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The CARMENES survey for M dwarf planets

A. Quirrenbach[1], P. J. Amado[2], I. Ribas[3], A. Reiners[4], J. A. Caballero[5], W. Seifert[1], J. Aceituno[6], V. J. S. Béjar[7], A. P. Hatzes[8], T. Henning[9], M. Kürster[9], D. Montes[10], J. H. M. M. Schmitt[11], and the CARMENES Consortium

[1] Landessternwarte, Zentrum für Astronomie der Universität Heidelberg, Königstuhl 12, D-69117 Heidelberg, Germany
[2] Instituto de Astrofísica de Andalucía (CSIC), Glorieta de la Astronomía s/n, E-18008 Granada, Spain
[3] Institut de Ciències de l'Espai (CSIC-IEEC), Campus UAB, Facultat Ciències, Torre C5 - parell - 2a planta, E-08193 Bellaterra, Barcelona, Spain
[4] Institut für Astrophysik (IAG), Friedrich-Hund-Platz 1, D-37077 Göttingen, Germany
[5] Centro de Astrobiología (CSIC-INTA), Campus ESAC, Camino Bajo del Castillo, s/n, E-28691 Villanueva de la Cañada, Madrid, Spain
[6] Calar Alto Observatory, Centro Astronómico Hispano-Alemán, Jesús Durbán Remón, 2-2, E-04004 Almería, Spain
[7] Instituto de Astrofísica de Canarias, Vía Láctea s/n, E-38205 La Laguna, Tenerife, Spain, and Dept. Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain
[8] Thüringer Landessternwarte Tautenburg, Sternwarte 5, D-07778 Tautenburg, Germany
[9] Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
[10] Departamento de Física de la Tierra y Astrofísica and IPARCOS-UCM, Facultad de Ciencias Físicas, Universidad Complutense de Madrid, E-28040, Madrid, Spain
[11] Hamburger Sternwarte, Gojenbergsweg 112, D-21029 Hamburg, Germany

Abstract. CARMENES is a pair of high-resolution spectrographs optimized for measuring radial velocities in the wavelength range from 0.52 to 1.71 μm; it has been in operation at Calar Alto Observatory since January 2016. The CARMENES survey is targeting 342 M dwarfs; it aims at obtaining at least 50 spectra for each of them. In the first three years of the survey, the signatures of several previously known planets have been detected, and new planets with masses almost down to 1 $M_\oplus$ have been discovered. The most remarkable discoveries include a cold super-Earth orbiting Barnard's star and a pair of Earth twins in the habitable zone of Teegarden's star. CARMENES has also been used for observations of evaporating atmospheres of hot Jupiters in the He I λ10830 Å line.

Key words. Instrumentation: spectrographs – Techniques: radial velocities – Stars: low-mass – Planetary systems

1. Introduction

M dwarfs are very interesting targets for searches for habitable planets. They are the most numerous type of star; therefore our closest cosmic neighbors may well live on a planet orbiting an M dwarf. It is also easier to look for Earth-like planets around low-mass stars, as they give rise to relatively large radial-velocity (RV) variations and deep transits. Third, planets of M dwarfs may be different from those of the Solar System as they experience stronger ultraviolet and X-ray irradiation. This provides opportunities for comparative studies of planetary atmospheres under varying conditions. Motivated by these considerations, we have built the CARMENES instrument, a pair of spectrographs optimized for RV measurements of cool dwarf stars. Here we report on progress of the CARMENES survey, which is targeting 342 M dwarfs.

2. The CARMENES instrument

The CARMENES instrument consists of two separate échelle spectrographs covering the wavelength range from 0.52 to 0.96 μm and from 0.96 to 1.71 μm, respectively (Quirrenbach et al. 2014, 2018). The resolution of the visible spectrograph is $R = 94,400$, the near-IR spectrograph provides $R = 80,400$. The detectors are a $4k \times 4k$ pixel CCD, and two $2k \times 2k$ pixel HgCdTe arrays. Each spectrographs is fed by two fibers from the Cassegrain focus of the telescope. The front end contains a dichroic beam splitter, an atmospheric dispersion corrector, and the fiber input optics. Guiding is performed with a separate camera; on-axis as well as off-axis guiding modes are implemented. Fiber sections with octagonal cross-section are employed to ensure good stability of the output in the presence of residual guiding errors. The fibers are continually actuated to reduce modal noise. Additional fibers are available for simultaneous injection of light from emission line lamps or alternatively from a thermally stabilized Fabry-Pérot etalon for RV calibration. The spectrographs are mounted on benches inside vacuum tanks located in rooms, which have been equipped with temperature control systems. Due to the large thermal mass of the optical benches, their temperatures do not drift by more than ± 7 mK over 24 h. The visible-light spectrograph is operated near room temperature, the NIR spectrograph is cooled to ~ 140 K (see Fig. 1).

During the commissioning and initial operation phases of CARMENES, we established basic performance data such as throughput and spectral resolution. We found that our hollow-cathode lamps are suitable for precise wavelength calibration, but their spectra contain a number of lines of neon or argon that are so bright that the lamps cannot be used in simultaneous exposures with stars. We have therefore adopted a calibration procedure that uses simultaneous star and Fabry Pérot etalon exposures in combination with a cross-calibration between the etalons and hollow-cathode lamps during daytime. With this strategy it has been possible to achieve 1-2 m/s precision in the visible and 5-10 m/s precision in the near-IR; further improvements are expected from ongoing work on temperature control, calibration procedures and data reduction. Comparing the RV precision achieved in different wavelength bands, we find a preferred range between 0.7 and 0.9 μm, where deep TiO bands provide rich RV information in mid-M dwarfs (Reiners et al. 2018). This is in contrast to pre-survey models, which predicted comparatively better performance in the near-IR around 1.0-1.1 μm, and explains in large part why our near-IR RVs do not reach the same precision level as those taken with the visible spectrograph.

3. The CARMENES survey

The main scientific motivation for building CARMENES was the possibility to carry out an unbiased survey of ~ 300 M dwarfs, with sufficient sensitivity to find planets down to a few $M_\oplus$ in general, and to $\sim 1\,M_\oplus$ in the most favorable cases. The 750 useable nights allocated to this survey should be sufficient for obtaining at least 50 spectra for each of the stars. The actual CARMENES survey sample is shown in Fig. 2. It consists of 342 stars and covers all spectral subtypes of the M class. CARMENES has a "sweet spot" in the M3-M4 range: for these stars CARMENES is more sensitive than spectrographs working at bluer wavelengths (such as HARPS), and there are many bright stars that can be included in the survey sample. For the later spectral subtypes, all stars at $\delta \geq -23°$ that are sufficiently bright

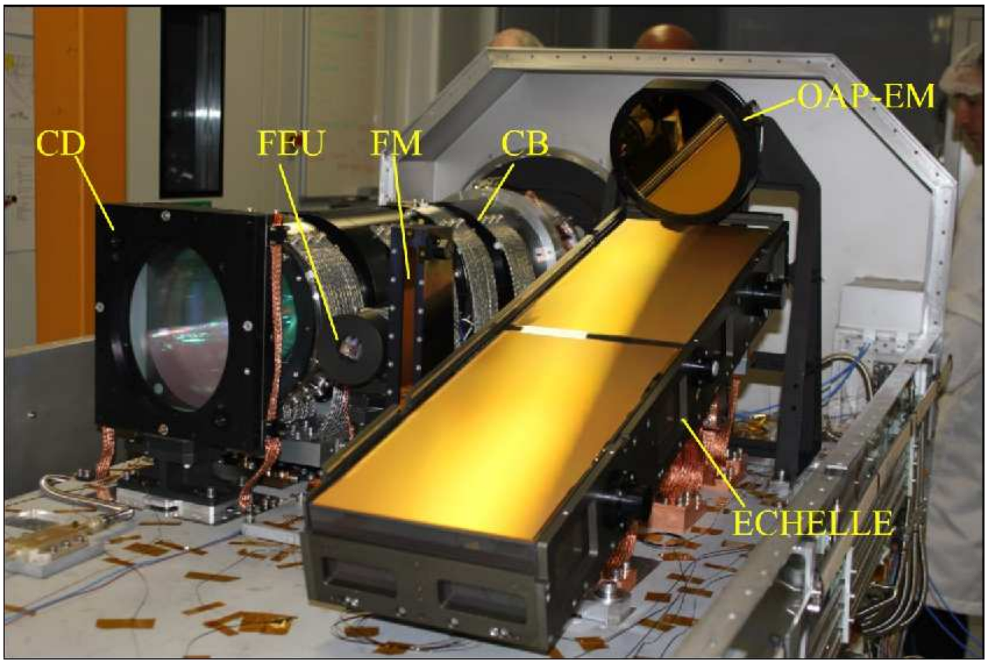

Fig. 1. The NIR spectrograph of CARMENES during its integration. The optical components are labeled as follows: FEU – Fiber Exit Unit, FM – Folding Mirror, CD – Cross Disperser, CB – Camera Barrel, OAP-EM – Off-Axis Parabola of the Exposure Meter, ECHELLE – Échelle grating. See also Becerril et al. (2016).

to allow a precise RV measurement with an integration time of at most 30 minutes are covered by the survey. (This excludes "problematic" stars such as close binaries in which contamination by the secondary spectrum could spoil the RV determination). Early M stars are included to enable statistical analyses of the exoplanet population for host star masses ranging from the hydrogen burning limit all the way up to $0.6\,M_{\odot}$. Conveniently, the set of early M dwarfs also constitutes a pool of bright poor-weather targets. No pre-selection on activity indicators or $v \sin i$ was done so as to enable investigations of the relation between stellar activity and precise RV measurements with the CARMENES data. While the survey targets do not constitute a volume-limited sample, the very simple selection criteria (essentially the brightest "Northern" stars in each spectral subtype) have been adopted to facilitate a statistical census of the Solar neighborhood – the average distance of the CARMENES stars is only 13 pc.

4. Planets from CARMENES

During the first few months of operation, a significant amount of time was devoted to observations of previously known planets. With these data, it was possible to establish that the RV performance compares favorably with instruments such as HARPS and HIRES/Keck; in addition, the new planet GJ 1148 c was discovered by combining data from CARMENES and HIRES (Trifonov et al. 2018). The survey strategy was optimized such that at least 50 spectra were taken on a fair number of stars early on (see Fig. 2). This helped to assess the overall stability and data quality, and led to the discovery of a number of planets in the super-

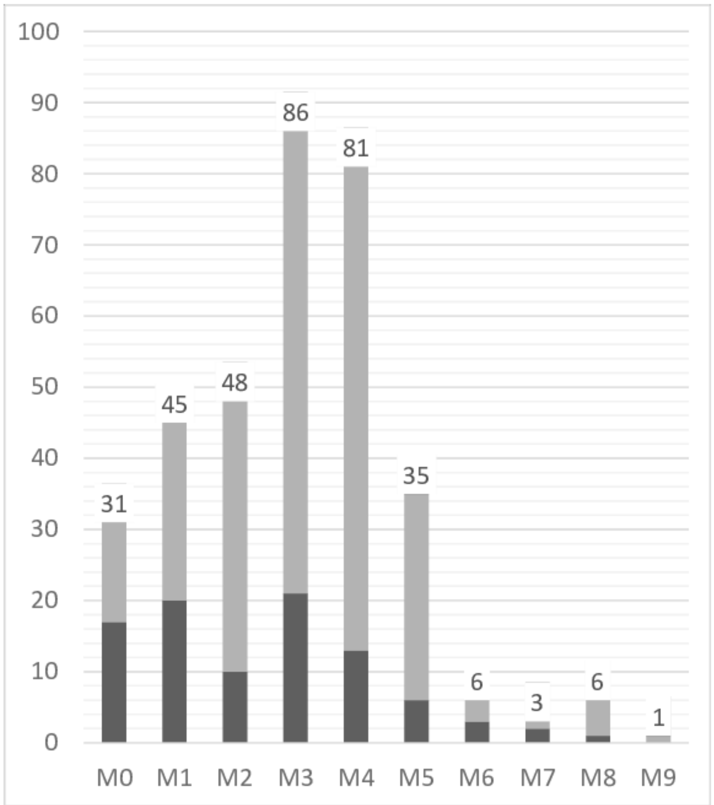

Fig. 2. The spectral type distribution of the 342 stars in the CARMENES Survey Sample. The dark sections of the bars indicate stars for which at least 50 spectra have already been obtained.

Earth to Neptune mass range. Great care was taken to analyze not only the radial velocities but also activity indicators, and in some cases archival data from other instruments could be used to boost the significance of the detections. A good example of this strategy is the discovery of the Neptune-mass planet HD 180617 b (Kaminski et al. 2018).

The M dwarfs in the CARMENES survey show an RV "jitter" (i.e., RV variations due to activity and surface inhomogeneities) with a median value of ~ 3-4 m/s. Nevertheless, it is possible to detect planets with RV semi-amplitudes down to $K \sim 1$ m/s by taking a sufficient number of spectra. For Barnard's star, 201 data points from CARMENES were combined with 570 measurements from other spectrographs to reveal a planet with $K = 1.20$ m/s and an orbital period of 233 d; this corresponds to $m \sin i = 3.2\,\mathrm{M}_\oplus$ and an equilibrium temperature of 105 K (Ribas et al. 2018).

CARMENES was built to search for Earth-like planets in the habitable zones of cool dwarf stars. This is exactly what was found in 223 survey observations of Teegarden's star, which is an M7 V star with a mass of $0.09\,M_\odot$, just above the hydrogen burning limit: Teegarden's star is orbited by two planets with $m_b \sin i = 1.1\,\mathrm{M}_\oplus$, $m_c \sin i = 1.0\,\mathrm{M}_\oplus$, $P_b = 4.9$ d and $P_c = 11.4$ d (Zechmeister et al. 2019). In these short-period orbits, the planets should be kept quite cozy by their dim host star; the flux they receive is 1.08 and 0.36 times, respectively, the terrestrial value.

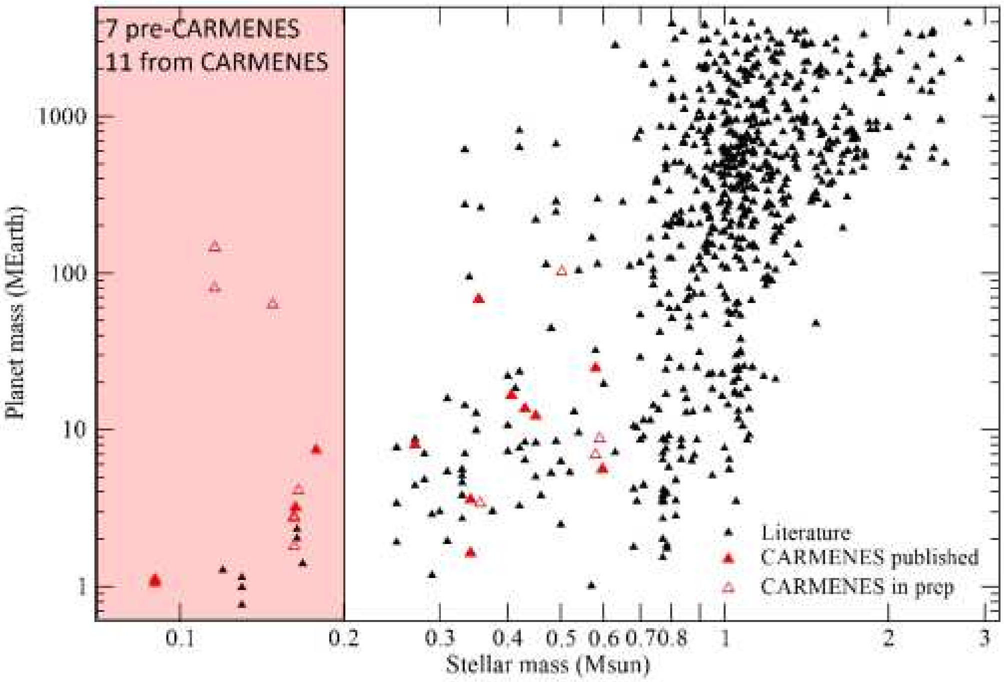

Fig. 3. Planets with masses determined from RV measurements. The majority of the known planets with host star masses below 0.2 $M_\odot$ have been discovered through the CARMENES Survey.

Together with TRAPPIST-1, Teegarden's star provides evidence that systems with multiple Earth-like planets are common around ultra-cool dwarf stars – otherwise we would have been incredibly lucky twice to get a discovery from a small target sample.

5. Outlook

With its combination of high spectral resolution, large simultaneous wavelength coverage, and high RV precision, CARMENES is a powerful instrument for exoplanet characterization and stellar astrophysics beyond the unbiased RV survey described above. An immediate extension of this survey is the follow-up of transiting planets discovered by space missions. Observations of K2-18 (Sarkis et al. 2018) and GJ 357 (Luque et al. 2019) have already demonstrated the capabilities of CARMENES for this purpose and yielded very interesting results: masses (and thus densities) of the transiting planets, and additional non-transiting planets. *TESS* has just begun its survey of the Northern sky, which will provide even more promising targets for CARMENES, in particular small planets orbiting bright mid-M dwarfs. In the future, CARMENES may play an important role in the characterization of planets transiting cool stars found by the European *Plato* mission.

CARMENES also offers unique capabilities for investigations of the atmospheres of transiting planets with high-resolution spectroscopy. Particularly nice examples for this are observations of evaporating atmospheres of hot Jupiters in the He I λ10830 Å line (Nortmann et al. 2018, Salz et al. 2018, Alonso-Floriano et al. 2019), which benefit from the high spectral resolution and thus contain more information and achieve much higher signal-to-noise than observations of the same line with WFC3 on *HST*.

One can also foresee many potential uses of CARMENES as a “general purpose” tool for stellar astrophysics, but the topics discussed above, i.e. planet surveys, determination of the masses of transiting planets, and studies of planetary atmospheres, will likely remain at the forefront.

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