

CARMENES: searching for exoplanets and much more

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Abstract

CARMENES is a next-generation radial-velocity instrument designed and built to search for exo-Earths around M dwarf stars. But it also is a unique instrument with two separate echelle spectrographs covering the wavelength range from 550 to 1700 nm at a spectral resolution of $R = 82,000$. In this presentation, a brief review of the current status of the project and its main science case will be provided together with a description of the potential of this instrument for other science cases like asteroseismology, magnetic activity, GRBs or Solar system astronomy.

1 The CARMENES science case

This section presents an update of the status of the instrumental project and its science case, known already to most readers as the project was presented for the first time in the previous SEA science meeting in 2012. Therefore part of the information provided here was already presented there, focusing this contribution to present the progress achieved in the project in the past two years.

The idea for building an instrument like CARMENES arises from the need of part of the Spanish exoplanet and stellar communities to contribute to the revolution initiated in this field 19 years ago, which has brought us from the discovery of the first hot Jupiters to the first temperate terrestrial exoplanets. To date (at the time of giving this oral contribution in September 2014) there exist 21 Earth-like exoplanets (planets with masses or radii near the Earth values) in the habitable zone (HZ) of their stars. Only 16 of them have been confirmed and half of these are too far away to be studied in detail. Therefore, the number of confirmed Earth-like planets in the HZ is still small in a statistical sense (Fig. 1).

The Spanish contribution to the field would be achieved through the use of CARMENES for 1) the detection of this type of exoplanets orbiting a sample of M dwarfs in the Solar neighbourhood, and 2) the deepening in our knowledge of the global system star-exoplanet

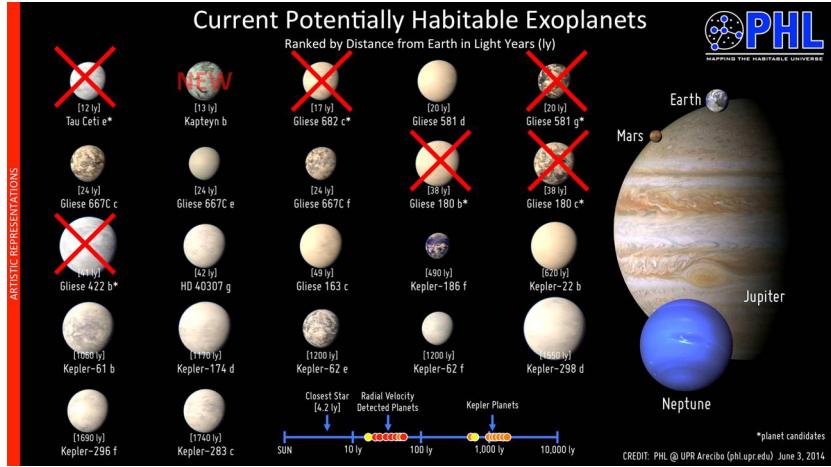


Figure 1: To date (September 2014) number of potentially habitable exoplanets, both confirmed and unconfirmed (crossed out) (<http://phl.upr.edu/projects/habitable-exoplanets-catalog>)

through the better understanding of its variability due to magnetic activity and possibly pulsations ([26, 27]) and, through the latter, the stellar internal structure and the system's evolution.

The aim of CARMENES ([22]) is to perform high-precision measurements of stellar radial velocities with long-term stability. The fundamental science objective is to carry out a survey of late-type main sequence stars (with special focus on moderately active stars of spectral type M4V and later) with the goal of detecting low-mass planets in their habitable zones. For stars later than M4-M5 ($M < 0.20 M_{\odot}$), a radial velocity precision of 1 m/s (per measurement; σ_i) will permit the detection of super-Earths of $5 M_{\oplus}$ and smaller inside the entire width of the habitable zone with $2\sigma_i$ radial-velocity amplitudes (i.e., $K_p = 2$ m/s). For a star near the hydrogen-burning limit and a precision of 1 m/s, a planet as small as our own Earth in the habitable zone could be detected. In addition, the habitable zones of all M-type dwarfs can be probed for super-Earths. The CARMENES survey will be carried out with the 3.5-m telescope on Calar Alto, using at least 600 clear nights in the 2016-2018 time frame. We plan to survey a sample of 300 M-type stars for low-mass planet companions (see also [19, 8]). This will provide sufficient statistics to assess the overall distribution of planets around M dwarfs: frequency, masses, and orbital parameters. The seemingly low occurrence of Jovian planets should be confirmed, and the frequency of ice giants and terrestrial planets should be established along with their typical separations, eccentricities, multiplicities, and dynamics.

The study of M-type stars is gaining momentum as an alternative fast track method to discover and possibly characterise hot and temperate rocky exoplanets. M-type stars are the most abundant type of stars in our Galaxy (frequency $\sim 80\%$), and therefore obtaining statistics of planet occurrence and architecture is of great importance to understand the physics of planet formation and evolution and its dependence on stellar host mass. As shown

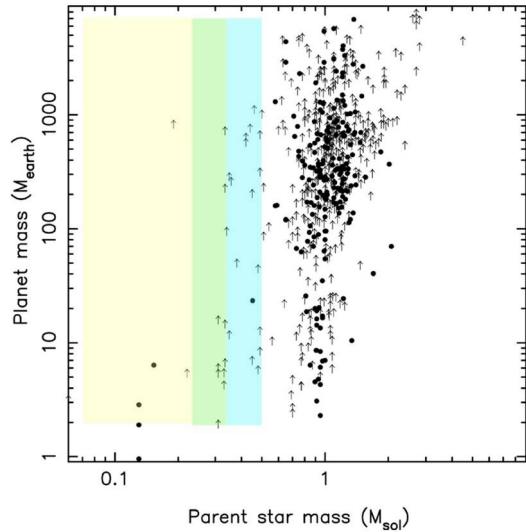


Figure 2: CARMENES science case niche. Planet masses in Earth masses versus the mass of the hosting star. The coloured region correspond to that to be sampled by CARMENES observations.

above, planet searches around M-type stars (with masses in the range of $0.1\text{--}0.6\text{ }M_{\odot}$) have the main advantage of the larger radial velocity signal, the smaller star-planet contrast and the shorter orbital period of a planet in the HZ. This has been exploited to find some of the low-mass exoplanets known so far both with radial velocities ([17, 2]) and transits ([10]), although the current number of detections is still low compared with solar analogues (see Fig. 2). In spite of that, some studies have already been carried out (again with ESO-HARPS) and yield results similar to Sun-like stars but still with poor statistical significance ([5]). In particular, the abundance of planets as a function of mass and orbital distance is very loosely constrained, and the much-sought value of η_{\oplus} , i.e., the relative abundance of Earth-type planets in the HZ, still has a $1-\sigma$ interval of 0.28 to 0.95. In addition, all the results obtained from RV surveys are only valid for M-type stars of spectral types earlier than M2–M3 ($M_* > 0.3\text{--}0.4\text{ }M_{\odot}$). The faintness of the targets and the intrinsic stellar jitter have traditionally limited the investigation of even lower mass stars. Therefore, the scientific niche of the instrument is practically untouched and largely unexplored, due to the lack of specific instrumentation like CARMENES.

Stars less massive than $0.25\text{ }M_{\odot}$ (i.e., later than M4) have temperatures lower than $T_{\text{eff}} \sim 3300\text{ K}$ and emit the bulk of their flux at wavelengths beyond 1000 nm. Although a number of planets around early-M dwarfs have been found with optical spectrographs, mid and late-M dwarfs are normally far too faint at this wavelength range to reach the data quality required for the detection of planets. Redwards of $\sim 1000\text{ nm}$, the flux emitted by these stars is several factors higher than in the optical so that at near-IR wavelengths, many low-mass stars are in principle bright enough to be observed at very high precision. CARMENES will observe simultaneously, with its two spectrographs, in the wavelength region between 550nm

Basic engineering parameters	VIS channel	NIR channel
$\Delta\lambda$ [nm]	550-950 (53 orders)	950-1700 (29 orders)
Cross disperser	Grism, LF5 glass	Grism, infrasil
Working T [K]	~295	~140
Detector(s)	1 x 4kx4k e2v CCD231-84	2 x 2kx2k Hawaii 2-RG (2.5 μ m)
Calibration λ	Th-Ar-Ne [F-P etalon]	U-Ne [F-P etalon]
Optical parameters	Fixed R=82,000, 2.8-pix sampling (>2.3 pix), 7-pix inter-fibre spacing	

Figure 3: Specifications of the CARMENES instrument and its two spectrographs, the VIS and the NIR spectrographs.

and 1700nm, characteristic that is world-wide unique. The only instrument providing such a coverage is X-shooter, but at a resolution much lower than that of CARMENES.

2 The CARMENES instrument

CARMENES is a single-purpose, high-stability instrument designed specifically to achieve the precision requirement of ~ 1 m/s (goal for NIR) in radial velocity measurements. The basic engineering parameters are given in Fig. 3, where it can be seen the much higher spectral resolution of 82,000 with respect that provided by X-Shooter of around 17,000.

Figure 4 shows a scheme of the instrument. The light from the object being observed and the calibration light are injected at the front-end, the interface between the instrument and the telescope. There, the light is carried by two circular fibres to the Coud room of the telescope, where a change from the circular fibres to octagonal fibres is made to improve scrambling and, therefore, illumination stability to reduce errors. The spectrographs are placed at the end of these fibres, inside vacuum tanks and in climatic rooms, thermo-mechanically stabilised.

3 The CARMENES current status and schedule

The project is currently in its Manufacturing, Assembly, Integration and Verification (MAIV) phase, with all but only a few smaller subsystems already purchased. In fact, around 85% of all the CARMENES hardware is being manufactured or has already been delivered.

The CARMENES instrument is a scheduled-driven project, with a fixed date for its delivery which was included as a pre-requisite for the continuation of operations of the CAHA in the addendum to the agreement between CSIC and MPG. This condition and the agenda,

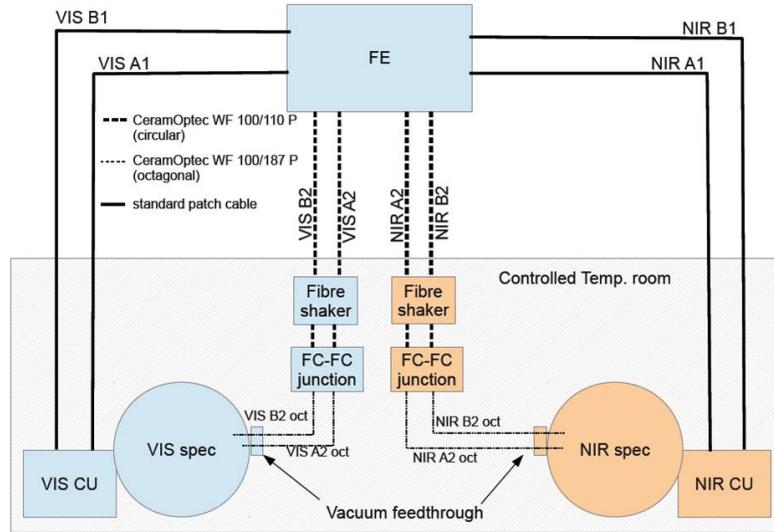


Figure 4: CARMENES instrument scheme: The front-en (FE) feeds the two VIS and NIR spectrographs through fibres. The calibration light from the Calibration Unit (CU) is also fed with fibres to the FE and, from there, to the spectrographs in the Coud room of the telescope.

which has been and still is extremely tight and without contingency, has put a lot of pressure on the German and Spanish teams that build it. Nonetheless, the project runs according to the project plan, foreseeing that all the subsystems should be delivered and accepted by the end of November 2014. The integration of the two channels and the front-end should start even before this happens, if the subsystems needed were already delivered and accepted by the two institutes carrying out the integration, viz., the IAA-CSIC (Granada) and the LSW (Heidelberg). Figure 5 shows pictures of some of the most important subsystems of the NIR channel already manufactured and delivered to Granada.

4 CARMENES: exoplanets...and much more

Back to science issues, CARMENES main science case is the search for exoplanets, but an instrument like this can be useful for many more cases, especially those that need:

- measuring RVs with extremely high precision (a must if your amplitudes are small),
- obtaining high-resolution, large-spectral-coverage spectra in the NIR,
- increasing the spectral information by adding to the NIR the simultaneous observations in the VIS,
- comparing the information provided by the simultaneous spectra taken in the VIS and the NIR.

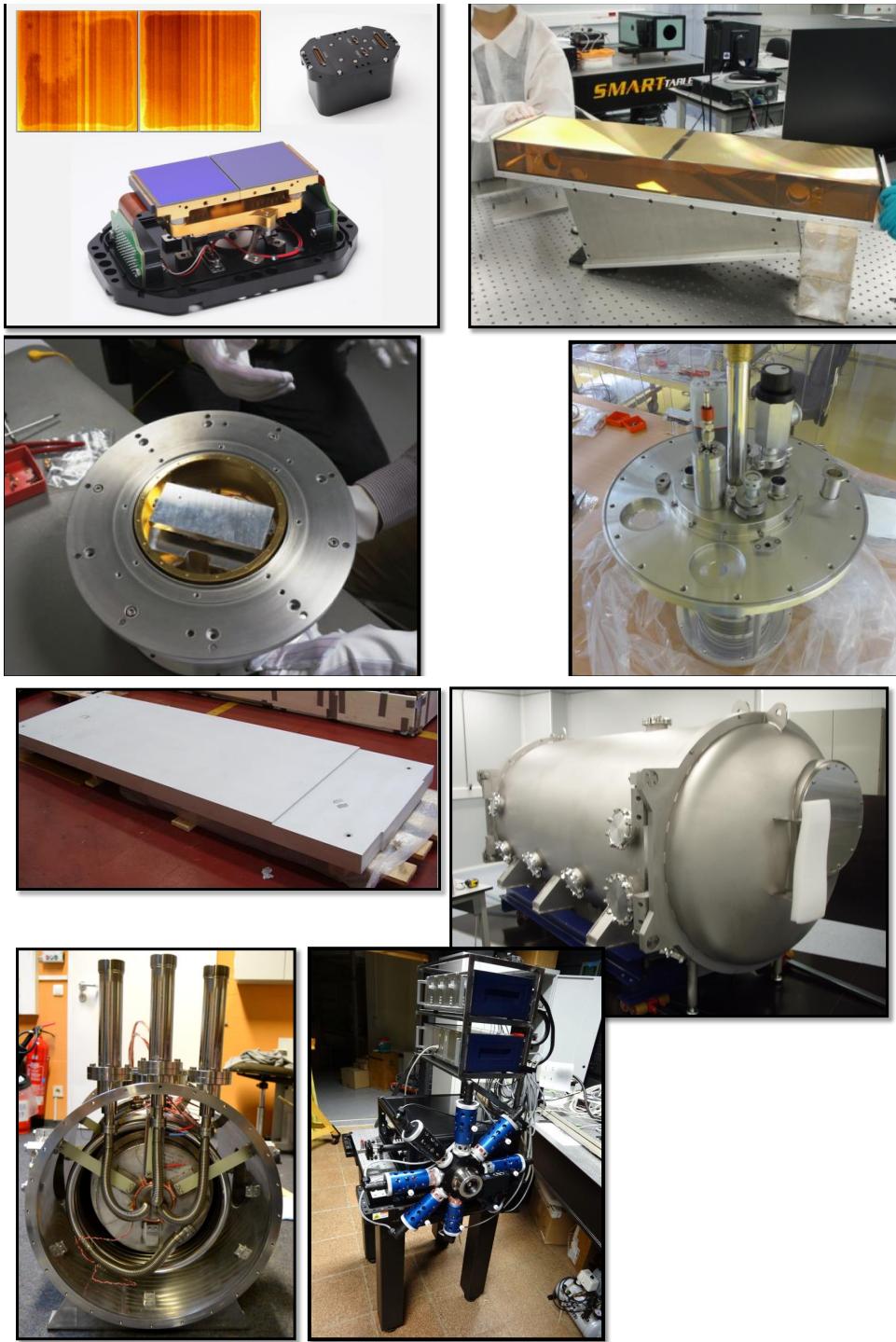


Figure 5: From top to bottom and from left to right, some of the most important subsystems of the NIR channel: NIR detector mosaic and images, echelle grating, detector head, detector cryostat, optical bench, vacuum tank, nitrogen gas preparation unit of the cooling system, calibration unit.

Below, information on the possible science cases that may benefit from using CARMENES spectra is provided. Some of them are only listed, but they will be filled in with more details by the interested community in an upcoming meeting about additional science cases with CARMENES. This list is probably not complete, only a subjective one of the most obvious cases that may need CARMENES data.

Asteroseismology: The search for pulsations in M stars, the study of solar-like oscillations in red giants and the attempt to perform mode identification in the complicated frequency spectrum of classical pulsators in both the MS and PMS phase, with or without planets will benefit from high resolution, simultaneous VIS+NIR observations with large spectral coverage.

Asteroseismology has experienced great progress in the past few years, shown by the success of several photometric space missions (MOST, CoRoT and Kepler). However, asteroseismology of M stars is a very recent field of research which was only based on very few theoretical analysis, observational ones are even more scarce, on possible physical mechanisms producing oscillations in these small, compact, cool stars, until [26] showed that indeed these oscillations become excited by these mechanisms and provided the theoretical instability strip for them [27]. The excitation mechanisms working in stars of solar spectral type and lower are the stochastic and the epsilon mechanism. The first one excites the normal oscillating modes of the star by generating sound at the surface of the star through the turbulent flows of the external convection zone. In principle, any star with a significantly large outer convective zone will show stochastic pulsations. However the small amplitudes and short oscillation periods of solar-like pulsations combined with the lower luminosities and higher densities of main sequence low-mass stars make the observational discovery of oscillations in low-mass stars a real challenge. The second one produces oscillations in the star via the sensitivity of nuclear reactions to temperature changes which make pre-main sequence, low-mass stars vibrationally unstable, as first suggested by [14].

Several attempts have been recently made to detect epsilon-mechanism-driven pulsations in very-low-mass stars and brown dwarfs ([12, 13]) and none so far for the detection of those stochastically driven in stars with spectral types lower than K1 (see the results on the K1V star, α Cen B, with CORALIE, by [9]). The detection and study of these oscillations could have profound impact in the study of exoplanets around low-mass stars for two reasons: 1) it will allow asteroseismology to be used for these stars, providing a tool for determining very accurately the global physical properties of these hosting stars in order to better characterize the planets (in particular those in the habitable zone) and the planetary systems, and 2) it will help understanding stellar intrinsic radial velocity jitter and help discerning this jitter from radial velocity variations produced by an orbiting body. But, on top of the obvious benefits to the exoplanet science case, the implications for the understanding of the internal structure and evolution of these M dwarfs would be large. If these pulsations were to be discovered, they would allow to put observational constraints on the information provided by the models on the resonant cavity inside the stars. This, in turn, would observationally constrain the exact position in the HR diagram of the line separating stars with fully convective and partially convective interiors, for which only theoretical studies exist (see Fig. 6, [24]), allowing a deeper study of this region both in the MS and PMS phases.

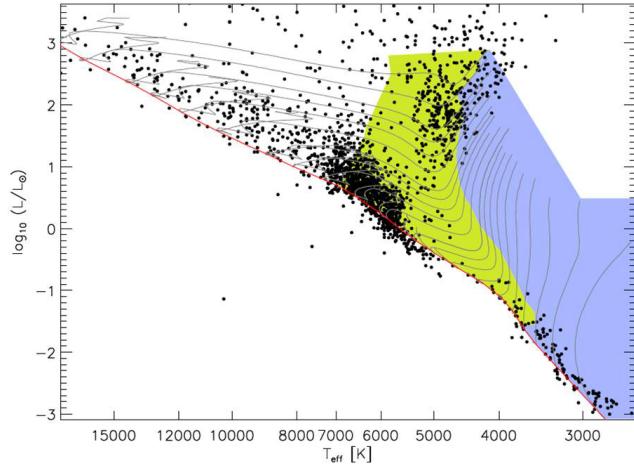


Figure 6: HR diagram showing the regions where partial convection (green) and full convection (blue) is present in the interior of the stars [24]. Evolutionary tracks are from [28]

Asteroseismology of pulsating stars hosting planets has been proved to work for hotter stars. For instance, in the context of the NASA space mission Kepler, it has been shown by the asteroFLAG team (within the Kepler Asteroseismology Science Consortium), that it is possible to highly increase the precision of stellar radii of solar-like hosting stars, from 40% to only 3% in radii errors (see [29]). This has been already confirmed by the first results from the space missions CoRoT and Kepler. [11] found, using Kepler data, that the planet-host star HAT-P-7 is a solar-like pulsator. With this asteroseismic information, they increased one order of magnitude the accuracy in the knowledge of the stellar radius and mass, and two orders in the stellar mean density. For classical pulsators, [20, 21] have studied the case of HR 8799, a gamma Dor-type pulsator with four imaged planets, to investigate, through asteroseismology, the nature of its lambda-Bootis nature, the scenario of formation of its abundance peculiarities and its age.

Asteroseismology for most of the stars is based on the identification of the quantum numbers (l, m) associated to an oscillation eigenmode, which is a challenging but necessary step in order to perform a seismic analysis of any pulsating star. This mode identification problem can be tackled using photometric or spectroscopic techniques or, ideally, both simultaneously. The use of a large wavelength baseline by using red and near infrared magnitudes together with blue and optical ones greatly improves the significance of this mode identification ([3]). The phase differences measured for the near infrared wavebands are especially discriminating for different modes ([4]). In the case of spectroscopic data, high-resolution spectroscopy is required to detect the pulsations signatures in the spectral line profiles. The moment method ([6]) and the IPS method ([30]) were developed for deriving the l and m numbers from the analysis of spectral line variations in the visible wavelength range for observed modes in several types of pulsating stars, as for β Cepheid ([7]) or δ -Scuti ([32]) from high-resolution spectroscopic data. However, these methods still lack precision in the determination of these numbers and the results usually present non-uniqueness problems that

hinder the identification of the modes. NIR spectroscopy has never been explored as a mode identification tool, mainly due to the insufficient spectral resolution and wavelength coverage provided by existing instruments, but the first results of [1] using this new instrumentation are encouraging.

Stellar magnetic activity: magnetic activity in (ultra) cool dwarfs, exoplanet-induced activity and the effect in RVs will benefit from high resolution, simultaneous VIS+NIR observations.

Stellar magnetic activity is observed for a wide variety of cool stars (spectral types F, G, K, M), and from the youngest stars (pre-main sequence) to the evolved ones. All these stars have an outer differentially rotating convection zone that, through the dynamo mechanism, produces intense magnetic fields. As in the Sun, a positive temperature gradient has been found in the outer atmosphere of these stars. Above the photosphere, the temperature increases towards the chromosphere, where a temperature of 104 K is reached, the transition region and the corona, where 106 K is reached. Despite the considerable progress during the last fifty years, we are yet far from understanding how the magnetic field is generated in the Sun and other cool stars, even further when trying to quantify how the magnetic field originates the wide variety of activity phenomena observed at different atmospheric levels. The most recent studies show different behaviours in very active stars and the Sun. The behaviour of the magnetic activity in extremely cool stars (late M type and cooler, transition between stellar and substellar objects) has never been deeply studied. Some works ([15, 18, 25]) indicate that the frequency and intensity of the chromospheric activity increases from K7 to M7, but quickly decreases in the M8 to L4 spectral range, and that young objects present lower activity levels than older ones. In addition, recent studies ([31, 24]) found evidences that all L and T dwarfs are rapid rotators and the lack of a rotation-activity connection. A sudden change in the strength of rotational braking appears at the threshold mass to full convection, and strong evidence exists for rotational braking weakening with lower mass. A probable explanation is that the field topology changes from dipolar to small-scale structure as the objects become fully convective. This is, therefore, a completely open research field, which yet needs a great theoretical and observational effort.

The analysis of the optical (Ca II H & K, He ϵ , H β , He I D3, Na I D1, D2, and H α) and NIR (Ca II IRT lines (0.8498, 0.8542, 0.8662 μm), He I (1.0830 μm); Pa α (1.875 μm), Pa β (1.282 μm), Pa γ (1.005 μm), Br γ (2.166 μm), Br δ (1.945 μm)) indicators provides information about the rotational modulation of the chromospheric activity, detection of flares, and possible long-term variations (activity cycles). The unique parallel observation with the CARMENES visual and NIR spectrographs will enable very detailed studies of activity and related temporal variations in M dwarfs, and will be fundamental for a clear discrimination between activity-induced radial velocity signals (e.g. by spots) or motion around the barycentre of the system.

Stellar fundamental parameters: Determination of effective temperature (T_{eff}), surface gravity ($\log g$), rotation velocity ($v \sin i$) and abundances will benefit from the CARMENES high resolution and large spectral coverage that extends to the near infrared, specially for bright massive stars that present very few lines in their optical spectrum.

Exoplanetary atmospheres: The observation of molecular bands in the transmission and emission NIR spectra of giant planet atmospheres will benefit from high resolution observation

that would allow resolving those molecular bands in individual lines. Observing many of these lines simultaneously would allow to measure their doppler displacement and detect specific molecules in the atmosphere of the exoplanet.

Follow-up for space missions: although not a proper science case, many space mission (Gaia, CHEOPS, TESS, JWST, PLATO) and larger telescopes (GTC) will benefit from the time series obtained with CARMENES for confirmation of planet candidates or asteroseismic/activity analysis and from snapshots for target characterization. For instance, Gaia could use VIS CARMENES spectroscopy of red targets to calibrate its CaII Infrared triplet observations for metallicity determinations.

Eventually, other many science cases, which may not even be listed here will find extremely useful the contribution made to them by CARMENES data. some of these may be, for instance, chemical abundance determinations of planet hosts (high res and large spec. cov.) for comparing stars with and without planets; Planetary debris on the surface of white dwarfs (a HIRES@ELT science case); Proto-planetary and proto-stellar disks (HIRES@ELT); Proper motion moving groups and cluster member kinematics; Binaries: High precision for eclipsing binaries (Rossiter-McLaughlin effect) and NIR spectra for embedded objects; Planetary nebulae; Solar System; GRBs, etc.

Acknowledgments

PJA acknowledges support from the Ministry of Research through grant AYA2011-30147-C03-01, from Junta de Andalucía through a “project of excellence” grant FQM7363 , from CSIC i-LINK+ program i-LINK0867 and from the EC through FEDER funds.

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