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The CARMENES survey: A search for terrestrial planets in the habitable zones of M dwarfs

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Abstract. CARMENES (**C**alar **A**lto high-**R**esolution search for **M** dwarfs with **E**xo-earths with **N**ear-infrared and optical **E**chelle **S**pectrographs) is a next-generation instrument under construction for the 3.5 m telescope at the Calar Alto Observatory by a consortium of eleven Spanish and German institutions. The scientific goal of the project is a five-year exoplanet survey targeting 300 M stars with the completed instrument. The CARMENES hardware consists of two separate échelle spectrographs covering the wavelength range from 0.55 to 1.7 μm at a spectral resolution of $R = 82,000$, fed by fibers from the Cassegrain focus of the telescope. Both spectrographs are housed in a temperature-stabilized environment in vacuum tanks, to enable a long-term radial velocity precision of 1 m s^{-1} employing a simultaneous calibration with Th-Ar-Ne and U-Ne emission line lamps.

Keywords. (stars:) planetary systems, instrumentation: spectrographs, techniques: radial velocities, surveys, stars: late-type, stars: activity, astrobiology

1. Introduction

Exoplanet research has made enormous progress over the past two decades. After the first report of an exoplanet discovered around a main-sequence star (Mayor & Queloz 1995), new discoveries have been made at an ever-increasing pace. Today more than 750 exoplanets are known, mostly from high-precision radial-velocity (RV) measurements and increasingly also from photometric transit observations.

An Earth-mass planet around a solar-type star induces an RV signal of about $10\,\mathrm{cm\,s^{-1}}$, which is beyond the capability of the most precise spectrographs today, which reach accuracies of order $1\,\mathrm{m\,s^{-1}}$ (e.g., Udry et al. 2007), although claims have been made of rms residuals as low as $0.2\,\mathrm{m\,s^{-1}}$ (e.g., Lovis et al. 2006). For a given planet mass, the RV amplitude increases with decreasing stellar mass, making low-mass stars an obvious choice for searches for terrestrial planets. This has already been done with visible-light spectrographs, and low-mass planets (so-called "super-Earths" with masses between 2 and $10\,\mathrm{M}_\oplus$) have already been found around some early M-type stars.

However, the faintness of the targets and the intrinsic stellar jitter limit the use of even lower-mass stars. Another way to increase the planetary signal is to focus on short orbital distances, and correspondingly short periods. Such short distances usually mean heavily irradiated planets and high planet temperatures. For low-mass stars, however, their lower intrinsic luminosity implies that planets with relatively close-in orbits may have mild equilibrium temperatures and will thus potentially be habitable.

2. Goals of the CARMENES Survey

The fundamental scientific objective of the CARMENES project is to use the 3.5 m telescope on Calar Alto for a survey of ~ 300 late-type main sequence stars with the goal of detecting low-mass planets in their habitable zones (see also Quirrenbach et al. 2010, 2012). In the focus of the project are very cool stars later than spectral type M4 and moderately active stars. In particular, we aim at being able to detect a $2\,M_\oplus$ planet in the HZ of an M5 star. A long-term radial velocity precision of $1\,\mathrm{m\,s^{-1}}$ per measurement will permit to attain such goals. 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.

CARMENES will provide wide wavelength coverage from the visible ($0.55\,\mu$m) to the near-IR ($1.7\,\mu$m). This will yield the highest possible precision for the targeted M-type stars while permitting at the same time the identification of false-positive RV signals caused by stellar activity. Activity-induced RV variations are expected to be wavelength dependent, which is not the case for variations due to the presence of a companion. The wavelength dependence of activity-induced RV signals will result in at least a factor of 2 to 3 different amplitude in the range $0.55 \ldots 1.7\,\mu$m, and thus provide an efficient and safe way to discard spurious signals (Reiners et al. 2010). The wavelength dependence will also yield valuable information on the spot temperature and distribution. As a bonus, the high-resolution near-IR data will allow us to study the target stars with unprecedented detail, including their full characterization regarding atmospheric parameters and activity.

3. The CARMENES Sample

To carry out a proper selection and characterization of our targets, we have created the CARMENCITA database (CARMENes Cool star Information and daTa Archive), in which we are consolidating information available in the literature (see also Quirrenbach et al. 2012). We are also collecting additional data (e.g., low-resolution spectra, where

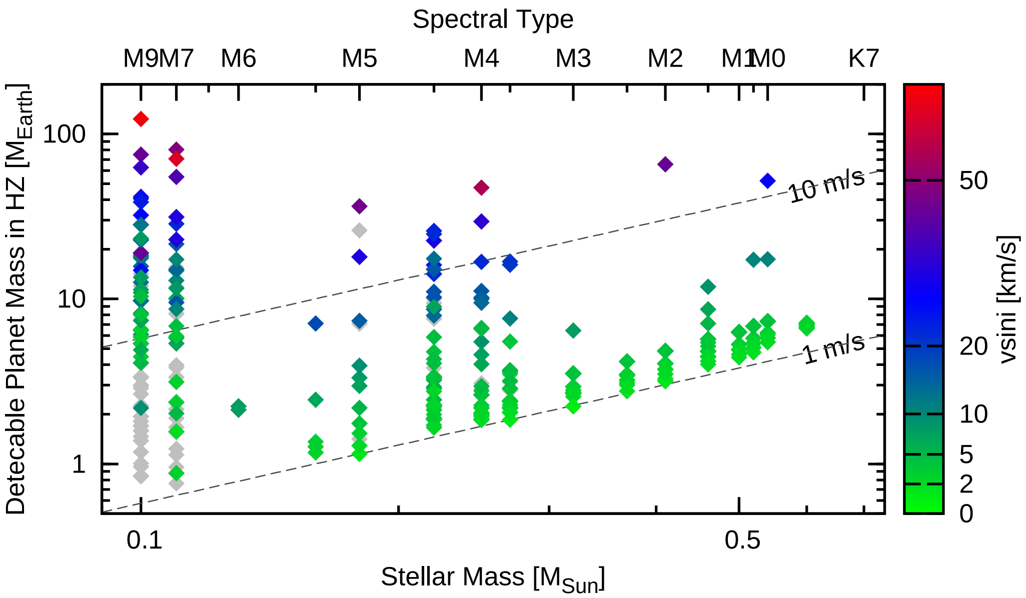

Figure 1. Sample detection limit. The colored diamonds give realistic detection limits for integration times not exceeding 20 minutes per visit, yielding S/N = 150 for $J < 9$ mag. The grey diamonds are for fainter stars, which would require longer integration times to reach S/N = 150 in the J band.

not available), and performing homogeneous analyses to obtain spectral types and other stellar parameters (Klutsch et al. 2012). At the start of the CARMENES survey, we will observe ~ 450 stars; after further "cleaning" (i.e., removal of unsuitable targets after a few initial observations), we aim at arriving at three sub-samples of 100 stars each:

- **S1** – $M < 0.25 M_\odot$ (spectral type M4 and later);
- **S2** – $0.25 M_\odot < M < 0.30 M_\odot$ (spectral type M3-M4);
- **S3** – $0.30 M_\odot < M < 0.60 M_\odot$ (spectral type M0-M2), relatively bright.

Sample S1 is designed to cover the spectral type domain that is very faint in the visible and can only be studied by CARMENES. Sample S2 is selected to address a pool of targets for which CARMENES is very efficient but comparable to visible spectrographs, so that a cross-check with other surveys is possible. Sample S3 will have the highest fraction of bright targets and will therefore be best suited as a "poor weather" sample. Taken together, studying all three samples will provide a comprehensive view of the planet population around low-mass stars.

We have performed simulations of the planet detection capabilities of CARMENES using a preliminary target sample that includes 63 very late M dwarfs (M7-M9) and 370 mid and early M dwarfs (M0-M6). Figure 1 summarizes the detectable mass of planets in the middle of the habitable zone. For a given stellar mass, the vertical spread is due to the different rotational line widths $v \sin i$ of the stars (color coded). For S/N = 150 in J, a total precision of $1\,\mathrm{m\,s^{-1}}$ could be reached for all spectral types. However, for very late spectral types this would imply integration times longer than 20 minutes due to the faintness of these stars. This leads to a minimum of the detectable planet mass at $M = 0.2 M_\odot$, suggesting that with CARMENES the lowest-mass planets could be discovered around M dwarfs with spectral types near M5. The goal of being able to detect habitable super-Earths can be attained over a large mass range.

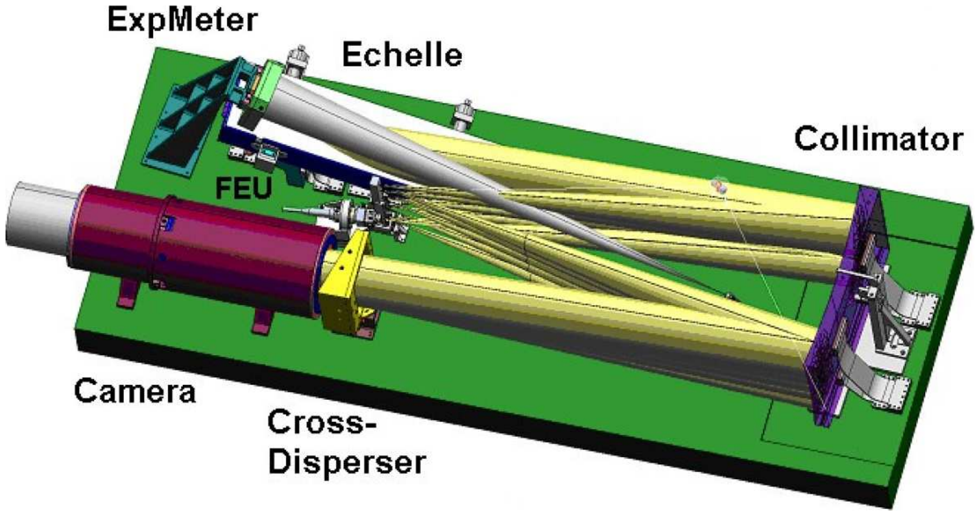

Figure 2. Layout of the optical bench for the CARMENES near-infrared spectrograph. The fiber entrance unit (FEU) contains fore-optics and the image slicer. The design for the optical spectrograph is very similar.

4. The CARMENES Instrument

The CARMENES instrument is fully optimized for the scientific goals described above. 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 0.95 μm, and 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 hardware components of CARMENES are the following:

- *Visible-Light Spectrograph.* The visible-light échelle spectrograph covers the wavelength range 0.55 ... 1.05 μm with a resolving power of $R = 82,000$ and a mean sampling of 2.8 pixels per resolution element. It accepts light from two fibers; 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, stabilized to ± 0.01°C. The detector is a back-side illuminated 4112×4096 pixel CCD.
- *Near-Infrared Spectrograph.* The design of the near-IR spectrograph is very similar to that of its visible counterpart (see also Figs. 2 and 3). It provides $R = 85,000$ over the range 0.95 ... 1.7 μm with a mean sampling of 2.5 pixels per resolution element. It is cooled to 140 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).
- *Nitrogen Preparation Unit.* 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).
- *Front End.* The front end is attached to the Cassegrain focus of the 3.5 m telescope and contains an acquisition and guiding system, an atmospheric dispersion compensator, the dichroic beam splitter, a shutter (only in the visible channel), input selectors (to switch between the sky and calibration light), and fiber heads. The first mirror in the front and is motorized; when it is detracted the light passes straight through to a separate

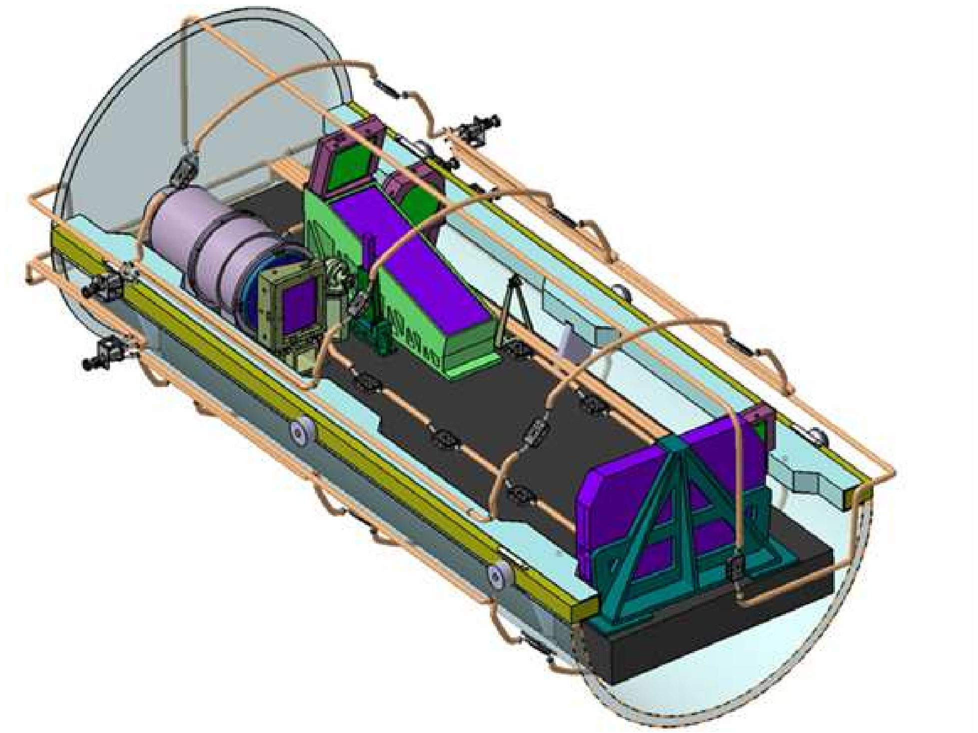

Figure 3. Schematic layout of the near-infrared spectrograph. The optical bench is mounted inside a vacuum vessel. It is kept at constant temperature through a continuous-flow cooling system attached to a radiation shield.

instrument (e.g., the integral-field spectrograph PMAS). It is thus possible to switch rapidly between CARMENES and PMAS.

• *Fibers.* The optical fibers transporting the light from the front end to the spectrographs fulfill the important task of "scrambling", i.e., of reducing the jitter of the input into the spectrograph with respect to guiding errors and seeing at the fiber input. Because of their superior scrambling properties, fibers with octagonal cross-section will be used. The fiber diameter has been chosen to provide a $1\farcs5$ acceptance cone on the sky, matched to somewhat worse than median seeing on Calar Alto.

• *Calibration Units.* CARMENES uses hollow-cathode emission line lamps (Th-Ar-Ne for the visible channel, U-Ne in the near-IR) for spectral calibration. As lamps used nightly show ageing effects, they need to be monitored by comparison with master lamps that are used only occasionally. 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 is routed to photomultiplier tubes, which provide a record of the received intensity with high time resolution. This information is needed for an accurate conversion of the observed radial velocity to the barycenter of the Solar System, and it can also be used to make real-time adjustments to the integration time depending on atmospheric conditions.

• *Instrument Control System.* The CARMENES Control System includes a scheduler that can autonomously prioritize and select targets for observation (Guàrdia et al. 2012).

• *Infrastructure.* The CARMENES spectrographs and ancillary equipment will be located in the coudé room of the 3.5 m telescope dome. Each spectrograph will be sited within a temperature-controlled chamber, providing shielding from annual temperature variations and from heat sources such as electronics, pumps, and calibration lamps.

At the time of writing (late 2012), the design of CARMENES has been nearly completed, and the items with the longest lead times (échelle gratings, detectors, cameras) have been ordered. It is expected that on-sky commissioning of the instrument will commence in mid-2014.

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