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CARMENES: Blue planets orbiting red dwarfs

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Abstract. The 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) consortium, consisting of eleven Spanish and German institutions, has been established to conduct a radial-velocity survey of M dwarfs with the 3.5 m telescope at the Calar Alto Observatory. This survey will target ~300 M stars, with emphasis on spectral types M4V and later. The CARMENES instrument is currently under construction; it consists of two independent échelle spectrographs covering the wavelength ranges $0.55 \ldots 1.05\,\mu$m and $0.95 \ldots 1.7\,\mu$m, respectively, at a spectral resolution of $R = 82,000$. The spectrographs are fed by fibers from the Cassegrain focus of the telescope; calibration is performed simultaneously with emission-line lamps. The optical benches of the spectrographs are housed in vacuum tanks and climatic chambers, which provide the temperature-stabilized environments necessary to enable a 1 m/s radial velocity precision.

1. INTRODUCTION

Radial-velocity (RV) surveys of M dwarfs are gaining momentum as an important complement to surveys of more massive stars, and as a method to discover and possibly characterize hot and temperate rocky exoplanets. M-type stars, with masses in the range of $0.1 \ldots 0.6\,M_{\odot}$, are the most abundant type of stars in our Galaxy (frequency ~80 %), and therefore obtaining statistics of planetary system occurrence and architecture for these stars is of great importance to understand the physics of planet formation and evolution in general, and its dependence on stellar host mass. Radial-velocity searches for planets around M dwarfs benefit from a larger signal, and a shorter orbital period of planets in the habitable zone (HZ). These advantages, along with the larger transit depths, have been exploited to find some of the low-mass exoplanets known so far, both with the radial-velocity method (e.g., Mayor et al. 2009, Anglada-Escudé et al. 2012), and with transits (Charbonneau et al. 2009). However, the current number of planet detections with M-star hosts is still low compared with solar analogs. Therefore the abundance of planets as a function of mass and orbital distance is not well constrained at the moment, and the much-sought value of $\eta_\oplus$, i.e., the abundance of Earth-analog planets in the HZ, still has a large uncertainty. In addition, present RV surveys cover only M-type stars of spectral types earlier than M2 or M3, corresponding to $M_* \geq 0.3$ to $0.4 M_\odot$. The faintness of the targets in the visible wavelength range and the intrinsic stellar jitter have up to now limited the investigation of stars with even lower masses.

The 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; see also Quirrenbach et al. 2010, 2012) project is aimed at filling this gap, by constructing a radial-velocity instrument optimized for planet searches of mid- to late-type M dwarfs.

2. THE CARMENES SURVEY

2.1 Survey goals

The main scientific driver for CARMENES is the search for very low-mass planets (i.e., Earth-analogs and "super-Earths") around mid- to late-type M dwarfs, and around moderately active M dwarfs in general. Specifically, we aim at a long-term RV precision and stability of $1\,\mathrm{m\,s^{-1}}$ per measurement, sufficient to detect a $2\,M_\oplus$ planet in the middle of the HZ of an M5 star. For stars later than $\sim$M4 ($M < 0.25 M_\odot$), such precision will yield detections of super-Earths of $5 M_\oplus$ and smaller inside the entire width of the HZ.

Our survey strategy is to intensively monitor a well-characterized sample of about 300 M dwarfs. We can estimate the percentage of stars with low-mass planets by extrapolating current results of planet surveys to lower stellar masses. If we assume that about 30–40% of the M dwarfs have low-mass planets and a high chance of some being in the habitable zone, we may expect to find between 50 and 100 suitable planets. This estimate is obviously rather uncertain, but even if the real frequency is much lower, still a substantial number of detections will be available, and CARMENES will put tight constraints on the abundance and orbital parameters of low-mass planets in the investigated mass regime.

The expected CARMENES planet harvest is, at any rate, sufficient to carry out a reliable statistical analysis of the planet population and shed light on the architecture of planetary systems and on their formation mechanisms. The CARMENES survey will also provide valuable constraints on $\eta_\oplus$ for M dwarfs. Given the transit probability and the favorable selection bias, there is a good chance of finding 1 or 2 transiting low-mass planets in the habitable zone. These hold extraordinary value for future investigations since they will be orbiting some of the nearest stars in the solar neighborhood and thus their discovery merits substantial efforts.

2.2 Sample definition and observing strategy

The sample selected for intensive monitoring with CARMENES will be composed of three subsamples, matched to the expected instrument performance and to a range of weather and seeing conditions:

- **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-M3), relatively bright.

Sample S1 contains the main targets of the survey and covers the spectral type domain that cannot be easily accessed by optical spectrographs. Sample S2 is selected to address a pool of targets for which CARMENES is very efficient but comparable to optical spectrographs and will provide a cross-check with other surveys. Sample S3 will have the highest fraction of bright targets and will therefore be best suited as a "poor weather" sample. The brightest stars of all three samples have the potential for very frequent observations, and thus for the lowest thresholds for planet detections. Given the objective of establishing a final target sample of 300 objects, we will necessarily have to start with a larger list, and to eliminate unsuitable stars such as binaries and rapid rotators.

For the final core sample of 300 stars we plan to obtain at least 60 measurements per object, and at least 100 measurements or more for the most interesting systems. The experience gathered with similar surveys indicates that many exoplanets can already be identified reliably with about 30 measurements. However, ~ 100 measurements per object are clearly needed for the detection of a planet with RV semi-amplitude close to the measurement error, and to discern multiple-planet systems, which seem to be quite abundant when composed of mainly low-mass planets. We will thus have to acquire $\sim 22{,}500$ spectra to achieve the goals of the CARMENES survey.

To observe the sample we will use a typical maximum integration time of 900 s, guaranteeing a signal-to-noise ratio of 150 for targets with $J = 9$. When considering the expected instrument overheads this leads to an estimate of some 3.5 measurements per hour or some 30 measurements per night, thus adding up to about 750 clear nights.

2.3 Preparatory observing program

To optimize the scientific return of CARMENES, a careful analysis of the targets prior to their selection is necessary. A number of critical stellar properties are needed for each individual target candidate, including effective temperature and spectral type, near-IR and visible photometry, distance, projected rotational velocity, and main activity indicators (Hα and X-ray luminosity). In addition, we also collect non-critical information for as many sample candidates as possible, including kinematics (proper motions, radial velocities, Galactocentric space velocities), element abundances, ages, variability (photometry and spectroscopy), multiplicity (from spectroscopy and imaging), and secondary activity indicators. We are currently conducting a dedicated observing program (high- and low-resolution spectroscopy, high- and low-resolution imaging) to obtain these parameters in a systematic way whenever they cannot be found in the literature.

An example illustrating the importance of these preparatory observations is shown in Fig. 1 (see also Klutsch et al. 2012 and Alonso-Floriano et al. 2013). Here we plot spectral types from our $R \approx 1,500$ CAFOS spectra against those listed by Lépine and Gaidos (2011), which are based on photometric data. It is obvious that the spectra types derived from optical / near-infrared colors are typically 1 to 2 sub-types later than those determined spectroscopically; in some cases the discrepancy is as large as 5 sub-types. A target selection based on catalog spectral types would thus lead to a sample with systematically higher masses than intended, and to a non-optimal choice of the individual stars.

2.4 The CARMENCITA data base

All relevant information about the potential target stars is collected in a data base dubbed "CARMENCITA" (**CARMEN**es **C**ool star **I**nformation and da**T**a **A**rchive). The stars in CARMENCITA are assigned to four different classes (Alpha, Beta, Gamma, and Delta) according to their spectral types, magnitudes and the radial velocity precision that can be obtained with CARMENES. Alpha is the nominal CARMENES Input Catalog and contains stars that reach zenith distances $z_{\rm min} < 50^\circ$ at meridian transit on Calar Alto. The Beta class contains stars that are up to one magnitude fainter than the nominal limit and that reach zenith distances between 50° and 60°, except in the case of M6V type stars and later which are considered as Alpha targets up to $z_{\rm min} = 60^\circ$. Beta objects are "back-up"

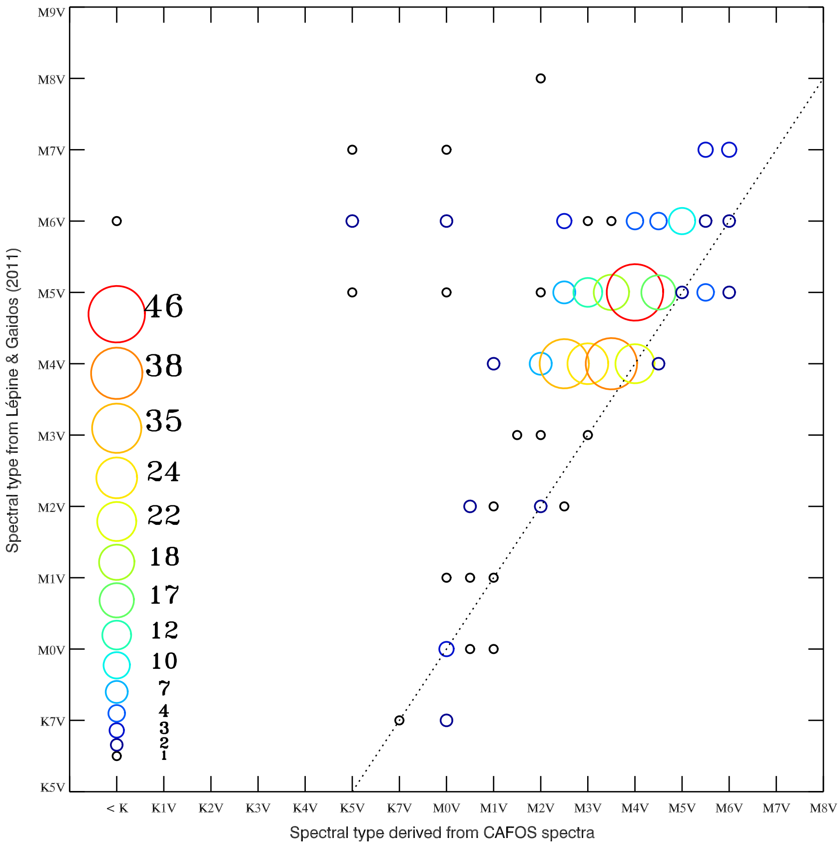

Figure 1. Spectral types from our CAFOS spectra (resolution $R \approx 1,500$) compared to those derived by Lépine and Gaidos (2011) from photometric data. Spectral types determined from optical / near-infrared colors are typically 1 to 2, and in some cases up to 5 sub-types, later than those from the spectroscopy.

sample stars. Finally, the Gamma and Delta classes are created to keep track of the rejected objects that will most likely not be observed. CARMENCITA will eventually become a comprehensive resource for research on M stars and their planetary systems.

3. THE CARMENES INSTRUMENT

The CARMENES instrument is designed and optimized specifically for the radial-velocity survey described above. The front end of CARMENES is attached to the Cassegrain focus of the 3.5 m telescope; it contains an atmospheric dispersion corrector and a dichroic beam splitter at 0.95 μm to separate the visible and near-infrared light. The front end is connected by optical fibers to two completely independent spectrographs, which are mounted on optical benches inside vacuum tanks located in the coudé laboratory of the 3.5 m dome. The hardware of CARMENES consists of the following main components:

3.1 Visible-light spectrograph

The CARMENES spectrographs are based on an échelle design with grism cross-dispersion and a white pupil, working in quasi-Littrow mode (Seifert et al. 2012). To keep the beam size manageable,

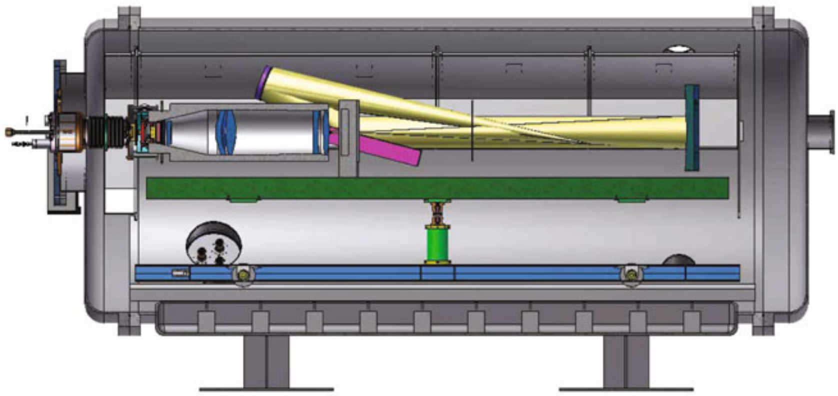

Figure 2. Design drawing of the CARMENES near-infrared spectrograph mounted inside the vacuum vessel. The camera with the detector cryostat is at the left, the collimator at the right. The arrangement of the visible-light spectrograph is very similar.

each spectrograph contains an image slicer that accepts two beams and divides their pupils into two slices. The visible-light spectrograph covers the wavelength range $0.55 \ldots 1.05\,\mu$m with a resolving power of $R = 82,000$ and a mean sampling of 2.8 pixels per resolution element (ppre). (Due to strong anamorphism introduced by the R4 échelle, the sampling varies strongly along each order, from 2.3 ppre at the blue end to 4.0 ppre at the red end of the free spectral range in the most extreme case.) The spectrograph is mounted on a bench inside a vacuum vessel (see Fig. 2). The detector is a back-side illuminated 4112×4096 pixel CCD supplied by e2v (model CCD231-84). The visible-light spectrograph is operated near room temperature, with an anticipated temperature stability of $\pm 0.01^{\circ}$C within 24 hours. There are no moving parts inside the vacuum vessel to maximize mechanical stability and to avoid heat dissipation.

3.2 Near-infrared spectrograph

The optical and mechanical design of the near-IR spectrograph is very similar to that of its visible counterpart. The near-IR spectrograph provides $R = 82,000$ over the wavelength range $0.95 \ldots 1.7\,\mu$m with a mean sampling of 2.5 ppre. Since CARMENES does not use any light longward of $1.7\,\mu$m, it would be convenient to employ near-IR detectors with a cut-off near that wavelength. However, whereas some detectors with that cut-off have been delivered and tested, they have not yet reached the technical and operational maturity of devices with a "standard" $2.5\,\mu$m cut-off. For that reason, the detector of the near-IR channel in CARMENES is a mosaic of two 2048×2048 pixel HAWAII-2RG infrared arrays with a long-wavelength cutoff at $2.5\,\mu$m (see also Amado et al. 2012). With this choice of detector, it is necessary to cool the spectrograph to 140 K.

3.3 Cooling system and 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). This nitrogen gas is coupled with heat exchangers to a radiation shield within the spectrograph tank. The stabilization of the shield, together with the large thermal inertia of the optical bench, ensures excellent stability (to within ± 0.01 K over 24 hours) of the optical system.

3.4 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 head of the visible-light fiber is located behind a small hole in a mirror; guiding is performed on the image of the target star reflected by this mirror towards the guide camera. Off-axis guiding is foreseen as an alternative operation mode. The first mirror in the front end is motorized; when it is detracted the light passes straight through to a separate instrument port (supporting, e.g., the integral-field spectrograph PMAS). It is thus possible to switch rapidly between CARMENES and PMAS.

3.5 Optical fibers

The diameter of the optical fibers transporting the light from the front end to the spectrographs has been chosen to provide a 1$''$.5 acceptance cone on the sky, matched to somewhat worse than median seeing on Calar Alto. The fibers 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 (e.g., Avila & Singh 2008). Because of their superior scrambling properties, fibers with octagonal cross-section will be used. Extensive lab tests to characterize the near-field as well as the far field of these fibers are underway; some results are shown in Fig. 3.

3.6 Calibration units

CARMENES uses hollow-cathode emission line lamps (Th-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 regularly through comparisons with master lamps that are used only occasionally, and ultimately with super-masters that ensure long-term stability. 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. The super-master lamps are stored in a dedicated tank filled with a low-pressure Ne atmosphere. The calibration units are also compatible with calibration schemes using Fabry-Pérot etalons, which are under development for a potential future upgrade.

3.7 Exposure meters

The zeroth-order light from the échelle gratings is collected and routed via fibers to photomultiplier tubes, which provide a record of the received intensity with high time resolution. This information provides a precise measurement of the photon-weighted midpoint of each exposure, which is needed for an accurate conversion of the observed radial velocity to the barycenter of the Solar System. The running photon counts can also be used to make real-time adjustments to the integration time depending on atmospheric conditions.

3.8 Instrument control system

The CARMENES Control System supervises and manages the sensors and subsystems of the instrument, and it coordinates the taking of exposures with the Telescope Control System. The control software includes a scheduler that can autonomously prioritize and select targets for observation (Guàrdia et al. 2012).

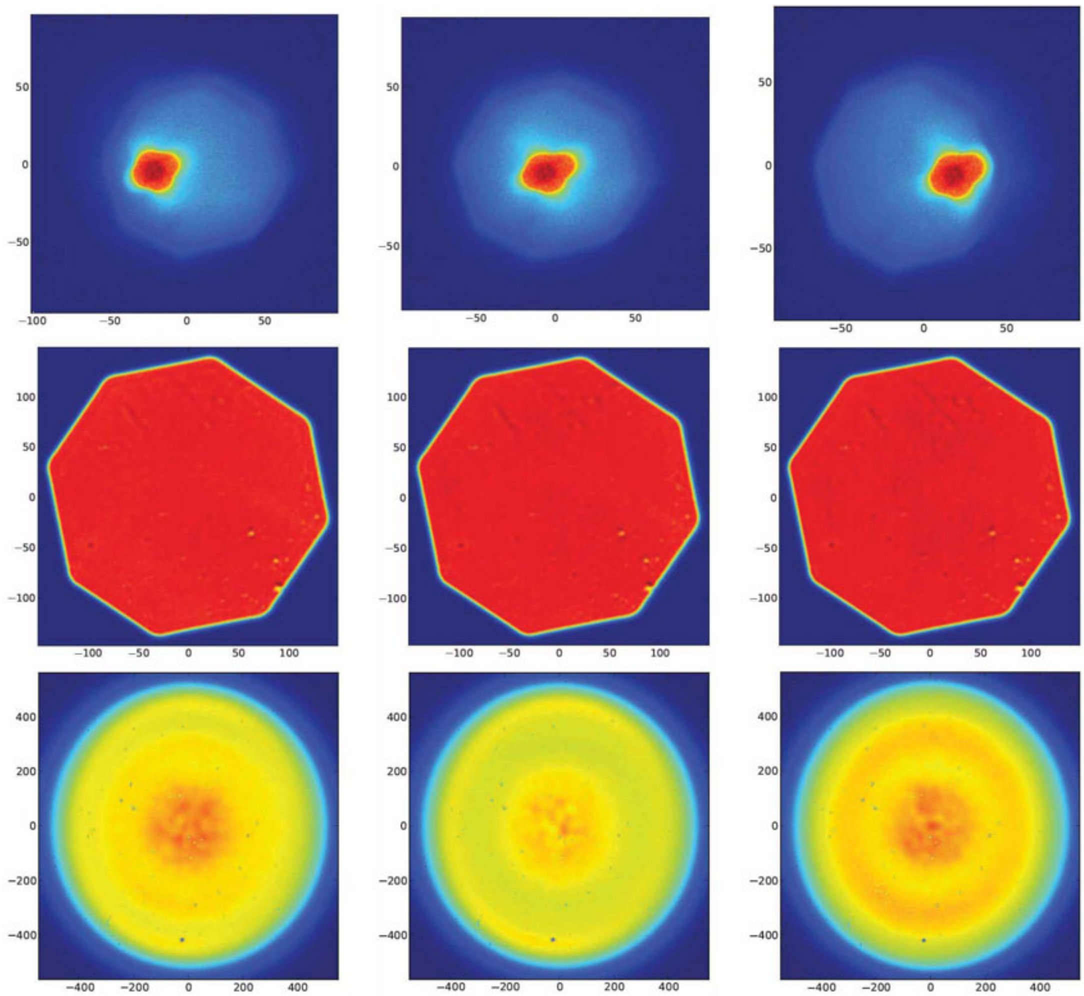

Figure 3. Input (top row), near field (middle) and far field (bottom) of a CeramOptec WF 67/125 octagonal fiber. The illuminating spot was moved at the fiber input from the center of the fiber (middle column) 20 μm to the left (left column) and $-20\,\mu$m to the right (right column).

3.9 Infrastructure

The CARMENES spectrographs and ancillary equipment will be located in the coudé room of the 3.5 m telescope dome, which will be refurbished for this purpose. 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. The spectrographs will be lifted from the ground floor into the dome by the crane that is regularly used to lift heavy pieces of equipment such as the primary mirror. Moving them from the dome floor into the coudé lab will then be possible by temporary removal of a light wall.

4. OUTLOOK

CARMENES passed its Final Design Review in February 2013, and contracts for the components with the longest lead times have been placed. The optical spectrograph and front end will be assembled, integrated, and tested in Heidelberg; the near-IR spectrograph will go through these processes in Granada. Delivery of these sub-systems to Calar Alto is foreseen for the second half of 2014. It is thus anticipated that the CARMENES survey will be conducted from 2015 through 2018.

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