MARVEL: extracting high-precision radial velocities of exoplanet hosts

N. Jannsen★[a], D. Seynaeve[a], J. De Ridder[a], J. Stürmer[b], J. Pember[a,c], C. Schwab[c], L. A. Buchhave[d], G. Raskin[d], B. Vandenbussche[a], H. Sana[a], A. Tkachenko[a], P. Royer[a], W. De Meester[a], H. Van Winckel[a], and I. Riba[e]

[a]Institute of Astronomy, KU Leuven, 3001 Leuven, Belgium
[b]Landessternwarte Königstuhl (LSW), 69117 Heidelberg, Germany
[c]Department of Physics and Astronomy, Macquarie University, NSW 2109, Australia
[d]DTU Space, National Space Institute, Technical University, Kgs. Lyngby, Denmark
[e]Institut de Ciències de l'Espai (ICE, CSIC), E-08193 Bellaterra, Barcelona, Spain

ABSTRACT

The future ESA space mission PLATO aims to detect thousands of exoplanets, including Earth-like planets, and constrain their radius and mean density. To achieve this goal, the space based photometric observations are not enough but need to be complemented by ground-based observations to measure the Radial Velocity (RV) of the exoplanet host stars. MARVEL is such a facility consisting of four 80 cm telescope linked through optical fibers to a single high-resolution échelle spectrograph, designed for high-precision RV measurements with a uncertainty of $\sim 1\,\mathrm{m\,s^{-1}}$. MARVEL is build by a consortium led by the KU Leuven with contributions from the UK, Austria, Australia, Sweden, Denmark, and Spain, and will be commissioned in 2023. To reach such high RV precision, not only ultra-stable hardware is currently being developed, but also a state-of-the-art data processing pipeline for which we present the first results in this poster.

Keywords: Exoplanets, Radial velocity, Spectrograph, Pipeline, Simulations, Telescopes

1. INTRODUCTION

The impact of the Radial Velocity (RV) method on planetary sciences were revolutionized by the first discoveries of exoplanets almost three decades ago. Since then, ground- and space-based photometry have overtaken the stage and it now the biggest contributor for planet detections via the transit technique. Although being an additional tool to detect multi-planet systems from Transit Timing Variations (TTVs), or to confirm exoplanets using multi-color photometry, transit measurements nevertheless only provides the relative size of the exoplanet w.r.t. the host star. Thus, high precision RV measurements are ultimately necessary to determine planet orbits and masses, and hence the planets bulk composition. As 30-100 RV measurements are generally needed to make a solid confirmation of the planetary nature and to constrain the planet's mass [1], RV follow-up surveys face a challenging task in providing enough on-sky telescope time needed to keep track of future planet candidates. In hindsight, facilities like MARVEL will be critical to meet these requirements and to push the frontier of planet statistics.

The upcoming MercAtor high-precision Radial VELocity facility, MARVEL[1] [2], is a near-future RV follow-up project dedicated to confirm and characterize exoplanets detected by ongoing and future space missions. Being an extension of the existing Mercator telescope (and the HERMES spectrometer [3]), MARVEL will be commissioned in 2023 at the Roque De Los Muchachos Observatory on La Palma (Spain). The conceptual design of a single high-resolution échelle spectrograph fiber-fed by four 80 cm diameter primary mirror robotic telescopes, will make it possible to acquire very precise RV measurements down to an intrinsic precision of $1\,\mathrm{m\,s^{-1}}$. Naturally to achieve this precision, temperature and pressure variations, which alter the stability of the spectrograph and imprints their effect by mimicking RV signals on the extracted spectra, will be mitigated by

★nicholas.jannsen@kuleuven.be
[1]https://fys.kuleuven.be/ster/instruments/marvel

installing the MARVEL spectrograph on a temperature controlled optical bench placed within a large vacuum vessel. The multi-telescope design will enable either four bright stars to be observed at once or gain higher spectrophotometric precision of a single fainter star using all four telescopes simultaneously. MARVEL will have the ability to efficiently detect and confirm thousands of exoplanets and thus help deduce planet masses, orbits, and fundamental parameters of current and future exoplanet space missions, such as TESS [4], PLATO [5], and ARIEL [6].

MARVEL has specifically been designed to fit the niche of following up planet candidates of the future ESA PLATO mission, set for launch in late 2026. From first hand estimates of the MARVEL performance [2] a Signal-to-Noise Ratio (SNR) of ~ 200 per resolution element in a 1 h exposure will be feasible for solar-like stars of $m_V \lesssim 9$ using a single telescope and stars of $m_V \lesssim 11$ using all four telescopes simultaneously. This is exactly inline with the limited magnitude of $m_V < 11$ for the dwarf and subdwarf stars (F5-K7) comprising the core and bright samples (P1 and P2) of the PLATO Input Catalogue (PIC) [7]. The current observational strategy for PLATO is to have two long pointing fields of > 2 years in both hemispheres (the so-called North and South PLATO Field; NPF and SPF, respectively) [8]. Aiming to provide up to 20,000 $1\,\mathrm{m\,s^{-1}}$ measurements per year, MARVEL will thus not only play a key role in PLATO's RV follow-up program [5], but also provide a major proportion of the follow-up observations for bright NPF exoplanet host stars.

Looking beyond the PLATO mission, the mass measurements provided by MARVEL will also be important for the selection of targets suited for follow-up studies of e.g. habitable planets orbiting M dwarfs, planet atmospheric studies with space bourne observatories like JWST [9], and future direct imaging missions like LIFE [10]. Although Earth-like planets in the habitable zone (with up to dozen expected to be detected by PLATO [5]) is out of MARVEL's reach and needs to be followed-up on larger telescopes, the small apertures of the MARVEL telescopes allows a compact instrument with high throughput efficiency. MARVEL will thus be competitive with comparable spectrographs on medium-class 4 m telescopes, for which time allocation to observe multi-epoch planet RV follow-ups are typically limited.

With an exquisite hardware design of MARVEL the fidelity of the software counterpart is essential if MARVEL shall meet its mission goals. Soon to belong to a class of high-precision RV spectrographs (like MAROON-X [11], ESPRESSO [12], HARPS [13], and EXPRES [14]) a (extremely) high-precision MARVEL reduction pipeline is fundamental to recover the full potential of the instrument. As part of the construction of a state-of-the-art spectroscopic pipeline, realistic simulations are needed to shape it and ultimately test the scientific yield of MARVEL. In this contribution we thus first present the joint setup of existing open software to perform realistic simulations of MARVEL échelle spectra, and next dive into the current status of the MARVEL pipeline.

2. SYNTHETIC INPUT SPECTRA

Since quantitatively accessing the performance of each individual pipeline component is subject to great uncertainties prior to first light measurements, as part of mission preparation realistic simulations are a requite for testing and designing a robust and reliable spectroscopy extraction pipeline. Hence, for MARVEL we likewise accommodate potential precision bottlenecks with simulations of synthetic spectra. Such spectra are naturally constructed from a set of realistic simulations modelling end-to-end the incoming photons, their way through the optical train of the spectrograph, and lastly their registration and conversion to digital units by the CCD readout electronics.

To efficiently provide simulations on demand for the assessment and design study of the MARVEL spectroscopic extraction pipeline we here present the open-source MARVEL spectrum simulator, MARVELsim[2]. This software tool builds on the heritage of two novel open source software packages called PyEchelle[3] [15] and Pyxel[4] [16]. PyEchelle is fast and generic spectrum simulator (updated from its predecessor Echelle++), and is used to generate synthetic 2D object and calibration spectra. On the other hand Pyxel is an end-to-end simulation framework for imaging detectors, which is used to efficiently add-on all necessary CCDs effects.

[2] https://github.com/nicholasjannsen/MARVELsim/
[3] https://gitlab.com/Stuermer/pyechelle
[4] https://gitlab.com/esa/pyxel

Table 1: Overview of the MARVEL CCD detector parameters (left column) and CCD effects included in the Pyxel simulations (right column). Notice that the inclusion of cosmic rays and shot noise are random noise sources with their own model dependence, while all other effects inherently dependents on (fast/slow) CCD readout mode.

Detector specification		**Pyxel CCD effect**	
Parameter	*Value*	*Effect*	*Detail*
CCD type	STA1600 back-illuminated	Cosmic rays	Rate: $0.33\,\gamma\,\mathrm{s}^{-1}$
Material	Silicon	Shot noise	Poisson model
Image area	$10,560 \times 10,560$ pixel	Read noise	
Pixel size	$9 \times 9\,\mu\mathrm{m}$	Bias level	
Pixel thickness	$40\,\mu\mathrm{m}$	Dark current	
Full-well capacity	800.000 e	Full-well capacity	
Quantum efficiency	0.9	Persistence	
Charge readout sensitivity	$7\,\mu\mathrm{V}\,\mathrm{e}^{-1}$	Charge Transfer Inefficiency	

The general formalism of PyEchelle is to simulate a 2D spectrum by tracing individual photons through optical element of a spectrograph model provided by the user. The MARVEL spectrograph model was constructed in ZEMAX as part of the conceptual design phase [2]. While simulating non-constant intensity sources, PyEchelle provides libraries to map the spectral energy of the incoming photons, e.g. several options are available off standard wavelength calibration lamps. For stellar spectra the PHOENIX library [17] of high-resolution synthetic stellar spectra is used. Fig. 1 shows the layout of the 2D échellogram on the STA1600 CCD detector. As illustrated here the spectrum covers a large wavelength range from around 390 nm to 920 nm, and owing to the very large CCD image area of $10.3\,\mathrm{k} \times 10.3\,\mathrm{k}$ $9\,\mu\mathrm{m}$ pixels (95×95 mm) the design makes it possible to image five spectral channels simultaneously. Thus, important for the spectral extraction, the cross disperser provides a sufficient order separation to accommodate the five interlaced spectra, ranging from 240 pixels at 390 nm to 82 pixels at 900 nm. With an optical ZEMAX model in place, PyEchelle easily produce science and calibrated spectra with units of flux we can interpret as incoming photo-electrons detected per pixel. Also thanks to PyEchelle's usage options it is directly possible to generate an observation of four different target stars simultaneous with each science fiber, which is sensible as long as they are of similar magnitude.

For now PyEchelle only has the option to include a CCD bias level as well as the CCD read noise, hence, we utilise the open-source software, Pyxel, to include more advanced well-known image detector effects in our simulations. Also being a state-of-the-art software, with Pyxel we can easily load the simulated 2D PyEchelle spectra into the detector framework. We do this by loading charge to the detector and add each detector effect we wish to include in a modular fashion. An overview of some important parameters of the STA1600 detector together with all the CCD effects included in our simulation are shown in Tab. 1. For the inclusion of cosmic ray hits we use the in-built CosmiX cosmic ray event simulator [18] initially developed for space-based missions such a Gaia and PLATO. In lack of a proper model description of the hit rate and morphology of cosmic rays for ground-based conditions, typical for a site like Roque de los Muchachos, La Palma, as a worst case scenario we use CosmiX feed by a model reconstructed of incident solar and galactic cosmic rays from Gaia observations (which generally have much larger energy deposits and trail lengths). To model the shot noise we use a simple Poisson distribution.

From the perspective of the MARVELsim user, we distinguish between a *science mode* and *calibration mode*. Intuitively the science mode can be used to simulating a RV time series for which a cross-dispersion displacement in the simulated spectra is generated by the presence of e.g. an exoplanet orbiting its stellar host. The calibration mode is a mimic of a standard sequence of calibrated spectral images typically conducted during the afternoon prior to the nightly observations. A standard "afternoon calibration" sequence consist of full-frame bias, dark, spectral flat, and wavelength reference images. The spectral flats are constructed from a constant intensity source with spectral response similar to that of a standard Halogen lamp. For the wavelength reference spectrum the current strategy is based on the transmission spectrum from a Fabry-Perot Etalon (FPE), and the emission line spectrum from a Thorium-Argon (ThAr) hollow cathode lamp used for cross-referencing the FPE spectrum.

In order to provide simulations on demand for the pipeline development, MARVELsim has been designed to run on a High Performance Computing (HPC) facility. Seen from a computational point of view PyEchelle is the

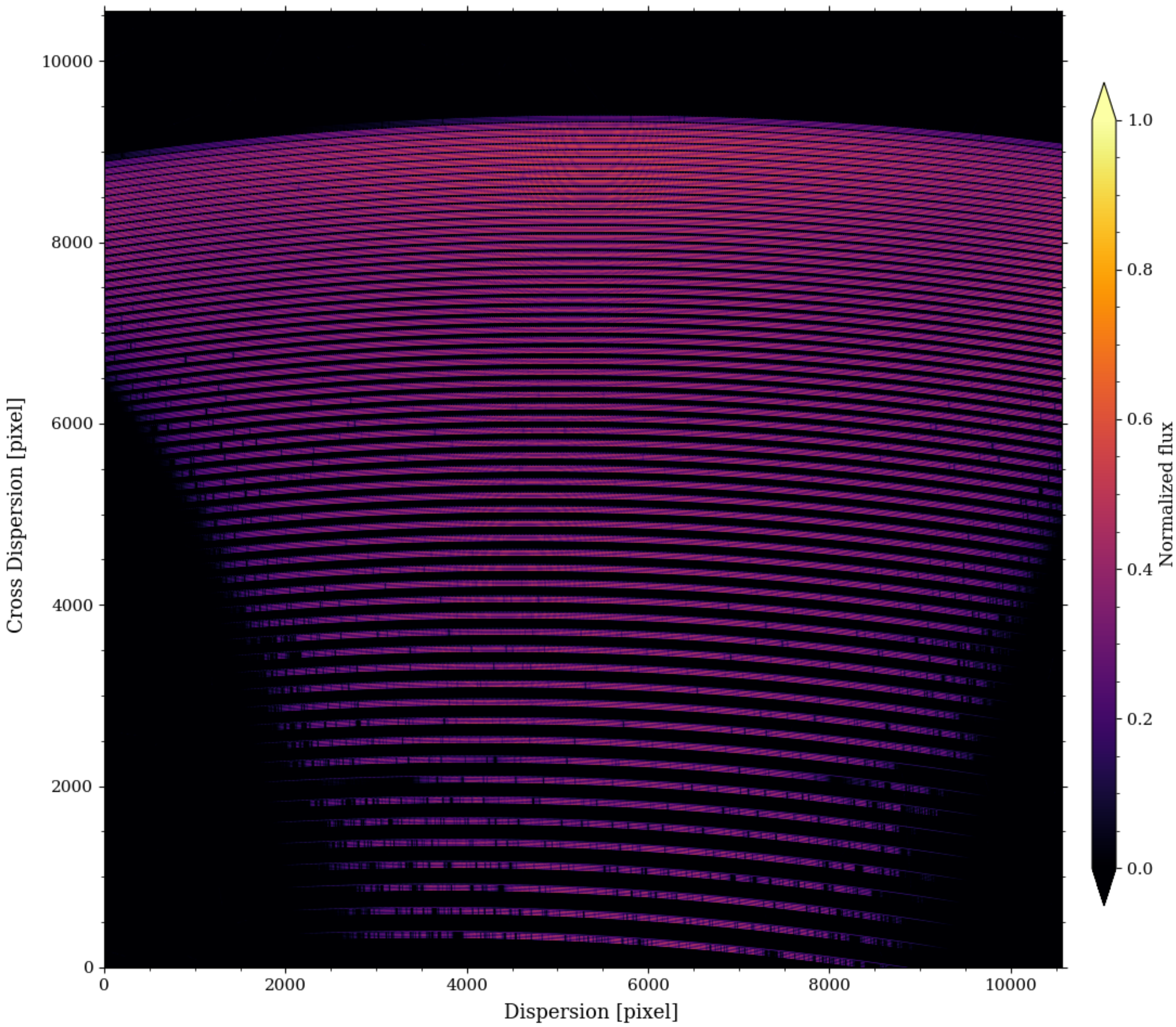

Figure 1: Overview of a 2D science spectrum on the CCD detector simulated with MARVELsim. This exposure shows an useable wavelength coverage between 940 nm (near-infrared top) to 380 nm (near-UV bottom). Following MARVEL's future simultaneous observing mode, here the spectrum of Sun-like spectral analogue has been recorded (fiber 1-4) together with a Fabry-Perot etalon wavelength reference spectrum (fiber 5).

natural bottleneck due its novel light tracing methodology. Luckily the design of PyEchelle allows to compute each 2D spectrum in parallel either using normal CPU slaves or using CUDA NVIDIA hardware typically available for GPU nodes on most computing clusters. Especially employing simulations on CUDA GPU cores has a dramatic decrease of the computational time (e.g. usually from hours to minutes for a single full frame spectrum). Furthermore, MARVELsim can split up the computation from PyEchelle and Pyxel completely independently, such that first each spectrum is generated using GPUs and afterwards the Pyxel detector effects are added by normal parallel CPU computations. This further beats down the computation time since Pyxel do not support the usage of GPUs.

As part of the MARVELsim software toolkit a small generic script is available to generate the RV time series as input for science mode simulations. This small utility explores the python library RadVel[5] [19] for calculating

[5] https://radvel.readthedocs.io/en/latest/index.html

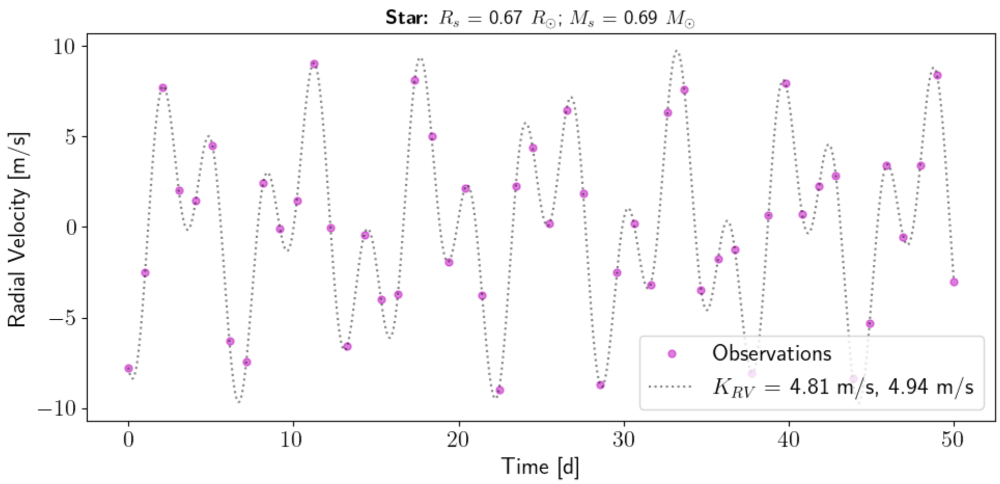

Figure 2: Illustration of a simulated noise-less RV time series for the K6V spectral type star TOI-1260 hosting two (transiting) mini-Neptunes on circular orbits. The dotted line shows the combined RV response model and the purple dots show equidistant observations with a one day separation.

the true anomaly for a given set of input time point over the observed duration. The modelling of the RV time series are then calculated using the expression for the observed RV signal (Eq. 65) given by [20]. Seen in Figure 2, we here show an example of a generated RV time series of the stellar host TOI-1260 with two mini-Neptunes planets orbiting on (assumed) circular orbits.

3. SPECTROSCOPIC PIPELINE

To achieve high-precision RVs of exoplanet host stars, and to explore the wealth of information stored in their spectra, an efficient and robust reduction pipeline is needed to compliment and utilize the MARVEL's state-of-the-art hardware. Generally the reduction steps of a fiber-fed échelle spectroscopy pipeline consist of several modules: (1) image reduction (2) extraction to 1D, (3) deblazing, (4) wavelength calibration, (5) order merging, (6) continuum flux normalisation, and (7) a RV determination if desired. With a conceptual design similar to that of the MAROON-X spectrometer [11], the modular design of MARVEL's spectroscopy pipeline builds naturally from the MAROON-X pipeline.[6] Though sharing a lot of modules of the general reduction workflow mentioned above, the conceptual design of the MARVEL pipeline does deviate slightly. We show a schematic overview of the pipeline workflow in the lower panel of Fig. 3 and will go into more details in the following.

As a first step of the image reduction full-frame median combined master frames are constructed from the biases, darks, spectral flats, and ThAr arcs. Next the master images are used to perform a bias subtraction and dark current subtraction. For all the calibrated images we assume that the removal of cosmic rays is automatically done from pixel median combination. For the object extraction cosmic rays are removed as part of the flat-relative optimal extraction technique as will be discussed later. From left to right, the top panel of Fig. 3 shows a 2D master image-snippet of a spectral flat, science plus FPE, FPE plus ThAr, and ThAr arc spectrum, respectively.

Considering the noise properties of the two readout modes and the overall dark current estimates provided by the contractor, we expect that the dark images (i.e. unilluminated images of non-zero exposure times) show a very low dark current even for long exposures of tens of minutes. However, a lesson learned from the MAROON-X pipeline, also using a simultaneous FPE calibrator for object observations, is that dark images can efficiently be used to correct for the leakage of diffuse background light of the extended wings of the FPE intensity spots into the neighbouring science fiber. To minimize this effect a neutral density filter wheel will be used to fix the FPE intensity level independently (but configurable) as function of the exposure time.

[6] https://sites.google.com/uchicago.edu/maroonx-data-handbook/home

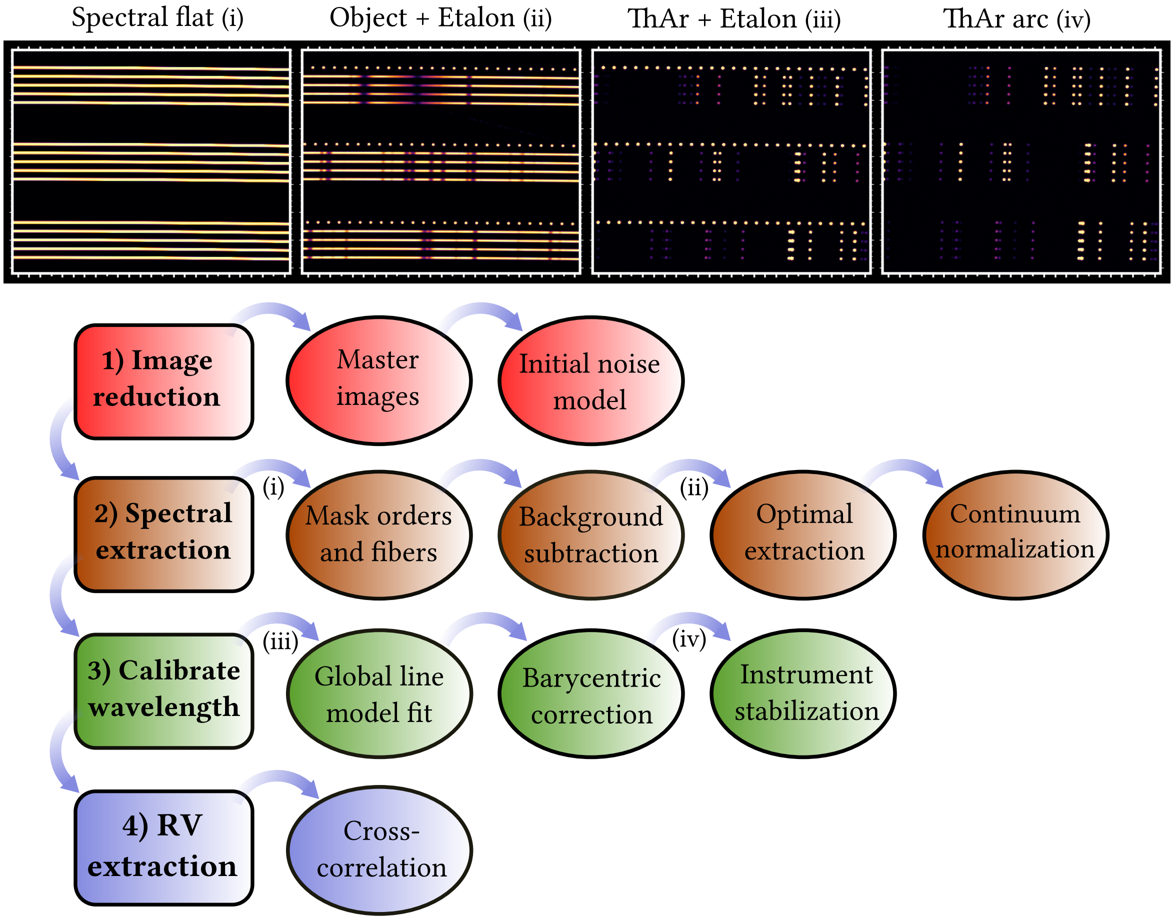

Figure 3: Illustration of the raw image product from MARVELsim (top panels) and a schematic overview of the MARVEL reduction pipeline (bottom color boxes). The synthetic spectra shown from left to right is a spectral flat, a ThAr arc, a ThAr arc (fiber 1-4) plus a FPE spectrum (fiber 5), and a stellar spectrum of a Sun-like star (fiber 1-4) plus a simultaneous FPE spectrum (fiber 5), respectively. The MARVEL pipeline is generally divided into four main reduction steps: 1) image reduction, 2) spectral extraction, 3) wavelength calibration, and 4) RV extraction, each with their individual subroutines. The lower capital Roman numbers indicates the approximate each calibrated data product entrance point of particular high importance (since most data products are dependent upon one another.

Next we construct a binary pixel-mask selecting all pixels encompassing all the flux for each spectral orders and fibers (hereafter order-fiber). We employ a module similar to that of the MAROON-X pipeline to construct the order-fiber mask. This module use the spectral master flat to find the maximum count in cross-dispersion of each order-fiber and use a SNR weighted optimization technique to trace the intensity distribution (and discard data below a certain SNR threshold). Each central order-fiber position is then turned into a global order-fiber mask using a cross-order width customized for the MARVEL instrument. Next the inverse mask (i.e. the inter-order-fiber mask) is used to model the stray light background of the spectrograph. We model the 2D background using the library Astropy[7] [21] tweaked to our needs. Next the order-fiber mask is used as input for the optimal extraction.

To transform the 2D spectrum into a 1D spectrum we use a flat-relative optimal extraction technique outlined by [22], which particularly is suitable for pressure and temperature stabilized fiber-fed spectrographs (like in our case). As suggested by the name, a high SNR master-flat image is used as a reference image while the order-fiber mask is used to determine the exact mask profile for the extraction and from it a 1D order-fiber spectral-flat

[7] `https://photutils.readthedocs.io/en/stable/index.html` (see utility: `photutils.background`)

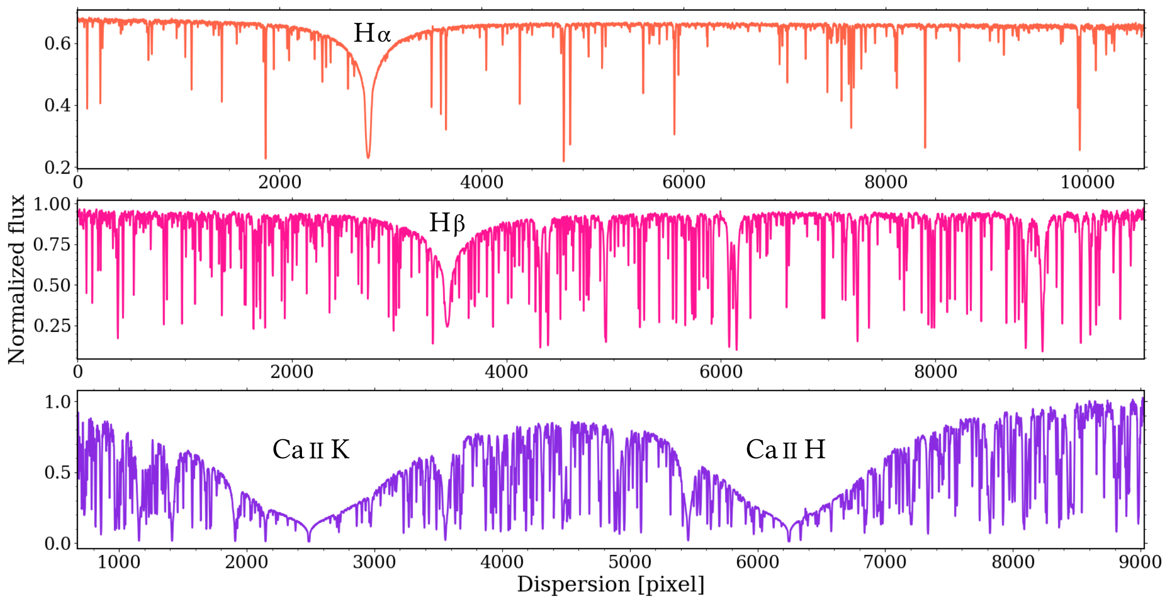

Figure 4: This figure shows three optimally extracted spectral orders (#45, #26, and #9 from top to bottom, respectively) for science fiber 3 of a Sun-like star. Indicated in the plot, the tree orders illustrate the well-known H_α, H_β, and Ca II H & K absorption lines. The extracted spectrum (as shown) will be parsed to the wavelength calibration and continuum normalization before the final RV extraction is applied.

reference spectrum. The idea is then to use this 1D spectrum as a weight (or scaling factor) relative to the cross-section of un-normalized master flat and obtain the optimal extracted science spectra by minimizing the residuals of the linear least-squares fit model. A clear advantage of this simple extraction methodology is that it automatically corrects first of all for the spatial profile of the instrument and the blaze (hence making deblazing redundant). Secondly, systematic instrumental effects inherent to the extraction mask (like CCD pixel-to-pixel sensitivity variations, grating ghosts due to an imperfect grating, etc.) are automatically accounted for. Thirdly, like any other optimal extraction technique [23], we identify cosmic ray hits in the science spectra as outliers w.r.t. the inherent noise model. As an example Fig. 4 shows three optimally extracted spectral orders that contain the well-known H_α, H_β, and Ca II H & K absorption lines in a Sun-like spectrum, respectively.

While the wavelength calibration, flux normalization, and RV extraction are modules under development, we will here highlight the current plan for their implementation. Whether or not a synthetic stellar spectrum should be used for the flux normalization is still under investigation. Typically the exact implementation depends heavily on the ability to locate the real physical continuum, which depends on many factors like the spectral-photometric quality, the contamination level of molecular bands and/or metal lines (typically TiO bands and Fe lines for solar-like stars), and the presence of residual blaze variations in the extracted spectra. Since a flat-relative optimal extraction formalism is used the resultant stellar flux continuum is simply defined by the division between the stellar continuum and the flat arc continuum [22]. While both of these are slowly varying functions, a linear model fit has been shown to describe each spectral order with as sufficiently precision (see e.g. the EXPRES pipeline [24]). For pixels contained in absorption lines, outliers will be removed iteratively with standard σ-clipping rejection technique. We might emphasize that for the spectral orders that include the Ca II H & K lines (see lower panel of Fig. 4) another alternative empirical continuum fit method has been found to be optimal for solar-like stars [25].

As mentioned earlier, in addition to the ThAr calibration lamp, which provides absolute wavelength references but with emission lines distributed unevenly in both wavelength spacing and relative brightness, MARVEL will also implement a Fabry-Perot Etalon (FPE) as a simultaneous wavelength calibrator, providing many regularly-spaced reference lines at roughly equal brightness across the entire spectral bandpass. The FPE plays a key role in order for MARVEL to reach its goal and push down the RV uncertainties for the detection of $\mathrm{m\,s^{-1}}$

level exoplanet detections. Since laser-frequency combs are expensive and complicated systems, the plan for MARVEL is to use a broadband FPE illuminated with white light. This choice also reside from recent advents in making these systems extremely stable and affordable. For more information on the method to be employed for the etalon calibrator of MARVEL see [26, 27]. Since the ThAr lamp will be used as cross-reference for the FPE calibrator, the pipeline likewise needs to handle arcs of hollow cathode lamps.

Since the flat-relative optimal extraction gives a noise model, we can in principle use the posterior distribution of uncertainties as weights when searching for FPE transmission and ThAr emission lines. Such a methodology differs from a standard cross-correlation line identification method, since here the exclusion of uncertainties systematically shifts the model fits. This method has been shown to be very effective for the EXPRES pipeline [24]. While using a list of spectral lines from the line atlas NIST[8], we thus identify the ThAr peaks and fit a 2D polynomial model and determine the degree of the polynomials iteratively by a standard Akaike Information Criterion (AIC) model comparison. We note that daily instrumental wavelength calibration images, which simply is the FPE spectrum calibrated against ThAr spectra, will most likely be a part of the calibration procedure to monitor the long term stability of the FPE and generally the instrumental model (see the spectrum in the third panel in the top plot of Fig. 3).

The reflex motion of star-planet system around their mutual center-of-mass give rise to Doppler wavelength shift of the emitted light w.r.t. an "stationary" rest frame. The measured RV amplitude is, however, not only steaming from this Doppler shift of the stellar host, but other effect also contributes like the Earth's rotation and orbital motion, the solar systems motion relative to the observed star, and the motion of the object itself. Accounting for all of these effects, defined here as a Barycentric Correction (BC), we seek to explore the tool BARYCORR [28] which typically performs with a BC error of $1\,\mathrm{cm\,s^{-1}}$ compared to non-relativistic approaches. However, as shown by [29], we note that a photon-weighted midpoint time used to estimate an overall chromatically dependent BC, introduce systematic RV uncertainties of up to $10\,\mathrm{cm\,s^{-1}}$ for challenging observational conditions (long exposure times, high airmass, and/or high seeing). Hence, since MARVEL will have an exposure meter, in operation we can on the other hand determine a photon-weighted average BC. Compared to the photon-weighted time-midpoint BC, the photon-weighted average BC determine a photon average flux from equidistant exposure meter time points of multiple wavelength bins across the stellar spectrum. A smoothly varying (low-order polynomial) function can then be fitted to these averages and a wavelength dependent BC can then be applied to the wavelength solution in priori to the RV extraction.

In spectroscopy usually the RV shift is determined by cross-correlating a line-mask, a high resolution spectrum of a standard star, or with a solar spectrum (typically done in solar activity studies). These different method are all planned to quantitatively be tested in order to select the optimal solution for MARVEL. Lastly, regarding the pipeline structure, all reduction steps are saved and added to a database quick-lookup table. This system likewise saves the trouble of running previous computed data products again, as it automatically bookkeep all modules that have been rendered and which files that have been produced.

4. FUTURE PROSPECTS

Below we list future prospects for the MARVEL simulations and pipeline:

- **Scattered light:** Since a background model for light scattering has not been implemented in MARVELsim yet, the module to model and subtract the diffuse background in the science spectra is currently obsolete. Since the light scattering depends on the instrument setup, any model applied before the commissioning phase will only imitate the truth. Thus, instead of only using one model specific for MARVEL, to make the background module more robust one strategy could be to add real background models of similar high-resolution spectrographs (like MAROON-X, EXPRES, HARPS, ESPRESSO, etc.) to the simulations and perform a simple rebinned projection onto the MARVEL CCD focal plane.
- **Cosmic rays:** The modelling and removal of cosmic ray events is important for the calibrated data products (bias, darks, flats, and arcs) in priori to the optimal extraction of the science spectra, but also the science spectra themselves. Naturally the median combined master calibrated images do effectively remove

[8] https://www.nist.gov/

cosmics, and a sanity check against a smoothed image version could be used to detect outliers and mask them. Since a median image cannot be created for science spectra, the removal of cosmic ray hits needs to be handled differently. As mentioned the flat-reference optimal extraction provides the noise model to effectively remove outliers (like cosmics) in the order-fiber mask as part of the extraction procedure. Cosmic ray hits in the inter-order-fiber mask pixels, however, can potentially skew the smooth fit procedure when estimating the background of scattered light. Hence, an an iterative rejected procedure of cosmic rays (e.g. using a 5σ outlier rejection) is planned to be implemented.

- **Telluric lines:** In priori to the wavelength calibration, telluric lines needs to be identified in order to not be confused with lines of the calibrator. A promising method to identify telluric lines is to use the software SELENITE [30] or YARARA [31], which have been designed for high-resolution spectroscopy.
- **Residual systematics:** Exquisite RV post-processing tools exist today which could greatly benefit the MARVEL pipeline. As an example, the post-processing pipeline YARARA, which uses a principle component analysis approach, has shown significant improvements for the removal of (observational and instrumental) residual systematics in high S/N HARPS spectra [31]. Taking advantage of the wealth of information in spectra time-series, opposed to individual spectra, seems like the future road to further push down the RV precision.
- **Non-ideal spectrograph models:** We have assumed that, in the image, the main dispersion is oriented in a more or less horizontal direction and the cross-dispersion in a vertical direction. With PyEchelle we can directly introduce a spectrograph disturber model to add perturbations which will prepare the pipeline for future challenges.
- **Ultra-high resolving power:** We note that all simulation in this contribution has been generated using a spectral resolving power of $\mathcal{R} = \lambda/\Delta\lambda = 90,000$, however, a future plan of testing precision of a ultra-high resolution mode of $\mathcal{R} \sim 150,000$ is planned in order to push down RV precision below the project goal of $1\,\mathrm{m\,s^{-1}}$.

5. CONCLUSION

In this poster proceeding we have presented the current status and future prospects on developing a highly accurate and robust RV pipeline for the MARVEL instrument. A fast and generic software MARVELsim, most efficiently being launched with parallel computing, has been developed to provide input 2D spectra on demand for the pipeline development. The MARVEL pipeline shows promising results to reach the mission goal of $1\,\mathrm{m\,s^{-1}}$ RV measurements requirement. With the MARVEL commission in 2023, a future plan has been presented in order for the MARVEL pipeline to perform in accordance with the novel hardware. Proving multi-epoch high-precision RV measurements from the single-handed MARVEL facility is thus a unique opportunity to fill a niche of being a fundamental PLATO follow-up instrument, which avoids potential instrumental biases from multiple facility observations.

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