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CN2023A-5
Galactic panel
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Spectroscopic follow-up of visual and spectroscopic binaries

Abstract

We propose an Echelle spectroscopic follow-up of strategically selected Hipparcos southern visual doubles, and Geneva-Copenhagen spectroscopic binaries, for which high-precision orbital parameters are being determined by an on-going Speckle campaign at SOAR and Gemini South, and for which precise parallaxes are provided by Gaia. The combination of high-resolution spectroscopy (yielding radial velocities, stellar parameters and metallicities), with orbital parameters and distances will allow for high quality estimates of idividual masses and luminosities of these stars. Our targets span the entire HR diagram, which will allow us to place tight constrains on the basic properties of a wide variety of spectral types. This program will provide a fundamental data set for stellar astrophysics. Southern binaries are currently being monitored systematically only by our team, which makes our survey unique, and in a way a low cost legacy survey. Concerns from the TAC have been addressed.

Observing Blocks

Instrument/Telescope	Req. time	Min. time	1^{st} Option	2^{nd} Option
FEROS/MPG 2.2-m	4 nights	3 nights	May Any	June Any
FEROS/MPG 2.2-m	4 nights	3 nights	August Any	September Any

CoIs

Name	Institution	e-mail	Observer?
Rene Mendez	UCH	rmendez@uchile.cl	True
Jennifer Anguita	UCH	janguita@das.uchile.cl	False
Venu Kalari	UCH	vkalari@das.uchile.cl	False
Camila Caballero	UCH	camila.caballero@ing.uchile.cl	False
Maximiliano Dirk	UCH	dirkmaximiliano@das.uchile.cl	False

Status of the project

- Past nights: 16
- Future nights: 16
- Long term: False
- Large program: False
- Thesis: False

List of Targets

ID	RA	DEC	Mag
HIP-45139	9:11:48.9	-42:17:44	V=11.6
HIP-77725	15:52:8.4	10:52:30	V=9.59
HIP-112816	22:50:47.1	-65:42:52	V=8.64
HIP-90198	18:24:17.4	-04:05:18	V=7.53
HIP-20802	04:27:26.6	-29:11:49	V=7.75
HIP-80817	16:30:13.4	-14:39:48	V=12.27

SCIENTIFIC AIM AND RATIONALE

Double-line spectroscopic binaries (SB2) with known radial velocity (RV) curves and precise astrometric orbits are among the best laboratories to determine astrophysical parameters (e.g. mass; Kiefer et al. 2018), as well as parallax-free distances -allowing an independent assessment of *Gaia's* trigonometric parallaxes (Pourbaix 2000, Mason 2015). For example, in Anguita et al. (2022) we have shown that using a Markov Chain Monte Carlo approach, and combining an astrometric orbit with a RV orbit, it is possible to obtain individual component masses for double-line spectroscopic binaries with a formal uncertainty as small as $0.01M_{\odot}$ (see Student Thesis).

However, the number of SB2 systems is limited and, furthermore, those for which an RV curve and astrometric orbit is available is even smaller. Fortunately, a newly developed Bayesian methodology based on the MCMC algorithm No-U-Turn sampler (Videla et al. 2022) to address the orbital parameters inference problem in single-line binaries (SB1) -including a determination of the individual component masses- now allows to also use these latter (far more numerous) to the same end. Using this approach, we are currently obtaining percent errors of 2.2% and 13% for the mass of the primary and secondary, respectively (Anguita et al., in preparation - see Student Thesis).

This proposal seeks to determine RV curves and stellar parameters for a subset of southern binary systems (SB2 and SB1) from the *Hipparcos* visual doubles and Geneva-Copenhagen Spectroscopic Binaries (GCSB) catalogs, which are being monitored by our HRCam@SOAR + Zorro@GS Speckle survey (see e.g. Tokovinin et al. 2021; Mendez et al. 2021). Our survey, along with parallaxes from *Gaia*, is providing high precision orbital parameters and mass sums for systems within 250 pc of the Sun. Our program complements the northern Speckle survey carried out with the WIYN and DCT telescopes by Horch et al. (2017); together they will provide the first all-sky, volume-limited, determination of orbital parameters and distances for the above samples. Extension of this work to the south will also significantly improve the science in terms of the metallicity range that can be studied (given the Galactic distribution of the sources), and will open the door to many tests of stellar evolution theory.

We shall add a large number of new points to the mass-luminosity relation (MLR), and thus we will be able to investigate effects such as metallicity and age on the MLR for the first time. Currently, the best MLR for main sequence stars are those of Torres et al. (2010) and Benedict et al. (2016), but neither of them include low metallicity stars. In cases where one component has evolved off of the main sequence, age determinations will also be possible. In addition to having confirmed and resolved many systems, notable results from our observations include the discovery of many inner or outer subsystems in previously known binaries (i.e., trinary systems), as well as two quadruple system. Several publications have already resulted from this effort.

Securing high-resolution spectroscopy for these systems -yielding RVs, stellar parameters and metalicities- will further enable high quality estimates of their *individual* masses, (parallax-free) distances and luminosities, allowing us to place tight constraints on the mass to luminosity relationship and, in general, on current stellar models. Our Speckle + Echelle survey will provide a fundamental data set for stellar astrophysics and other astrophysical areas, such as star formation and comprehensive studies of the solar neighborhood.

Figures 1 and 2 show the astrometric orbit and RV curve, respectively, of HIP 38414, an SB1 binary being targeted by our astrometric/spectroscopic survey. The astrometric orbit includes 11 resolutions made at SOAR, between 2012 and 2021, and the RV curve old RVs from the 1980's plus our FEROS observations from 2022. Further astrometric/spectroscopic monitoring of this system, together with a future precise parallax from *Gaia* (DR3 or later) will lead to very well determined individual masses.

Southern binaries are currently being monitored systematically only by our team, which makes our survey unique, and in a way a low cost legacy survey.

Specific goals & procedures

Here we propose to target all fast binaries that have been resolved at least 6 times with SOAR between 2011 and 2022. Our sample consists of approximately 100 systems, covering the whole RA range (we note that these numbers do not match those in our latest SOAR/CNTAC proposal because the target list of the present program has been frozen).

Our targets span a broad range in spectral types and luminosity class. They define an heterogeneous sample, composed principally of dwarfs, but also includes giants, supergiants, pre-main sequence stars and sub-dwarfs. Thin and thick stars are expected to be included, and both low and high metallicity stars. Our combined survey (astrometric orbits + RV curves) will therefore allow us to place tight constraints on the fundamental properties of a wide variety of stars.

For RV curve determinations, we need to secure high-resolution spectra for each system on **multiple-epochs**. Envisioning a program with a time-scale of four years, we will require **two separate visits per system per semester** to obtain well-sampled RV curves for all our targets. Given their brightness range ($V\sim$ 6–12), two Echelle setups are ideal for our needs: the Echelle@duPont@LCO and FEROS@MPI 2.2m@La Silla. Both cover the required wavelength range (roughly λ: 3700-7000Å) and provide enough resolution (R ~45,000/48,000) for precise RV determinations ($\sigma_{RV} < 1$ kms^{-1}). This wavelength coverage includes the spectral lines needed to determine spectral types and luminosity classes: H-Balmer lines, He lines for hot stars and enough metal lines for the cooler targets. Through model atmosphere fitting, the spectroscopy will also allow us to determine effective temperature $T_{\rm eff}$, surface gravity ($\log g$), and elemental abundances for these stars. Spectroscopic parameters will also yield a precise placement of these stars on the HR diagram.

Our program was started using both setups, but since the duPont Echelle may no longer be available, we shall complete it using only FEROS. This latter has proven to be the perfect balance considering aperture, resolution and availability. In response to a concern from the panel, we note that at the start of our survey we did consider CHIRON@1.5m@CTIO as an alternative, but the smaller aperture is not adequate for our fainter targets. Also, service mode is **not** ideal for this type of program.

References

- Benedict, G. et al. 2016, AJ, 152, 141
- Brahm, R., Jordán, A., Espinoza, N. 2017, PASP, 129, 034002
- Horch, E., et al. 2017, AJ, 153, 212
- Kiefer, F., et al. 2018, MNRAS, 474, 731
- Mason, B. 2015, IAU General Assembly, 23, 2300709
- Mendez, R.A., Clavería, R. & Costa, E. 2021, AJ, 161, 155
- Pourbaix, D. 2000, A&AS, 145, 215
- Tokovinin, A., et al. 2021, AJ, 162, 41
- Torres, G., Andersen, J. & Giménez, A. 2010, A&ARv, 18, 67
- Videla M., Méndez R.A., Clavería, R.M., Silva J.F. & Orchard M.E. 2022, AJ, 163, 220.

Comment on target list

We could not upload the complete file. For this reason, in List of Targets we have included only 6 examples, which illustrate well the sky distribution of our objects and their magnitude range.

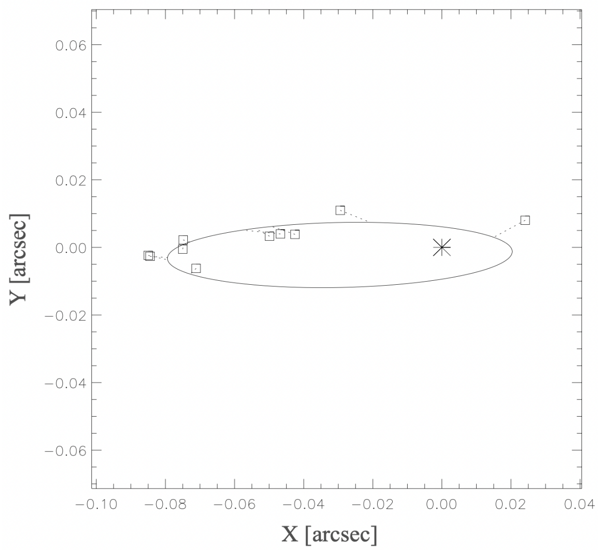

Figure 1: Astrometric orbit for HIP 38414 (Tok195), a K1.5II giant at 111 pc with P=7.2 yr, a=55 mas, and an estimated q=0.4. Between 2012 and 2021 it has been resolved 11 times at SOAR

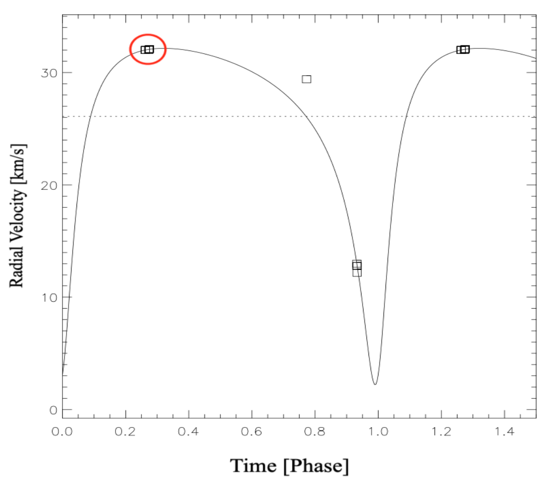

Figure 2: RV curve for HIP 38414 (Tok195), based on old RV determinations made in the 1980's and our new observations made with FEROS in 2022 (circled in red)

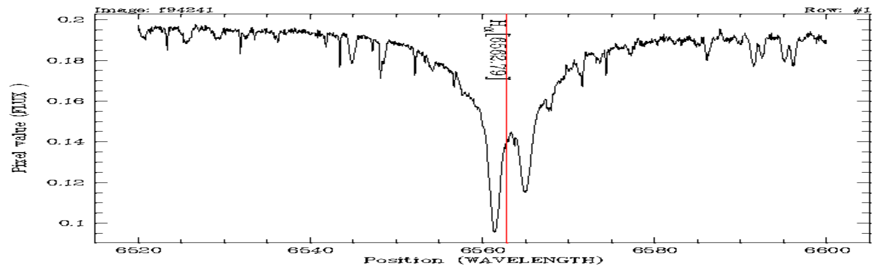

Figure 3: Section in the region of Hα, of a FEROS Echelle spectrum of the SB2 spectroscopic binary HIP 48273

CURRENT STATUS OF THE PROJECT

In 2019A we were awarded 4 nights (2 epochs) with the du Pont Echelle; runs that had a poor outcome due to weather conditions. In 2019B we were awarded 4 nights (one epoch) with FEROS; run which was only partially successful. In 2020A we were awarded 5 nights (2 epochs) with the duPont Echelle, but these observations were **never carried out** due to the Pandemic. Finally, in 2022A we were awarded 8 nights (2 epochs) with FEROS: April (100% succeesful) and August (**completely lost**; the observatory was shut down for weeks due to a snowstorm).

Our FEROS data has been reduced, which was done using the well-tested pipeline CERES (Brahm et al. 2017). We have recently incorporated new students to this program (Camila Caballero and Maximiliano Vega) who helped speed-up data reduction.

Publications of the proposers in the last three years, relevant to the proposal (resulting mainly from our SOAR Speckle program) are:

- Anguita-Aguero, J., **Méndez, R. A**, Videla, M.., **Costa, E.**: ”Individual masses of single-line spectroscopic binaries with a visual orbit using Bayesian inference and suitable priors”. In preparation.
- Anguita-Aguero, J., **Méndez, R. A**, Clavería, R., **Costa, E.**, 2022, AJ, 163, 118: ”Orbital Elements and Individual Component Masses from Joint Spectroscopic and Astrometric Data of Double-line Spectroscopic Binaries”
- Gomez, J., Docobo, J., Campo, P., Andrade, M., **Méndez, R.A., Costa, E.** 2021, MNRAS.tmp.2373G: ”20 Orbits of binaries based on soar speckle observations”
- **Mendez, R.A.**, Clavería, R., **Costa, E.** 2021, AJ 161, 155: ”Orbits and Masses of Binaries from Speckle Interferometry at SOAR”
- Tokovinin, A., Mason, B., **Mendez, R. A., Costa, E.**, Horch, E., 2020, AJ 160, 7: ”Speckle Interferometry at SOAR in 2019”
- Tokovinin, A., Mason, B., **Mendez, R.A., Costa, E.**, et al. 2021, AJ 162, 41: ”Speckle Interferometry at SOAR in 2020”
- Tokovinin, A., Mason, B., **Mendez, R. A., Costa, E.**, 2022, AJ 164, 58: ”Speckle Interferometry at SOAR in 2021”

STUDENT THESIS

Mrs. Jennifer Anguita, a graduate student who is co-I of this proposal, has used some data from this program to obtain combined orbits for GCSB systems resolved by SOAR. The observations requested here are however **not** critical for her thesis, which relies mainly on historic RV data. In her thesis (near completion) she shows that using a Markov Chain Monte Carlo approach, and combining an astrometric orbit from SOAR with a RV orbit, it is possible to obtain individual component masses for double-line spectroscopic binaries with a formal uncertainty as small as $0.01M_\odot$ (Anguita-Aguero et al. 2022).

In a second work in preparation, she is using data for SB1 binaries from this program, and the newly developed Bayesian methodology based on the MCMC algorithm No-U-Turn sampler (Videla et al. 2022) to determine the individual component masses. For our example SB1 system, HIP 38414, she has obtained percent errors of 2.2% and 13% for the mass of the primary and secondary, respectively.

TECHNICAL DESCRIPTION

To be able to use multiple lines (which vary in intensity depending on Spectral Type) to measure RV, we need a high SNR (∼100). For the original 2019B/22A versions of this proposal we used the FEROS ITC, with airmass=1.5 and IQ=1.3, to carry out tests for various magnitude/spectral type combinations and thus estimate the exposure times required to reach our SNR goal (at the central wavwlength). The ITC predictions were certainly "in the ballpark", but here we have determined the integration times from examination of the data obtained in average conditions with this instrument in early April 2022.

Our **real life** experience with FEROS showed that in the case of our brightest objects a SNR of ∼100 could be achieved, in average conditions, with an exposure time of ∼100 sec, while in the case of the faintest targets exposure times as long as ∼3000 sec were required in good conditions. Adding telescope pointing, readout, quick look. etc. overheads -which in the case of the brighter targets are significant- this resulted in that we could do about 25 pointings per night; including two bright RV standards (which provide a sanity check; see below). Given the size of our current sample (∼100 systems), we thus need 8 nights per semester to reach the goal of two separate visits per target, per semester. From our poor weather runs with Dupont@LCO, we also learned that a fairly good sky condition is mandatory, and that only the brightest targets can be observed successfully in bad weather.

Because of the high resolution, efficiency and stability of FEROS, our RV precision goal ($\sigma_{RV} < 1$ kms^{-1}) was easily surpassed. Multiple observations of RV standards show internal precisions for our radial velocities varying between 0.0025 and 0.0053 km/sec. The rms of the average of the differences between our RV (determined with CERES) and published RV for the same radial RV standards turned out to be 0.07 km/sec. We must note however, that the RV precison attainable depends strongly on the profile of the spectral lines of each particular object; as much as on the instrument's capabilities.

The resolution of FEROS was confirmed as sufficient to separate the components of most SB2 binaries. As an example, in Fig.3 we present a section centered on Hα, of a FEROS Echelle spectrum of the SB2 system HIP 48273. This binary has been resolved on multiple epochs during our SOAR Speckle survey