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CARMENES: Commissioning and first scientific results at the telescope. A precursor for HIRES@E-ELT

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Abstract

CARMENES is the next generation instrument built for the CAHA 3.5m telescope by a large international consortium of 11 institutes in Spain and Germany. It consists of two separate highly-stabilized, high-resolution echelle spectrographs covering both the visible, from 550 to 950 nm, and the near-IR, from 950 to 1700 nm, wavelength ranges with spectral resolution of R=82,000. They are fed by fibres from the Cassegrain focus of the telescope and were designed and built to achieve high-accuracy radial velocities of nearby M-dwarf stars. This contribution overviews the main and unique design characteristics of CARMENES. The instrument MAIV phase was achieved in the last two years (2014-2015) and started commissioning in November 2015. The commissioning phases, both technical and scientific, took six full weeks in the last two months of 2015. They have shown that the instrument is well within requirements and performing to be able to achieve its objective, not proven before in the near-infrared, of providing radial velocities precisions of 5 ms^{-1}, with a goal of 1 ms^{-1}. The Guaranteed Time Observations (GTO) program has started in January 1st, 2016. CARMENES is, therefore, currently conducting a radial-velocity survey of 300 M dwarfs with a precision sufficient for detecting Earth-like planets in their habitable zones. It is also being offered in open time by the CAHA. Its modular design is the idea in which HIRES, the next very high-resolution, high-fidelity spectrograph with wide wavelength coverage at the E-ELT, is based on. This E-ELT instrument might consist of four different high-resolution spectrographs covering the blue, the visible, the near-infrared (Y, J and H bands) and the K band. A proposal to the ESO call for Phase-A studies for a HIRES at the E-ELT was submitted by the HIRES consortium last December. This proposal was accepted by ESO and the Phase-A kick-off meeting between ESO and the consortium took place in March 22, 2016.

1 The CARMENES science case

This contribution presents an update of the status of the instrumental project and its science case. The project was presented for the first time at a SEA meeting in 2012 and was updated in the meeting in 2014. 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 aim of CARMENES ([11], [1]) 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 ms^{-1} (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., $K_\mathrm{p} = 2$ ms^{-1}). For a star near the hydrogen-burning limit and a precision of 1 ms^{-1}, 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 [10, 5]). 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 characterize hot and temperate rocky exoplanets. M-type stars are the most abundant type of stars in our Galaxy (frequency $\sim 70\%$), 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 above, planet searches around M-type stars (with masses in the range of 0.1-0.6 $M_\odot$) 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 ([9, 3]) and transits ([6]), although the current number of detections is still low compared with solar analogues (see Fig. 2 in [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 ([4]). In particular, the abundance of planets as a function of mass and orbital distance is very loosely constrained, and the much-sought value of $\eta_\oplus$, i.e., the relative abundance of Earth-type planets in the HZ, still has a 1-σ 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 ($M_* > 0.3 - 0.4$ $M_\odot$). 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 $M_\odot$ (i.e., later than M4) have temperatures lower than Teff $\sim$ 3300 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

Basic engineering parameters	VIS channel	NIR channel
Δλ [nm]	520-960 (61 orders)	960-1710 (28 orders)
Cross disperser	Grism, LF5 glass	Grism, infrasil
Working T [K]	In vacuum at ~295	In vacuum at ~140
Detector(s)	1 x 4kx4k e2v CCD231-84	2 x 2kx2k Hawaii 2-RG (2.5 μm)
Calibration λ	UNe & UAr lamps [F-P etalon]	UNe [F-P etalon]
Optical parameters	R=93,500, 2.5-pix sampling (>2.3 pix), 7-pix inter-fibre spacing	R=80,400, 2.8-pix sampling(>2.3 pix), 7-pix inter-fibre spacing

Figure 1: Specifications of the CARMENES instrument and its two spectrographs, the VIS and the NIR spectrographs.

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 ∼1000 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 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 5 ms^{-1} (goal of 1 ms^{-1}) in radial velocity measurements. The basic engineering parameters are given in Fig. 1, and Figure 4 in [2] shows a scheme of the instrument. The light from the object and from the calibration source are injected simultaneously at the front-end, the interface between the instrument and the telescope. There, the light is carried by two circular fibres down to the Coudé 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 instrumental project schedule and current status

The CARMENES instrument has been a scheduled-driven project with a fixed date for its delivery, which was included, as a pre-requisite for the continuation of the observatory operations, in the addendum to the agreement between CSIC and MPG. This condition and the agenda, which were extremely tight and without contingency, put a lot of pressure on the German and Spanish teams that built it. Nonetheless, the instrument was delivered and commissioned in time (see Figures 2 and 3).

The project, at the time of writing this proceedings (Oct. 2016), is ten months within its official scientific survey. During the previous year, we finished the Manufacturing, Assembly, Integration and Verification (MAIV) phase and delivered and successfully commissioned the instrument. Preliminary acceptance with the observatory was signed on Dec 31, 2015, and GTO granted and the official survey started on Jan 1, 2016.

All 300 M-dwarf stars of our sample have at least one spectrum acquired with both spectrographs, with several of them with tens of RV measurements already. The format of the raw images delivered by the instrument is that of a typical echelle spectrograph, as shown in the top part of Fig. 4, which, for CARMENES, yields reduced extracted spectra covering the large wavelength range from 520 to 1700 nm shown in the bottom part of that Figure. CARMENES Instrument Control System and pipeline make observing and data reduction very simple, the latter producing fully reduced, extracted and wavelength calibrated (no flux-calibrated) spectra and radial velocities.

The RV data being gathered have already, at this early stage since the start of the operations, a precision to allow for the detection of new terrestrial planets orbiting these stars. The data of stars already known to host planets already show this. Figure 5 shows the phased RV curve of one of these M-dwarf hosts, GJ436b, which is known to be orbited by a Neptune-like planet. The residuals to the fit show a dispersion that includes, together with the instrumental errors, the stellar intrinsic jitter produced by magnetic activity in the star. The eventual results from our survey should provide robust statistics on the architecture of planetary systems around very nearby M dwarfs. They will also leave a legacy of three hundred very high signal-to-noise ratio and resolution spectra of the stars (first release expected by the beginning of 2017) and the detection of a few transiting very nearby planets that could be followed-up for the characterization of their atmospheres.

CARMENES can be useful also for many more cases, especially those that need i) measuring RVs with extremely high precision (a must if your amplitudes are small), ii) obtaining high-resolution, large-spectral-coverage spectra in the NIR, iii) increasing the spectral information by adding to the NIR the simultaneous observations in the VIS, and iv) comparing the information provided by the simultaneous spectra taken in the VIS and the NIR.

In [2], information on the possible science cases that may benefit from using CARMENES spectra is provided. This list is probably not complete, only a subjective one of the most obvious cases that may need CARMENES data. In fact, since the publication of the proceedings of the last SEA meeting, many other groups have expressed interest in CARMENES for many other different science cases.

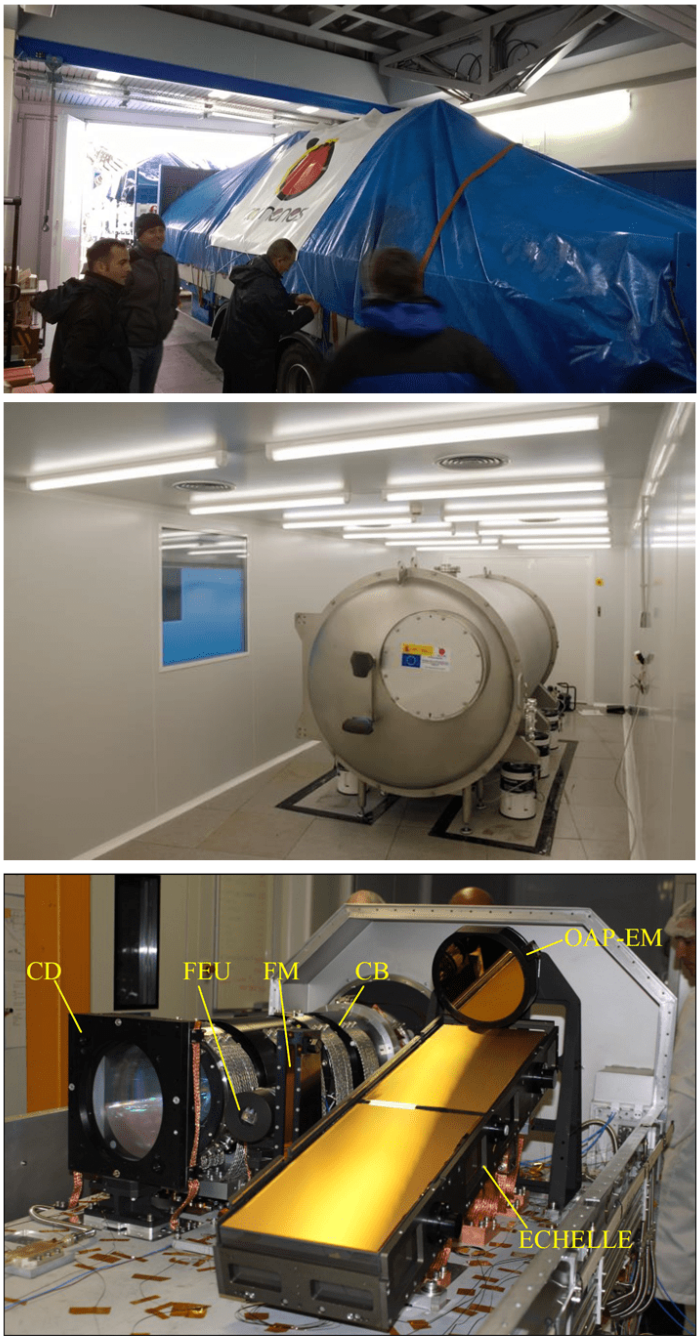

Figure 2: From top to bottom and from left to right, Front-End installation at the Cassegrain focus of the 3.5-m telescope, which arrived on April 23 2015. Loading of the NIR channel vacuum tank, with the spectrograph partially integrated inside, on the transport at the IAA premises on Oct 20, 2015. Lifting the NIR channel from the transport, at the ground floor of the 3.5-m telescope building to the Coudé pit, one floor below the main observing deck.

Figure 3: From top to bottom, a few more details on the transport (top) final location of the channel inside its climatic temperature-stabilised room (middle) and some of the subsystems (not all of those showed here traveled inside the spectrograph during the transport) of the NIR spectrograph (bottom).

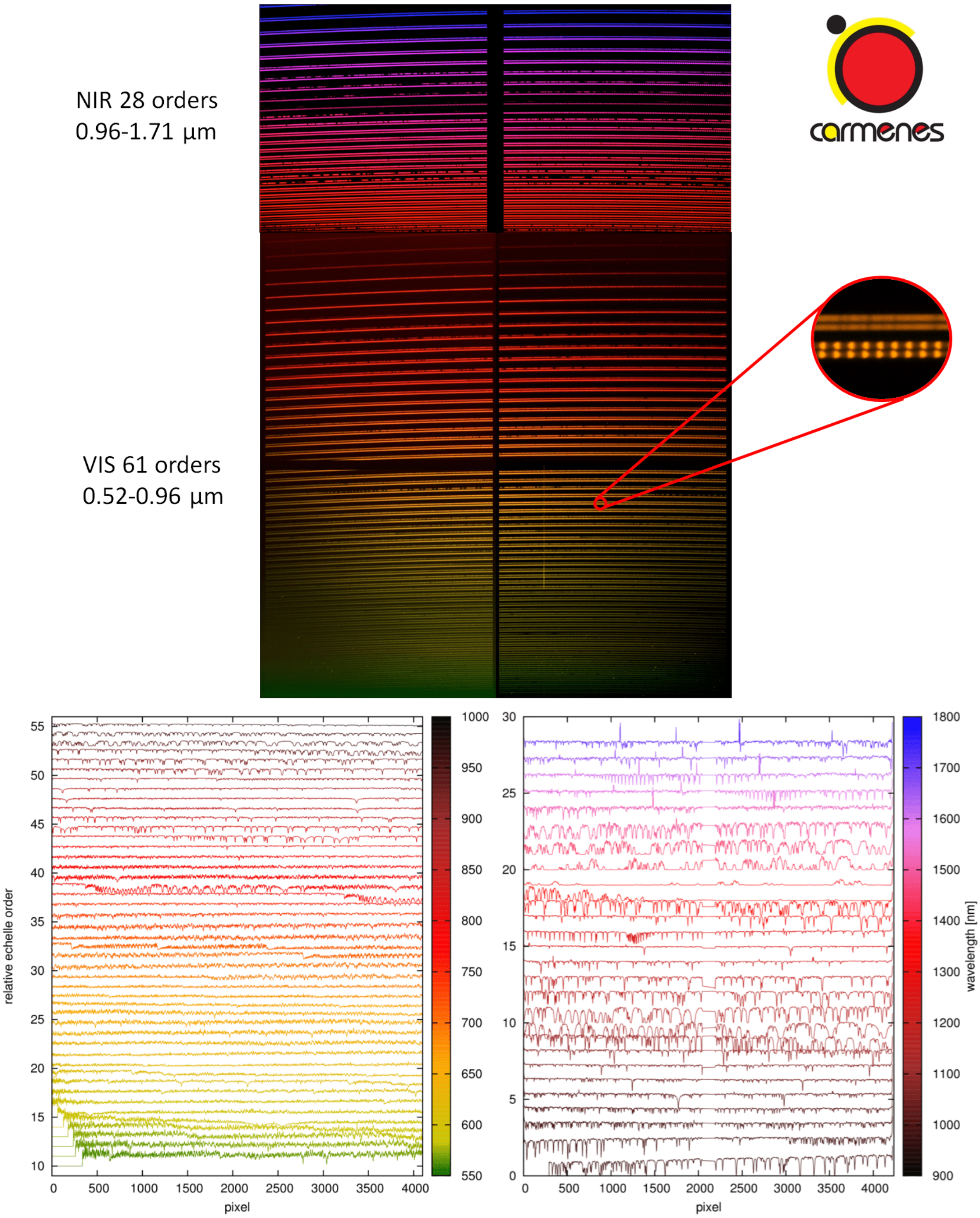

Figure 4: Top: Raw 2D format of the data produced by CARMENES. The top 28 orders of the echelle spectrum correspond to those produced by the NIR channel, while the 61 orders at the bottom are generated by the VIS spectrograph. Bottom: Final spectrum, separated in orders, extracted from the raw data of the VIS (left) and NIR (right) spectrographs. These data are all from one of the CARMENES targets, and shows the immense potential of CARMENES for other science cases than that of the detection of exoplanets.

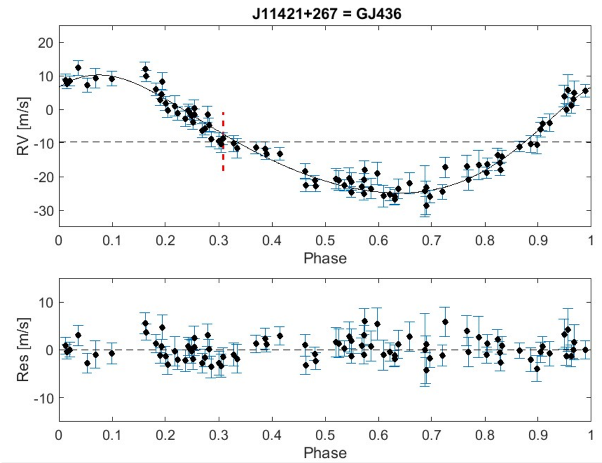

Figure 5: GJ 436 is a nearby early M (M2) dwarf included in our survey. It is already known to host a candidate giant planet (Neptune-like), GJ 436 b and possibly two other less massive planets still to be confirmed. The plot shows the data already collected by CARMENES for this object.

4 CARMENES as a precursor for EELT-HIRES

CARMENES is an instrument that, in some aspects, is unique and still a prototype. However, the experience gained with its design and development, in particular of the NIR channel, together with other instruments in the optical (in particular ESPRESSO) have put the institutions involved in those project in an excellent position to contribute to the new generation of this type of spectrograph for the E-ELT. The only concept currently under development through a 2-year Phase A study (conceptual design) is that for HIRES.

4.1 Science cases

The versatility of the instrument design allows for a large set of key science cases (see HIRES White Paper by [7]), from the characterization of planetary atmospheres to the study of the variation of the fundamental physics and cosmology constants. This is a brief summary of the science cases collected in the HIRES white paper: Exoplanets (characterization of planetary atmospheres and the detection of life signatures, exoplanets debris) , Star and planet formation (Protoplanetary disks), Stellar physics, chemistry and astro-archaeology (3D structure of stellar atmospheres, solar twins, stellar magnetic fields, isotope ratios and nucleosynthesis for the earliest and the latest stages of stellar evolution, chemical enrichment in the local group, extremely low metallicity stars, resolved stellar populations in extragalactic star clusters), Galaxy formation (Population III stars, reionization, intergalactic medium, massive galaxies evolution, supermassive black holes), and Fundamental Physics and Cosmology (variation of

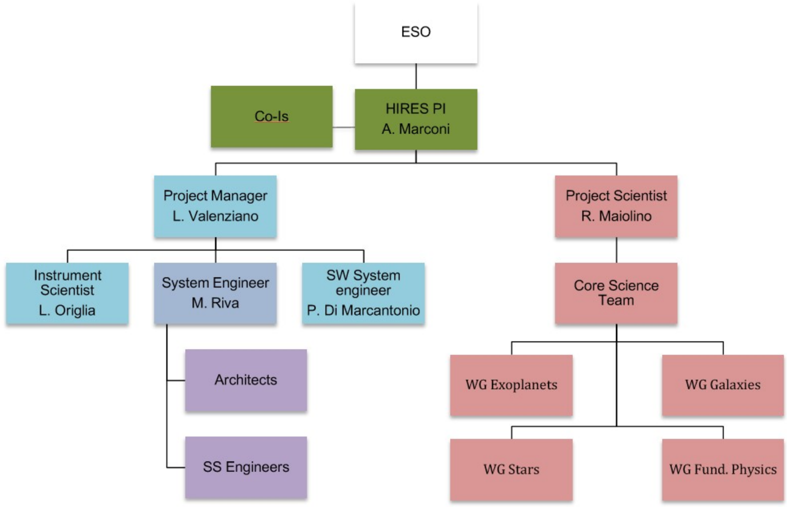

Figure 6: Consortium structure. Different colors denote different areas of activity (red - science team, green - executive board, blue - project office, magenta - technical team). Extracted from [8].

fundamental constants, constraints on Dark Matter and Dark Energy, constraints on non-standard physics, Sandage Test).

4.2 Requirements

The various science cases result in the following set of requirements: i) a primary high-resolution observing mode with R$\sim$100,000 and a simultaneous wavelength range 370-2500 nm (although the extension to 330 nm is desirable for some cases). For most science cases a stability of about 10 cms^{-1} and an accuracy of the relative wavelength calibration of 1 ms^{-1} are sufficient. The exoplanet radial velocity case also requires a wavelength accuracy down to 10 cms^{-1}. ii) The Sandage test requires a stability as good as 2 cms^{-1} over the duration of a night and also an absolute wavelength calibration of 2 cms^{-1}. These numbers are at the date considered as desirable goals more than design drivers. iii) The science cases of mapping the large scale structure matter distribution, galaxy evolution and extragalactic star clusters would greatly benefit from having, within the same wide spectral coverage (370-2500 nm), a moderate multiplexing capability (5-10 objects within a FoV of a few arcminutes) with a moderate spectral resolution mode (R$\sim$10,000-50,000). iv) Most of the extragalactic, high-z science cases require an accurate subtraction of the sky background, to better than 1%.

The preliminary studies made in early phases by the HIRES initiative for a modular concept fulfilling the requirements imposed by the key science cases concluded on a rough cost

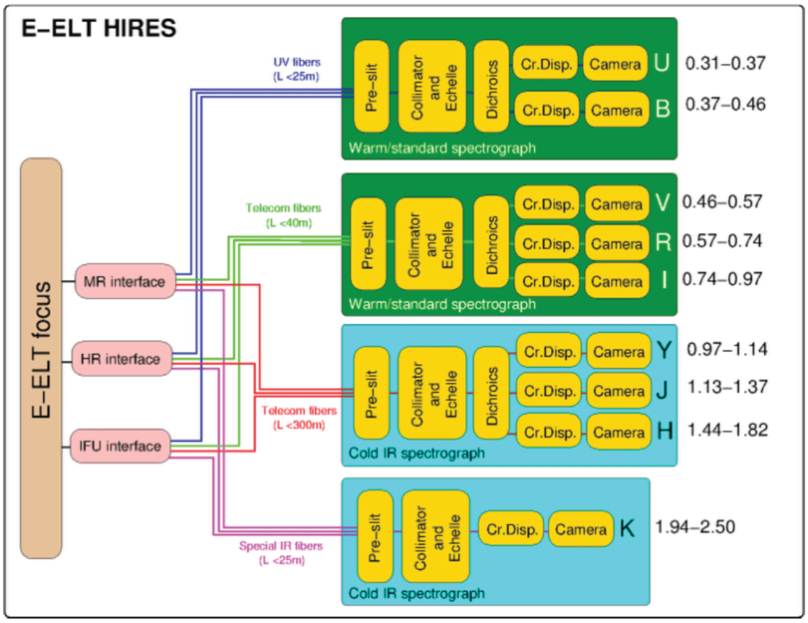

Figure 7: Possible HIRES architecture with wavelength splitting in four spectrographs. Wavelength splitting is indicated only for illustrative purposes and will be the results of the trade-o analysis conducted during the Phase A study.

estimation much larger that the cost cap of 18 MEuros imposed by ESO for the development of this instrument. Therefore, a baseline design fulfilling only a subset of the requirements driving the instrument design will have to be selected at the beginning of the Phase A study.

4.3 Instrument concept

A preliminary concept developed in a previous technical study by the HIRES initiative, starting point for that of the Phase A study, came up with a fibre-fed, cross-dispersed echelle spectrograph of modular nature, which offered the advantage of easy de-scoping to match the cost cap imposed by ESO. This concept is represented in Fig. 7. The four different modules of an instrument operating from the blue to the K band would require different detector technologies and working temperatures, needing cryogenic thermal environments beyond 1 micron.

The probabilities for the consortium reaching a successful Phase-A concept builds on the experience of some of its institute in designing and building similar instrumentation, like in the case of the IAC with ESPRESSO and the IAA with CARMENES (see Table 2 in [8]. This experience secures that an instrument able to provide high-resolution spectroscopy (100,000) over a wide wavelength range (370-2500 nm) can be built with currently available technology with no obvious show-stoppers (though some R&D is foreseen to maximise performance and/or reduce the cost).

4.4 Consortium

The HIRES consortium, to which Spain contributes, is integrated by 29 institutes from 12 different countries (Brazil, Chile, Denmark, France, Germany, Italy, Poland, Portugal, Spain, Sweden, Switzerland and United Kingdom). For each country, one institute ("Coordinating Institution") coordinates the contributions from all other institutes of that country. The Spanish institutions involved in HIRES are the Instituto de Astrofísica de Canarias (coordinating institution), the Instituto de Astrofísica de Andalucía and the Centro de Astrobiología de Madrid.

The Principal Investigator (PI; A. Marconi, INAF, Italy) of the HIRES consortium together with the Board of co-Investigators (co-Is; composed of one representative per country) take all decisions concerning the overall scientific performance and exploitation of the instrument and the organization of the consortium. During the meetings with the Board the PI is assisted by the Project Scientist (PS) and by the Project Manager (PM). The PS chairs the Science Advisory Team (SAT) and is responsible for analising the top level requirements and providing the link between the science and technical team. The SAT is composed of a science team at large and of a core science team. The science team is responsible for all matters that concern the science cases for the instrument, for instance for the prioritization of the key science cases that will allow to help defining the baseline design of the instrument.

Acknowledgments

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