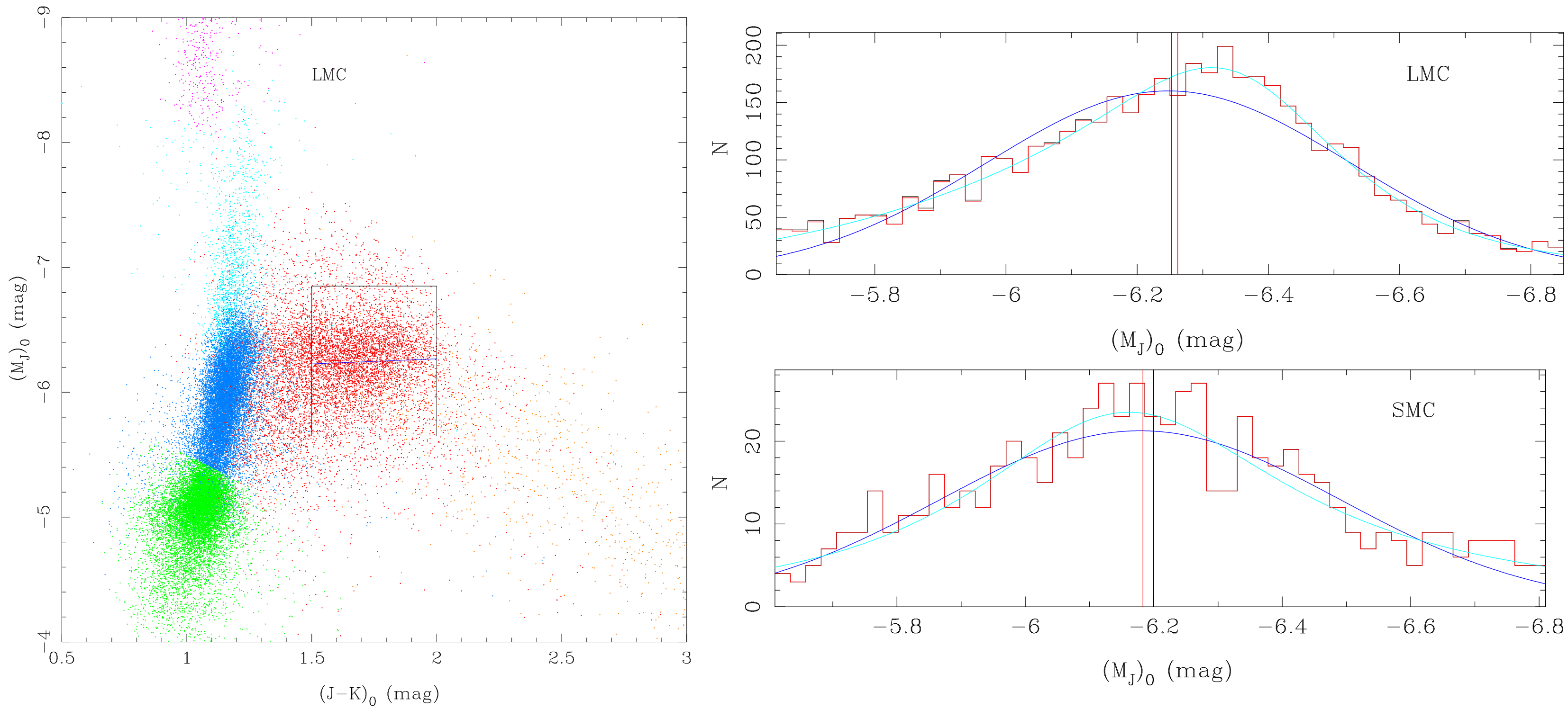
4) mean, median, $J(@(J-K)=1.6)$, peak of the distribution

$$G = \frac{N}{\sqrt{2\pi}\,\sigma} \exp\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right) + \\ + b + c\,(x - x_0) + d\,(x - x_0)^2$$

$$L = \frac{N}{1 + \left(\frac{x-\mu}{w}\right)^2 + s\,\left(\frac{x-\mu}{w}\right)^3 + k\,\left(\frac{x-\mu}{w}\right)^4} + \\ + b + c\,(x - x_0) + d\,(x - x_0)^2$$

Our work - Results MCs

In short: as previous results ....



mean, peak of the Gaussian distribution/mode, $J(@(J-K)=1.6)$ agree within 0.03 mag between SMC and LMC.

LF are not the same, as evidenced by the Lorentzian distribution (and the median)

Our work - Results MW

In short: problematic ...

$1.2 < J-K < 2.0$ M-star contam. 13% (SMC), 34% (LMC)
$1.5 < J-K < 2.0$ M-star contam. 4% (SMC), 1% (LMC)
MW: M-star contamination below 10% only for
$1.5 < J-K < 2.0$ mag.

Issues:

- Closest-by AGB stars (with best parallaxes) saturate in 2MASS
- 3D reddening maps
- parallax zero-point offset - Bailer-Jones+2021 (prior?)

Our work - Results MW

Tried remedies:

- Look for wide-binary companions and use that parallax
- AGB stars in clusters, and use cluster parallax
- Used a few-hundred stars observed in SAAO system (transformation)

(In the end, this does not have an impact, but ...)

Intermezzo I: Wide-binary systems

El-Badry+2021 (ElB)

1.1M pairs with $>$99% probability of being bound.

$\pi > 1$ mas

Subset: 20 800 objects with $1.3 < (J - K_{\rm s})_0 < 2.0$ mas
Similar size test sample from ElB with π close to 1 mas.
Implemented the selection rules of ElB.

Test sample: 14400 have a single WBS candidate
(in all cases the one listed by ElB)
7200 have potentially multiple matches.
Using a penalty function favouring the closer component
all but 15 are retrieved (triples ?).

Intermezzo I: Wide-binary systems

Applied to AGB sample: 65 candidates.

R Scl
secondary: 2.703 ± 0.017 mas
primary: 2.54 ± 0.08
independent: 2.77 ± 0.30
(Maercker+2018, phase-lag)

R Hya
secondary: 7.79 ± 0.20 mas
primary: 6.74 ± 0.46
independent: 7.93 ± 0.18
(VERA collaboration 2020, VLBI)

Intermezzo II: AGB stars in clusters

Cluster parallax is more precise and more accurate than the AGB star parallax

Marigo et al. (2022): 51 unique objects

They: DR2 data + recomputed DR3 with parallax zero-point offset for subsample
Here: DR3 with PZPO for all based on Lindegren+2021 (why PZPO: QSOs on average have non-zero parallax)

Cluster	$\pi \pm \sigma_\pi$ (μas)	$\pi \pm \sigma_\pi$ AGB stars (μas)
Berkeley 53	301.9 ± 12.0	233 ± 64, 274 ± 33, 345 ± 46, 356 ± 50
Ruprecht 112	382.8 ± 11.1	368 ± 39, 463 ± 57
Berkeley 54	159.4 ± 12.9	200 ± 37
Dias 2	248.9 ± 15.5	214 ± 34
FSR 154	264.0 ± 11.9	275 ± 55
FSR 1521	281.1 ± 13.0	200 ± 54
Haffner 14	274.5 ± 11.6	221 ± 21
NGC 559	358.1 ± 11.2	303 ± 37

Our work - Results MW

In the end, MW LF is based on 126 stars only

($1.5 < (J - K_{\rm s})_0 < 2.0$ mag and $\Delta(M_{\rm J})_0$= 1.2 mag)

LMC	SMC	MW	method
-6.2518 ± 0.0035	-6.1992 ± 0.0132	-5.897 ± 0.023	mean
-6.2609 ± 0.0039	-6.1830 ± 0.0147	-5.853 ± 0.030	median
-6.2454 ± 0.0045	-6.1761 ± 0.0195	-5.838 ± 0.041	peak Gaussian
-6.3104 ± 0.0065	-6.1732 ± 0.0191	-5.830 ± 0.086	peak Lorentzian
-6.2386 ± 0.0040	-6.1941 ± 0.0133	-5.847 ± 0.022	ZP@$(J - K_{\rm s})_0 = 1.6$ mag

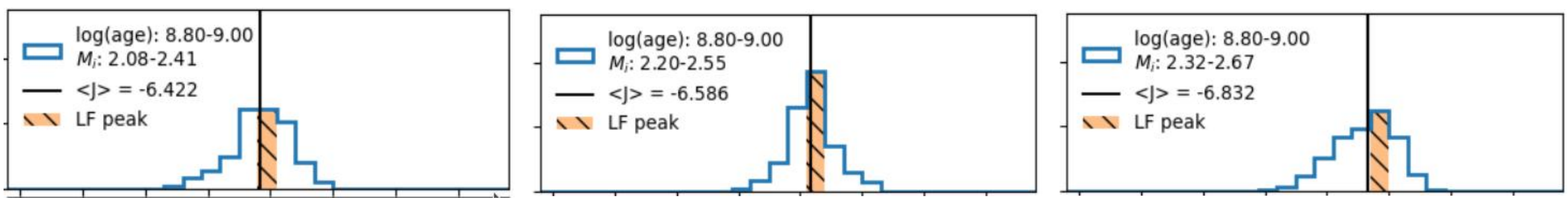
Future work: Models

PRELIMINARY calculations (Pastorelli et al. in prep).

COLIBRI-PARSEC tracks (Marigo+17) +
TRILEGAL population synthesis code (Girardi+05)

"Calibrated" in SMC and LMC (Pastorelli+19, Pastorelli+20)

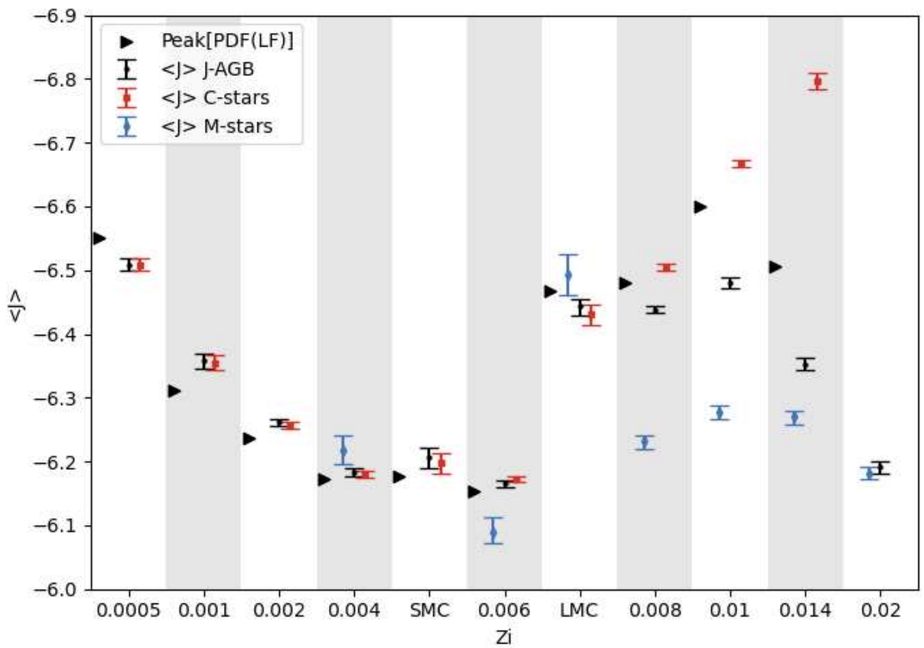
Models: constant SFR, $1.3 < J - K < 2.0$

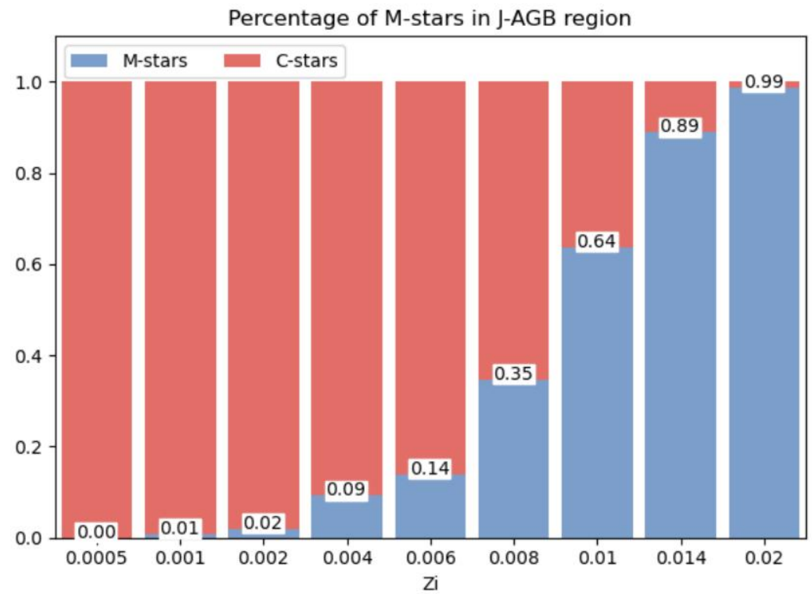


Z= 0.004, 0.008, 0.014

(x-axis goes from -4.5 to -8.5 mag)

Theoretical Models





Prospects & Conclusions

(ArXiv: 2410.05974)

- Methodology and understanding needs more work !
- SMC and LMC LF are not symmetric
- LF MW is uncertain
  (saturation, incompleteness, *Gaia* parallaxes)

  $\Rightarrow$ Get ground-based NIR data for a few hundred nearby AGB stars

Prospects & Conclusions

Bypass ground-based NIR: directly use JWST

Lee+ 2408.0347: F115W (F356W or F444W)
7 SNIa host galaxies, tied to NGC 4258
$H_0 = 67.96 \pm 1.85 \pm 1.90$ km/s/Mpc

Alternative route: TRGB - SBF
(Anand+ 2405.03743, 2408.16810)

THE END