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Eniric: Extended NIR Information Content

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Software

- Review
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With recent high-precision spectrographs targeting radial velocity (RV) precision at the 10 cms^{-1} level (e.g. F. Pepe et al., 2014), in the quest to find smallest planets it is important to understand the theoretical precision attainable in stellar spectra. *Eniric* provides a simple way to calculate the theoretical spectral quality and RV precision (i.e., information content) of synthetic and/or observed stellar spectra given vectors of wavelength and photon flux.

Written in *Python 3*, *Eniric* calculates the fundamental photon noise RV precision as formulated in Connes (1985) and F. Bouchy, Pepe, & Queloz (2001). It is an improved version of the software used in Figueira et al. (2016) for calculating the RV precision of synthetic M-dwarf spectra in the near-infrared (NIR) bands. The code was refactored, and hard-coded constraints were removed, making it faster and simpler to explore a larger combination of parameters (e.g. not limited to M-dwarfs and NIR wavelengths).

Eniric contains several independent functions to transform observed and synthetic spectra, such as wavelength selection, broadening, SNR normalization and to compute RV precisions.

Eniric performs rotational and instrumental broadening of spectra through convolution with a rotational kernel (Gray, 2005) and gaussian kernel respectively. Both kernels are wavelength dependant and do **not** require a uniformly spaced wavelength vector, unlike the convolution functions given in PyAstronomy. *Eniric* utilizes the *embarrassingly parallel* nature of the convolutions (each pixel can be calculated independently of its neighbours) to compute the convolutions in parallel; the convolution results are also cached using Joblib to avoid re-computation. This improves the convolution performance but not to the level achievable by algorithms that require an equal wavelength spacing and use fixed kernels (only valid for small wavelength regions), e.g. the "fast" convolutions provided in PyAstronomy.

Eniric enables the relative precision between synthetic spectra by allowing for normalization to a user defined signal-to-noise ratio (SNR) per pixel at a specific wavelength. Although user definable the default choice is a SNR of 100 at the center of the J-band (1.25 μm) as used in Figueira et al. (2016).

The precision calculations are not limited to the large spectroscopic bands, but can also be performed on narrow wavelength slices, along the entire spectrum. This allows one to explore the RV precision across the entire spectrum and perform comparision between observations and synthetic libraries (e.g. É. Artigau et al., 2018).

Extraneous information not included in the spectra (i.e., not photon noise, or line content information) can be included in the precision calculation through the use of a spectral mask. This mask be use to can indicate which spectral lines are to be included/excluded or if some sections should receive more statistical weight for an external reason. For example, masks derived from an atmospheric absorption spectrum can be used to explore

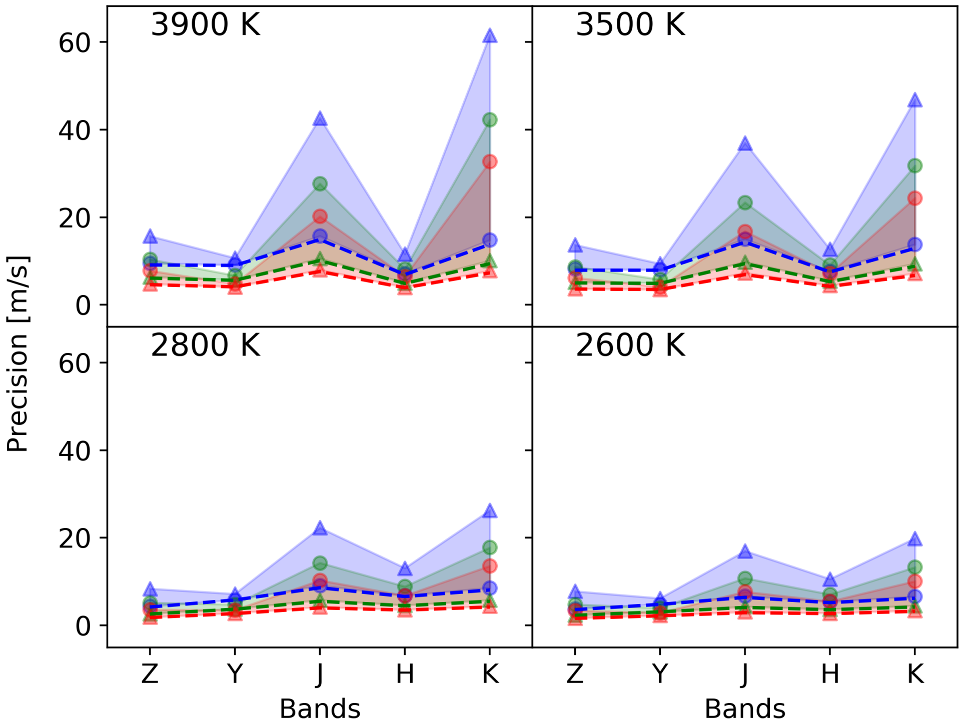

Figure 1: Precision achieved with *Eniric* as a function of spectral band for stars with a rotational velocity of vsini=1.0 kms^{-1} and temperatures 3900 K, 3500 K, 2800 K, 2600 K, corresponding to spectral types M0, M3, M6, and M9 respectively. The dashed line represents the theoretical limits imposed by the full spectrum, and the filled area represents the values within the limits set by the complete removal of atmospheric absorption regions (circles) and the perfect correction of atmospheric absorption (triangles); blue, green, and red represent the results obtained for resolutions of 60000, 80000, and 100000, respectively. The spectra were normalized to have a SNR of 100 per resolution element as measured at the center of the J-band. This is similar to Figure 1 from (Figueira et al., 2016) but with updated precision values.

the treatment and correction the atmospheric absorption on the RV precision (Figueira et al., 2016).

The script `phoenix_precision.py` is provided to compute relative RV precisions of any synthetic spectra in the *PHOENIX-ACES* (Husser et al., 2013) and *BT-Settl* (CIFIST2011-2015) (Baraffe, Homeier, Allard, & Chabrier, 2015) synthetic libraries, given the identifying spectral parameters using *Starfish*'s Grid Tools (Czekala, Andrews, Mandel, Hogg, & Green, 2015). The RV precision is computed under the three separate conditions of Figueira et al. (2016) and tabulated for all combinations of the spectral parameters, SNR, instrument resolutions, rotational velocities, pixel sampling, and wavelength choices provided to the script. An example of relative precision results is shown in Figure 1.

Eniric has been recently used to calculate relative RV precision of M-dwarf spectra for use in the Exposure Time Calculators of *NIRPS* (F. Bouchy et al., 2017) and *SPIRou* (É. Artigau et al., 2014), two new high-resolution NIR spectrographs. For *SPIRou* these were specifically calculated for the instruments resolution (R=75,000) and for all stellar temperatures between 2500–4000 K. It is also currently being used to compare the theoretical precision between observed *CARMENES* spectra (A. Reiners et al., 2018) and their synthetic library counterparts.

Eniric is available on *Github* with documentation found in `README.md` and on the wiki page with usage examples provided as Jupyter notebooks.

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