The CHARA/SPICA Science Group Kick-Off Meeting

The CHARA/SPICA astrophysical objectives

N. Nardetto

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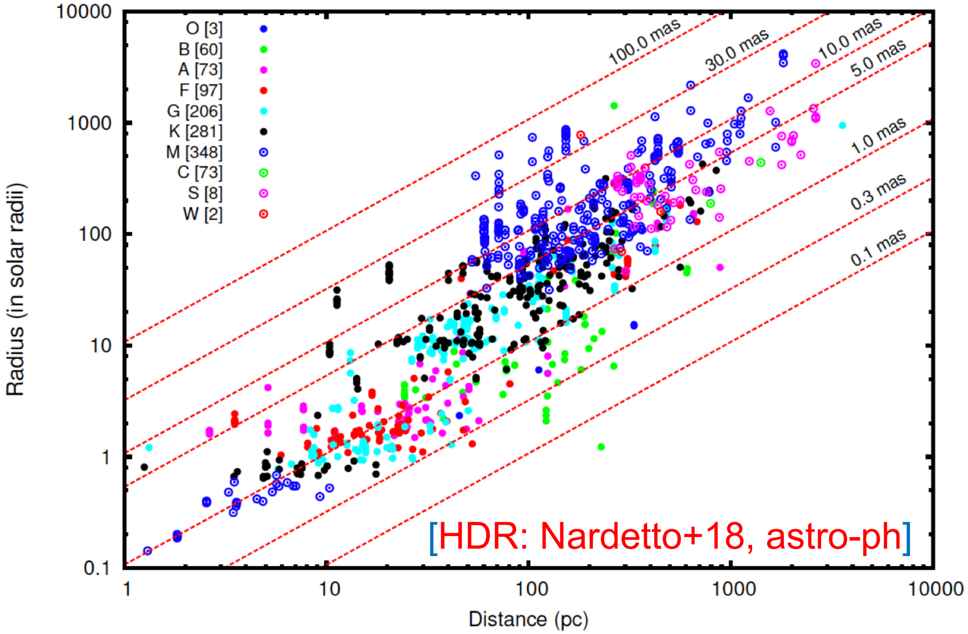
Facts:

- 1478 stellar angular diameter measurements in history up to dec. 2016 (JMDC catalogue, Duvert+16) from different techniques (lunar occultation, intensity interferometry and optical interferometry).
- 11% (resp. 22%) of stars have their angular diameter measured with a precision better than 1% (resp. 2%). It corresponds to 159 and 323 measurements, respectively.



[HDR: Nardetto+18, astro-ph]

1150 measurements in these diagram (stars with well-defined spectral type) corresponding to 627 different stars

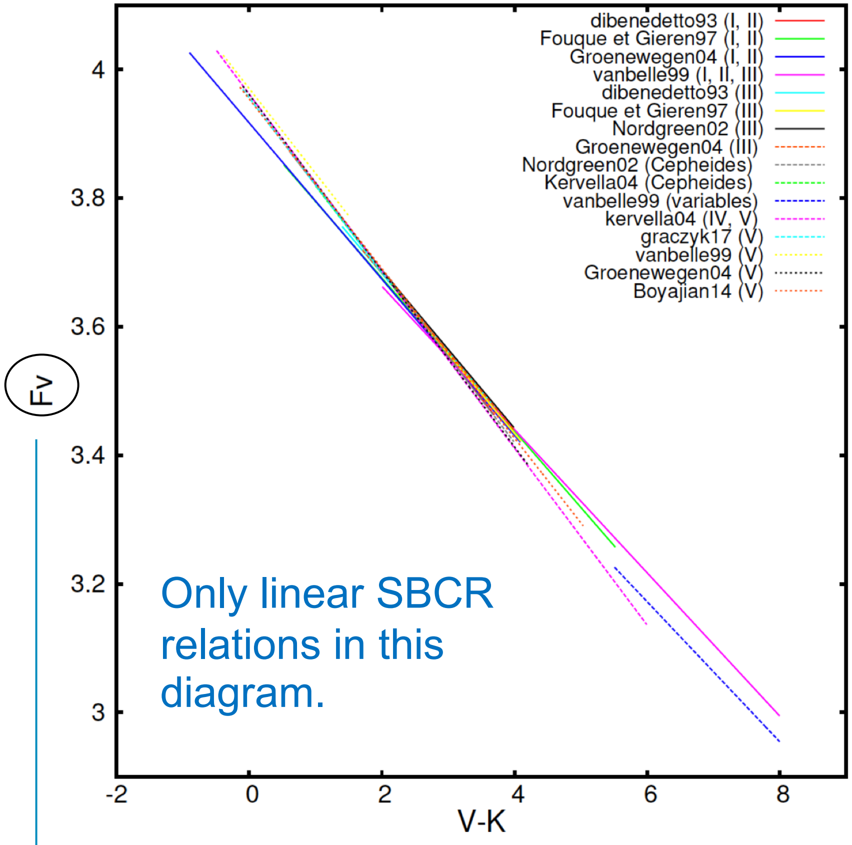
With CHARA/SPICA:

with $\delta > -30°$, $m_V < 8$ and $\theta > 0.2$ mas ~7700 Stars can have their angular diameter potentially measured with a 1 % precision. In 3 years (70 nights per year), we could derive the angular diameter of 800 stars and do images (or characterize) 200 stars

Why ?

- Indeed, the JSDC (Chelli+16) provides the angular diameter of 453000 stars with a median statistical uncertainties of 1.1%
- But, if we consider the 23 surface-brightness color relations (SBCR) available in the literature, we have inconsistencies

1. $S_V = V - 5\log\theta_{LD} = \sum a_k (V-K)^k$
2. $F_V = 4.2207 - 0.1 S_V = \alpha + \beta(V-K)$
3. $\log\theta_{LD} = d_1 + c_1 1(V-K) - 0.2V$
4. $\theta_{LD}(V=0) = 10^{A+B(V-K)}$
5. $\Phi_V = \frac{\theta}{9.305*10^{\frac{-V}{5}}} = \sum z_k (V-K)^k$



Only linear SBCR relations in this diagram.

Linked to mV and the angular diameter

. If we apply the 23 SBCR to an hypothetic star of mV=6; we obtain a dispersion the derived angular diameters of :

- 2% if V-K=3
- 9% if V-K=0 (early-type stars)
- 9% if V-K=5 (late-type stars)

. Conclusion: We are probably far from being able to estimate the angular diameter of stars with a 1% precision and accuracy.

Diagnostic:

- The 23 SBCR are based on various types of data and the methods used are also different.
- The subsets of data used are also very heterogeneous. Indeed, the 23 SBCR are based on samples of stars of 18 to 239 stars. No SBCR is using all the database (perhaps JSDC2 ?)
- There is also the problem of the V and K photometry. We need homogeneous data.
- And physically, as soon as the star is not a black body, we can have potentially a deviation from the SBCR. In other words stellar activity (spots, convection, winds & environment, rotation, and multiplicity) should be also taken into account.

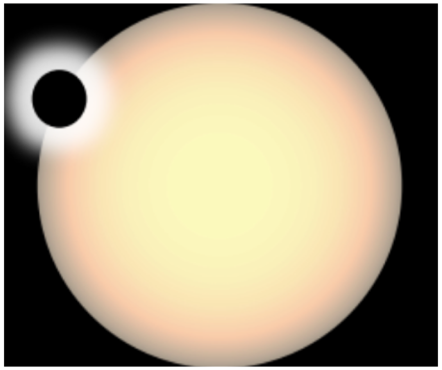
With CHARA/SPICA:

- We can derive the angular diameter of 800 stars with a 1% precision (or better).
  - ➢ This would double the number of stars for which we have an angular diameter.
  - ➢ This would increase by a factor 5 the number of stars for which we have a 1% precision
  - ➢ It would provide a unprecedented sample of stars with homogeneous angular diameters
- We can do images and/or characterize the stellar activity of 200 stars

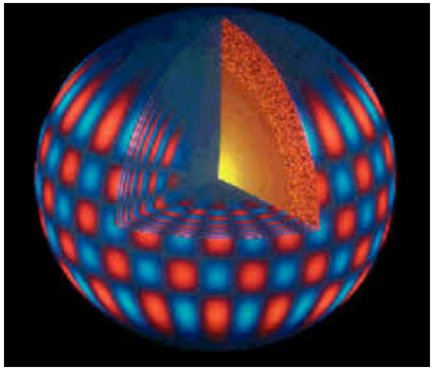
=> CHARA/SPICA is “an angular diameter machine and an picture box”

Why is it crucial to derive the angular diameter of stars with a 1% precision and accuracy ?

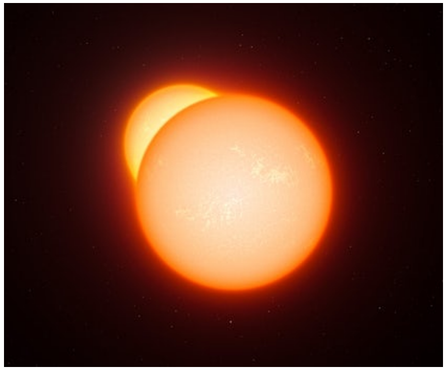
Three astrophysical objectives of CHARA/SPICA:



1. Exoplanet Host Stars



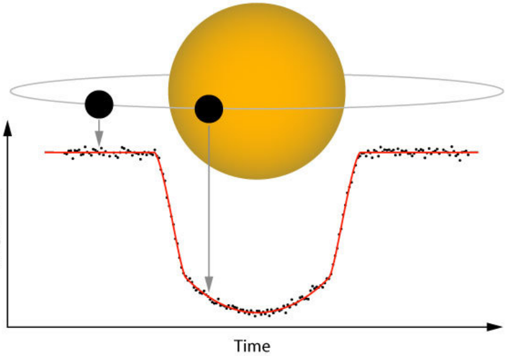
2. Asteroseismology



3. SBCR: for the distance of the eclipsing binaries and PLATO

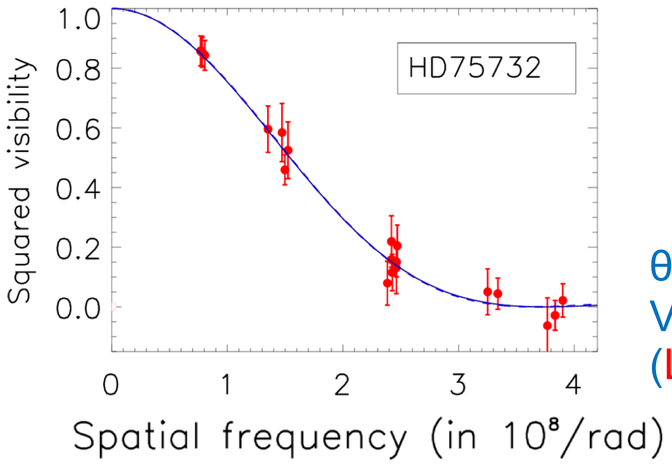
Objective 1: The Exoplanet Host Stars

Rp/R* at 1% from CoRoT, Kepler, K2, TESS or PLATO



+

θ* at 1% from CHARA/SPICA



θ* of 55 Cnc with VEGA/CHARA at 1.6% (Ligi+16)

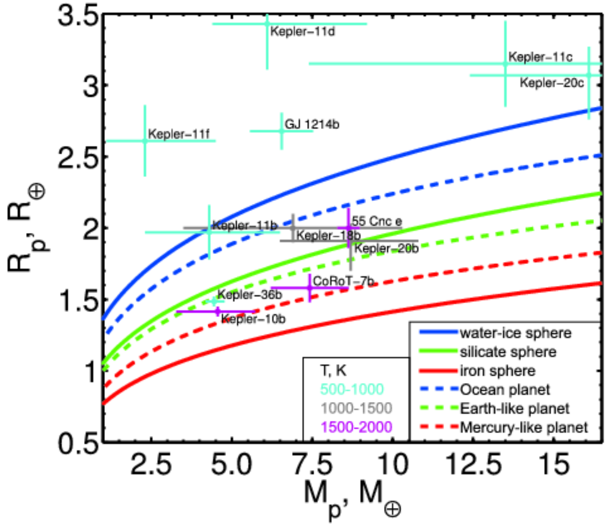
+

π parallax of Gaia at 1%

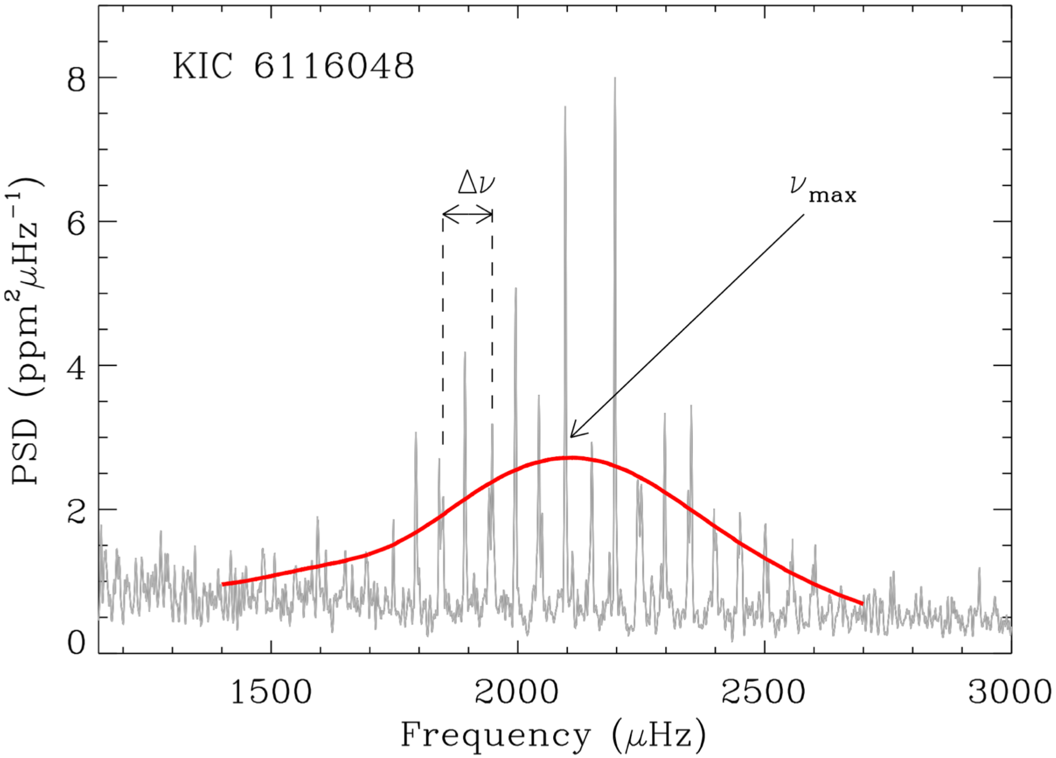
=

Rp i.e. the radius of the planet at 1%

If velocimetry provides the mass of the planet (Mp), we get the density, useful for planet models



Objective 2: Asteroseismology



Scaling relations : $\Delta\nu \propto \sqrt{<\rho>}$ $\nu_{\mathrm{max}} \propto g/c_{\mathrm{s}}$

$$\frac{M}{\mathrm{M}_\odot} \simeq \left(\frac{\nu_{\mathrm{max}}}{\nu_{\mathrm{max},\odot}}\right)^3 \left(\frac{\langle\Delta\nu\rangle}{\langle\Delta\nu_\odot\rangle}\right)^{-4} \boxed{\left(\frac{T_{\mathrm{eff}}}{T_{\mathrm{eff},\odot}}\right)^{3/2}}$$

$$\frac{R}{\mathrm{R}_\odot} \simeq \left(\frac{\nu_{\mathrm{max}}}{\nu_{\mathrm{max},\odot}}\right) \left(\frac{\langle\Delta\nu\rangle}{\langle\Delta\nu_\odot\rangle}\right)^{-2} \boxed{\left(\frac{T_{\mathrm{eff}}}{T_{\mathrm{eff},\odot}}\right)^{1/2}}$$

$$T_{\mathrm{eff}} = \left(\frac{4\,F_{\mathrm{bol}}}{\sigma\underset{\nearrow}{\theta}^2}\right)^{1/4}$$

Asteroseismology: first example

The diameter of the CoRoT target HD 49933

Combining the 3D limb darkening, asteroseismology, and interferometry

L. Bigot[1], D. Mourard[2], P. Berio[2], F. Thévenin[1], R. Ligi[2], I. Tallon-Bosc[3], O. Chesneau[2], O. Delaa[2], N. Nardetto[2], K. Perraut[4], Ph. Stee[2], T. Boyajian[5], P. Morel[1], B. Pichon[1], P. Kervella[6], F. X. Schmider[2], H. McAlister[7,8], T. ten Brummelaar[8], S. T. Ridgway[9], J. Sturmann[8], L. Sturmann[8], N. Turner[8], C. Farrington[8], and P. J. Goldfinger[8]

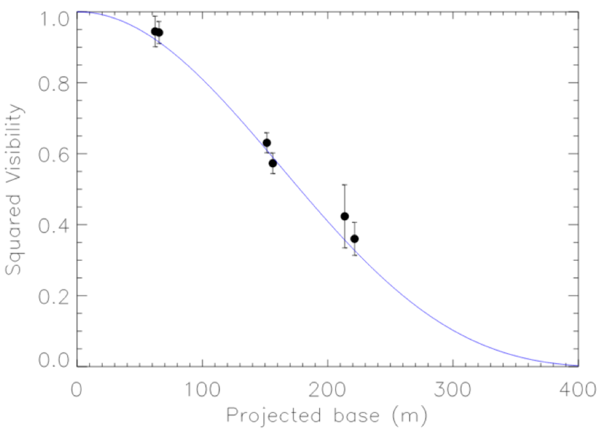


Fig. 2. Our best-fit model of the observed squared visibilities (black dots) with the calculated one (full line) with a reduced $\chi^2 = 0.47$. The angular diameter is $\theta_{\rm LD} = 0.445$ mas.

VEGA/CHARA θ* of the CoRoT target at 2.7% of precision (Bigot+11)

Table 1. Our stellar evolution model for HD 49933.

$M/M_\odot$	$R/R_\odot$	$\log g$	Y_0	$(Z/X)_0$	α	$\alpha_{\rm ov}$	Age (My)	$T_{\rm eff}$ (K)	$\log L/L_\odot$	$X_{\rm c}$	$Y_{\rm s}$	$(Z/X)_{\rm s}$	[Fe/H]
1.200	1.42	4.21	0.29	0.016	1.00	0.35	2690	6640	0.55	0.47	0.20	0.011	–0.38

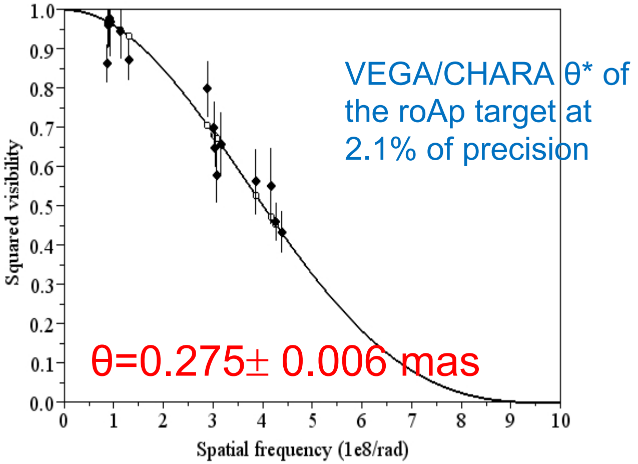
Notes. The mass M, initial helium content Y_0, metallicity $(Z/X)_0$, core overshoot $\alpha_{\rm ov}$, and mixing length α are adjusted to reproduce the radius obtained by interferometry and the observed large and small separations.

Asteroseismology: second example

The fundamental parameters of the roAp star 10 Aquilae★

K. Perraut[1], S. Borgniet[1], M. Cunha[2], L. Bigot[3], I. Brandão[2], D. Mourard[3], N. Nardetto[3], O. Chesneau[3],
H. McAlister[4,5], T. A. ten Brummelaar[5], J. Sturmann[5], L. Sturmann[5], N. Turner[5], C. Farrington[5], and P. J. Goldfinger[5]

A&A 559, A21 (2013)
DOI: 10.1051/0004-6361/201321849



VEGA/CHARA θ* of the roAp target at 2.1% of precision

θ=0.275± 0.006 mas

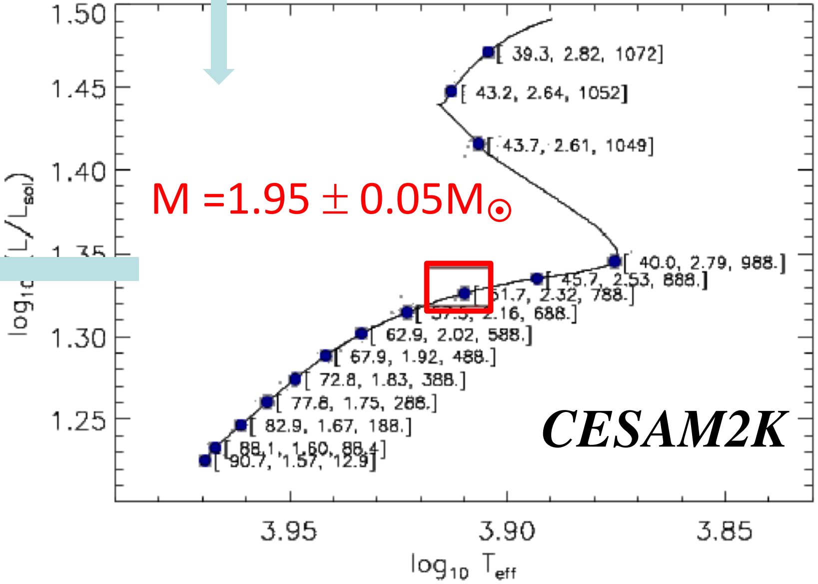
+ Parallax

R = $2.317 \pm 0.070\, R_\odot$

+ bolometric flux

L = $18 \pm 1 L_\odot$

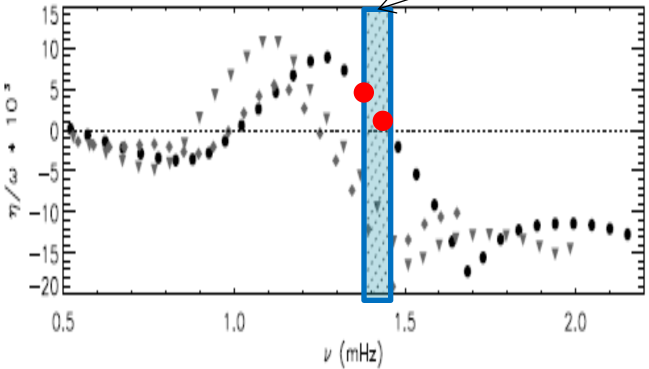
Teff = 8000 ± 210K



CESAM2K

M =$1.95 \pm 0.05 M_\odot$

Observed ν



Cunha+ 2013 models with:
(full circles) inputs HRA
(triangles) inputs photo
(diamonds) inputs spectro

Objective 3: SBCR and the distance of eclipsing binaries

LETTER

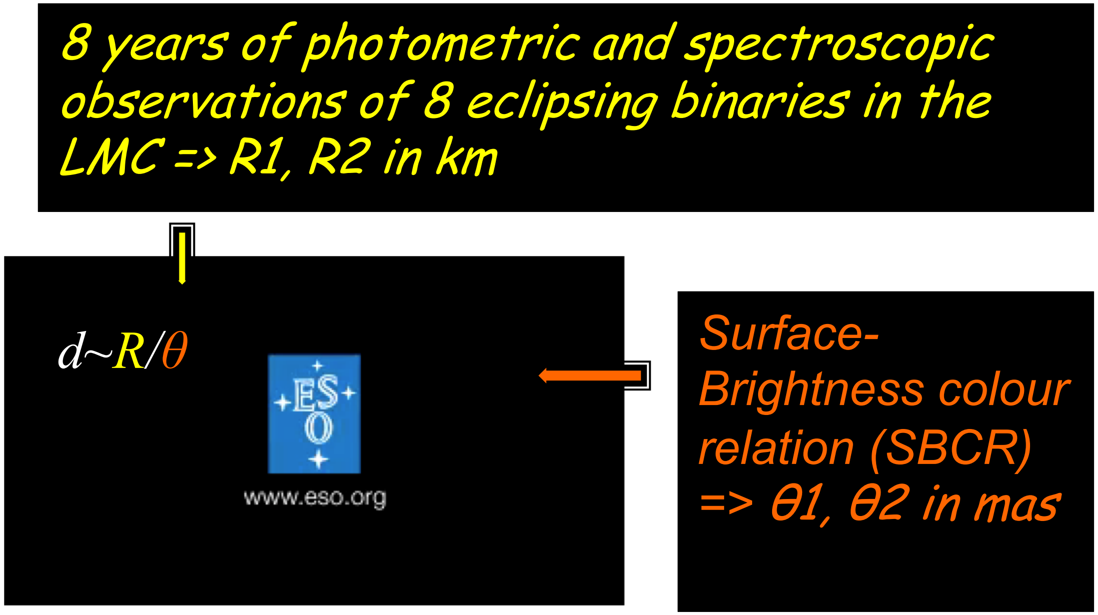
doi:10.1038/nature11878

An eclipsing-binary distance to the Large Magellanic Cloud accurate to two per cent

G. Pietrzyński[1,2], D. Graczyk[1], W. Gieren[1], I. B. Thompson[3], B. Pilecki[1,2], A. Udalski[2], I. Soszyński[2], S. Kozłowski[2], P. Konorski[2], K. Suchomska[2], G. Bono[4,5], P. G. Prada Moroni[6,7], S. Villanova[1], N. Nardetto[8], F. Bresolin[9], R. P. Kudritzki[9], J. Storm[10], A. Gallenne[1], R. Smolec[11], D. Minniti[12,13], M. Kubiak[2], M. K. Szymański[2], R. Poleski[2,14], Ł. Wyrzykowski[2], K. Ulaczyk[2], P. Pietrukowicz[2], M. Górski[2] & P. Karczmarek[2]

Nature, 2013, 495, 76

credit: press release ESO



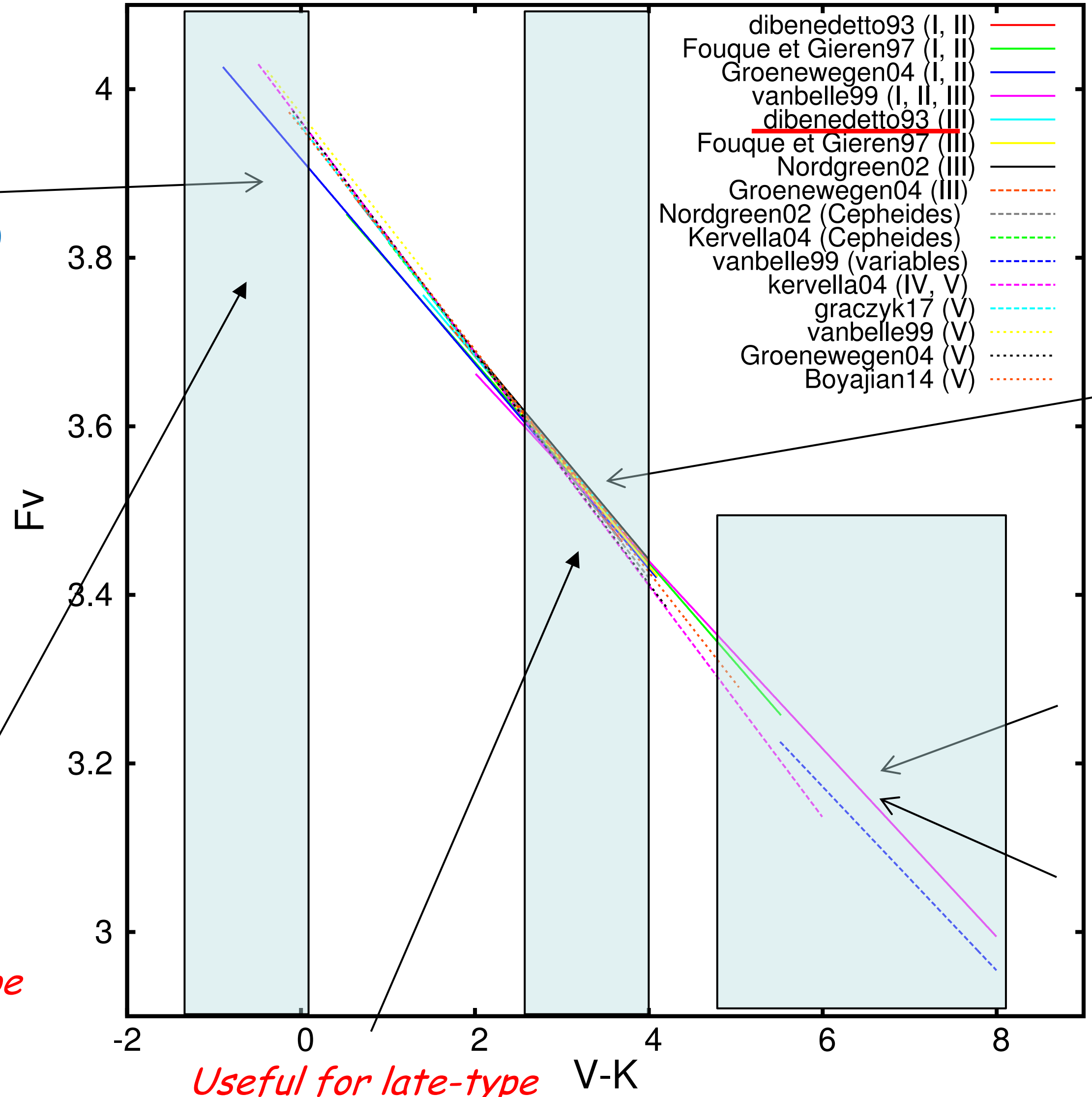
8 years of photometric and spectroscopic observations of 8 eclipsing binaries in the LMC => R1, R2 in km

$d \sim R/\theta$

Surface-Brightness colour relation (SBCR) => θ1, θ2 in mas

Distance to LMC with a 2.2% precision:
49.97 +/- 0.18 (stat.) +/- 1.1 (syst.) kpc
Uncertainty Budget: amplitude of velocity curves K1, K2 (0.5%), Stellar radii (0.5%), inclination (0.2%), reddening (0.8%), metallicity (0.3%), photometry (0.5%) and SBCR (2%).
SBCR = di Benedetto 05

SBCR for distances, but also for faint targets of PLATO



1. $S_{\mathrm{V}} = V - 5\log\theta_{\mathrm{LD}} = \sum a_{\mathrm{k}}(V-K)^k$
2. $F_{\mathrm{V}} = 4.2207 - 0.1 S_{\mathrm{V}} = \alpha + \beta(V-K)$
3. $\log\theta_{\mathrm{LD}} = d_1 + c_1 1(V-K) - 0.2V$
4. $\theta_{\mathrm{LD}}(V=0) = 10^{A+B(V-K)}$
5. $\Phi_{\mathrm{V}} = \frac{\theta}{9.305*10^{\frac{-V}{5}}} = \sum z_{\mathrm{k}}(V-K)^k$

Not precise (9%)
Incoherent (8%)

2% of precision (even 1% for KIII)

Good precision (1-2%) but incoherent (9%)

Useful for PLATO
. K-M Giants for asteroseismology ?
. K-M dwarfs for planets ?

Useful for early-type eclipsing binaries in M31/M33 (O, B, A)
M31 to 4.4% (Ribas+05, Vilardell+10)
M33 to 5.5% (Bonanos+06)

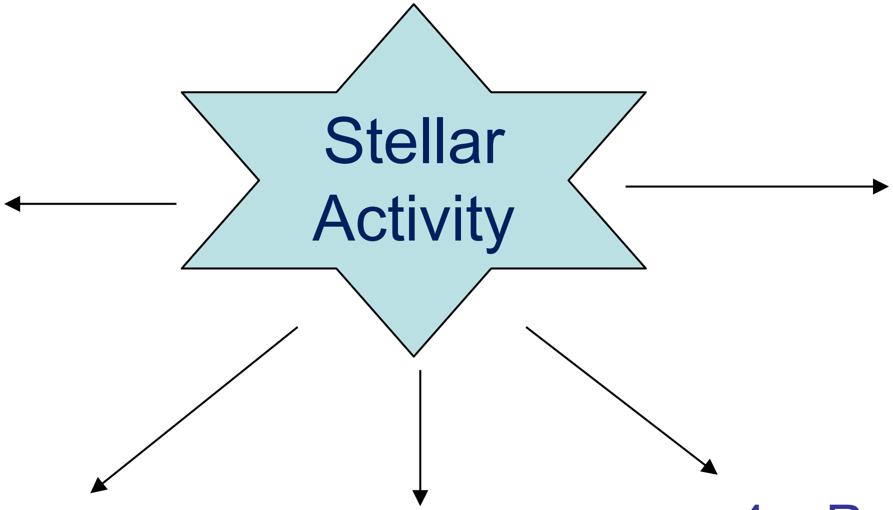
Useful for late-type eclipsing binaries In LMC/SMC (KIII)

LMC to 2.2% (Pietrzynski+13)
LMC to 1% (Pietrzynski+19)
SMC to 3% (Graczyk+14)

Three objectives:

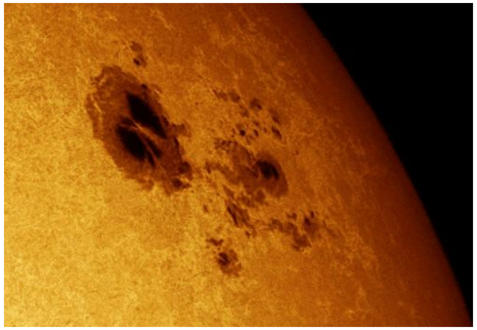
1. Exoplanet Host Stars
2. Asteroseismology
3. SBCR for distances of EB and PLATO

For these three objectives, stellar activity has to be taken into account:



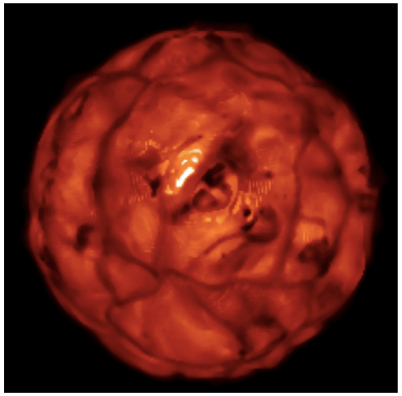
Stellar Activity

1 – Spots

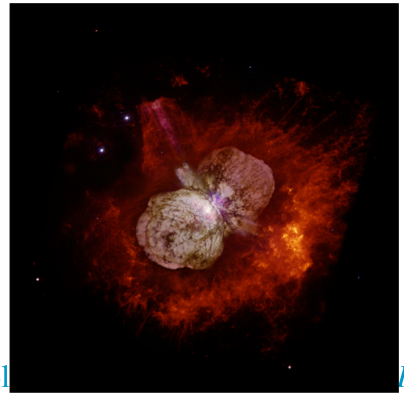


5 – Binarity

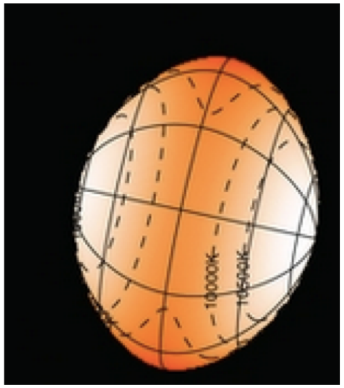
2 – Convection



3 – Wind & environment



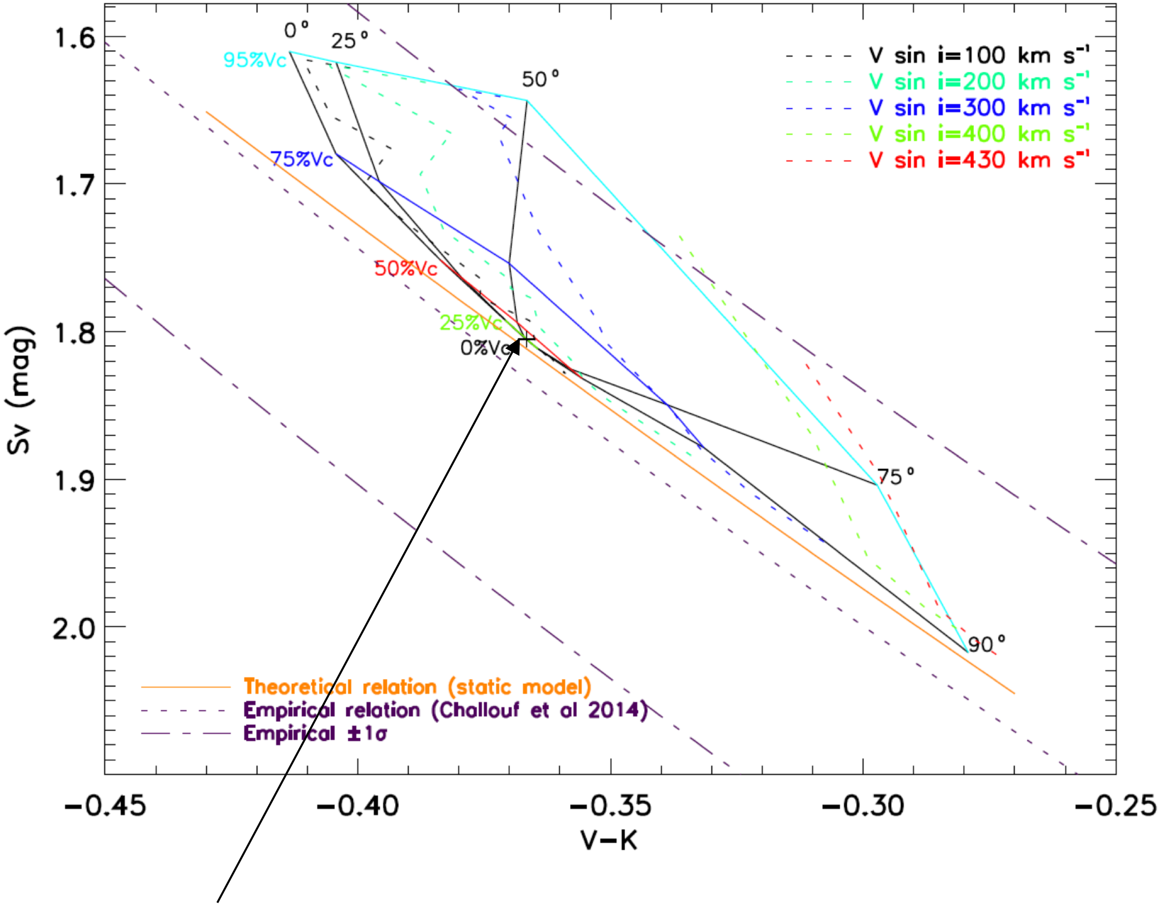
4 – Rotation



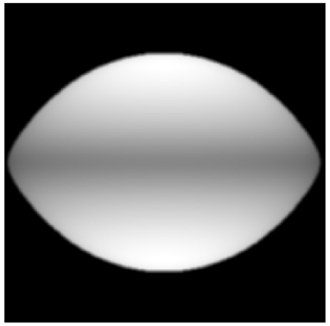
Theoretical impact of fast rotation on calibrating the surface brightness-color relation for early-type stars

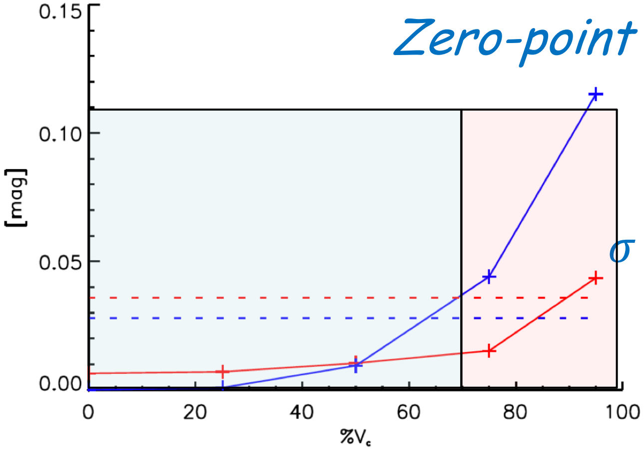
A&A, **2015**, A&A, 579, 107

M. Challouf[1,2], N. Nardetto[1], A. Domiciano de Souza[1], D. Mourard[1], H. Aroui[2], P. Stee[1], O. Delaa[1], D. Graczyk[3], G. Pietrzyński[3,4], and W. Gieren[3,5]



CHARON Model
Domiciano+02,12





Model of a standard stars, then exploration of parameters space (rotation velocity, inclination) for different interferometric configurations. Calculation of the impact of rotation on the SBCR

Objectives and timeline for CHARA/SPICA

Phase 1 during the preparation of the PLATO space mission (~2026). Derive the angular diameter of 800 stars with a 1% precision and obtain images for 200 stars.

1/ observe **known stars hosting exoplanet in transit.** Observe also exoplanet host stars without transit *(~180 objects already identified*).

2/ observe interesting **known asteroseismic targets** (from WIRE, MOST, CoRoT, Kepler, TESS, …). We identified for instance *~400 objects from TESS catalogue.*

3/ complete the sample of 800 stars observing benchmark stars in the HR diagram in order to derive a or several **Surface-Brightness Color Relation**(s) (depending on the color/class) taking also into account (i.e. correcting) the 'activity' of stars. Distances of SMC, LMC, M31 and M33. New anchors for Ho.

4/ **characterize ~200 active stars** in order to quantify the impact of activity(spots, wind & circumstellar environment, convection, rotation and multiplicity) on the three astrophysical objectives.

Phase 2: during the PLATO space mission.

1/ perform a follow-up of interesting **bright** (mV < 7-10) PLATO targets: stars hosting planet(s) in transit, asteroseismic targets

2/ apply the SBCR(s) corrected of activity (from phase 1) to **faint (i.e. all)** PLATO targets, **and use our activity diagnostics (SED)** to make additional corrections on their derived angular diameter.

CHARA/SPICA

Atmosphere models
($T_{\rm eff}$, log(g), Z, v_t)

. Session 1: Definition of objectives 1, 2, 3

. Session 2: age$_\star$ R$_\star$ M$_\star$T$_{\rm eff,\star}$ How ? Taking into account evolution/atmosphere models and binarity (mass)

. Session 3: impact of stellar activity on the three objectives

θ cal

V^2(cal)

V^2 (sci, brut)

Transfert function (strategy)

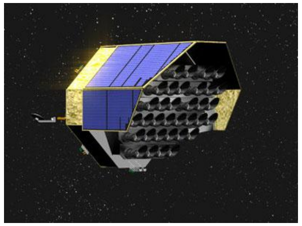
LD Law

θ_{UD} (sci)

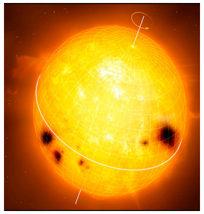
θ_{LD} (sci)

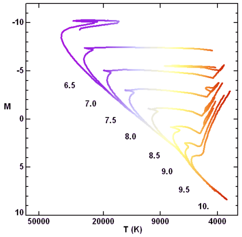
Phase 1: 1000 bright stars (mv<8)

Phase 2: PLATO follow-up



Stellar Activity
Spots
Granulation
Wind/Environment
Rotation
Multiplicity





EXOPLANET HOST STARS

Evolution Atmosphere Models Binarity

π *Gaia*

Stellar activity

age$_\star$ R$_\star$ M$_\star$T$_{\rm eff,\star}$

Transits
$\rho_\star$

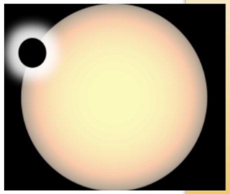
RV

R_p M_p

ρ_p

Objective 1 : Life Habitable Zone

Model of Planets



ASTEROSEISMIC TARGETS

Evolution Atmosphere Models Binarity

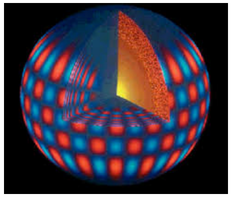
π *Gaia*

Stellar activity

Scaling relations

age$_\star$ R$_\star$ M$_\star$T$_{\rm eff,\star}$

Objective 2: Fundamental parameters



STANDARD STARS

Evolution Atmosphere Models Binarity

SED Analysis Diagnostic of activity

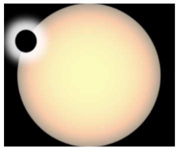
Homogeneous Photometry

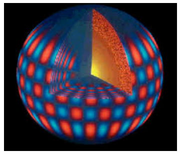
age$_\star$ R$_\star$ M$_\star$T$_{\rm eff,\star}$

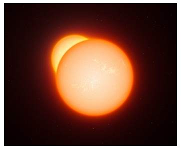
Objective 3a: Surface-Brightness Color Relations (SBCR) for all types and classes corrected from stellar activity

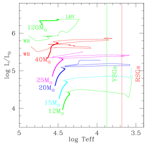
Tool for faint stars observed by PLATO (phase 2)

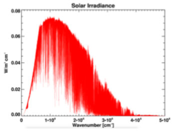
Objective 3b: Distance scale Ho

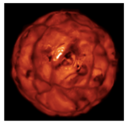


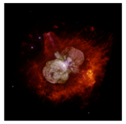


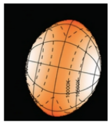












	Exoplanet Host Stars	**Asteroseismology**	**SBCR (distances & PLATO faint targets)**
Objectives (session 1)			
Stellar parameters (session 2)			
Spots			
Convection			
Winds Environment			
Rotation			
Binarity			

CHARA/SPICA will also serve a wide variety of **additional programs**. The instrument will be very active for 3 years and then will enter a follow-up phase (~2026) which permits to give access to a lot of time. Based on the **white book of visible interferometry** (Stee et al., 2017, arXiv170302395S), we identify the following objectives.

1. Cepheids:

1. Limb-darkening measurement in the visible domain (stronger in visible).
2. Precise angular diameter curves of northern Cepheids (BW method)
3. Study of the circumstellar environment of Cepheids in the visible domain (like for e.g. on delta Cep with VEGA/CHARA: Nardetto+16).
4. Study of Cepheids in binaries in order to derive their masses.

2. Synergy between SPHERE imaging of exoplanet and interferometric measurements. A precise angular diameter of the star helps to constrain the age of the system (see for e.g. GJ504, Bonnefoy et al. 2018).

3. Fundamental parameters of roAp stars (spots, magnetism, asteroseismic targets). Direct measurements (as done with VEGA: Perraut+) or using SBCR (phase 1) relations for faint stars.

4. Fundamental parameters of metal poor stars (Gaia benchmark). Direct measurements (as done with VEGA: Creevey+15) or using SBCR (phase 1) relations for faint stars. Connection with Galactic Archeology.

5. Environment of Young Stellar Objects (YSOs). In the visible domain, one can constrain the relation between the accretion disk, the star and the jet (with VEGA: Perraut+).

6. The circumstellar disk of Be stars. Constrain of the continuum measurement.

7. Images of binaries in interaction (for e.g. Beta Lyrae, SS Lep).

8. Pulsating stars: RR Lyrae, delta-Scuti, beta Cep. Study of their fundamental parameters, pulsation and environment when possible.

9. Nova