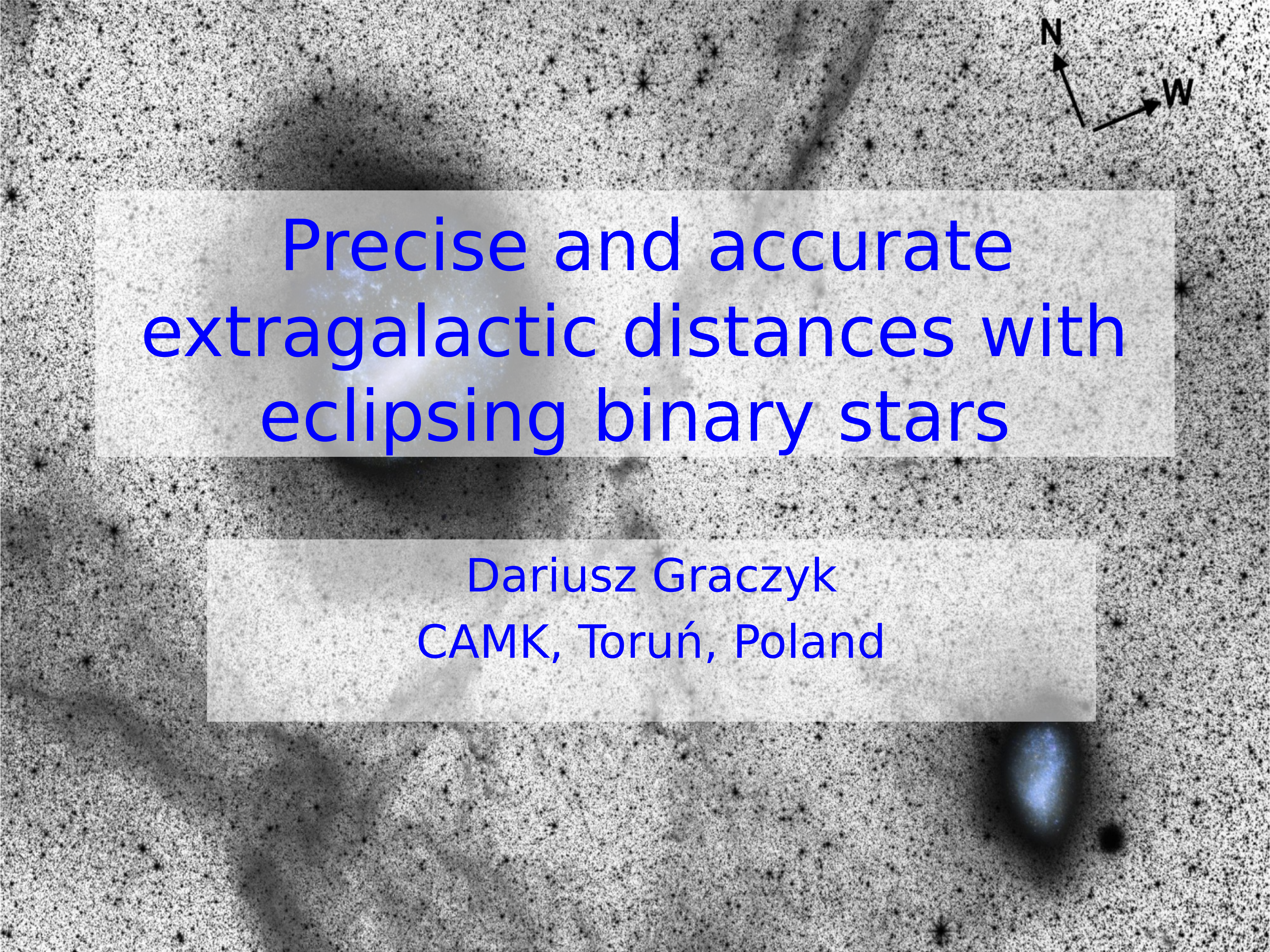
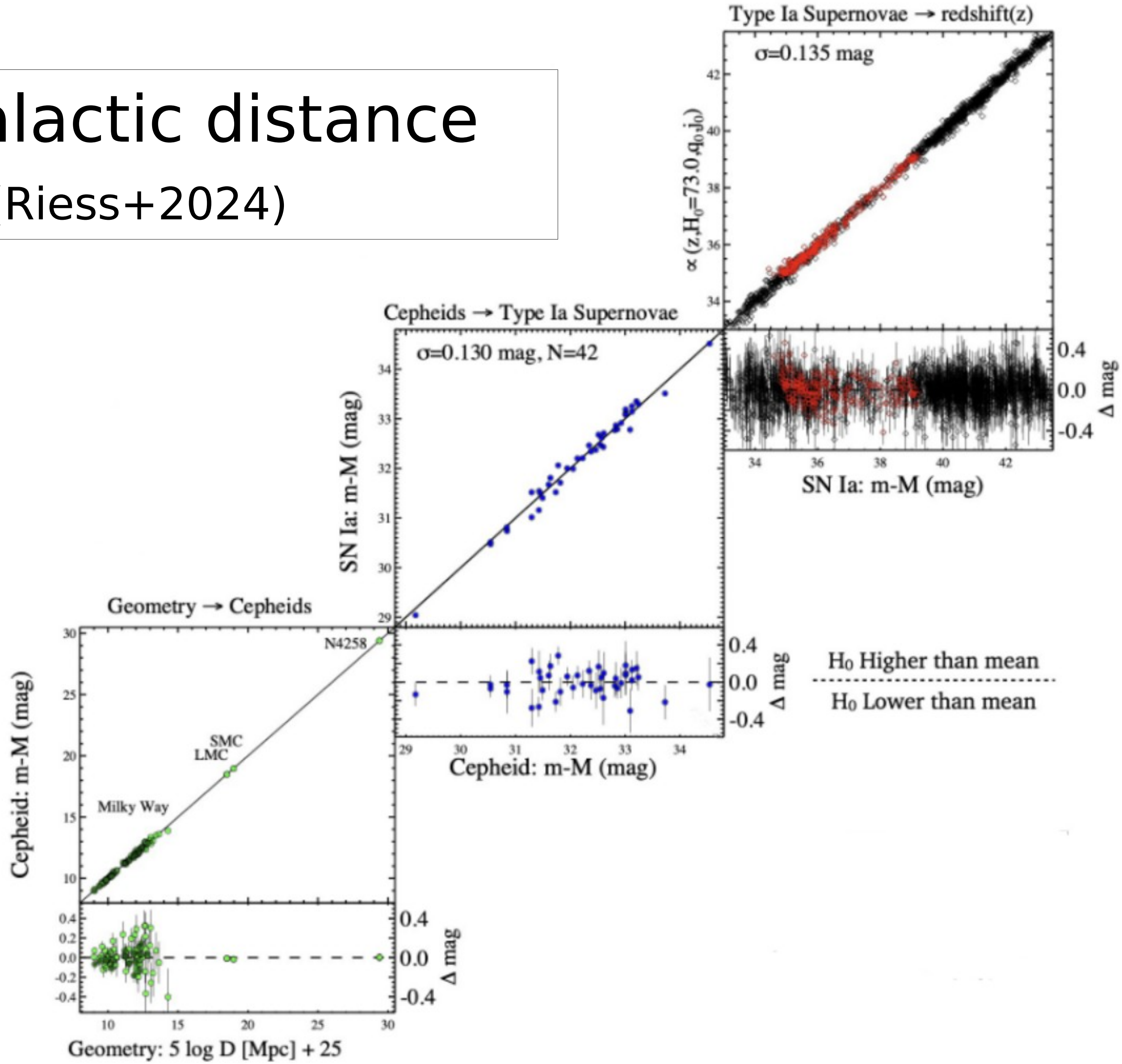
Precise and accurate extragalactic distances with eclipsing binary stars

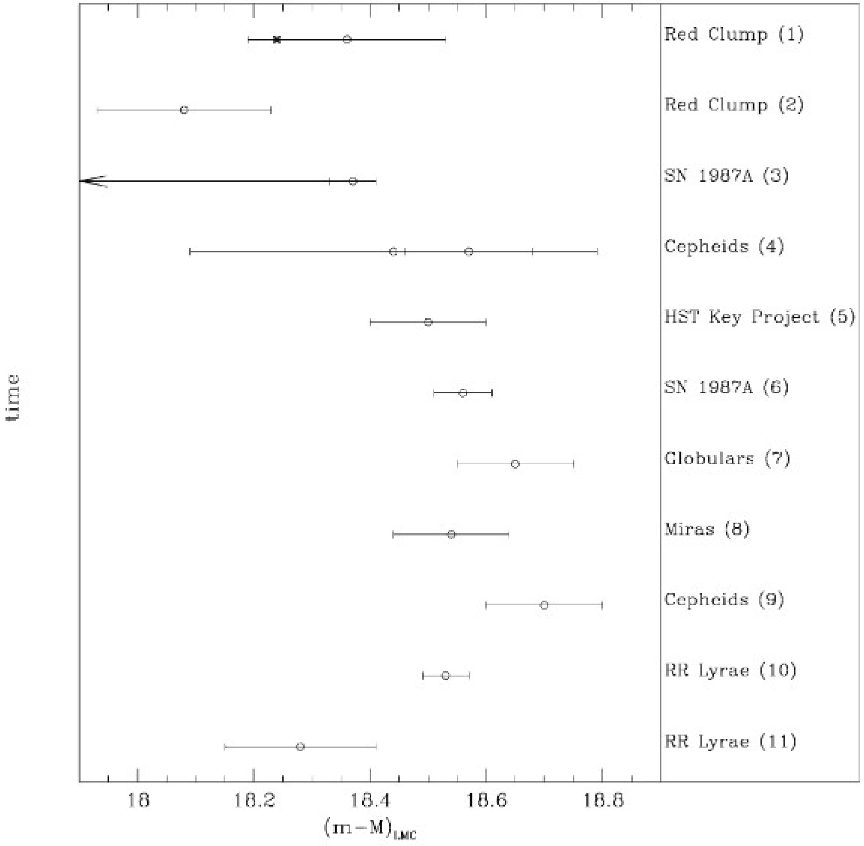
Dariusz Graczyk
CAMK, Toruń, Poland



Extragalactic distance ladder (Riess+2024)



The LMC distance dispute



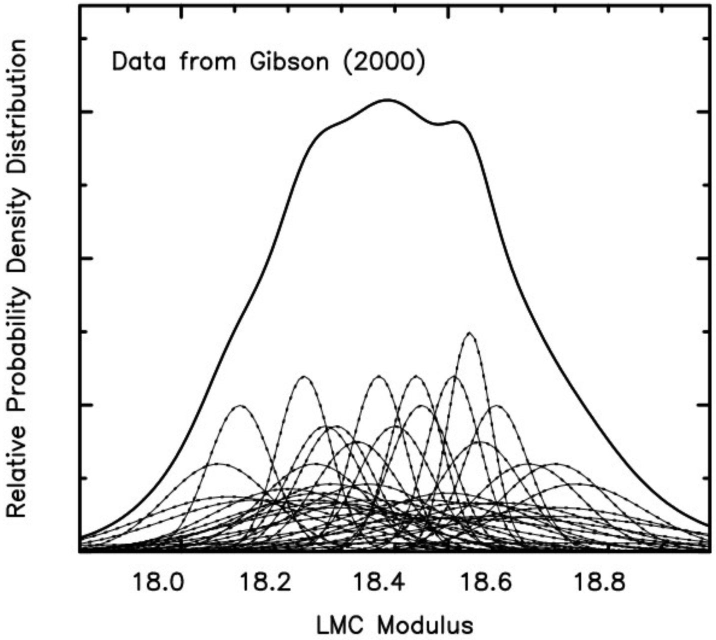
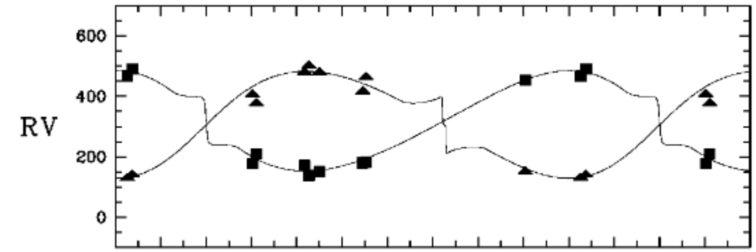


FIG. 5.—Frequentist probability density; distribution of LMC distance moduli as compiled by Gibson (2000) plotted as a continuous probability density distribution built up from the sum of individual unit-area Gaussians centered at the quoted modulus, and broadened by the published internal random error.

Cole,1998,ApJL,500,137

$(m\text{-}M)_{LMC}$=18.50±0.10 mag
Freedman+2001(ApJ,553,47)

THE ASTROPHYSICAL JOURNAL, 509:L21–L24, 1998 December 10

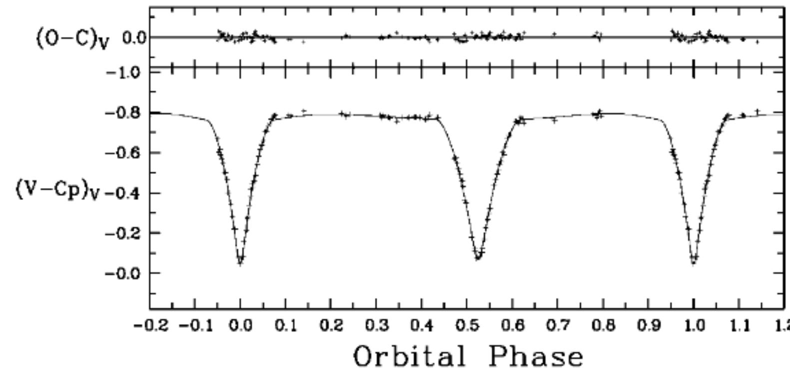


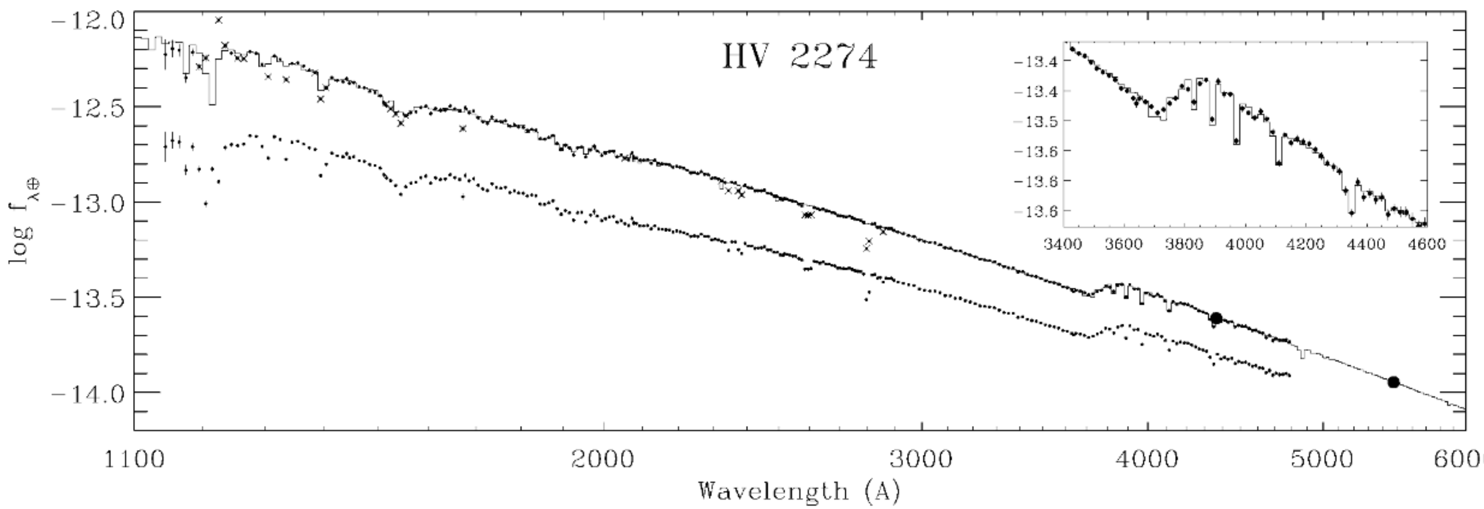
THE DISTANCE TO THE LARGE MAGELLANIC CLOUD FROM THE ECLIPSING BINARY HV 2274

E. F. GUINAN,[1] E. L. FITZPATRICK,[1] L. E. DEWARF,[1] F. P. MALONEY,[1] P. A. MAURONE,[1] I. RIBAS,[2]
J. D. PRITCHARD,[3] D. H. BRADSTREET,[4] AND A. GIMÉNEZ[5]
Received 1998 August 28; accepted 1998 October 20; published 1998 October 29

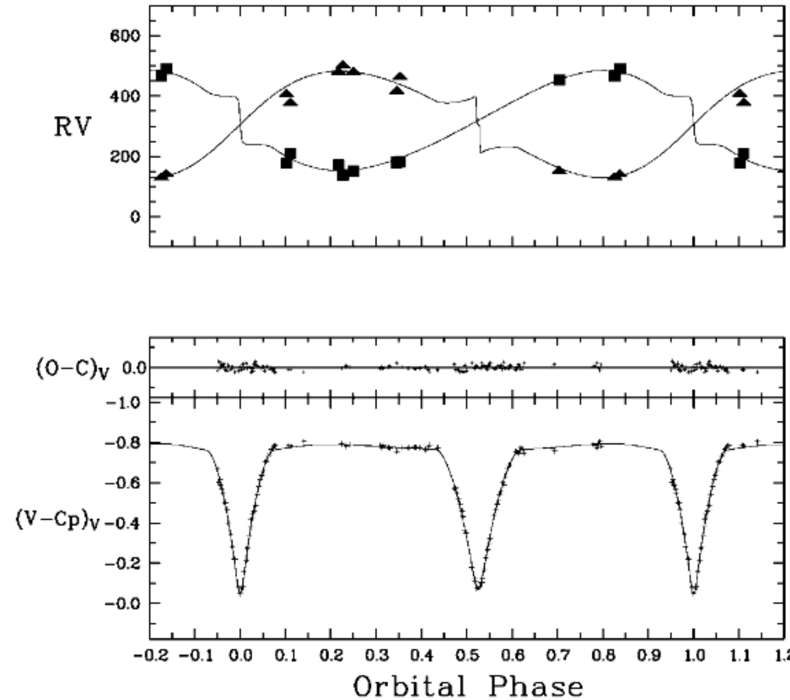
ABSTRACT

The distance to the Large Magellanic Cloud (LMC) is crucial for the calibration of the cosmic distance scale. We derive a distance to the LMC based on an analysis of ground-based photometry and *Hubble Space Telescope* (*HST*)–based spectroscopy and spectrophotometry of the LMC-eclipsing binary system HV 2274. Analysis of the optical light curve and the *HST*/Goddard High-Resolution Spectrograph, radial velocity curve provides the masses and radii of the binary components. Analysis of the *HST*/Faint Object Spectrograph, UV/optical spectrophotometry provides the temperatures of the component stars and the interstellar extinction of the system. When combined, these data yield a distance to the binary system. After correcting for the location of HV 2274 with respect to the center of the LMC, we find $d_{\rm LMC} = 45.7 \pm 1.6$ kpc or $(V_0 - M_v)_{\rm LMC} = 18.30 \pm 0.07$ mag. This result, which is immune to the metallicity-induced zero-point uncertainties that have plagued other techniques, lends strong support to the "short" LMC distance scale as derived from a number of independent methods.





THE ASTROPHYSICAL JOURNAL, 509:L21–L24, 1998 December 10



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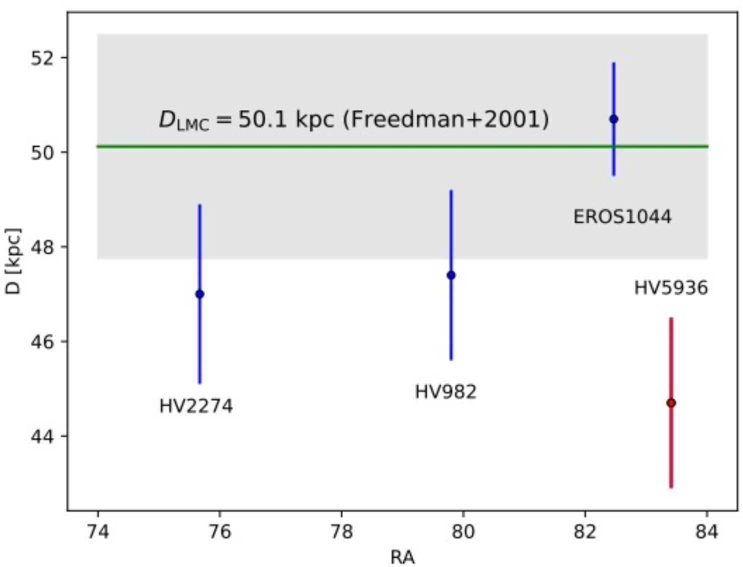
independent methods.



THE ASTROPHYSICAL JOURNAL, 509:L21–L24, 1998 December 10

THE DISTANCE TO THE LARGE MAGELLANIC CLOUD FROM THE ECLIPSING BINARY HV 2274

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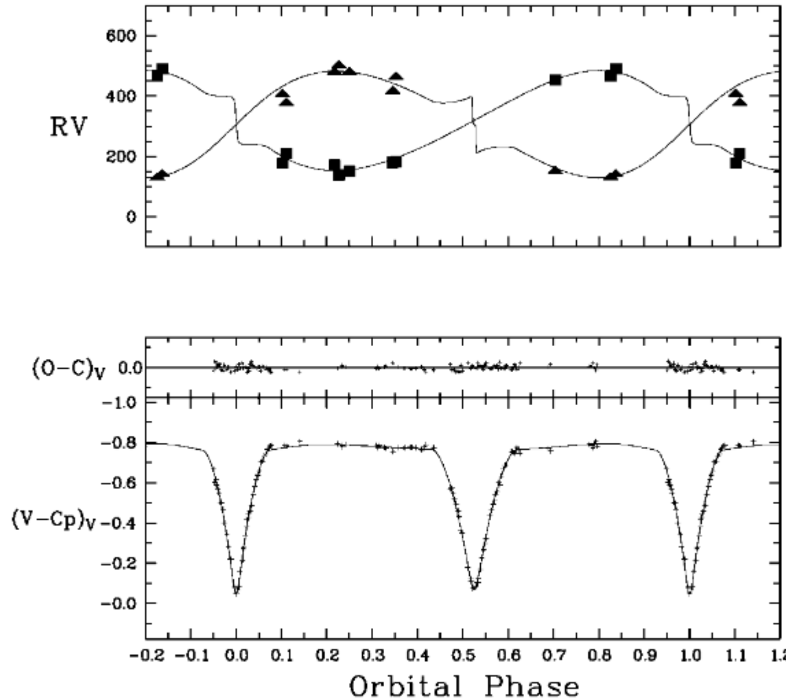
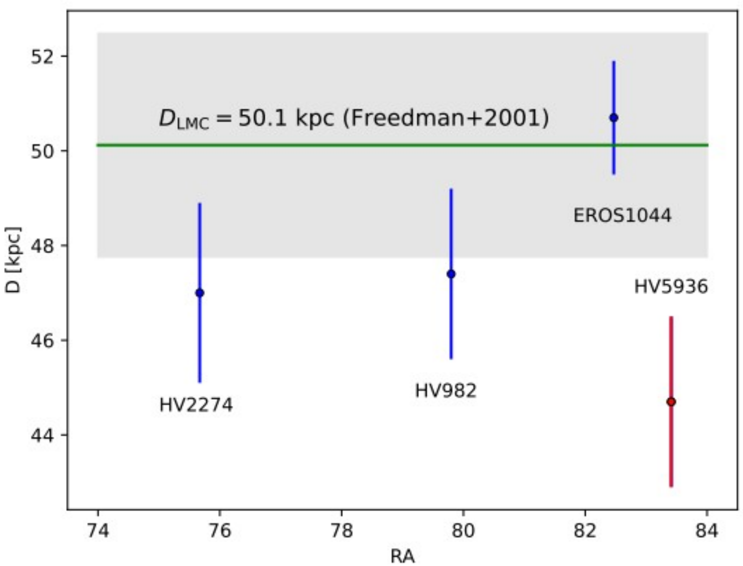




Systematic uncertainties:

- use of theoretical models of hot stars to predict fluxes
- model dependent determination of the extinction
- HV5936 – semidetached configuration

1996:

Detached eclipsing binaries as primary distance and age indicators †

By BOHDAN PACZYŃSKI

Princeton University Observatory, 124 Peyton Hall, Princeton, NJ 08544-1001, USA

Detached eclipsing double line spectroscopic binaries offer an opportunity to measure directly stellar parameters: mass, luminosity, radius, as well as the distance. The only non-trivial step is the need to determine surface brightness of each component on the basis of something measurable, like the color or the line ratios. Modern model atmospheres provide a fairly good calibration of that relation, but empirical verification is possible, and it is needed to achieve the highest accuracy. When this approach is fully developed the detached eclipsing binaries should provide direct (single step) distances with $\sim 1\%$ accuracy to all galaxies in the Local Group.

2001:

PHOTOMETRIC SOLUTIONS FOR DETACHED ECLIPSING BINARIES: SELECTION OF IDEAL DISTANCE INDICATORS IN THE SMALL MAGELLANIC CLOUD

J. S. B. WYITHE[1,2] AND R. E. WILSON[3]

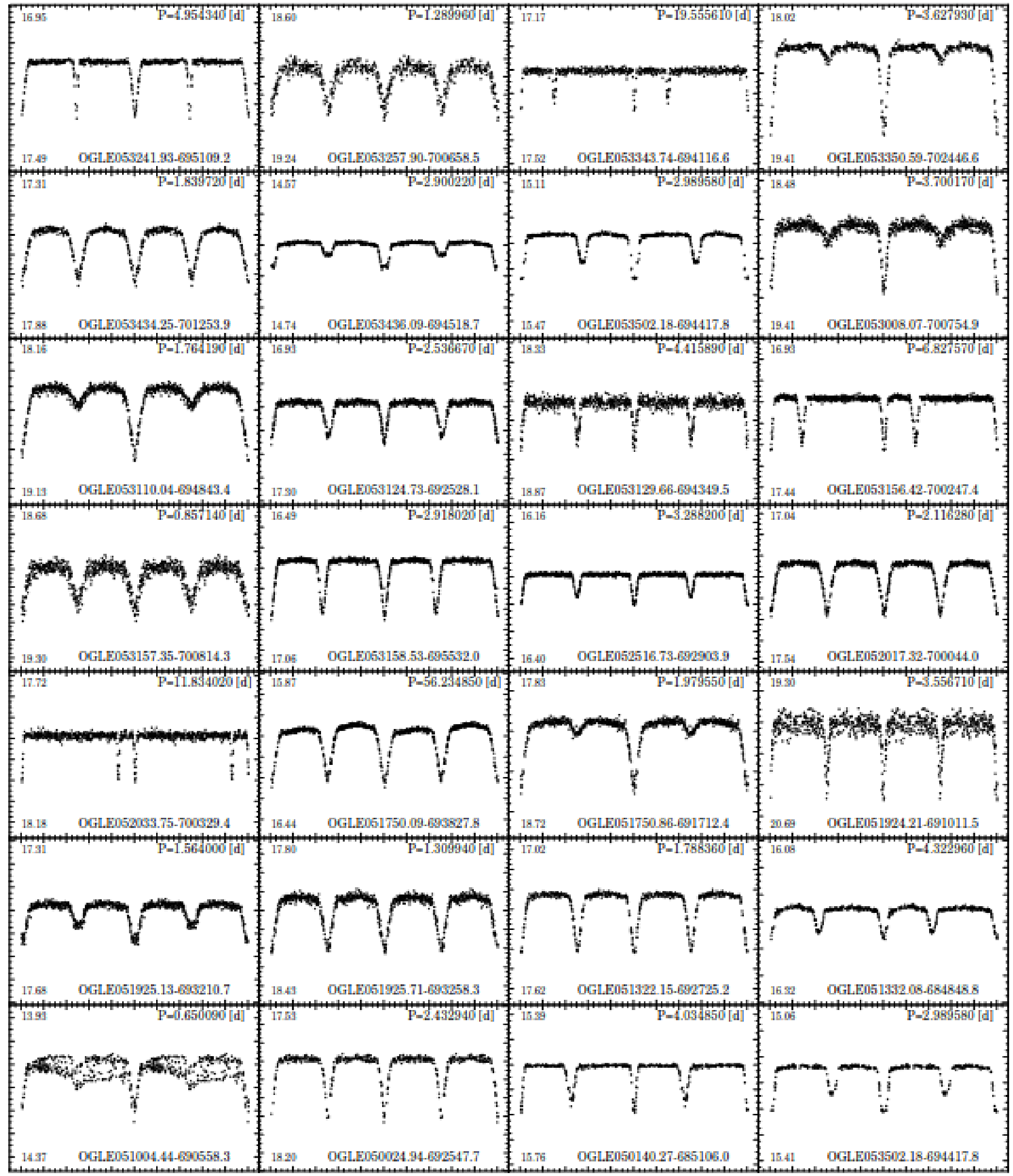
Received 2001 April 5; accepted 2001 May 23

ABSTRACT

Detached eclipsing binary stars provide a robust one-step distance determination to nearby galaxies. As a by-product of Galactic microlensing searches, catalogs of thousands of variable stars including eclipsing binaries have been produced by the OGLE, MACHO, and EROS collaborations. We present photometric solutions for detached eclipsing binaries in the Small Magellanic Cloud (SMC) discovered by the OGLE collaboration. The solutions were obtained with an automated version of the Wilson-Devinney program. By fitting mock catalogs of eclipsing binaries, we find that the normalized stellar radii (particularly their sum) and the surface brightness ratio are accurately described by the fitted parameters and estimated standard errors despite various systematic uncertainties. In many cases these parameters are well constrained. In addition, we find that systems exhibiting complete eclipses can be reliably identified where the fractional standard errors in the radii are small. We present two quantitatively selected subsamples of eclipsing binaries that will be excellent distance indicators. These can be used both for computation of the distance to the SMC and to probe its structure. One particularly interesting binary has a very well determined solution, exhibits complete eclipses, and is made up of well-detached G-type class II giants.

Wyrzykowski+2002:
2580 EBs from OGLE-II observations in the Large Magellanic Cloud

5 good candidates:
red, long period, detached eclipsing binaries with giant stars, V≈16-18 mag !



THE ASTROPHYSICAL JOURNAL, 697:862–866, 2009 May 20 doi:10.1088/0004-637X/697/1/862

THE ARAUCARIA PROJECT. DETERMINATION OF THE LARGE MAGELLANIC CLOUD DISTANCE FROM LATE-TYPE ECLIPSING BINARY SYSTEMS. I. OGLE-051019.64-685812.3*

GRZEGORZ PIETRZYŃSKI[1,2], IAN B. THOMPSON[3], DARIUSZ GRACZYK[1], WOLFGANG GIEREN[1], ANDRZEJ UDALSKI[2], OLAF SZEWCZYK[1], DANTE MINNITI[4], ZBIGNIEW KOŁACZKOWSKI[1,5], FABIO BRESOLIN[6], AND ROLF-PETER KUDRITZKI[6]
[1] Universidad de Concepción, Departamento de Astronomia, Casilla 160-C, Concepción, Chile; pietrzyn@astrouw.edu.pl, darek@astro-udec.cl, wgieren@astro-udec.cl, szewczyk@astro-udec.cl, zibi@astro-udec.cl
[2] Warsaw University Observatory, Al. Ujazdowskie 4, 00-478, Warsaw, Poland; udalski@astrouw.edu.pl
[3] Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 911101-1292, USA
[4] Departamento de Astronomia y Astrofisica, Pontificia Universidad Católica de Chile, Casilla 306, Santiago 22, Chile; dante@astro.puc.cl
[5] Astronomical Institute, University of Wroclaw, Kopernika 11, 51-622 Wroclaw, Poland
[6] Institute for Astronomy, University of Hawaii at Manoa, 2680 Woodlawn Drive, Honolulu, HI 96822, USA; bresolin@ifa.hawaii.edu, kud@ifa.hawaii.edu
Received 2008 December 4; accepted 2009 March 11; published 2009 May 5

ABSTRACT

We have analyzed the double-lined eclipsing binary system OGLE-051019.64-685812.3 in the LMC which consists of two G4 giant components with very similar effective temperatures. A detailed analysis of the Optical Gravitational Lensing Experiment *I*-band light curve of the system, radial velocity curves for both components derived from high-resolution spectra, and near-infrared magnitudes of the binary system measured outside the eclipses has allowed us to obtain an accurate orbit solution for this eclipsing binary and its fundamental physical parameters. Using a surface brightness $(V - K)$–color relation for giant stars we have calculated the distance to the system and obtained a true distance modulus of 18.50 mag, with an estimated total uncertainty of $\pm 3\%$.

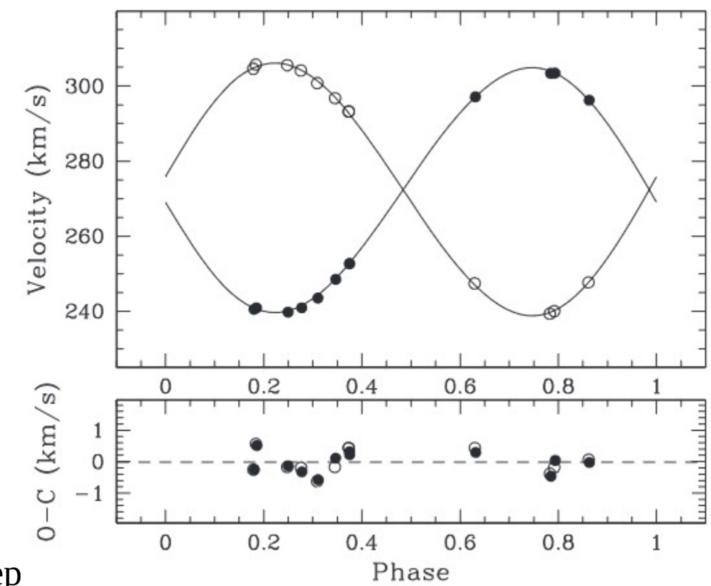
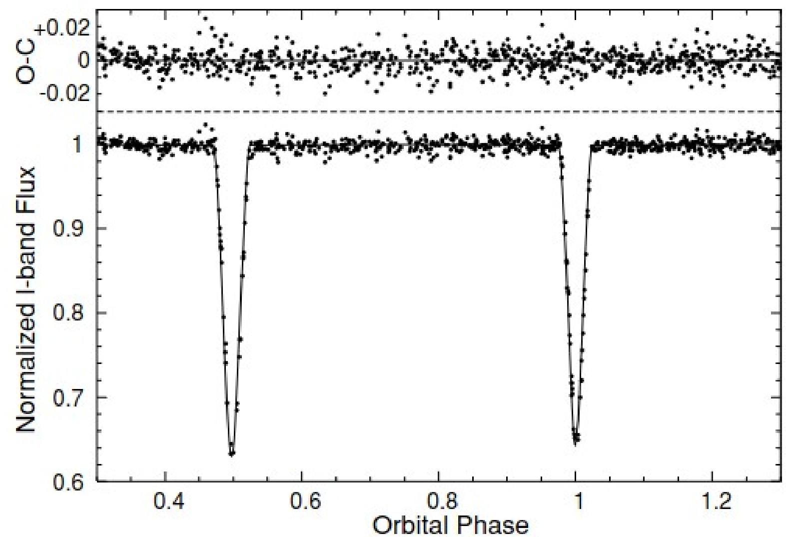
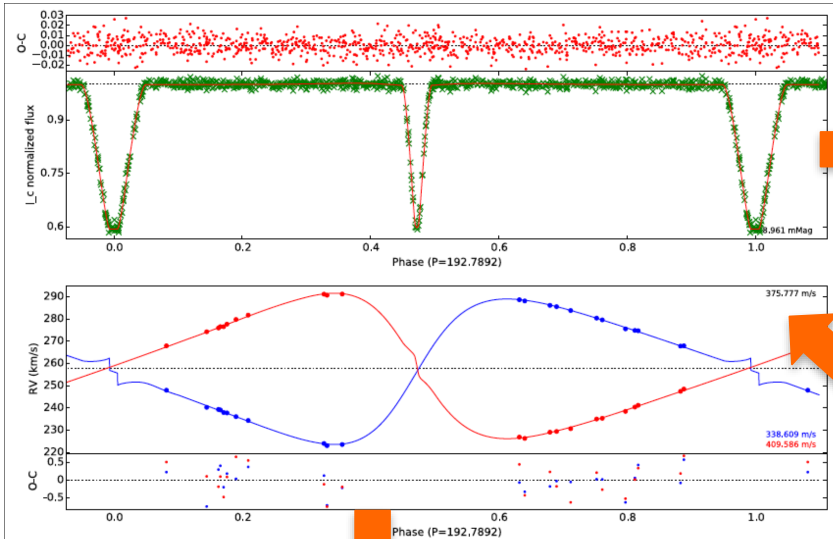
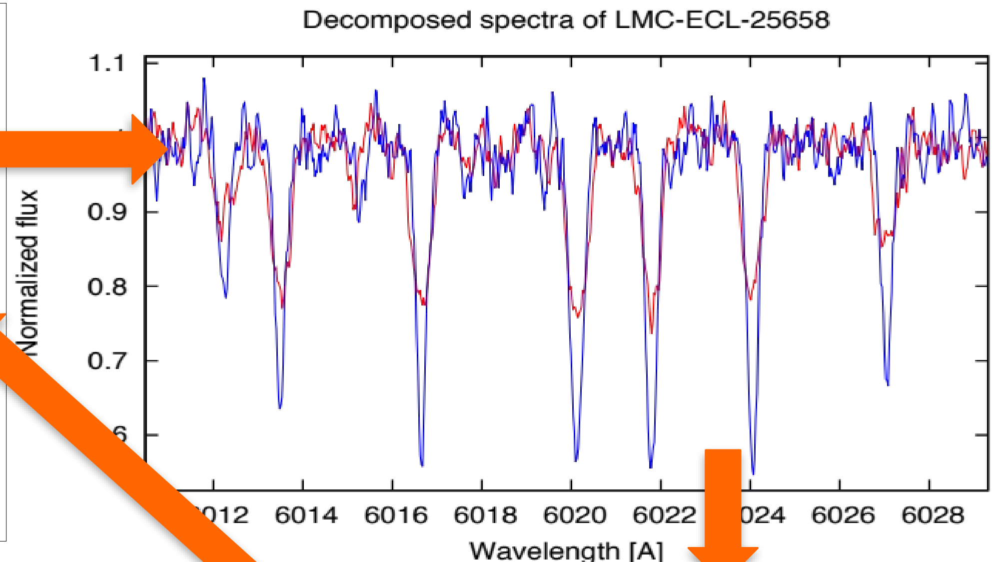


Figure 1. Spectroscopic orbit of OGLE-051019.64-685812.3.







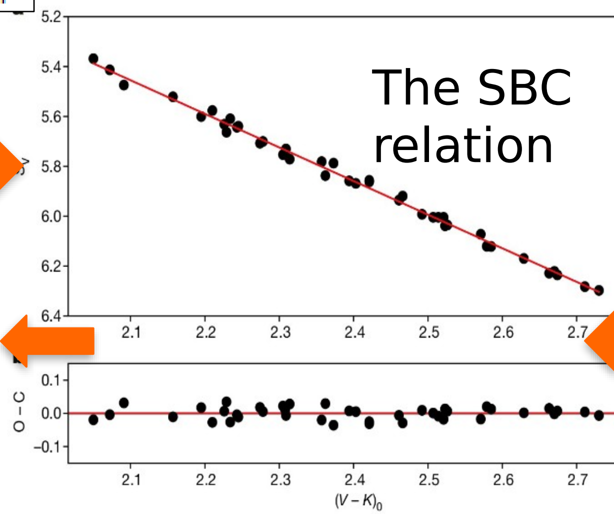
Physical Properties of GLE-LMC-ECL-25658

Property	Primary	Secondary
Spectral Type	G8 III	G9 III
Mass M ($M_\odot$)	2.229 ± 0.019	2.230 ± 0.019
Radius R ($R_\odot$)	21.41 ± 0.15	27.57 ± 0.24

Atmospheric Parameters

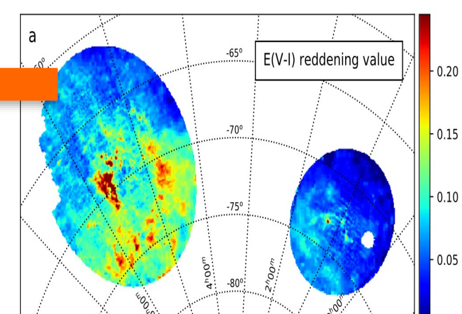
	$T_{\rm eff}$	[Fe/H]	v_t
Primary	4860	−0.65	1.70
Secondary	4730	−0.62	1.80

SOFI, NIR photometry



The SBC relation

Extinction (Skowron+2021)

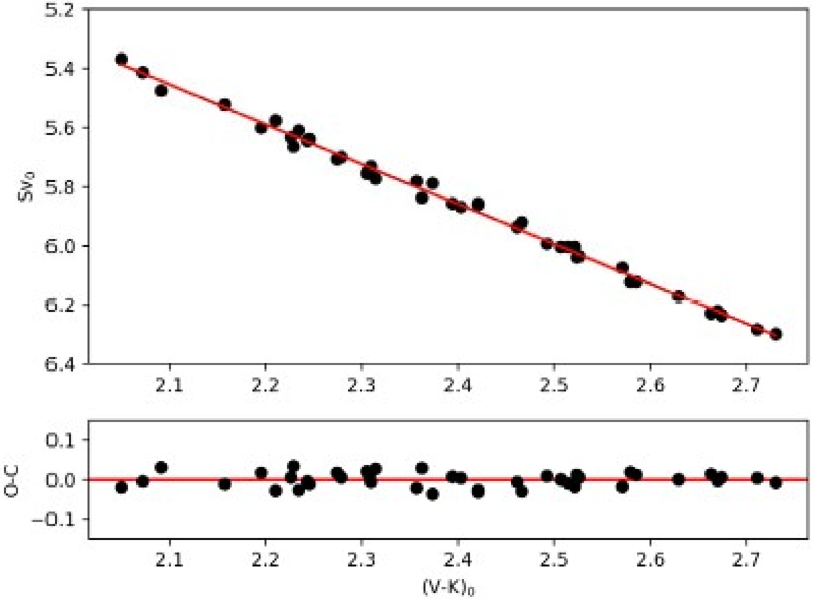


$$d\ [\mathrm{pc}] = 9.2984 \cdot \frac{R\ [R_\odot]}{\phi\ [\mathrm{mas}]}$$

D(25658): 49.03 +/- 0.53 (stat) +/- 1.04 (syst) kpc

Revised eclipsing binary distance to the LMC
(Graczyk+2018, Gallenne+2018, Pietrzyński+2019)

The new surface brightness - color calibration (**0.8%** precision)



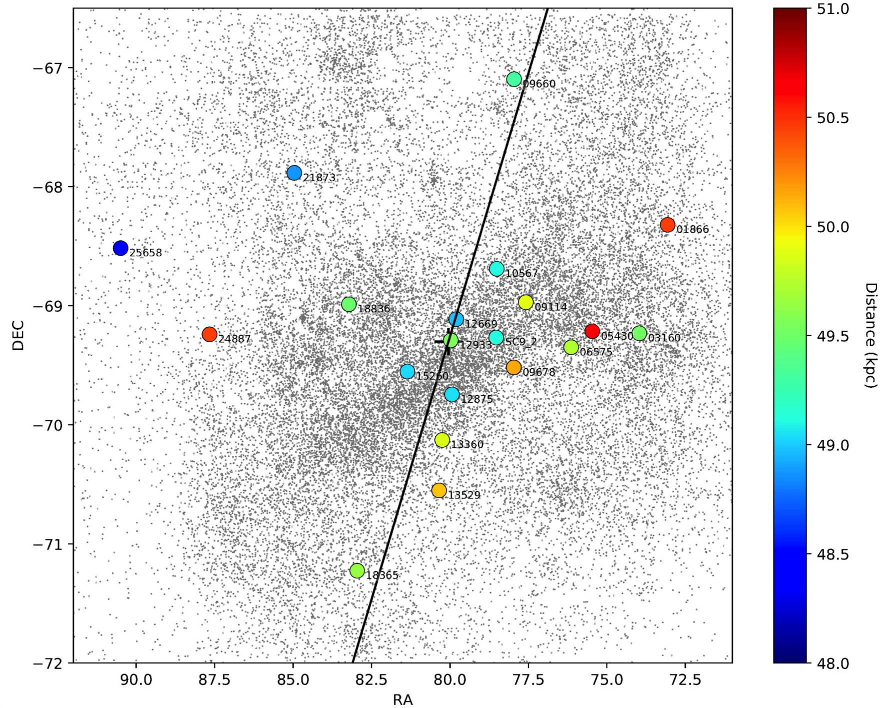
Resulting distance modulus:

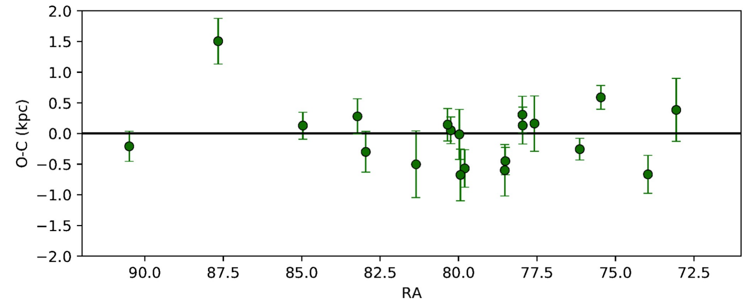
18.477 ± 0.004 ± 0.026 mag

Distance:

49.59 ± 0.09 ± 0.54 kpc, (1.1%)

(Pietrzyński+2019, Natur,567,200)





Distance to the Small Magellanic Cloud (LMC)

THE ASTROPHYSICAL JOURNAL, 904:13 (14pp), 2020 November 20
https://doi.org/10.3847/1538-4357/abbb2b

CrossMark

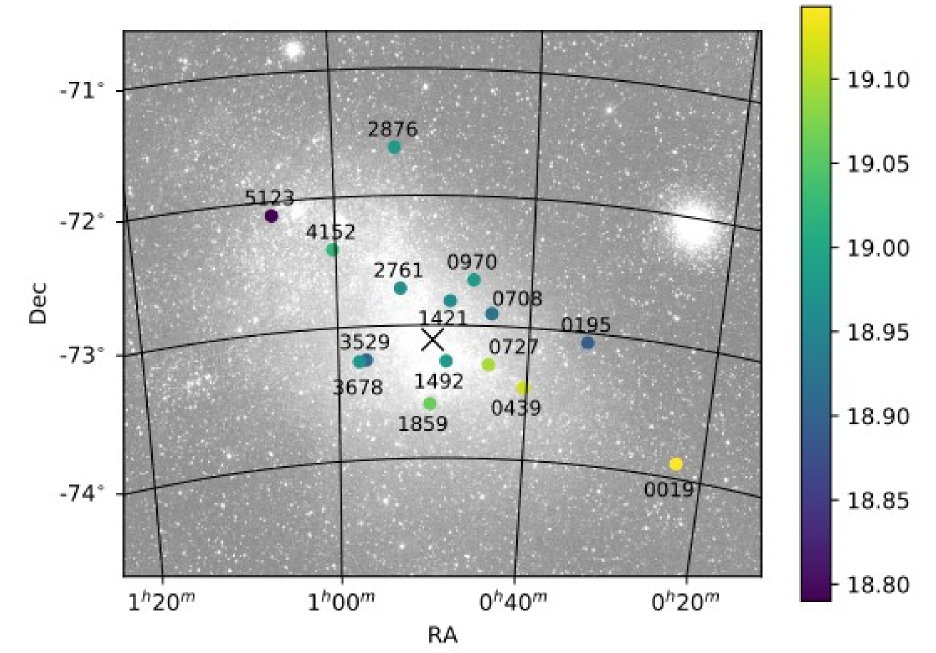
A Distance Determination to the Small Magellanic Cloud with an Accuracy of Better than Two Percent Based on Late-type Eclipsing Binary Stars

Dariusz Graczyk[1], Grzegorz Pietrzyński[2], Ian B. Thompson[3], Wolfgang Gieren[4], Bartłomiej Zgirski[2], Sandro Villanova[4], Marek Górski[2], Piotr Wielgórski[2], Paulina Karczmarek[4], Weronika Narloch[4], Bogumił Pilecki[2], Monica Taormina[2], Radosław Smolec[2], Ksenia Suchomska[2], Alexandre Gallenne[2,5,6,7], Nicolas Nardetto[6], Jesper Storm[8], Rolf-Peter Kudritzki[9,10], Mikołaj Kałuszyński[2], and Wojciech Pych[2]
[1] Centrum Astronomiczne im. Mikołaja Kopernika, Polish Academy of Sciences, Rabiańska 8, 87-100, Toruń, Poland; darek@ncac.torun.pl, darek@astro-udec.cl
[2] Centrum Astronomiczne im. Mikołaja Kopernika, Polish Academy of Sciences, Bartycka 18, 00-716 Warsaw, Poland

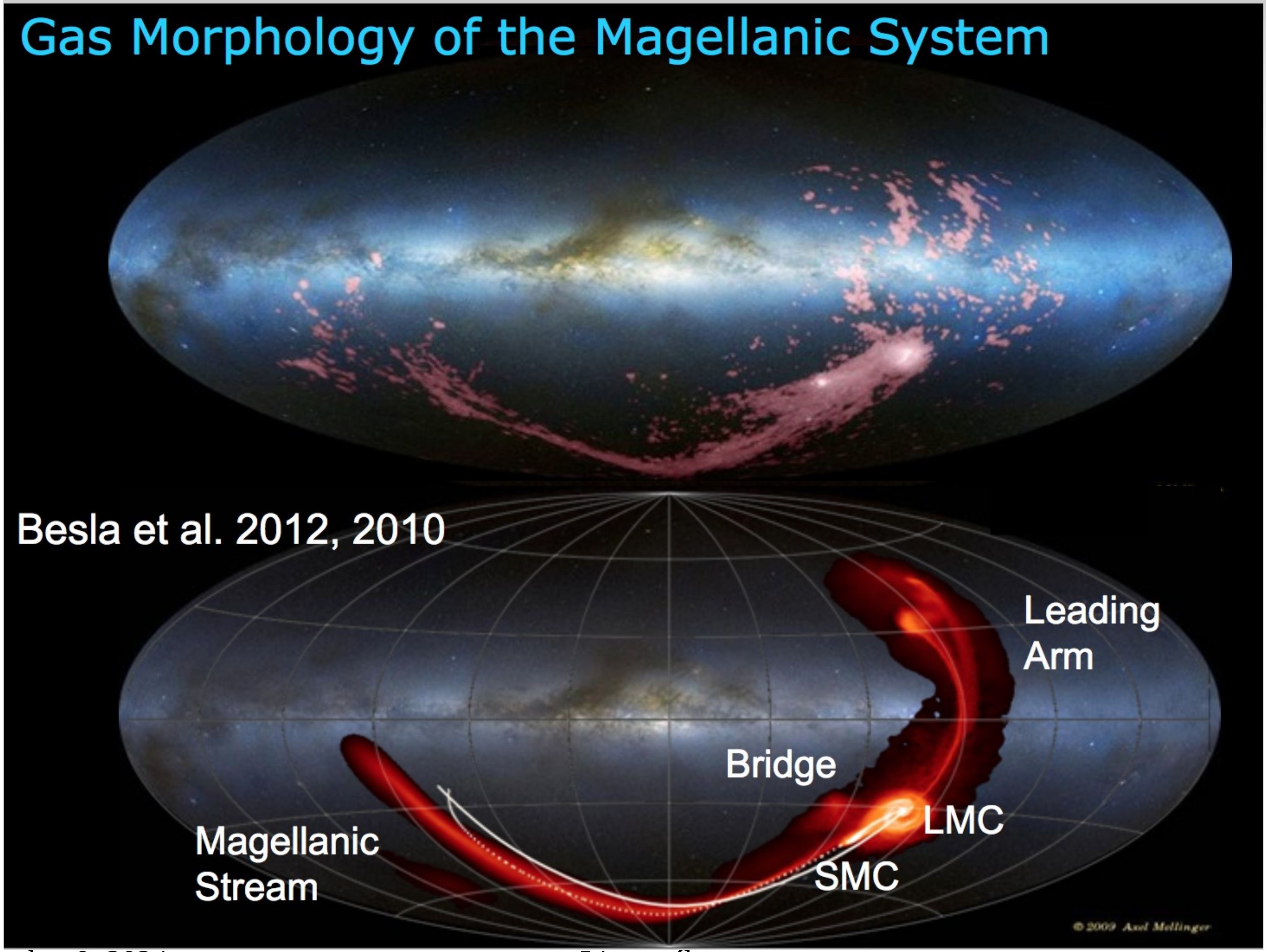
We applied the new SBC relation
(Pietrzynski+2019,Nature,567,200)
to 15 late-type eclipsing binary stars

Resulting distance modulus:
18.977 ± 0.016 ± 0.028 mag
and distance:
62.44 ± 0.47 ± 0.81 kpc
(precision of **1.5%**)

Goal: setting extragalactic distance scale with 1% precision



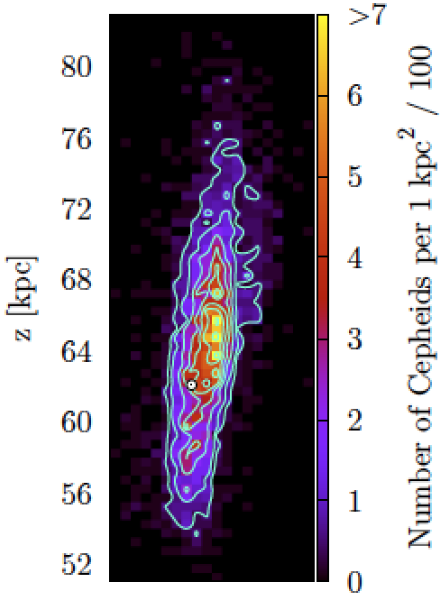
Structure of the SMC

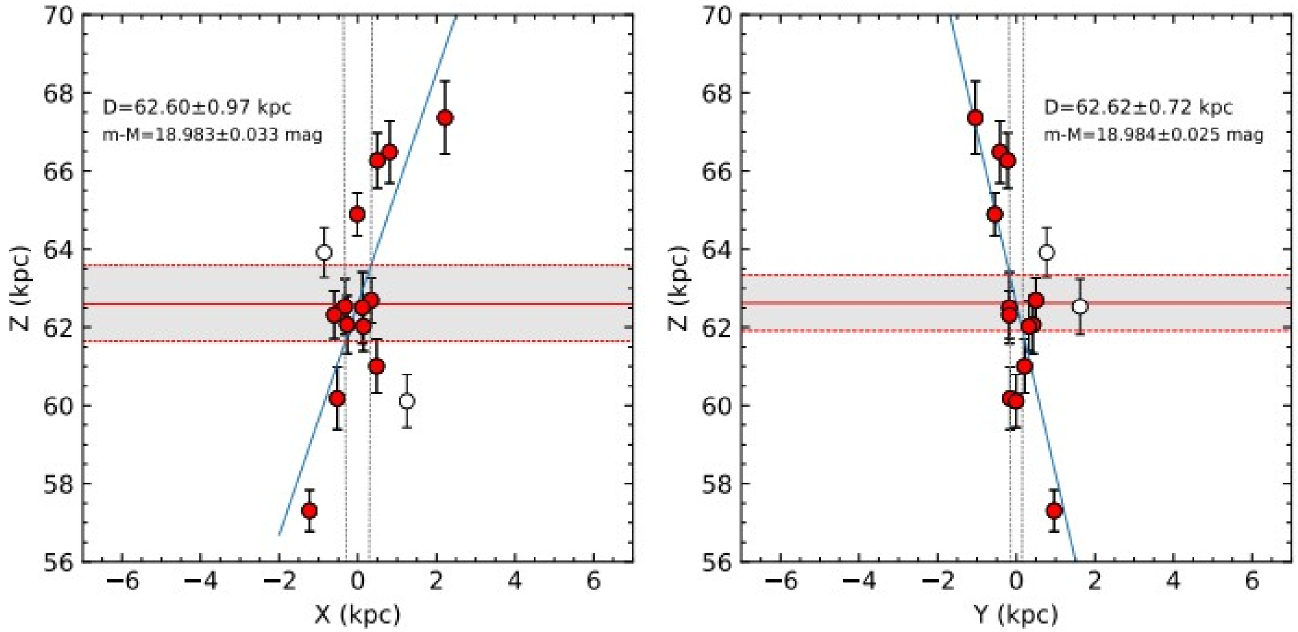


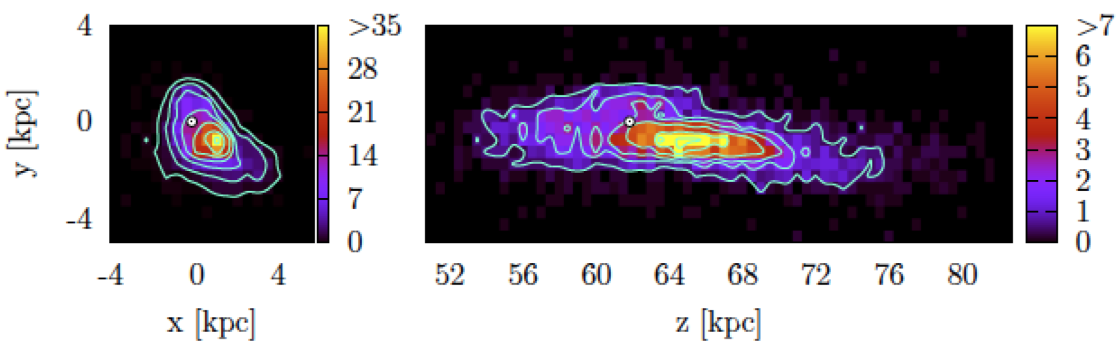
Structure of the SMC

Cepheids

(Jacyszyn-Dobrzeniecka, 2016,AcA)

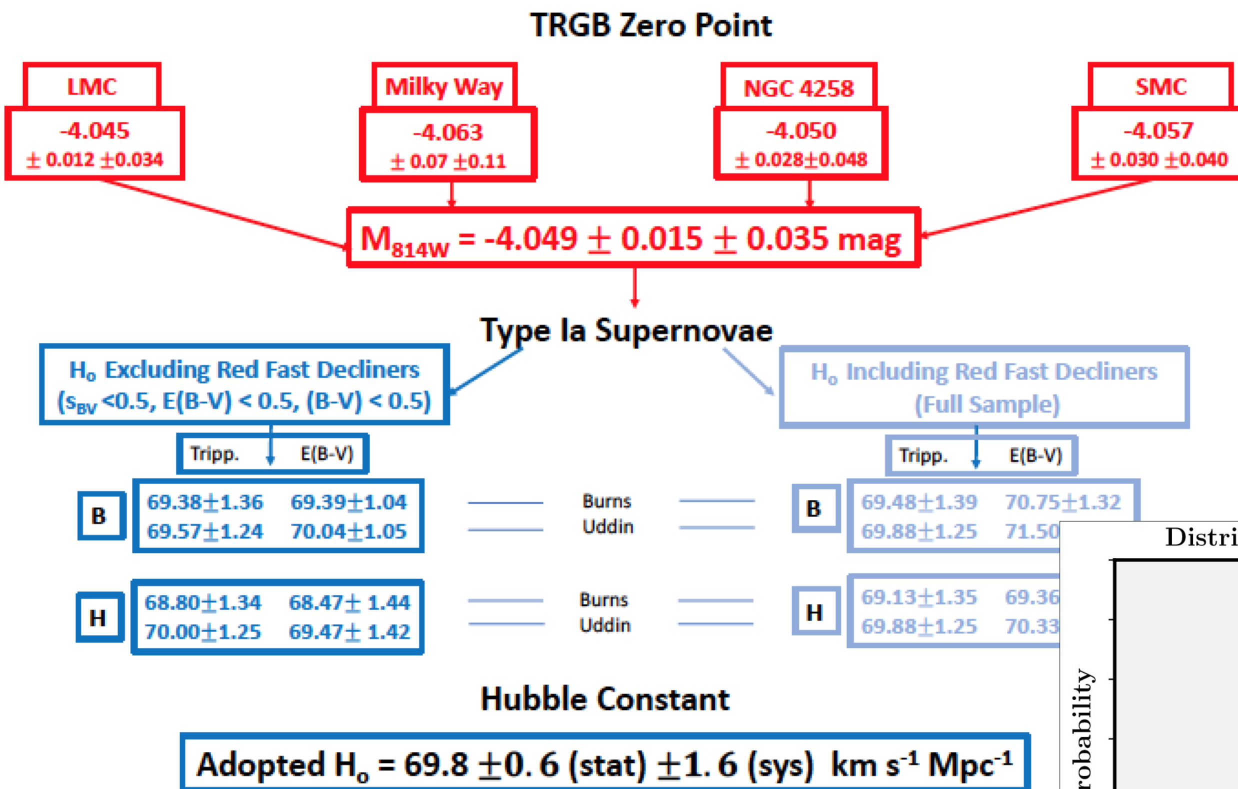


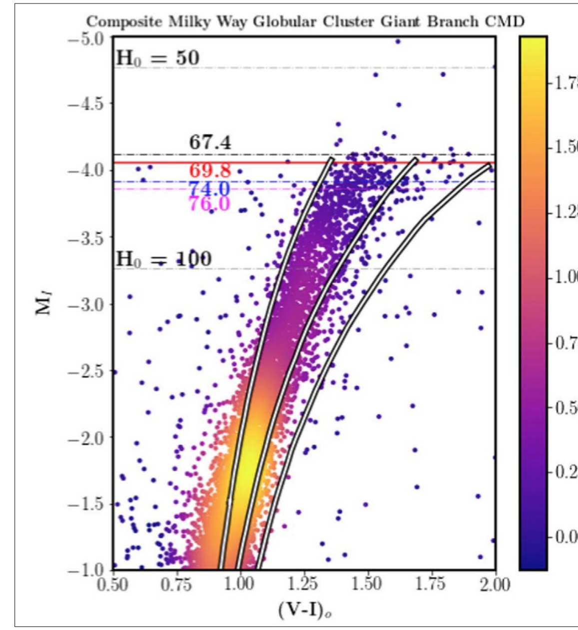


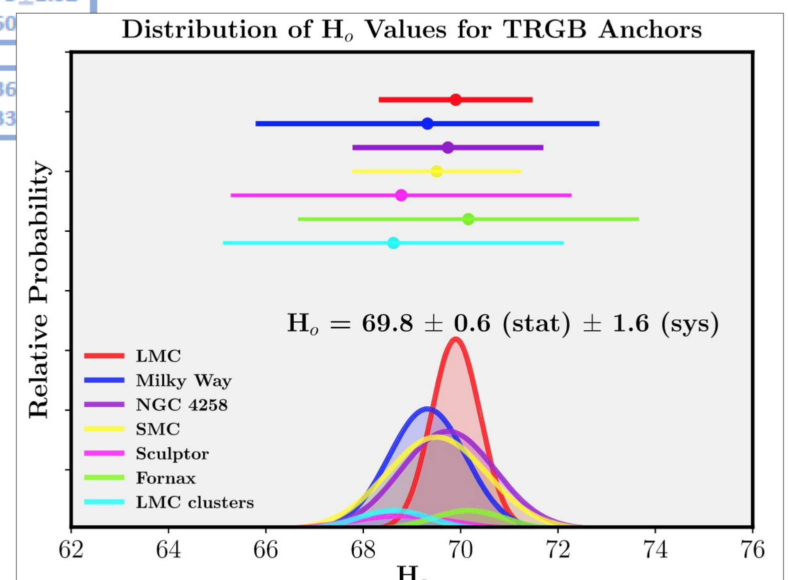


Calibration of the extragalactic distance scale

(e.g. Freedman 2021, ApJ, 919, 16)







Steer(2020,AJ,160,199):

Table 1
Redshift-independent Distance Indicators ($n = 77$)

Indicator	Tree Rank
Primary Standard Candle	
Asymptotic Giant Branch (AGB) Stars	14
Carbon stars	15
Cepheids	1
Color-Magnitude Diagram (CMD)	10
Flux-Gravity-Luminosity Relation (FGLR)	6
Globular Cluster Luminosity Function (GCLF)	9
Horizontal Branch	7
Miras	12
Planetary Nebulae Luminosity Function (PNLF)	13
Red Clump	4
RR Lyrae	3
Surface Brightness Fluctuations (SBF)	8
Supernovae, Type 1a (SNIa)	5
Supernovae, Type 1a SDSS (SNIa SDSS)	16
Tip of the Red Giant Branch (TRGB)	2
Type II Cepheids	11
Primary Standard Ruler	
Eclipsing Binary	1
Globular Cluster (GC) Radius	4
Maser	2
Proper Motion	5
Supernovae, Type II (SNII Optical)	3

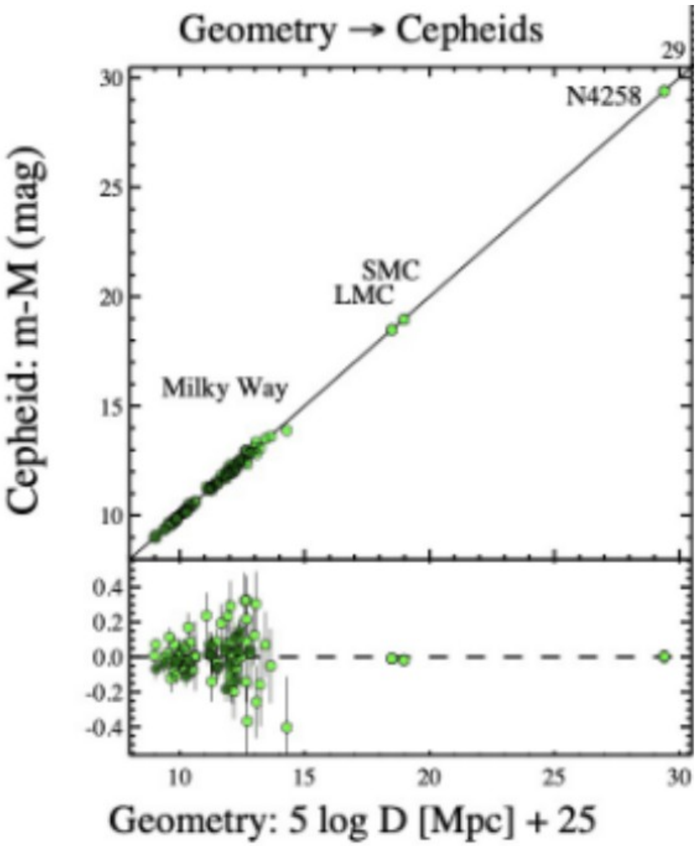
Advantages of measuring distances with eclipsing binary stars:

Near-geometric method, as long as a SBCR is used!
Only little sensitive to the reddening, as long as …
Well known physics used in data analysis
Potentially a lot of candidate targets in any galaxy

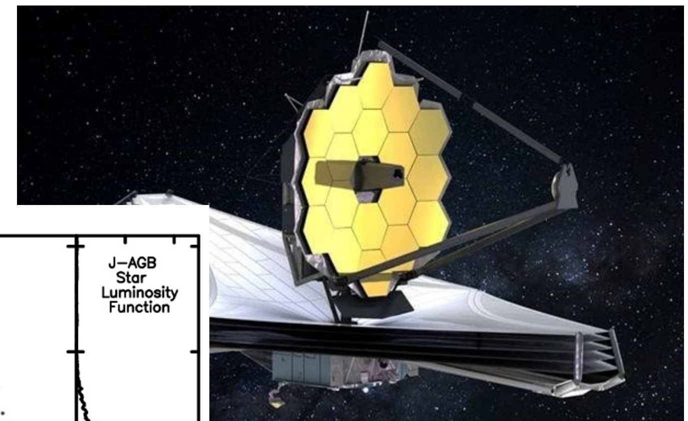
Disadvantages:

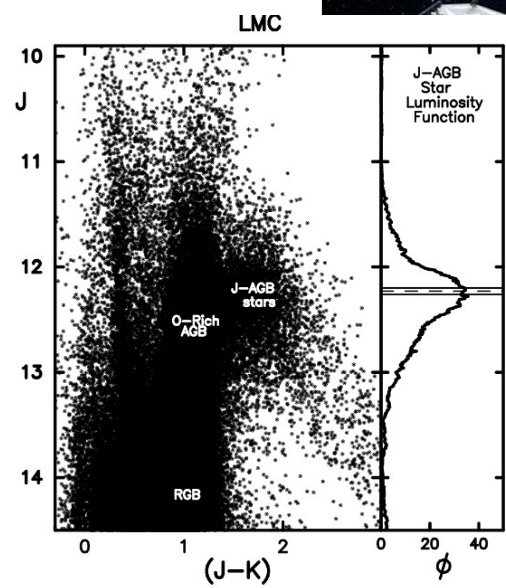
Time expensive – observations and data analysis
Requires large telescopes even in closest galaxies and limited to about 1 Mpc with present facilities
Sensitive to unrecognized multiplicity
Lack of precise SBCR for massive, bright stars

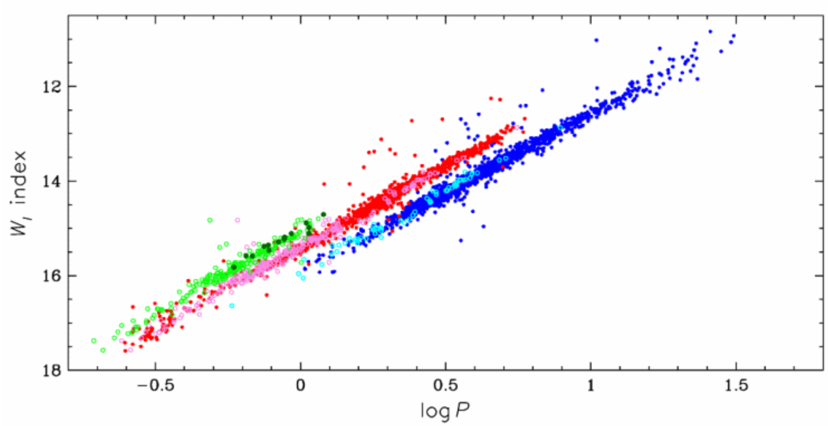
Beyond Magellanic Clouds

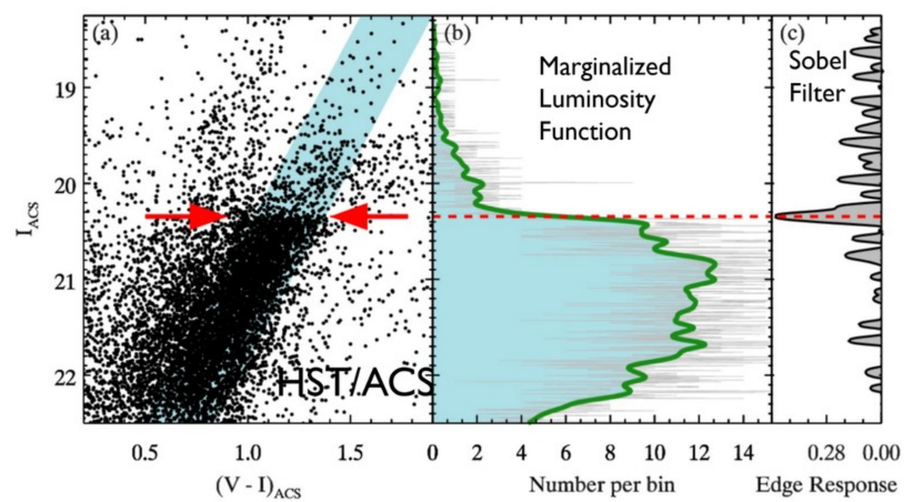


James Webb Telescope

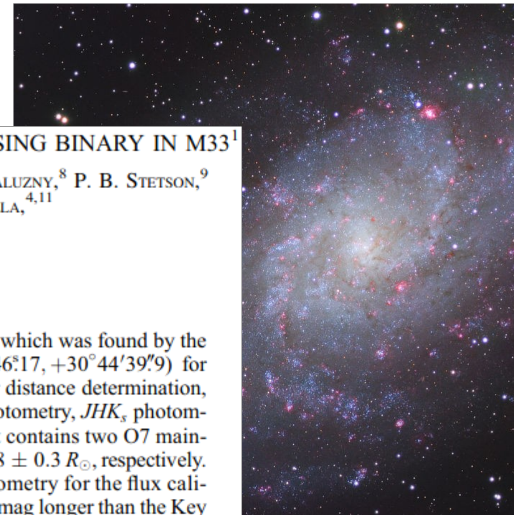


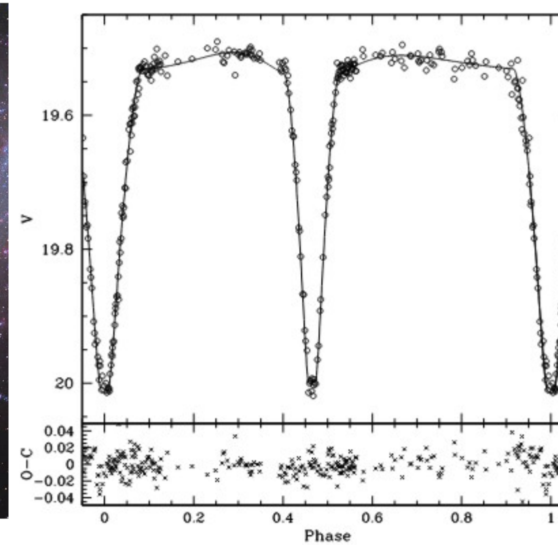






Beyond Magellanic Clouds





THE FIRST DIRECT DISTANCE DETERMINATION TO A DETACHED ECLIPSING BINARY IN M33[1]

A. Z. Bonanos,[2] K. Z. Stanek,[3] R. P. Kudritzki,[4] L. M. Macri,[5,6] D. D. Sasselov,[7] J. Kaluzny,[8] P. B. Stetson,[9] D. Bersier,[10] F. Bresolin,[4] T. Matheson,[5] B. J. Mochejska,[8] N. Przybilla,[4,11] A. H. Szentgyorgyi,[7] J. Tonry,[4] and G. Torres[7]

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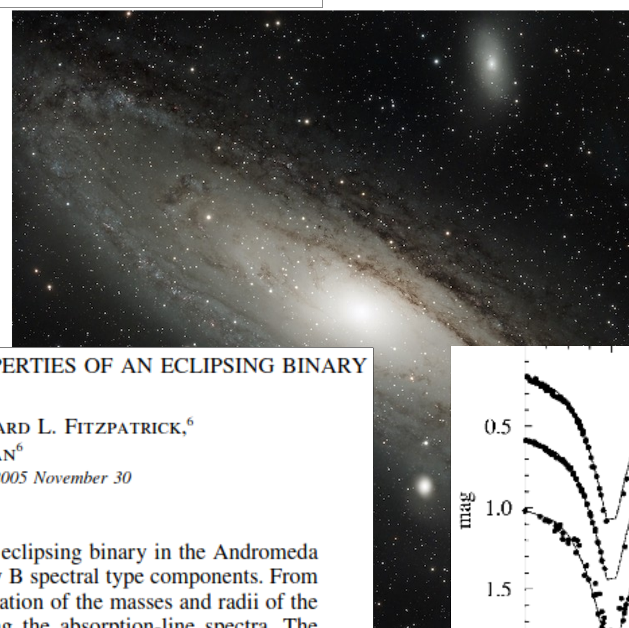
ABSTRACT

We present the first direct distance determination to a detached eclipsing binary in M33, which was found by the DIRECT Project. Located in the OB 66 association at coordinates $(\alpha, \delta) = (01^h33^m46^s.17, +30^\circ 44' 39''.9)$ for J2000.0, it was one of the most suitable detached eclipsing binaries found by DIRECT for distance determination, given its apparent magnitude and orbital period. We obtained follow-up *BV* time-series photometry, JHK_s photometry, and optical spectroscopy from which we determined the parameters of the system. It contains two O7 main-sequence stars, with masses of 33.4 ± 3.5 and $30.0 \pm 3.3\ M_\odot$ and radii of 12.3 ± 0.4 and $8.8 \pm 0.3\ R_\odot$, respectively. We derive temperatures of $37{,}000 \pm 1500$ and $35{,}600 \pm 1500$ K. Using $BVRJHK_s$ photometry for the flux calibration, we obtain a distance modulus of 24.92 ± 0.12 mag (964 ± 54 kpc), which is ~ 0.3 mag longer than the Key Project distance to M33. We discuss the implications of our result and the importance of establishing M33 as an independent rung on the cosmological distance ladder.



FIRST DETERMINATION OF THE DISTANCE AND FUNDAMENTAL PROPERTIES OF AN ECLIPSING BINARY IN THE ANDROMEDA GALAXY[1,2]

Ignasi Ribas,[3,4] Carme Jordi,[4,5] Francesc Vilardell,[5] Edward L. Fitzpatrick,[6] Ron W. Hilditch,[7] and Edward F. Guinan[6]

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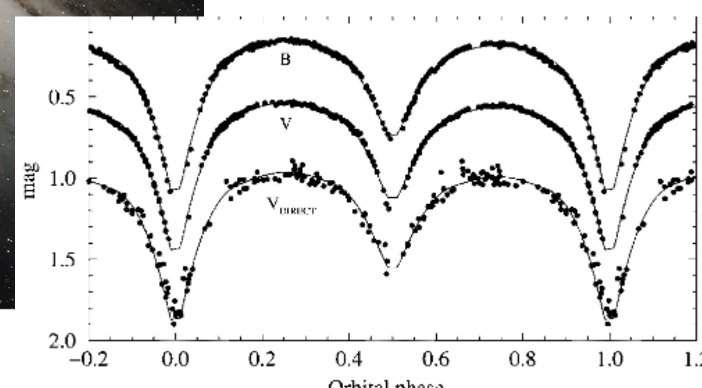
ABSTRACT

We present the first detailed spectroscopic and photometric analysis of an eclipsing binary in the Andromeda Galaxy (M31). This is a 19.3 mag semidetached system with late O and early B spectral type components. From the light and radial velocity curves we have carried out an accurate determination of the masses and radii of the components. Their effective temperatures have been estimated by modeling the absorption-line spectra. The analysis yields an essentially complete picture of the properties of the system, and hence an accurate distance determination to M31. The result is $d = 772 \pm 44$ kpc [$(m - M)_0 = 24.44 \pm 0.12$ mag]. The study of additional systems, currently in progress, should reduce the uncertainty of the M31 distance to better than 5%.



Beyond Magellanic Clouds

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Toward Early-type Eclipsing Binaries as Extragalactic Milestones. I. Physical Parameters of OGLE-LMC-ECL-22270 and OGLE-LMC-ECL-06782

Mónica Taormina[1], G. Pietrzyński[1], B. Pilecki[1], R.-P. Kudritzki[2,3], I. B. Thompson[4], D. Graczyk[5], W. Gieren[6], N. Nardetto[7], M. Górski[6], K. Suchomska[1], B. Zgirski[1], P. Wielgórski[1], P. Karczmarek[6], and W. Narloch[6]
[1] Centrum Astronomiczne im. Mikołaja Kopernika PAN, Bartycka 18, 00-716 Warsaw, Poland; taormina@camk.edu.pl
[2] Institute for Astronomy, University of Hawaii at Manoa, 2680 Woodlawn Drive, Honolulu, HI 96822, USA