Manufacturing, Assembly, Integration and Verification of CARMENES and Preparation of its Input Catalogue

A. Quirrenbach[1], J. A. Caballero[2], P. J. Amado[3], I. Ribas[4], A. Reiners[5], R. Mundt[6], D. Montes[7]

[1]*Landessternwarte (LSW), Zentrum für Astronomie der Universität Heidelberg, Königstuhl 12, D-69117 Heidelberg, Germany*

[2]*Centro de Astrobiología (CSIC-INTA), Campus ESAC, PO Box 78, E-28691 Villanueva de la Cañada, Madrid, Spain*

[3]*Instituto de Astrofísica de Andalucía (CSIC), Glorieta de la Astronomía s/n, E-18008 Granada, Spain*

[4]*Institut de Ciències de l'Espai (CSIC-IEEC), Campus UAB, Facultat Ciències, Torre C5 - parell - 2a planta, E-08193 Bellaterra, Barcelona, Spain*

[5]*Institut für Astrophysik (IAG), Friedrich-Hund-Platz 1, D-37077 Göttingen, Germany*

[6]*Max-Planck-Institut für Astronomie (MPIA), Königstuhl 17, D-69117 Heidelberg, Germany*

[7]*Departamento de Astrofísica, Facultad de Física, Universidad Complutense de Madrid, E-28040 Madrid, Spain*

Abstract. CARMENES is a next-generation radial-velocity instrument under construction for the 3.5 m telescope at the Calar Alto Observatory by a consortium of eleven Spanish and German institutions. It consists of two separate échelle spectrographs covering the wavelength range from 0.55 to 1.7 μm at a spectral resolution of R $\approx$ 82 000, fed by fibers from the Cassegrain focus of the telescope. CARMENES passed its final design review in February 2013 and is planned to start the Guaranteed Time Observations programme at the end of 2015. We discuss critical design decisions, present the final design, and report on the ongoing MAIV phase of the project. CARMENES will conduct a radial-velocity survey of 300 M dwarfs with a precision sufficient for detecting Earth-like planets in their habitable zones. We compile an exhaustive data base of M stars, dubbed CARMENCITA, from which the CARMENES guaranteed-time sample

will be selected. CARMENCITA contains information on all relevant properties of the potential targets. Dedicated imaging, photometric, and spectroscopic observations are underway to provide crucial data on these stars that are not available in the literature.

1. Introduction

CARMENES (`/kár-men-es/`, *Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs*[1]) is a next-generation instrument being built for the 3.5 m telescope at the Calar Alto Observatory by a consortium of German and Spanish institutions. It consists of two separated spectrographs covering the wavelength ranges from 0.55 to 0.95 μm and from 0.95 to 1.70 μm with spectral resolutions R $\approx$ 82 000, each of which shall perform high-accuracy radial-velocity measurements ($\sim$1 m s^{-1}) with long-term stability (Quirrenbach et al. 2014).

The CARMENES design has been optimized for a search for terrestrial planets in the habitable zones of low-mass stars, which may well provide our first chance to study environments capable of supporting the development of life outside the Solar System. With its unique combination of optical and near-infrared spectrographs, CARMENES will provide better sensitivity for the detection of low-mass planets than any comparable instrument (e.g. HPF, Mahadevan et al. 2012; IRD, Tamura et al. 2012; SPIRou, Thibault et al. 2012; ESPRESSO, Mégevand et al. 2012), and a powerful tool for discriminating between genuine planet detections and false positives caused by stellar activity, which have plagued planet searches employing spectrographs with a smaller wavelength coverage.

As set forth in an agreement between the Observatory and the CARMENES Consortium, the latter will receive Guaranteed Time Observations with the Calar Alto 3.5 m telescope, which amounts a minimum of six hundred (600) useful nights. This guaranteed observing time will be used to carry out a single large survey targeted at about 300 M dwarf stars in the solar neighborhood. This will allow us to obtain 60 observations on average for each of the 300 target stars, and more than 100 observations for selected objects. This is necessary to obtain secure detections and orbital parameters for planets with radial-velocity semi-amplitudes close to the measurement uncertainty.

With its clear scientific focus and the large number of nights available at the Calar Alto 3.5 m telescope during the time frame until 2018, the CARMENES survey will be a very competitive project, and leave a lasting legacy of 50 to 100 planets in the habitable zones of low-mass stars. We aim at being able to detect 2 $M_\oplus$ planets in the habitable zone of M5 V stars.

Besides the detection of the individual planets themselves, the ensemble of objects will provide sufficient statistics to assess the overall distribution of planets around M dwarfs: frequency, masses, and orbital parameters. The survey will confirm or falsify the seemingly low occurrence of Jovian planets around M stars, and the frequency of ice giants and terrestrial planets will be established along with their typical separations, eccentricities, multiplicities, and dynamics. Thus, the CARMENES survey can provide the first robust statements about planet formation in the low-mass star regime.

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[1] `http://carmenes.caha.es`

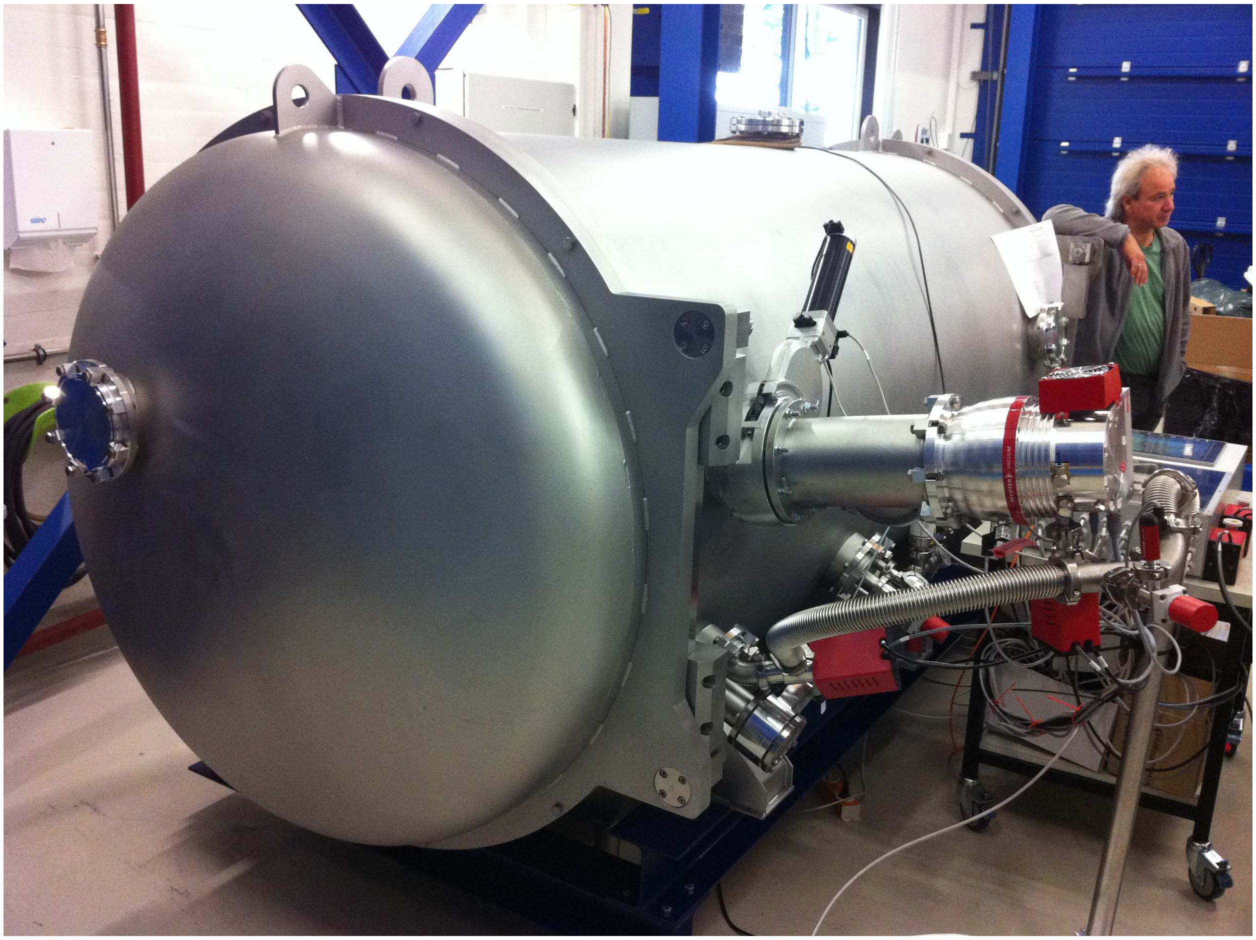


Figure .1: Empty VIS vacuum tank and valves (NTG), pumps (Pfeiffer) and interlocks system (Calar Alto) operating in the MPIA instrument assembly room in Heidelberg, Germany. The NIR vacuum tank, pumps, interlocks system, which are identical to the VIS ones, and nitrogen-gas preparation unit also operate normally in the IAA instrument assembly room in Granada, Spain.

Additionally, the CARMENES planet search experiment will deliver valuable targets for further characterization, both their bulk and detailed properties. This is especially tantalizing for low-mass planets in the habitable zone, since determining their nature (ice, telluric) becomes feasible. Further, their study can potentially reveal the existence of an atmosphere and, perhaps, determine its chemical composition. The exoplanets from CARMENES will be prime objects for further characterization, via photometric monitoring or direct detection, because most of the targets will be within 20 pc.

CARMENES will also be offered in open time to the Spanish and German astronomical communities, as well as to astronomers worldwide. Given the high resolution, wide wavelength coverage including the near-infrared, and efficiency of CARMENES, it will be an ideal instrument also to carry out a variety of programs, such as radial-velocity surveys of M giants, K dwarfs and solar-like stars, measurements of abundance and activity of stars of all

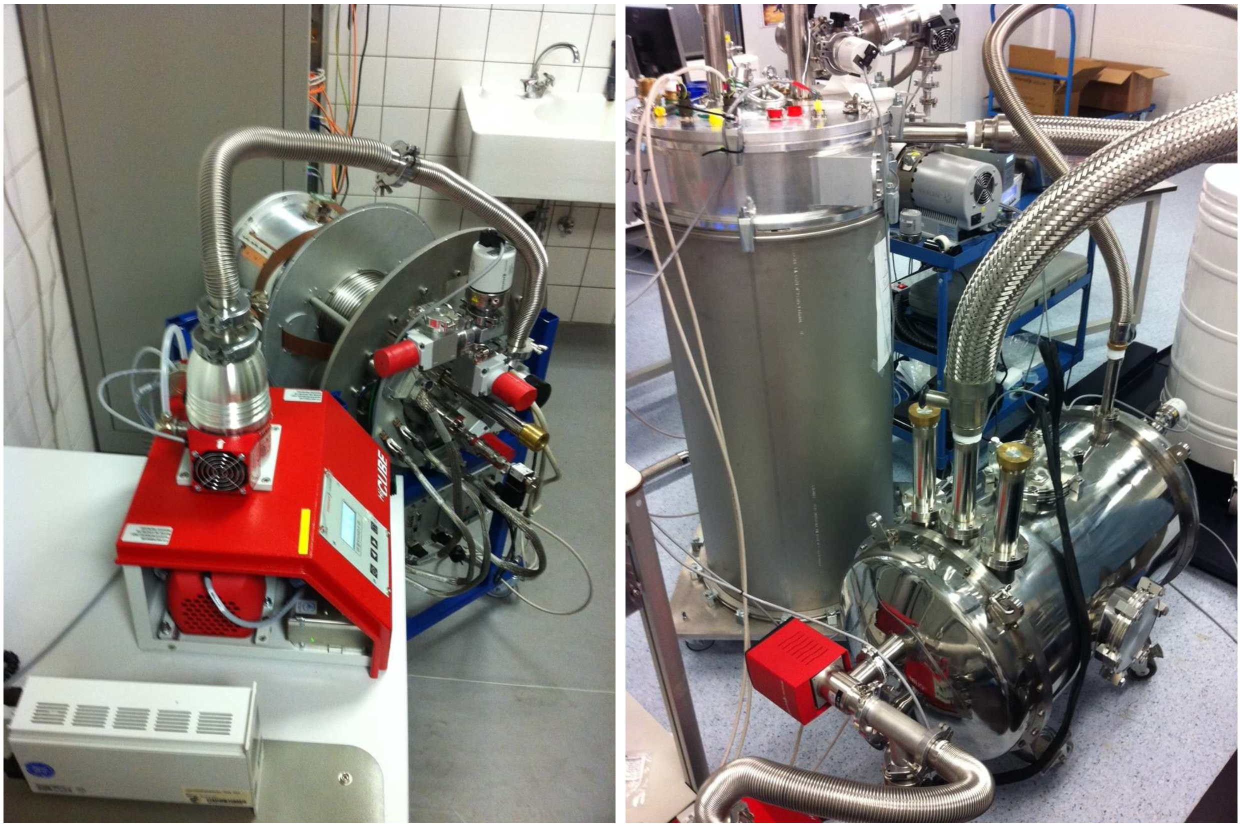


Figure .2: *Left panel:* ESO-made NIR detector cryostat attached to the read-out electronics and vacuum system, in Heidelberg; there was a mock up inside of the detector head, instead of the science-grade detector mosaic. The VIS detector cryostat, which is also in Heidelberg, is identical except for minor differences in the detector head. *Right panel:* ESO-made nitrogen-gas preparation unit attached to its test facility and a liquid nitrogen bottle, in Granada.

spectral types, precise determinations of basic stellar astrophysical parameters ($T_{\rm eff}$, $\log g$, $v \sin i$), etc.

2. Manufacturing, assembly, integration and verification of the instrument

The visible spectrograph (VIS) is equipped with a 4k × 4k e2v 231–84 CCD for the range 0.55–1.05 μm, while the near-infrared one (NIR) is equipped with a mosaic of two 2k × 2k Hawaii-2RG HgCdTe detectors with a cut-off at 2.5 μm for the range 0.90–1.70 μm. Each spectrograph is coupled to the 3.5 m telescope with two optical fibers, one for the target, and one for calibration light. The front end contains a dichroic beam splitter, which separates the VIS and NIR light at 0.95 μm, and an atmospheric dispersion corrector, to feed the light into the fibers leading to the spectrographs. Our pick-up mirror is mounted on rails, which allows a quick change of instrument at the 3.5 m Cassegrain focus, where the integral field unit PMAS (Roth et al. 2005) is permanently installed. Guiding is performed with a

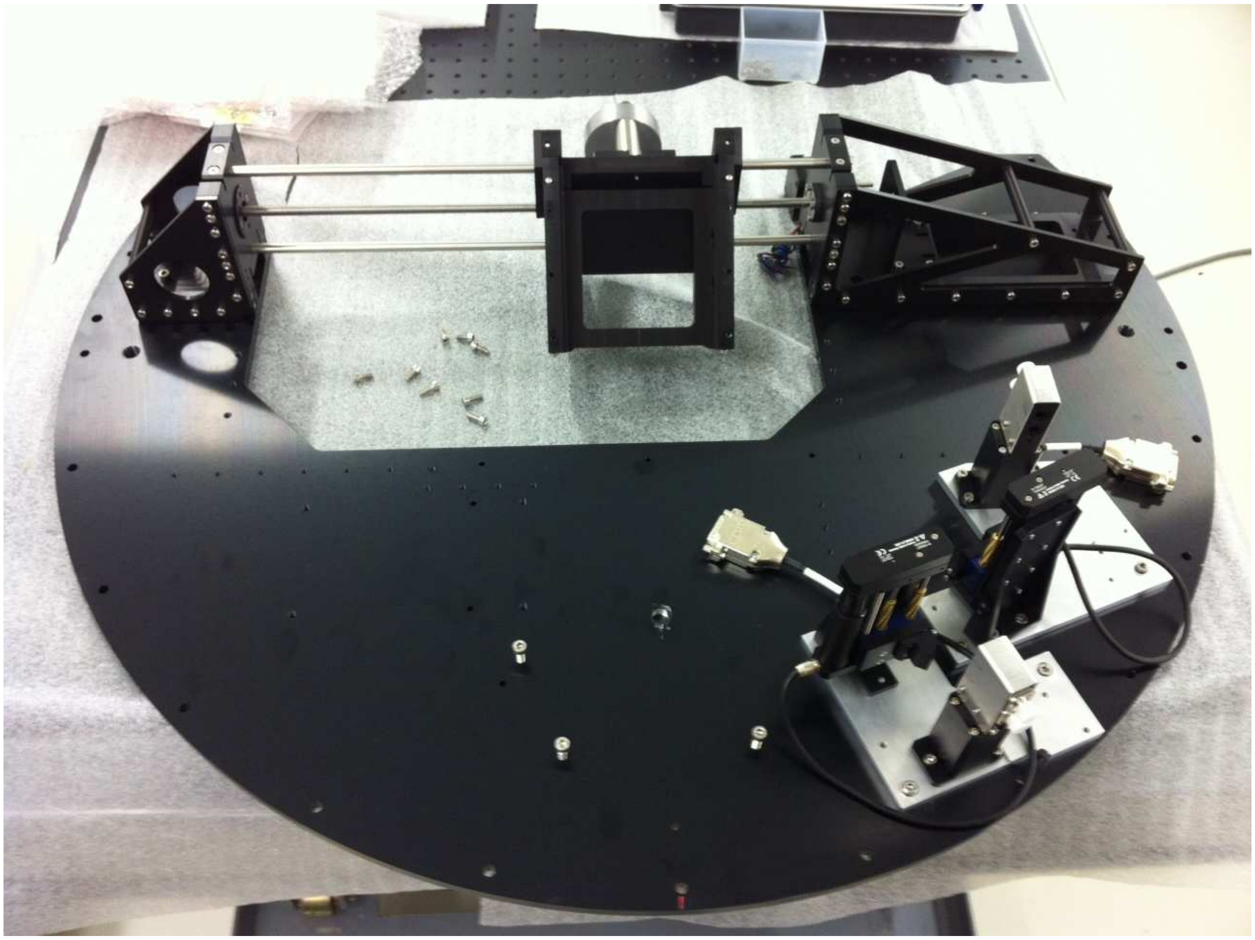
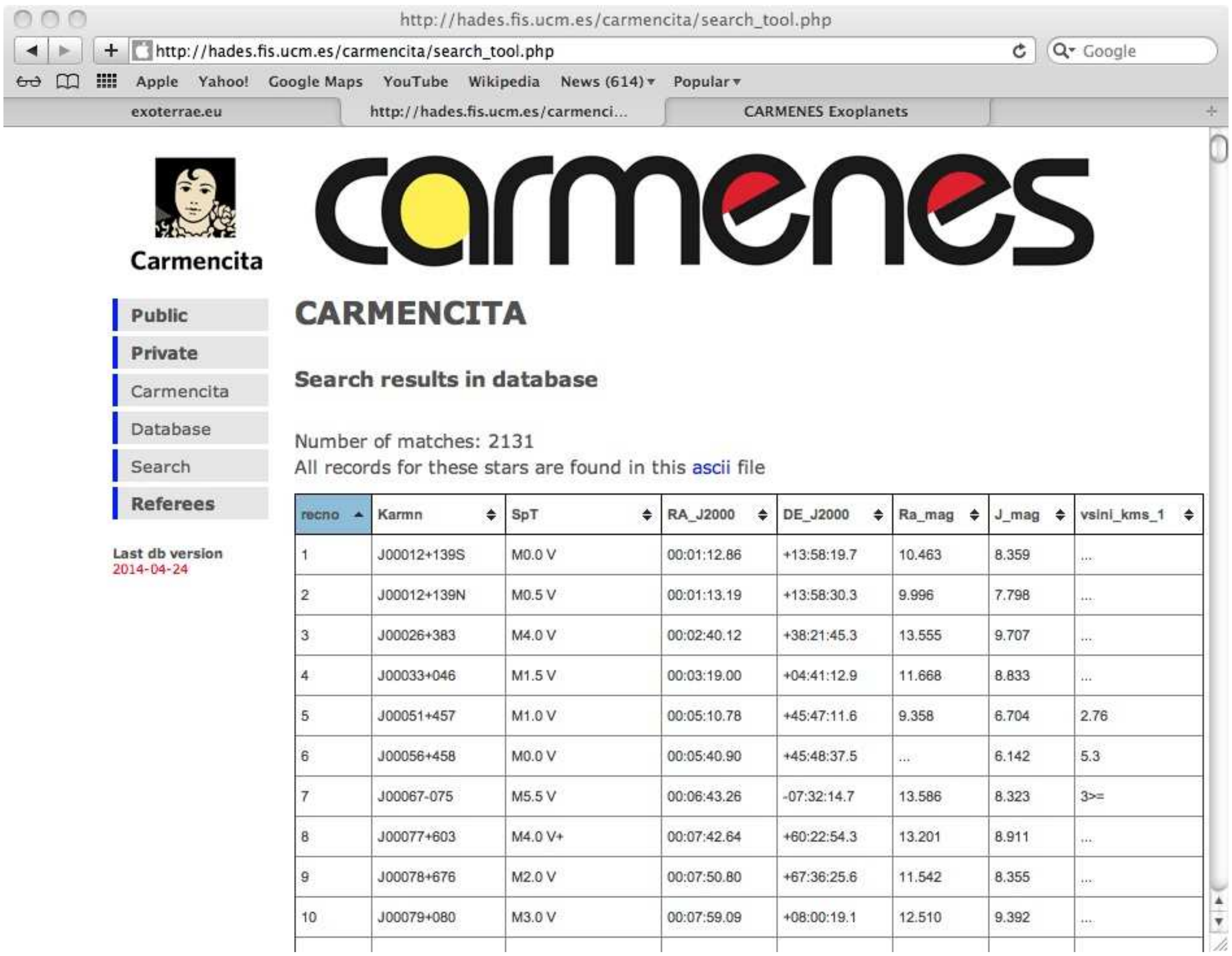


Figure .3: Mechanical components on the optical bench of the CARMENES front end in the middle of the integration phase, in the LSW instrument assembly room, in Heidelberg. The front-end just below the 3.5 m primary mirror allows the light to reach the integral-field unit instrument PMAS (Roth et al. 2005), also at the telescope Cassegrain focus, simply by moving a 45 deg pick-up mirror on its rails.

separate camera; on-axis as well as off-axis guiding modes are implemented (Seifert et al. 2012). Octagonal fibers are employed to ensure good stability of the output in the presence of residual guiding errors (scrambling); the fibers are continually shaken to reduce modal noise, especially in the *H* band (Stürmer et al. 2014). The spectrographs are mounted on benches inside vacuum tanks located in the coudé laboratory of the 3.5 m dome. Each vacuum tank is equipped with a temperature stabilization system capable of keeping the temperature constant to within ± 0.01 K over 24 hours. The VIS spectrograph will be operated near room temperature, while the NIR spectrograph will be cooled to $\sim$140 K with the help of a nitrogen-gas preparation unit (Becerril et al. 2010, 2012; Amado et al. 2012; Mirabet et al. 2014). To enable a $1\,\mathrm{m\,s^{-1}}$ radial velocity precision, we employ a ultra-stable simultaneous calibration with daily, master and supermaster, hollow cathode emission-line lamps (of Th-Ne for VIS and U-Ne for NIR; Sarmiento et al. 2014) and two Fabry-Pérot etalons. The minimization of time overheads, as well as the maximization of the efficiency of CARMENES and its numerous components, is guaranteed by a state-of-the-art instrument control system that brings an automated scheduler integrated into the control system architecture (Guàrdia et al. 2012; García-Piquer et al. 2014). For further details on the instrument concept and design of every component, see the references above and the overviews by Quirrenbach et al. (2012; 2014).



recno	Karmn	SpT	RA_J2000	DE_J2000	Ra_mag	J_mag	vsini_kms_1
1	J00012+139S	M0.0 V	00:01:12.86	+13:58:19.7	10.463	8.359	...
2	J00012+139N	M0.5 V	00:01:13.19	+13:58:30.3	9.996	7.798	...
3	J00026+383	M4.0 V	00:02:40.12	+38:21:45.3	13.555	9.707	...
4	J00033+046	M1.5 V	00:03:19.00	+04:41:12.9	11.668	8.833	...
5	J00051+457	M1.0 V	00:05:10.78	+45:47:11.6	9.358	6.704	2.76
6	J00056+458	M0.0 V	00:05:40.90	+45:48:37.5	...	6.142	5.3
7	J00067-075	M5.5 V	00:06:43.26	-07:32:14.7	13.586	8.323	3>=
8	J00077+603	M4.0 V+	00:07:42.64	+60:22:54.3	13.201	8.911	...
9	J00078+676	M2.0 V	00:07:50.80	+67:36:25.6	11.542	8.355	...
10	J00079+080	M3.0 V	00:07:59.09	+08:00:19.1	12.510	9.392	...

Figure .4: Basic data of the first ten CARMENCITA stars as they appear in our password-protected web server.

Since the successful final design review in February 2013, we have manufactured or ordered to manufacture most components, with some subsystems being fully integrated and characterized (e.g., NIR and VIS detectors, échelle gratings, calibration units, detectors+head+cryostat systems, main vacuum tanks and interlocks, cameras, NIR nitrogen-gas cooling unit) or being assembled and integrated (e.g., front-end, acquisition and guiding systems, exposure meters electronics, optical fibers, collimator mirrors, instrument control system). This contribution is illustrated with pictures of CARMENES components and subsystems taken in late May and early June 2014 (Figs. .1–.3). We strengthened our project management and system engineering through a contract with a private company, which leads us to follow our tight but realistic schedule. We plan to ship to Calar Alto the front-end in February 2015, the VIS channel in April, and the NIR channel in August. The full instrument commissioning will extend until December 2015, and the start of the guaranteed-time science survey will be in Jan 2006.

3. Preparation of the input catalogue

CARMENCITA (*CARMENES Cool dwarf Information and daTa Archive*) is the CARMENES input catalogue. Our list contains the over 2100 brightest M dwarfs for its spectral type observable from Calar Alto, and dozens of astrophysical parameters for each of them (astrometry, photometry, spectroscopy, multiplicity, activity...). During the 600 clear nights of guaranteed time, we will observe the 300 brightest, least active, latest, single M dwarfs in CARMENCITA. See the proceedings by Alonso-Floriano et al., Cortés-Contreras et al. and Montes et al. in this volume for details of the science preparation observations and selection.

In particular, for each star, CARMENCITA tabulates:

- Our identifier, with the format `Karmn Jhhmms±ddmX` (`X` = `E, W, N, S`).
- Component letter in multiple system, if not single (A, B, C, Aa, Ab, etc.).
- Discovery or given name, with a strict order of priority (e.g., Barnard's star, ι Hor, V374 Peg, HD 220140 B, BD+57 2735, Wolf 1051, Ross 271, GJ 1292, LP 704–015 A, G 273–093, StKM 1–2065, NLTT 56083, LSPM J2146+3813, etc.).
- Gliese-Jahreiβ number.
- Spectral type.
- Equatorial coordinates α and δ.
- Proper motions $\mu_\alpha \cos\delta$ and μ_δ.
- Parallax π and heliocentric d distance; we derive our photometric distance if parallax is not available.
- Radial velocity V_r.
- Galactocentric space velocities UVW.
- Photometry in the FUV, NUV, u, B_T, B, g, V_T, r, i, J, H, K_s, $W1$, $W2$, $W3$ and $W4$ bands from *GALEX*, SDSS DR9, Tycho-2, UCAC4, CMC14, 2MASS and *WISE*.
- Multiplicity type and Washington Double Star discovery code, angular separation ρ, wide/close companion name and basic parameters of primary (spectral type, J, metallicity).
- Pseudo-equivalent width of the Hα line pEW(Hα).

– Identifier, count rate and hardness ratios in the *ROSAT* All-Sky Survey.

– Rotational velocity $v \sin i$.

– Photometric period P.

– Some selected spectral indices.

– Flaring flag.

– Hyperlink to our science preparation data (low-res and high-resolution spectroscopy and imaging).

– Origin.

For every parameter, we tabulate its value, error, unit and reference. We look for and compare all parameter values in the literature and from our own observations, and list only the most accurate and reliable ones. We are including new parameters (e.g., claimed presence of exoplanet candidates, membership in moving groups or close young clusters, hyperlinks to public archival data –especially ESO spectra—, and basic astrophysical parameters derived as homogeneously as possible –$T_{\rm eff}$, $\log g$, [Fe/H], M, L, R, i–, etc.). We are also giving scheduling weights to our stars, depending on magnitude and spectral type (the latest and the brightest, the better), and on the presence of close companions that may affect radial-velocity measurements. We take special care in tagging all spectroscopic binaries (or triples) and close resolved multiple systems. We use a password-protected server for updating and sharing internally our CARMENCITA catalogue (Fig. .4), which will be eventually public as a CARMENES legacy.

All CARMENES spectra of the ∼300 M dwarfs observed during the consortium guaranteed time will also be eventually public through a virtual-observatory data archive after a proprietary time of about three years. However, we plan to make public well in advance at least one spectrum for each star (from 0.5 to 1.7 μm), or all spectra of M dwarfs without an appreciable radial-velocity signal, which can be useful for many astrophysical studies unrelated to radial-velocity exoplanet surveys (e.g., abundances, activity, comparison between observations and synthetic models).

Finally, CARMENES may operate for at least a decade and be the only instrument of a dedicated 4 m-class telescope, which could make it to be one of the most useful instruments for exoplanet confirmation and characterization in the Northern hemisphere once the ESA mission *Plato* is launched by 2024. In the meantime, some synergies are expected to be found with other space missions, such as *TESS* (NASA, 2017) or *CHEOPS* (ESA, 2017).

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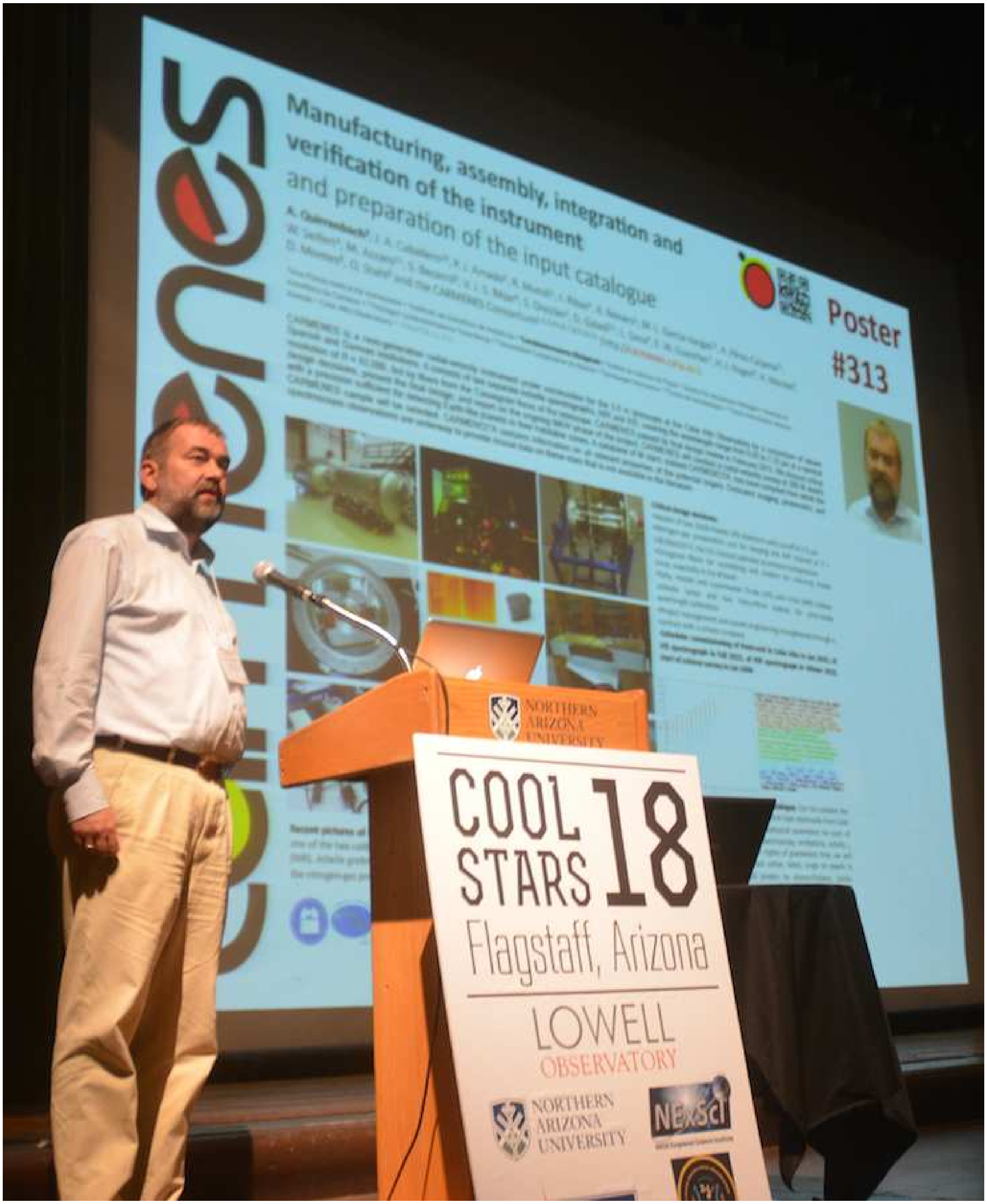

Andreas Quirrenbach during the poster pop-up presentation of the splinter session "Portraying The Hosts: Stellar Science From Planet Searches".