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Quick and Accurate Data Reduction for Intermediate-resolution Echelle Spectrographs at Magellan

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Abstract. We present the data reduction pipelines for the intermediate-resolution (R=5000–10000) slit echelle spectographs MagE and FIRE operated at the 6.5-m Magellan Baade telescope. The pipelines are implemented in IDL and share about 80% of the code. We use both thorium-argon and hydroxil lines to achieve the wavelength calibration good to 2–3 km/s across the whole wavelength range. The final data products are sky subtracted flux calibrated two-dimensional spectra corrected for telluric absorption. In addition, the pipeline extracts one-dimensional spectra taking into account the extraction profile variations along the wavelength range. The typical execution time of about 5–7 min per object on a modern laptop allows observers to perform the night time on-the-fly data reduction.

1. Introduction

Intermediate-resolution echelle spectrographs provide a unique opportunity to study faint stars, star clusters and galaxies at spectral resolution R=5000–10000 significantly exceeding that of typical low-resolution single-order spectrographs and, at the same time, cover a wide wavelength range in a single exposure. They are typically equipped with several short (6”–12”) slits and, therefore, can collect spatially resolved spectral information for extended objects. The ultimate example is X-Shooter operated at the ESO Very Large Telescope, which provides a simultaneous coverage from 0.3 to 2.5 microns at R=10000 in three channels. Two such spectrographs, a Folded-port InfraRed Echellette (FIRE; Simcoe et al. 2013) and an optical Magellan Echellette (MagE; Marshall et al. 2008) stay among frequently used instruments at the 6.5-m Magellan telescopes and produce a substantial amount of data.

2. Why do we need new pipelines?

There are existing MagE and FIRE data reduction packages implemented in IDL, MASE (Bochanski et al. 2009) and FIREHOSE. MagE is also supported in the Carnegie Python library (CARPY).

- Existing IDL pipelines are based on legacy packages (XIDL, SPEC2D) which underwent serious evolution outside the pipeline but have not been updated

- classical examples of a “multi-layered” code, which is very hard to maintain
- MagE was moved from the Clay to Baade telescope in 2015, which caused some shifts of its optical elements, so the old calibrations became invalid but the pipelines have never been updated
- All existing pipelines work with point sources only: the spatial information is lost during the reduction
- FIREHOSE performs very crude flux calibration and telluric correction

In 2013–2017 we carried out a large program using FIRE (Las Campanas Stellar Library: 2500 spectra for 1200 bright stars). It required a qualitatively and quantitatively better wavelength/flux calibration, so we decided to develop a pipeline from scratch. Later, we transformed our FIRE data reduction pipeline into a MagE pipeline.

3. Pipeline requirements

We defined the following set of requirements for the new pipelines:

- Possibility to use only day-time calibrations (flats + arcs + skyflats)
- 2D slit output (1D extracted spectra are optional)
- Homogeneous output: (i) constant R=6500 for FIRE 0.45” slit; (ii) no R variations along echelle orders
- Wavelength calibration uncertainties: 2-3 km/s
- Flux calibration uncertainties: (i) FIRE global <3% at 0.85-2.5um, local <0.5% in 200 nm windows; (ii) MagE global <5% at 0.35-0.95um, local <1.5% within each order; (iii) MagE fringing correction <2% at 0.9μm
- Telluric absorption correction <2% in the areas where transmission is >50%

We have also set the following coding requirements:

- IDL with minimal dependencies: NASA Goddard ASTROLIB, MPFIT
- Open source (GPL), git access (bitbucket)
- All calibration files are included in the package
- Execution time <10min per object on a laptop/desktop produced in 2014-15

4. Data Reduction Steps

The pipelines include the following data reduction steps:

- Primary data reduction / pre-processing: overscan subtraction (MagE); non-linearity, up-the-ramp fitting, dark subtraction (FIRE). The code to pre-process NIR data was borrowed from the MMIRS data reduction pipeline (Chilingarian et al. 2015).

- Tracing echelle orders and scattered light modeling: fitting gaps between orders with a 2D *b*-spline then subtracting the scattered light models from science and flat field frames

- Flat fielding without taking out the global flat field shape per order: this approach allows us to automatically remove the blaze function from the data given that the scattered light is well subtracted

- Wavelength calibration: we fit all echelle orders at once using a 3-dimensional polynomial of orders 8, 6, 1 (MagE) and 9, 6, 1 (FIRE) across the orders, along the orders, and along the slit respectively. For MagE, which has very low flexures we use the thorium-argon comparison lamp for the wavelength solution determination, which we then shift globally using OH lines in the two red orders. For FIRE, where flexures reach 3.5 pixels and two longest wavelength orders ($> 1.9\mu$m) cover very few ThAr lines, we first build a preliminary solution with a ThAr spectrum, then use it to predict positions of OH lines at wavelength $> 1.4\mu$m (they are well detected even in the shortest 20 sec long exposures), then define a 2-dimensional linear transformation to match the predicted OH positions with observed OH lines, apply this transformation to a ThAr and flat field frames and fit the final wavelength solution using a combined ThAr+OH+H2O line list.

- Sky Subtraction: we use the Kelson (2003) approach that fits an over-sampled sky spectrum obtained from all positions along the slit not covered by the target with a *b*-spline model and then evaluates it everywhere along the slit. This part is optional for bright stars in NIR because nodding and subsequent optimal extraction produce very accurate results

- 2D (and optionally 1D) order extraction, linearization in wavelength and rectification. We use optimal extraction for 1D spectra taking into account variations of the spatial point-spread-function along the wavelength

- Merging 2D (and optionally 1D) orders

- Telluric correction and flux calibration: We use a telluric standard to pin down small-scale (200 nm) flux calibration. Then we use broadband photometry (if available) to correct the global shape of a spectrum. We use a hybrid approach to the telluric correction by using both atmospheric transmission models and stellar template spectra. A stellar template is multiplied by an atmospheric model and convolved with a line-spread function. Then we obtain the best-fitting water vapor value and the best-fitting LSF parameterization. In addition, we get a radial velocity / rotational velocity of a star. For the telluric model we can estimate the telluric correction function and adjust it to a target airmass of a science observation.

5. Summary

We have succeeded to fulfill the data reduction quality requirements listed above. A few examples of FIRE data reduction pipeline products are shown in Fig. 1. They

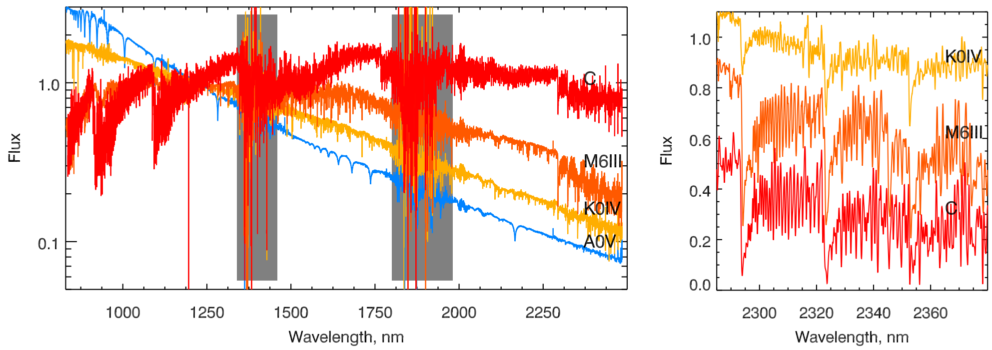

Figure 1. Data reduction quality provided by the FIRE pipeline. Left: Flux calibrated FIRE spectra of 4 stars having different effective temperatures and chemical compositions Spectra are normalized to the flux at 1225 nm. Gray areas denote regions of strong telluric absorption. Right: Zoom-in on the NIR *CO* series for a K subgiant, late M giant, and a carbon star.

demonstrate excellent quality of order merging, telluric correction, and flux calibration which is rarely available in the near-infrared domain.

As of Nov/2017, the FIRE pipeline is still under development and will be released in early 2018. The MagE pipeline is already publicly available at the following address: `https://bitbucket.org/chil_sai/mage-pipeline`.

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