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CARMENES – M Dwarfs and their Planets: First Results

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Abstract. CARMENES is a pair of high-resolution ($R \gtrsim 80,000$) spectrographs covering the wavelength range from 0.52 to 1.71 μm with only small gaps. The instrument has been optimized for precise radial velocity measurements. It was installed and commissioned at the 3.5 m telescope of the Calar Alto observatory in Southern Spain in 2015. The first large science program of CARMENES is a survey of ∼300 M dwarfs, which started on Jan 1, 2016. We present an overview of the instrument, and provide a few examples of early science results.

Keywords. planetary systems, stars: late-type, surveys, instrumentation: spectrographs, techniques: radial velocities, techniques: spectroscopic

1. Introduction

CARMENES is a new radial-velocity facility for the 3.5 m telescope of Calar Alto Observatory (CAHA) close to Almería, Spain (see also Quirrenbach *et al.* 2010, 2012, 2014, 2016). The main scientific objective of CARMENES is carrying out a survey of M-type main sequence stars, and the instrument has been optimized solely for this purpose. The CARMENES survey will characterize the population of planets around these stars, and detect low-mass planets in their habitable zones (HZs). In the focus of the project are very cool stars of spectral type M4 V and later, and moderately active stars, but the target list also comprises earlier and therefore brighter M dwarfs. In particular, we aim at being able to detect 2 $M_\oplus$ planets in the HZs of M5 V stars. A long-term radial velocity precision of ∼1 m/s per measurement will permit to attain this goal. The CARMENES survey will also produce a unique data base of high-resolution spectra of M dwarfs, enabling studies of stellar activity and improved determinations of stellar parameters. These data will thus be of high scientific value by themselves, and they will also be needed for disentangling the signatures of planetary companions from activity-induced radial-velocity variations.

2. The CARMENES Instrument

The CARMENES instrument has been optimized for obtaining precise radial velocities of cool stars. In the front end attached to the Cassegrain focus of the 3.5 m telescope, the light is separated by a dichroic beam splitter at 0.96 μm. The spectral ranges shortward and longward of this wavelength are sent to two separate spectrographs, which are mounted on benches inside vacuum tanks located in the coudé laboratory of the 3.5 m dome. The main instrument components of CARMENES are the following:

- *Front End.* The front end is attached to the Cassegrain focus of the 3.5 m telescope and contains a camera for acquisition and guiding, an atmospheric dispersion compensator, the dichroic beam splitter, a shutter in the visible channel, input selectors to switch between the sky and calibration light, and fiber heads (Seifert *et al.* 2012). The first mirror in the front end is motorized; when it is detracted the light passes straight through to a separate focus so that it is possible to switch rapidly between CARMENES and another Cassegrain instrument.
- *Fibers.* The optical fibers transporting the light from the front end to the spectrographs also fulfill the important task of "scrambling", i.e., of reducing the jitter at the spectrograph pseudo-slit with respect to guiding errors and seeing at the fiber input. For improved scrambling, the long circular fibers leading from the telescope to the coudé room are connected to shorter fiber sections with an octagonal diameter (Stürmer *et al.* 2014). The fiber diameter has been chosen to provide a $1\overset{''}{.}5$ acceptance angle on the sky, matched to somewhat worse than median seeing on Calar Alto.
- *Visible-Light Spectrograph.* The visible-light échelle spectrograph covers the wavelength range from 0.52 μm to 1.05 μm with a resolving power of $R = 94,600$ and a mean sampling of 2.8 pixels per resolution element. It accepts light from two fibers; the first fiber carries the light from the target star, while the second fiber can either be used for simultaneous wavelength calibration or for monitoring the sky. The optical design is a grism cross-dispersed, white pupil, échelle spectrograph working in quasi-Littrow mode using a two-beam, two-slice, image slicer. The spectrograph is housed in a vacuum vessel and operated at room temperature. The detector is a back-side illuminated 4112×4096 pixel CCD (model e2v CCD231-84).
- *Near-Infrared Spectrograph.* The design of the near-IR spectrograph is very similar to that of its visible counterpart. It provides $R = 80,400$ over the range 0.95 μm to 1.71 μm with a mean sampling of 2.5 pixels per resolution element. It is cooled to 138 K with a continuous flow of gaseous nitrogen. The detector is a mosaic of two 2048×2048 pixel HAWAII-2RG infrared arrays with a long-wavelength cutoff at 2.5 μm (see also Amado *et al.* 2012). The near-IR cooling system employs an external heat exchanger / evaporator unit that is fed by liquid nitrogen and provides a continuous flow of gaseous nitrogen to the near-IR spectrograph (Becerril *et al.* 2012).
- *Calibration Units.* CARMENES uses hollow-cathode emission line lamps and Fabry-Pérot etalons for spectral calibration. For each spectrograph, the arc lamps as well as quartz lamps for flat-fielding are housed in a calibration unit that is connected to the front end with a fiber link.
- *Exposure Meters.* The zeroth-order light from the échelle gratings in the two spectrographs is routed to photomultiplier tubes, which monitor the received intensity with high time resolution. This information is needed for an accurate conversion of the

Table 1. CARMENES installation and commissioning milestones

Date	Milestone
December 22, 2014	3.5 m coudé room refurbishment for CARMENES complete
April 23, 2015	Front end arrives at CAHA
April to June 2015	Commissioning of front end, first ICS tests
July 6, 2015	VIS vacuum tank arrives at CAHA
August 17, 2015	VIS spectrograph arrives at CAHA
September 1, 2015	Installation of VIS calibration unit at CAHA
October 3, 2015	First Light for the VIS spectrograph
October 20, 2015	NIR spectrograph arrives at CAHA
November 7, 2015	First Light for NIR spectrograph
November 9, 2015, 20:20:51UT	**CARMENES First Light** (VIS and NIR simultaneously)
November and December 2015	Commissioning of the complete instrument
December 30, 2015	Provisional Acceptance complete
January 1, 2016	**Start of CARMENES Survey**

observed radial velocity to the barycenter of the Solar System. It can also be used to make real-time adjustments to the integration time depending on atmospheric conditions.

- *Instrument Control System.* The coordination and management of the sub-systems of CARMENES is handled by the instrument control system (ICS), which provides a tool to operate the instrument in an integrated manner (Colomé *et al.* 2016). The ICS includes a scheduler that can autonomously prioritize and select targets for observation.
- *Infrastructure.* The CARMENES spectrographs and ancillary equipment are located in the coudé room of the 3.5 m telescope dome. Each spectrograph is placed within a temperature-controlled chamber, providing shielding from annual temperature variations and from heat sources such as electronics, pumps, and calibration lamps. An intelligent interlock system monitors the status of the instrument and of the auxiliary systems, and organizes information about their overall status and health (Helmling *et al.* 2016).

3. Installation and Commissioning

The subsystems of CARMENES were moved to Calar Alto and installed at the 3.5 m telescope in the course of 2015 (see Tab. 1). The front end was mounted at the Cassegrain flange in April, followed by extensive testing of the acquisition and guiding procedures and the software interfaces with the telescope control system. The optical fibers connecting the front end to the spectrographs were routed through the telescope fork at the same time. The visible-light spectrograph was shipped to the observatory in July. The optical bench and the vacuum system had been separately pre-integrated at Landessternwarte Heidelberg and at the Max-Planck-Institut für Astronomie, respectively; they were first integrated with each other on site. The near-infrared spectrograph was fully integrated at the Instituto de Astrofísica de Andalucía and moved to Calar Alto in October. The calibration system and the Fabry-Pérot etalons were installed in parallel. CARMENES had "First Light" – defined as taking stellar spectra with both spectrographs simultaneously – on Nov 9, 2015. This event marked the beginning of the commissioning, in which the whole instrument was tested and characterized. The CARMENES M dwarf survey started on Jan 1, 2016, after the instrument passed its provisional acceptance tests.

4. Calibration Strategy

Precision spectroscopy at red optical and infrared wavelengths requires a novel strategy for wavelength calibration. In a spectrograph like HARPS, for example,

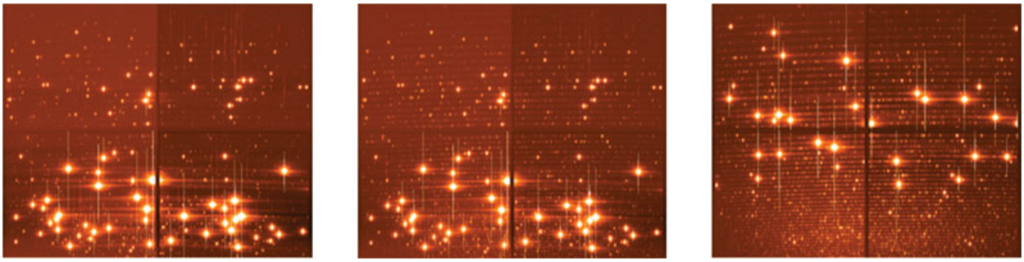

Figure 1. Exposures of hollow-cathode lamps (from left to right: Th-Ne, U-Ne, U-Ar) with the visible-light spectrograph. The spectra are rich in calibration information, but suffer from very bright noble gas lines.

Th-Ar hollow-cathode lamps (HCLs) provide a dense forest of emission lines that are not severely affected by noble gas emission (Ar) because it is strong only at wavelengths on the red side of the HARPS wavelength cutoff (680 nm). In contrast, CARMENES operates in the region where all HCL fill gases emit very bright lines (see Fig. 1). Some of these lines are much stronger than typical Th (or other cathode material) lines and can saturate the detectors. Furthermore, Th emits most of its lines at optical wavelengths but not so many in the infrared. In preparation for CARMENES, we investigated different HCLs and constructed new line lists (Sarmiento *et al.* 2014). In CARMENES, we are using three different types of emission lamps (Th-Ne, U-Ar, and U-Ne, see Fig. 1) to provide optimal coverage. In addition, we operate two passively stabilized Fabry-Pérot etalons (FPs) optimized for the two spectrographs in order to cover the entire CARMENES wavelength with dense emission lines. With more than 10^4 FP emission lines, we can construct a precise wavelength solution for the FP comb that is incorporated in our wavelength calibration scheme (Bauer *et al.* 2015). The FPs are also used during the night to monitor short-term spectrograph drifts; long-term stability is ensured by comparing the FPs to HCL exposures taking during daytime.

5. Data Reduction

During standard operation at night, each CARMENES spectrograph simultaneously receives light from a target in the first (science) fiber and the corresponding FP etalon in the second (calibration) fiber. (For faint targets, it is also possible to use the second fiber as a sky fiber.) The extraction of the spectra follows the reduction procedure described in Baranne *et al.* (1996). The data reduction software was built on the basis of REDUCE, a package for cross-dispersed échelle spectra reduction written in IDL (Piskunov & Valenti 2002). The key feature is the optimal extraction that we use together with a new algorithm optimized for stabilized spectrographs (Zechmeister *et al.* 2014). The measurement of radial velocities from the spectra is carried out following two complementary approaches, the method of least squares fitting (a detailed description of our algorithms and their applicability to M dwarfs is given in Anglada-Escudé & Butler (2012), see also Caballero *et al.* 2016), and the cross-correlation method using a consistent flux weighting algorithm (Pepe *et al.* 2002).

6. Stellar Spectra

In this section we show a few examples demonstrating the capabilities of CARMENES for stellar astrophysics. The CARMENES spectra cover the wavelength range from 0.52 to 1.71 μm with only minor gaps; an example in which some important chromospheric

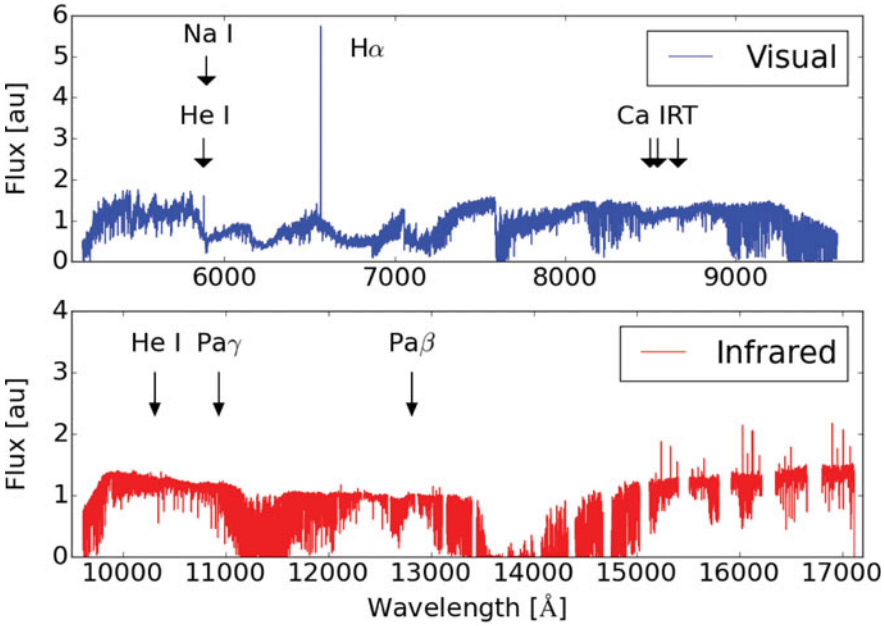

Figure 2. CARMENES spectrum of YZ CMi. Important chromospheric lines are identified. Courtesy S. Czesla.

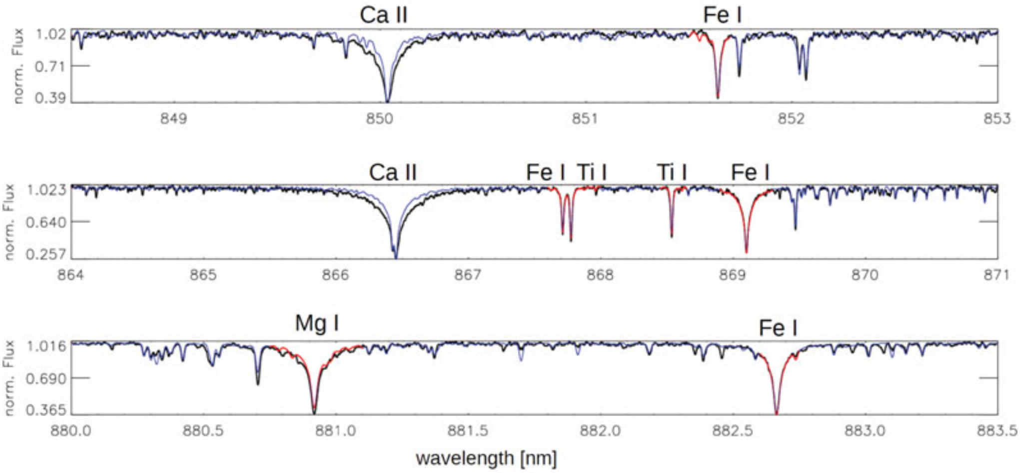

Figure 3. Section of the CARMENES spectrum of an M0.5 V star (black) and the best fit model (blue: model outside fit region, red: model inside fit regions for χ^2-minimization. Courtesy V. Passegger.

lines have been identified is shown in Fig. 2. The high signal-to-noise (typically 100 or more) that is needed for measuring precise radial velocities makes the spectra also very well suited for determining stellar parameters such as effective temperature, gravity, and metallicity. The result from fitting PHOENIX-ACES models (Husser *et al.* 2013) with a downhill simplex methods to a section of the spectrum of an M0.5 V star is shown in Fig. 3.

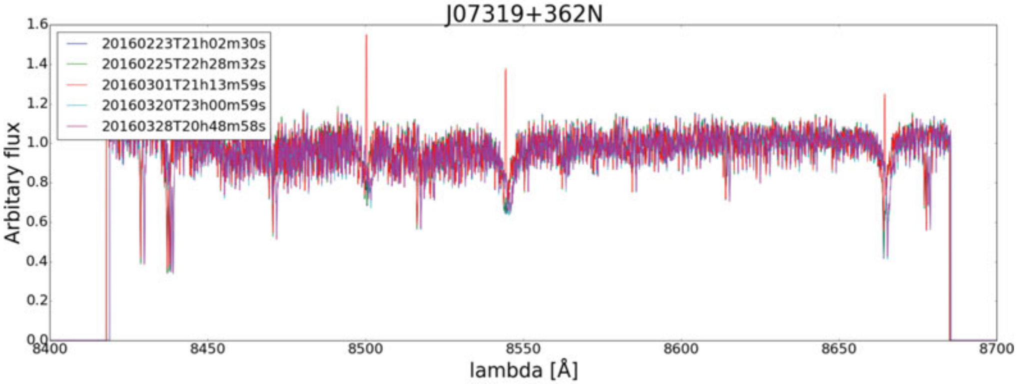

Figure 4. Sections of five CARMENES spectra of the active star BL Lyn around the Ca II infrared triplet taken in February / March 2016. The infrared triplet lines were in absorption during four epochs, but showed narrow emission components on March 1. Adapted from Brinkmöller (2016).

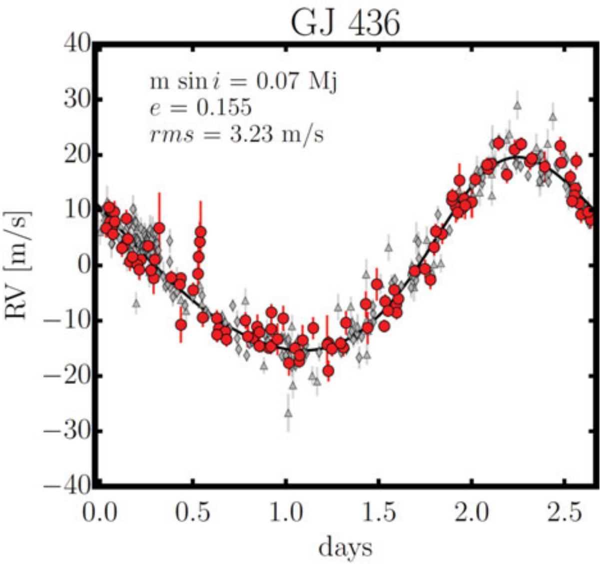

Figure 5. Phase-folded radial-velocity data and orbital fit for GJ 436. The grey triangles are literature data from Keck-HIRES (Maness *et al.* 2007) and HARPS (Lanotte *et al.* 2014), the red dots are data from the CARMENES visual spectrograph. Courtesy T. Trifonov.

In Fig. 4 we show sections of five spectra of the active star BL Lyn covering the Ca II infrared triplet. While the triplet lines are in absorption during four of the epochs, sharp emission components are apparent in the spectrum taken on March 1. Time series of spectra taken during the CARMENES survey will enable analyses of flaring activity, and of correlations between activity indicators and radial velocities.

7. Radial Velocities

CARMENES was designed with the goal of achieving a stability of 1 m/s for radial velocity measurements of late-type stars. An initial look at the data from the visual spectrograph shows that an r.m.s. velocity precision of a few m/s has in fact been achieved for most stars observed during the first few months of operation; several stars show a velocity scatter less than 2 m/s. Since this figure includes a contribution from stellar "jitter", it places an upper limit on the intrinsic stability of the spectrograph. CARMENES data on GJ 436, which is known to harbor a planet, are shown in Fig. 5 along with measurements from Keck-HIRES and HARPS, showing that CARMENES delivers data that are comparable to those from other state-of-the-art instruments.

Getting precise radial velocities from the NIR spectrograph is much more complicated for several reasons: The spectrograph needs to be actively cooled and stabilized (whereas the visible-light spectrographs rely on passive stabilization), the NIR detectors are more difficult to characterize and calibrate than CCDs, and the spectra are much more heavily contaminated by telluric absorption. Work on optimizing the calibration and stabilization of the NIR spectrograph is still ongoing, but observations covering several nights with high-cadence sampling and RV scatter of a few m/s have already been realized.

8. The CARMENES Survey

To define the CARMENES survey sample, we have ranked the M dwarfs with declination $\delta > -23^\circ$ by apparent magnitude within each spectral subtype, and selected the brightest stars in each subclass (not considering binaries with separation $< 5''$). This creates a sliding magnitude cut-off that helps biasing the sample towards later spectral subtypes, while maintaining a simple selection criterion that can be modeled easily in statistical analyses. We thus obtain a sample that takes advantage of the "sweet spot" for CARMENES in the M3 V to M4 V spectral range: Earlier M subtypes can be observed quite efficiently with spectrographs working at bluer wavelengths; reaching larger numbers of later stars requires near-IR spectrographs at larger telescopes.

During the first year of observations, more than 5,000 visible-light and 4,500 NIR spectra on 330 individual M dwarfs were taken. The first data product from CARMENES to be released in mid 2017 will be a library of single-epoch spectra of these stars.

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References

Amado, P.J., Lenzen, R., Cárdenas, M.C., *et al.* (2012). *CARMENES. V: non-cryogenic solutions for YJH-band NIR instruments.* In *Modern technologies in space- and ground-based telescopes and instrumentation II.* SPIE 84501U

Anglada-Escudé, G., & Butler, R.P. (2012). *The HARPS-TERRA project. I. Description of the algorithms, performance, and new measurements on a few remarkable stars observed by HARPS.* ApJS 200, 15

Baranne, A., Queloz, D., Mayor, M., *et al.* (1996). *ELODIE: A spectrograph for accurate radial velocity measurements.* A&AS 119, 373

Bauer, F.F., Zechmeister, M., & Reiners, A. (2015). *Calibrating echelle spectrographs with Fabry-Péerot etalons.* A&A 581, A117

Becerril, S., Lizon, J.L., Sánchez-Carrasco, M.A., *et al.* (2012). *CARMENES. III: an innovative and challenging cooling system for an ultra-stable NIR spectrograph.* In *Modern technologies in space- and ground-based telescopes and instrumentation II.* SPIE 84504L

Brinkmöller, M. (2016). *Analysis of the activity of M dwarfs observed by CARMENES assessed on the calcium infrared triplet.* BSc Thesis, Univ. Heidelberg

Caballero, J.A., Guárdia, J., López del Fresno, M., *et al.* (2016). *CARMENES: data flow.* In *Observatory operations: strategies, processes, and systems VI.* SPIE 99100E

Colomé, J., Guàrdia, J., Hagen, H.J., *et al.* (2016). *CARMENES: The CARMENES instrument control software suite.* In *Software and cyberinfrastructure for astronomy IV.* SPIE 991334

Helmling, J., Wagner, K., Hernández Castaño, L., *et al.* (2016). *CARMENES: interlocks or the importance of process visualization and system diagnostics in complex astronomical instruments.* In *Ground-based and Airborne Instrumentation for Astronomy VI.* SPIE 990890

Husser, T.O., Wende-von Berg, S., Dreizler, S., *et al.* (2013). *A new extensive library of PHOENIX stellar atmospheres and synthetic spectra.* A&A 553, A6

Lanotte, A.A., Gillon, M., Demory, B.O., *et al.* (2014). *A global analysis of Spitzer and new HARPS data confirms the loneliness and metal-richness of GJ 436 b.* A&A 572, A73

Maness, H.L., Marcy, G.W., Ford, E.B., *et al.* (2007). *The M Dwarf GJ 436 and its Neptune-Mass Planet.* PASP 119, 90

Pepe, F., Mayor, M., Galland, F., *et al.* (2002). *The CORALIE survey for southern extra-solar planets VII. Two short-period Saturnian companions to HD 108147 and HD 168746.* A&A 388, 632

Piskunov, N.E., & Valenti, J.A. (2002). *New algorithms for reducing cross-dispersed echelle spectra.* A&A 385, 1095

Quirrenbach, A., Amado, P.J., Caballero, J.A., *et al.* (2014). *CARMENES instrument overview.* In *Ground-based and airborne instrumentation for astronomy V.* SPIE 91471F

Quirrenbach, A., Amado, P.J., Caballero, J.A., *et al.* (2016). *CARMENES: an overview six months after first light.* In *Ground-based and Airborne Instrumentation for Astronomy VI.* SPIE 990812

Quirrenbach, A., Amado, P.J., Mandel, H., *et al.* (2010). *CARMENES: Calar Alto high-Resolution search for M dwarfs with Exo-earths with Near-infrared and optical Echelle Spectrographs.* In *Ground-based and airborne instrumentation for astronomy III.* SPIE 773513

Quirrenbach, A., Amado, P.J., Seifert, W., *et al.* (2012). *CARMENES. I: Instrument and survey overview.* In *Ground-based and airborne instrumentation for astronomy IV.* SPIE 84460R

Sarmiento, L.F., Reiners, A., Seemann, U., *et al.* (2014). *Characterizing U-Ne hollow cathode lamps at near-IR wavelengths for the CARMENES survey.* In *Ground-based and airborne instrumentation for astronomy V.* SPIE 914754

Seifert, W., Sánchez Carrasco, M.A., Xu, W., *et al.* (2012). *CARMENES. II: optical and opto-mechanical design.* In *Ground-based and airborne instrumentation for astronomy IV.* SPIE 844633

Stürmer, J., Stahl, O., Schwab C., *et al.* (2014). *CARMENES in SPIE 2014. Building a fibre link for CARMENES.* In *Advances in optical and mechanical technologies for telescopes and instrumentation.* SPIE 915152

Zechmeister, M., Anglada-Escudé, G., & Reiners, A. (2014). *Flat-relative optimal extraction. A quick and efficient algorithm for stabilised spectrographs.* A&A 561, A59