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# THE SCIENTIFIC PROJECTS OF THE INTERFEROMETRIC SURVEY FOR STELLAR PARAMETERS WITH CHARA/SPICA

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**Abstract.** To date, around 200 stars have a measured angular diameter with a precision at the 1% level. These measurements have been made with different instruments, using different techniques, and different spectral bands, which provide scattered and sometimes inconsistent results. The angular diameter is a key quantity to measure because it allows the determination of many other physical properties, like the stellar radius (if combined with the distance to the star), the effective temperature (when combined with the bolometric flux), or the radius of a planet if it transits its star.

The Interferometric Survey for Stellar Parameters (ISSP) is dedicated to the measurement of a thousand stars with a homogeneous data and analysis approach, and this will provide the largest catalogue of stellar diameters with a 1% precision. The main objectives of this survey are 1) the determination of exoplanet host star's radii, thus of exoplanetary parameters, 2) the determination of parameters of asteroseismic targets, to refine scaling laws and determine accurate ages, and 3) the calibration of surface brightness-color relations (SBCR). Five additional programs of this survey focus on limb-darkening, rotation, binarity, stellar winds and environments, with an additional objective to study these phenomena and control the systematics in the three main programs.

The survey exploits the new CHARA/SPICA instrument that combines light from the six telescopes of the array in the optical band. Here, we present the scientific objectives of the survey, the status of the instrument after first commissioning and the initial results of the observing campaign.

Keywords: Visible interferometry, stellar parameters

## 1 Introduction

Interferometry is a high angular resolution technique which measures the complex visibility of an object, a quantity composed of the modulus (often taken to the square), which yields the angular diameter of a star, and the closure phase, that gives information on the asymetries of an object. Today, 1478 stellar angular diameters have been measured with various interferometers (from the JMDC, the JMMC Measured Stellar Diameters Catalog, Duvert 2016), but the precision reached (1% for only 11% of the measurements) is not enough to obtain precise stellar parameters at the large scale (Mourard et al. 2022). These measurements have been performed with different methods, analysis, instruments, and the full star sample does not constitute a homogeneous set of angular diameters.

The development of the Stellar Parameters and Images with a Cophased Array (SPICA, Mourard et al. 2018) instrument on the Centre for High Angular Resolution Array (CHARA, ten Brummelaar et al. 2005) will be a turning point in optical interferometry for stellar physics. This new instrument takes advantage of the adaptive optics recently installed on CHARA, and is based on spatial filtering with single mode fibers. It potentially allows to measure the angular diameter of thousands of stars with 1% precision, but also to do image reconstruction of stars.

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## 2 The Interferometric Survey for Stellar Parameters (ISSP)

The ISSP – an ERC-funded project – aims at measuring the angular diameter of 800 stars and obtain the images of 200 stars (Fig.1, right). With the angular resolution allowed by CHARA, and the use of the SPICA instrument, the goal is to reach 1% precision on the diameters for stars with an angular diameter $\theta > 0.2$ mas and magV< 9. These data will be used to cover three important problematics in stellar physics : the characterisation of exoplanets host stars (Sec. 3.1), the calibration of asteroseismic scaling relation (Sec. 3.2) and the calibration of surface brightness-color relations (SBCR, Sec. 3.3). These objectives will be reached by the detailed control of the systematics (caused by stellar rotation, stellar wind, limb-darkening, binarity, see Sec. 3.4), that perturbs the interferometric measurements. On the other hand, better understanding these phenomena will bring valuable and unprecedented insight to stellar physics.

The survey can be achieved with a large amount of observing time : 4000 individual observations (which includes the observation of one target star surrounded by the observation of calibration stars) over 200 nights covering 3 years are required. This implies preparing an optimal observing strategy by observing stars that are close in hour angle and declination during each allocated night.

## 3 Objectives of the survey

### 3.1 Exoplanet host stars characterisation

Exoplanetary properties and stellar properties are closely linked. The radial velocity (RV) and the transit detection methods yields the ratio of the planetary to the stellar mass $M_{\rm p}\sin(i)/M_\star$, with $i$ the inclination of the system, and the planetary to the stellar radius $R_{\rm p}/R_\star$, respectively. For the transit method in particular, interferometry can play a major role because measuring the angular diameter, combined with the parallax usually given by the *Gaia* satellite, provides $R_\star$.

The focus on transiting exoplanet host stars (EHS) has another important advantage: from the transit light curve, one can derive the density of the star (Seager & Mallén-Ornelas 2003). With a direct measurement of the radius, we can then estimate the stellar mass, which is a parameter usually obtained through modelling. As many transiting exoplanetary systems are often followed in RV, we can also derive the exoplanets densities $\rho_{\rm p}$. These three parameters are mandatory to infer the internal structure of exoplanets, and to learn about their habitability. This kind of analysis has already been applied to two systems (Crida et al. 2018b,a; Ligi et al. 2019), where the mass was derived, allowing to confront the models with the data, and to constrain in detail the internal structure of the exoplanets (Fig.1, left).

Up to now, only a handful of transiting EHS could be measured with interferometry, mainly because of the limiting magnitude of interferometers. The vast majority of *Kepler* targets are faint, and their angular diameter is smaller than what CHARA allows. With SPICA, we expect to push the limiting magnitude, and to reach at the end of the survey magV<9. Moreover, the current and future missions dedicated to exoplanetary search, like PLATO and TESS, are aiming at bright stars in order to characterize them and will constitute a large amount of SPICA potential targets. We already identified 42 transiting exoplanets host stars accessible by SPICA, and more than 200 hundreds exoplanets hosts (without transits), and expect many more when PLATO is on sky. We will also benefit from the progresses made on SBCR that will provide angular diameters of stars for which a direct measurement is not possible, and thus characterize even the stars that are very faint and angularly small.

### 3.2 Asteroseismic stars

Scaling relations in asteroseismology link oscillation frequencies and global oscillation parameters ($\Delta\nu$, $\nu_{\rm max}$) to stellar parameters ($T_{\rm eff}$, $R_\star$, $M_\star$, $\rho_\star$, age). This domain has grown, in particular since the *Kepler* and CoRoT missions, and have led to the studies of several thousands of stars. Yet, these relations need to be calibrated by direct radius estimations. The advantages of combining interferometry and asteroseismology has been known for a long time (Creevey et al. 2007; Cunha et al. 2007; Huber et al. 2012, e.g.). The angular size provided by interferometry can be used with the bolometric flux to derive the effective temperature of stars. These parameters, obtained independently of models, are inputs to scaling laws, and help derive the mass and evolutionary stage with little model dependence.

The accuracy of the stellar diameter is important in this context, as reaching 1% on the radius is necessary to bring enough constraints on atmospheric and internal structure models of stars. With SPICA, we have the chance to measure the angular diameter of a selection of 400 seismic targets, spanning FGK dwarfs subgiants

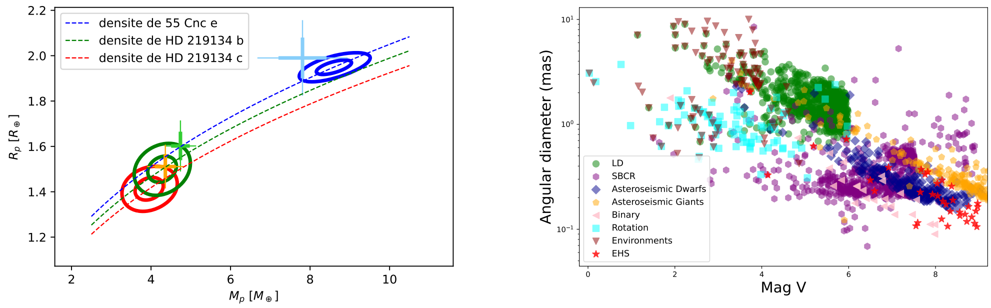


**Fig. 1. Left:** Contours at 1 and 2 $\sigma$ of the joint likelihood $M_{\rm p}$ -$R_{\rm p}$ (Crida et al. 2018b,a; Ligi et al. 2019). The ellipses are flattened along the iso-densities (dashed lines), showing the correlations $M_{\rm p}$ -$R_{\rm p}$. The crosses indicate previous values in the literature. **Right:** Angular diameter (in mas) according to the magnitude in the V band of the stars of the ISSP survey. The different colors and symbols show the stars of the different programs.

and giants. The primary objectives are 1) the calibration of the radius-seismic scaling relations covering a range of masses and metallicities, and to obtain independently derived masses by exploiting $\Delta\nu$, 2) detailed seismic analysis for providing high precision stellar parameters, and 3) testing different physical ingredients in stellar models. This analysis will also be applied to PLATO targets.

### *3.3 Calibration of surface brightness-color relations (SBCR)*

SBCRs are key tools for easily estimating the angular diameter of a star from photometric measurements. The SBCRs are used, for instance, to derive the distances of eclipsing binaries in the Magellanic clouds (Pietrzyński et al. 2013, 2019; Graczyk et al. 2020). The distance estimate of LMC was used by the SHOES team to constrain the Hubble-Lemaître constant, $H_0$, and tackle the difficult issue of the Hubble tension (Riess et al. 2019). The SBCRs are also of high interest for the study of transiting EHS (see Sec. 3.1). Our initial SBCRs, extracted from VEGA programs, are currently implemented in the pipeline of the PLAnetary Transits and Oscillation of stars (PLATO) space mission (Gent et al. 2022). Additionally, the physics of SBCRs is under deeper analysis. By applying a homogeneous approach on a large sample of data, recent studies have shown that the SBCRs depend not only on the temperature of stars, but also on their luminosity class (Salsi et al. 2020, 2021), a result corroborated using atmospheric models (Salsi et al. 2022). The SBCRs are also used to derive the distance to Cepheids (Nardetto et al. 2023), to estimate the angular diameter of interferometric calibrators, and for microlensing surveys.

The ISSP has 4 focussed objectives : 1) calibrate the SBCR to 2% or better for stars later than F5 (IV/V), to be applied in the context of the PLATO space mission, 2) calibrate the SBCR for KIII stars at the 1% level in order to verify and potentially improve the distance to LMC, 3) open a new road to $H_0$ by calibrating an SBCR at the 1-2% level for early-type stars (B1-3 IV/V). Such a relation will be used in the context of the Araucaria Project to derive the distance of eclipsing binaries in M31 and M33, 4) calibrate the SBCR all over the HR diagram in the most homogeneous way as possible with a precision of 1 to 2% in order to study the impact of spectral type, class and weak stellar activity (rotation, binarity, wind and environment). To reach these objectives our goal is to observe 2 stars per sub-spectral channels [B0-M3] and per class (V, IV, >III) which corresponds to a total of 324 stars.

### *3.4 Studying stellar physics all over the HR diagram : toward a control of systematics*

Limb-darkening (LD), binarity, rotation, winds and environment are crucial phenomena to understand various specific physical processes, leading to an improved determination of stellar parameters, directly or through a better definition of stellar models.

If their effect on the interferometric signal is weak, they can potentially perturb the visibility curve at high spatial frequencies, and then bias the derived angular diameters or the estimate of the LD. Indeed, the LD can only be measured if the star is resolved beyond the first visiblity minimum. For this reason, it has only been done a handful of times, e.g. for $\alpha$ Cen A and B Kervella et al. (2017). Yet, it can cause a variation of a few % in the angular diameter. LD is taken into account through correction grids computed from atmospheric models, which lack direct measurements for accurate calibration. Moreover, the LD is also important in exoplanet transit light curve exploitation, where it has to be accounted for (Maxted 2023). In addition, the knowledge of binarity constitutes a rare opportunity to directly measure the stellar mass, which is crucial to constrain evolution models. Moreover, rotation can generate surface flattening and gravity darkening that should be considered in detail when calibrating the SBCR (in particular for early-type stars) and when deriving the stellar diameter (50 km/s of $v\sin(i)$ corresponds to a flattening of about 1%). Rotation also has an important impact on the physical structure and evolution of stars and thus, is a key ingredient of stellar evolution models. Finally, studying wind and environments give information on mass loss, which has an impact of stellar evolution.

A direct measurement of all these phenomena through interferometry brings valuable constraints for stellar models, and the comprehension of systematics in the interferometric signal. For this reason, the ISSP survey forsees: 1) direct measurements of the LD of $\sim$ 160 targets for giants and dwarfs, 2) the observation of 50 detached eclipsing and spectroscopic binaries, with angular separations ranging from 0.15 to 10 mas, and covering the HR diagram, 3) the measurement of the rotation for hundreds of stars, 4) high spectral resolution observations of the CaII triplet to probe the presence and extension of the chromosphere of cool giants and supergiants, and low spectral resolution observations to constrain the visibility function and the fundamental stellar parameters.

## 4 First fringes and conclusion

The ISSP project officially started in September 2021 and will end in August 2026. It began with engineering nights with the SPICA instrument, and the scientific commissioning began in 2022. Even though the first commissioning months have been paved with bad luck (in particular, 2 meters of snow at CHARA!), the instrument is now working routinely. We obtained the first 15 fringes during the observing run of June 2023. In Fig. 2, we show the 2D Fourier Transform of the 15 dispersed fringes obtained by recombining the light from 6 telescopes. This is the first time that this many fringes have been obtained in the visible domain. The August observation run demonstrated that the instrument is now ready to work routinely. However, some improvements are still necessary, in particular in the injection process, in order to reach the magnitude limit of the survey, and in the routine operation of the fringe tracker SPICA-FT (Pannetier et al. 2022).

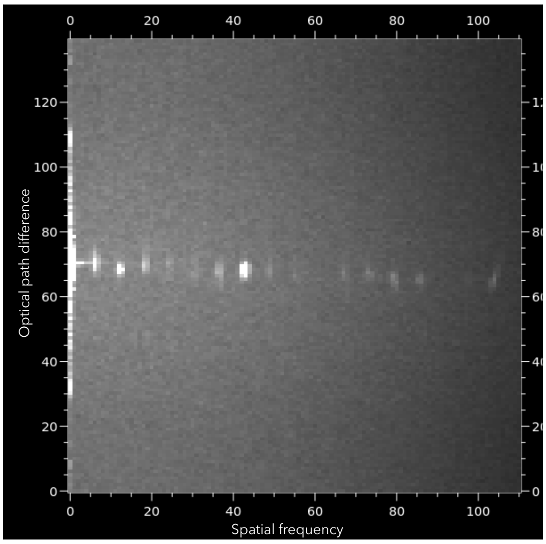


**Fig. 2.** 2D Fourier Transform of the dispersed fringes obtained during 20-second integrations, for the 15 baselines available at CHARA.

The ISSP covers wide aspects of stellar physics. It will provide very accurate and precise interferometric measurements of 1000 stars obtained with homogeneous data reduction, that will serve exoplanetary science, the determination of new SBCR, astroseismology, while tackling the problems linked to stellar activity. These topics are closely related to the current and future spatial missions dedicated to exoplanets search and characterisation (PLATO, TESS, CHEOPS. . . ), to the Auraucaria project, and will certainly reach many domains of Astrophysics.

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