Interaction history of the LMC and SMC: Spectroscopic observations with SALT telescope of Cepheids from the Magellanic Bridge

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S·A·L·T

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The Magellanic Bridge. Discovery

The Magellanic Bridge is a direct evidence of the Magellanic Clouds' interactions, has been a subject of interest of many research projects starting from Shapley (1940).

Bridge as a structure was discovered as a hydrogen feature by Hindman, Kerr and McGee (1963)

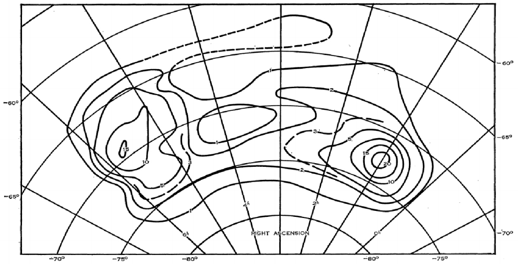
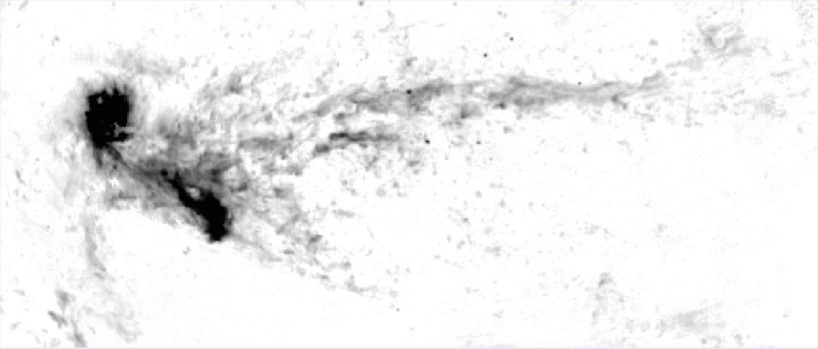


Fig. 1.—Contours of integrated brightness of neutral hydrogen in the Magellanic System. Contour unit = 2×10^{-16}W m^{-2} sr^{-1}.

The Magellanic Bridge

Bridge as a HI structure from Putman et al. (2003)



The Magellanic Bridge. Studies (1)

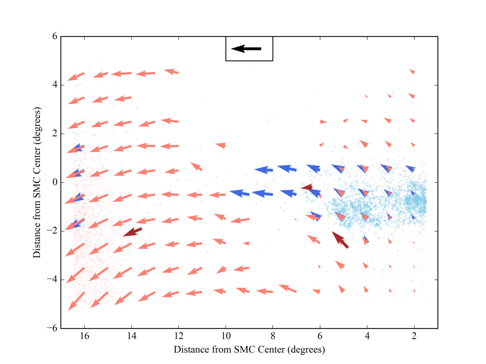
What is known up to now:

- The gaseous counterpart of MBR shows complicated, multi-phase structure
- Many studies were devoted to searching for young stars between the MCs and found an evidence of their presence
- The clumped pattern of stellar associations distribution between the Magellanic Clouds may suggest an ongoing process of forming a tidal dwarf galaxy
- Numerical models predict that connection between LMC and SMC was formed after their last encounter (200–300 Myr ago)

The Magellanic Bridge. Studies (2)

Stellar proper motions for both young and old population show that MBR is moving away from SMC towards the LMC

Results from Zivick et al. (2019)



Vector field of the residual PMs of the stellar populations in the Bridge relative to the SMC based on the Gaia Data Release 2 catalog and from Hubble Space Telescope (HST) Advanced Camera for Surveys data. The RG stars are displayed in red, and the MS stars are in blue.

Classical pulsators in the Magellanic Bridge

History:

- Soszyński et al. (2015), as part of the OGLE Collection of Variable Stars (OCVS), published a list of classical Cepheids (CCs) including new discoveries located in the MBR
- Jacyszyn-Dobrzeniecka et al. (2016) studied their three-dimensional distribution and classified nine as MBR members. Five of these objects seem to form a bridge-like connection between the Magellanic Clouds
- The last version of this sample is in the process of publication Jacyszyn-Dobrzeniecka et al. (2019/aph1904.08220).

Types of Cepheids

Classical Cepheids – Population I variable stars

- P = ~ 1 to ~ 200 days (depend on metallicity)
- M = 4–20 $M_\odot$ and L = up to 100000 $L_\odot$
- yellow bright giants and supergiants of spectral class F6–K2
- Some hundreds Myr old

Type II Cepheids – Population II variable stars

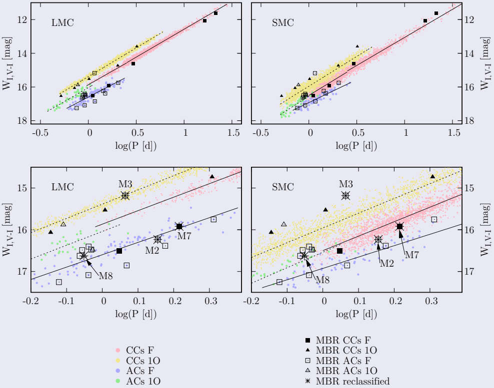
- P = 1 to 50 days
- M = ~ 0.5 $M_\odot$
- typically metal-poor, old (10 Gyr), low mass objects

Anomalous Cepheids – a group of pulsating stars on the instability strip

- P = less than 2 days
- M = 1–2 $M_\odot$
- Evolutionary: (1) intermediate-age stars with exceptionally low metallicity, or (2) they are coalesced old binary stars

Cepheids in MCs and MBR region

From Jacyszyn-Dobrzeniecka et al. (2019)

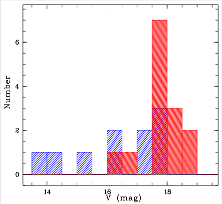


Period-luminosity relations for classical and anomalous Cepheids in the LMC and SMC

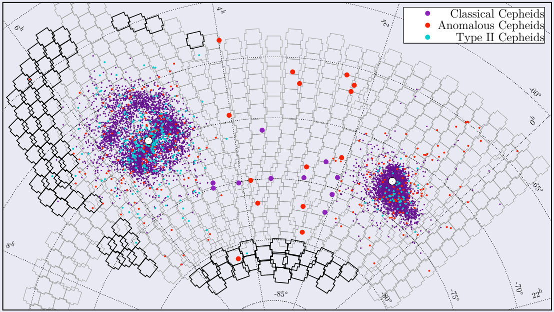
Our Sample

The total sample consist of 24 stars in the region of MBR: 10 classical Cepheids and 14 anomalous Cepheids.
Only 19 of them could be observed with SALT.

V-magnitudes for our sample



The sky distribution of Cepheids from our sample



Immediate Objectives

- We propose to acquire intermediate-resolution long-slit spectra (R$\sim$ 1000) for 19 out of 24 classical and anomalous Cepheids in the region of MBR to get $V_r \leq 10 - 20$ km/s
- The brightest ones could be additionally observed with echelle (R$\sim$ 35000) to make available detailes analysis of abundances
- If the Cepheids we propose to observe have indeed [Fe/H] ≈ -1.0 dex or even less, they will be the most-metal-poor Cepheids ever observed.
- The most-metal-poor Cepheids will be of paramount importance for the stellar pulsations modelling and more importantly, to the extragalactic distance scale as they will enable us to investigate the possiblle metallicity dependence of the period-luminosity relations down to lower metallicities. They would also be of interest for future Cepheid studies in lower-metallicity dIrrs.

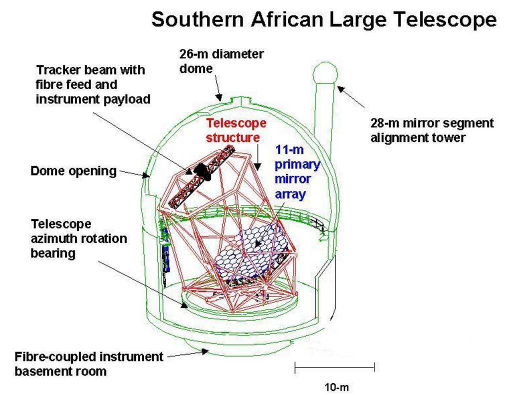
South African Astronomical Observatory (SAAO) and Southern African Large Telescope (SALT)

Sutherland

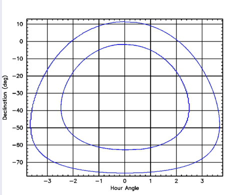
Telescopes at Sutherland

SALT is a specific telescope

SALT design



SALT visibility diagram



Observations, Data Reduction and Analysis

Observations with SALT

- Long-slit spectra with R$\sim$ 1000 were obtained for all 19 Cepheids
- Echelle spectra with R$\sim$ 35000 were obtained for three brightest classical Cepheids

Data Reduction and Analysis

- Primary Data Reduction with SALT pipeline (Crawford et al.,2010)
- Long-slit Data Reduction with SHyRAF (SHell+IRAF+MIDAS+...) by system RAIL created by Alexei Knyazev (SALT Report, 2006)
- Echelle Data Reduction with SALT HRS MIDAS pipeline (Kniazev et al. 2016) and used currently as the standard HRS data pipeline (`http://astronomers.salt.ac.za/software/hrs-pipeline/`)
- Data analysis of all taken spectral data using FBS software written by Ivan Katkov (MSU, Russia) and tested by Alexei Kniazev

Spectral data Analysis

Python software for the analysis of HRS spectra of binary systems

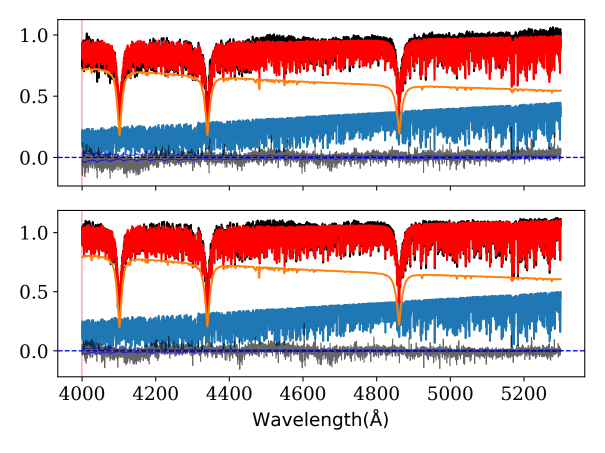
Software was designed to calculate amount of stellar parameters and velocities for components of binary systems:

- T_{eff1}, T_{eff2} (fix, = and !=)
- log g_1, log g_2 (fix, = and !=)
- $[M/H]_1$, $[M/H]_2$ (fix, = and !=)
- V $\sin(i)_1$, V $\sin(i)_2$ (fix, = and !=)
- E(B-V) (fix and =)
- Weight of each component into spectrum $(K_1 + K_2 = 1)$ (fix, = and !=)
- V_{hel1}, V_{hel2} – first spectrum (fix and !=)
  V_{hel1}, V_{hel2} – second spectrum (fix and !=)
  ...
  V_{hel1}, V_{hel2} – n-th spectrum (fix and !=)

Software is based on the stellar libraries like Coelho (2014) or Tlusty (http://nova.astro.umd.edu/), that were rebined to HRS LR/MR/HR resolutions using equstions for $R(\lambda)$ from Kniazev et al. (2019).

Example of our analysis of HRS Spectra

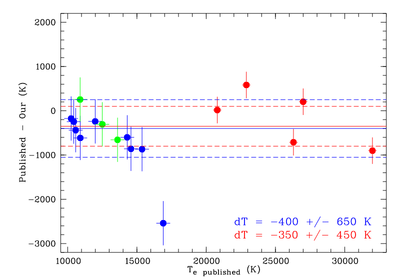
FP Car binary system



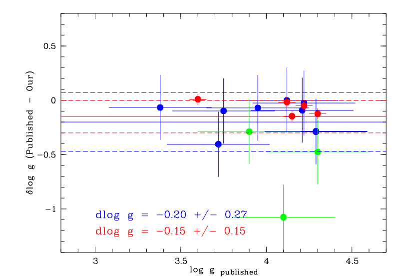
Calculation of External accuracy

The sample of early and late B-type stars based on FEROS echelle spectra and published by Hempel et al. (2003), Nieva et al. (2012) and Bailey et al. (2013).

Comparison for T_{eff}

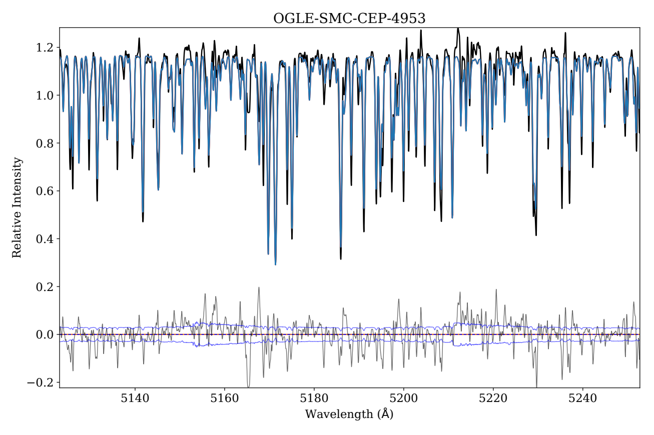


Comparison for log g



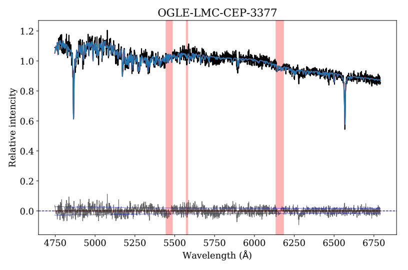
Analysis of Echelle data

Small part of SALT HRS spectrum of one Classical Cepheid

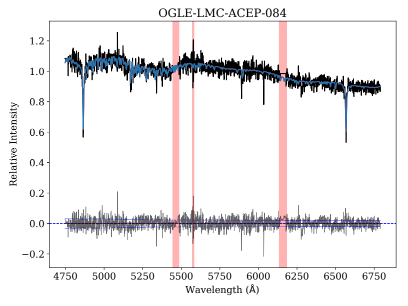


Analysis of RSS data

Spectrum of one classical Cepheid

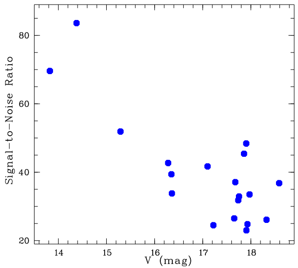


Spectrum of one anomalous Cepheid

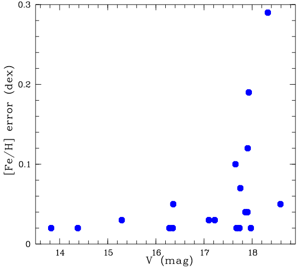


Long-slit Data quality

Median value of SNR for our long-slit spectra



The errors of metallicity obtained from RSS long-slit spectra



Comparison of HRS and RSS data

Parameters and Abundances from HRS data

T_{eff} = 5260 K
log g = 0.70

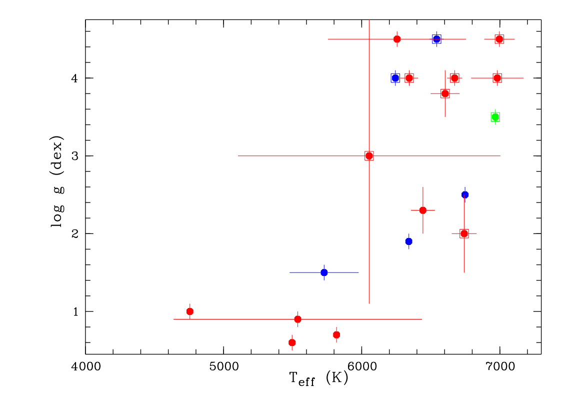
Ion	[M/H]	NL	log(M/H)
OI	-0.64±0.03	2	8.17
CI	-1.22±0.14	4	7.34
NI	-0.55±0.04	2	7.60
MgI	-0.81±0.00	1	6.79
AlI	-1.06±0.00	1	5.24
SiI	-0.75±0.16	9	6.76
SiII	-0.77±0.28	2	6.74
TiI	-0.67±0.08	7	4.28
TiII	-0.91±0.21	2	4.03
FeI	-0.74±0.11	144	6.76
FeII	-0.75±0.10	18	6.75

Parameters from RSS data

T_{eff} = 5530±50 K
log g = 1.00±0.1 dex
[M/H] = -0.58±0.14 dex

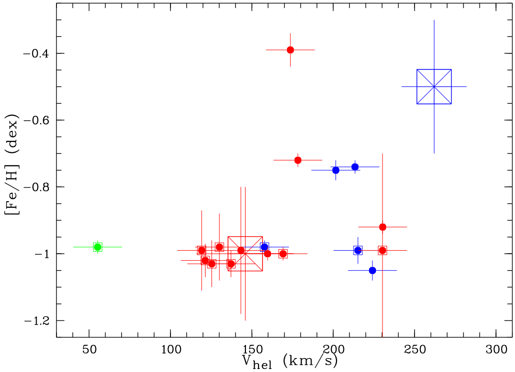
Result (1)

$T_{\rm eff}$ versus log(g) found with our FBS software for RSS spectra of 19 Cepheids from the Magellanic Bridge



Result (2)

$T_{\rm eff}$ versus log(g) found with our FBS software for RSS spectra of 19 Cepheids from the Magellanic Bridge



Conclusions

1. Echelle spectra of three classical Cepheids and Long-slit spectra of 19 classical and anomalous Cepheids were obtained
2. All taken data were reduced and primarily analysed
3. We are able to separate classical and anomalous Cepheids on the base of our long-slit spectral data with probability more than 90%
4. Our primarily analysis shows that 14 out of 19 observed Cepheids have metallicities and velocities close to SMC and possibly were formed from its material