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The SED Machine – Fast classification of transient objects

A. Ritter[1], C.C. Ngeow[1], N. Konidaris[2], R. Quimby[3] and S. Ben-Ami[4]

[1] *Graduate Institute of Astronomy, National Central University, 300 Zhongda Rd., Jhongli City, Taiwan, (E-mail: azuri.ritter@gmail.com)*

[2] *California Institute of Technology, CA, USA*

[3] *University of Tokyo, Japan*

[4] *The Weizmann Institute of Science, Israel*

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Abstract. The field of time-domain astronomy is expected to enjoy a golden age during this decade. However, the traditional method for the classification of transient candidates using spectra obtained with medium- to large-aperture telescopes is extremely time consuming and struggling to keep up with the discovery rate. The Spectral Energy Distribution (SED) Machine uses a new approach in order to overcome this shortcoming. It employs a lenslet-based Integral-Field Unit (IFU) with a Field-of-View (FoV) of $26'' \times 26''$ and 3,600 hexagonal $\sim 0.675''$ spaxels, as well as a 4-colour Rainbow Camera (RC) for flux calibration. The nearly constant resolution of R≈100 over an extremely wide wavelength range 360-980 nm is sufficient to effectively classify transients. Using off-the-shelf CCD cameras the costs of the instrument are moderate. The SED Machine is currently being tested on the Palomar 60-inch (P60) telescope.

1. Introduction

According to the Astro-2010 decadal report, the field of time-domain astronomy is expected to enjoy a golden age during this decade. The number of on-going and soon-to-be-commissioned optical surveys like the (intermediate) Palomar Transient Factory (PTF/iPTF; Law *et al.*, 2009; Kulkarni, 2013), PanSTARRS (Kaiser *et al.*, 2002), the Catalina Sky Survey (CSS; Larson *et al.*, 1998), SkyMapper (Keller *et al.*, 2007), and the Large Synoptic Survey Telescope (LSST; Tyson, Angel 2001) will keep the field vibrant well into next decade. With the number of newly discovered transient objects rising quickly, the traditional approach for the classification of Transient Object Candidates (TOCs) using medium- to large-aperture telescopes and high-resolution spectrographs is already struggling to keep up with the discovery rate. Therefore a new approach for the efficient classification of transients is needed. In this paper we describe the progress of the development and commissioning of the Spectral Energy Distribution (SED) Machine (Ben-Ami *et al.*, 2012) - a dedicated low-resolution spectrograph for the fast and efficient classification of TOCs discovered by (i)PTF.

2. The Palomar Transient Factory (PTF)

The Palomar Transient Factory (PTF; Law *et al.*, 2009) is a fully-automated, wide-field survey aimed at the systematic exploration of the optical transient sky. The transient survey is performed using a 8.1 square degree camera installed on the Palomar 48-inch (P48) Samuel Oschin telescope. With an exposure of 60 s the survey reaches a depth of approximately 21.3 in the g' band and 20.6 in the R band (5 sigma, median seeing). Colors and light curves for detected transients are obtained with the automated Palomar 60-inch telescope (P60). PTF discovers $\sim 7,000$ TOCs per year, but only $\sim 10\%$ are spectroscopically classified. To overcome this shortcoming, the SED Machine was built and is currently being commissioned on the P60 telescope.

3. The SED Machine

3.1. Spectroscopic TOC classification with low-resolution spectra

As shown in Fig. 1, spectra taken with a resolution of $R = \frac{\lambda}{\Delta\lambda} = 100$ provide sufficient information to effectively classify supernovae (SN). Plotted on the left side are spectra of different types of SN with a resolution of $R \approx 1\,000$, overplotted with $R \approx 100$ spectra. The predicted success rate of TOC classifications for $R \approx 100$ spectra is $\sim 90\%$.

3.2. The Instrument

The SED Machine is equipped with 2 distinct instruments – the Rainbow Camera (RC) taking simultaneous images in Sloan u, g, r, and i, and a lenslet-based Integral-Field Unit (IFU). The optical interfaces of the SED Machine from the P60 focal plane to the image plane of each subsystem is shown in Fig. 2. To maximise the throughput, no traditional beam splitter is used. Instead a small prism is utilised to redirect a small portion of the light perpendicularly into the IFU. The majority of the light continues as it came on, through a rainbow filter into the RC optics. The RC is used for target aquisition, guiding, and to correct the (flux-calibrated) spectra taken by the IFU for atmospheric extinction, seeing variations, and other time-dependant factors that affect the system transmittance. Doing so, we expect the final accuracy for the flux calibration of the spectra to be $\geq 95\%$.

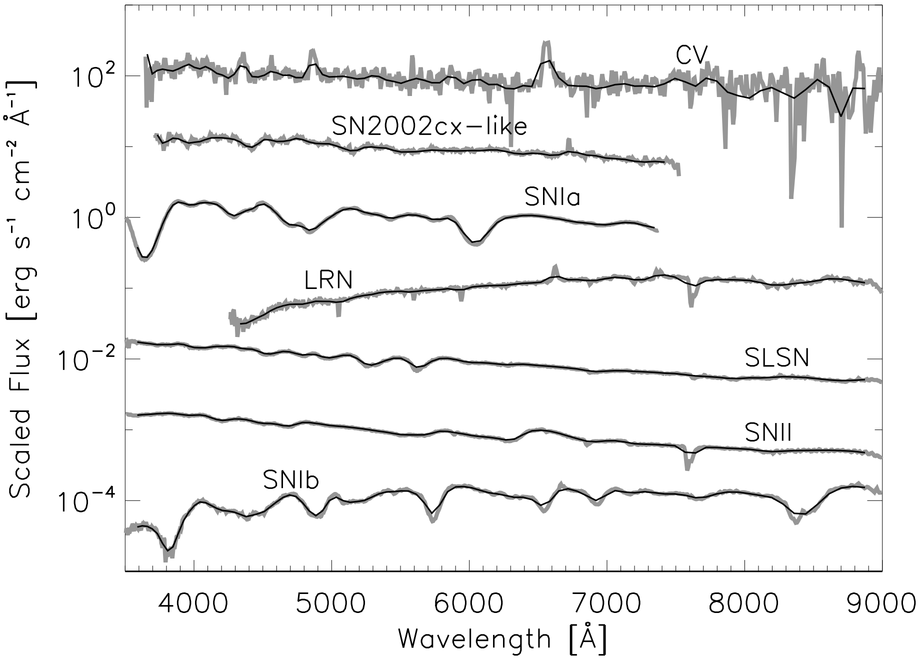

Figure 1. Comparison of $R \approx 1,000$ spectra to $R \approx 100$ spectra. $R \approx 100$ spectra contain sufficient information to classify TOCs with a high success rate.

3.2.1. The Rainbow Camera

The SED-Machine RC is a $12.5' \times 12.5'$ imager with he FoV divided into 4 different bands – Sloan u, g, r, i. After exiting the beam-splitting structure, the light passes through a series of optics held by a cylinder of delrin. The purpose of this is to have these optics be thermally equivalent to the expander doublet in the IFU so as the temperature changes during the night, both the RC and the IFU are translating along the beam axis in the same direction with the same magnitude. Upon exit from the delrin barrel there is a field flattener, followed by an E2V $2\text{k} \times 2\text{k}$ CCD detector with 13.5μ pixels, each pixel covering $0.376''$on the sky.

3.2.2. The Integral-Field Unit

The IFU has a FoV of $26'' \times 26''$ on the sky. Upon exit from the beam-splitting structure, the light passes through an expander doublet held in delrin. This expander doublet is used to thermally stabilise the resulting picture on the detector with the same picture that goes through the RC. The doublet is followed by a fold mirror to maintain the beam over the breadboard. The beam then en-

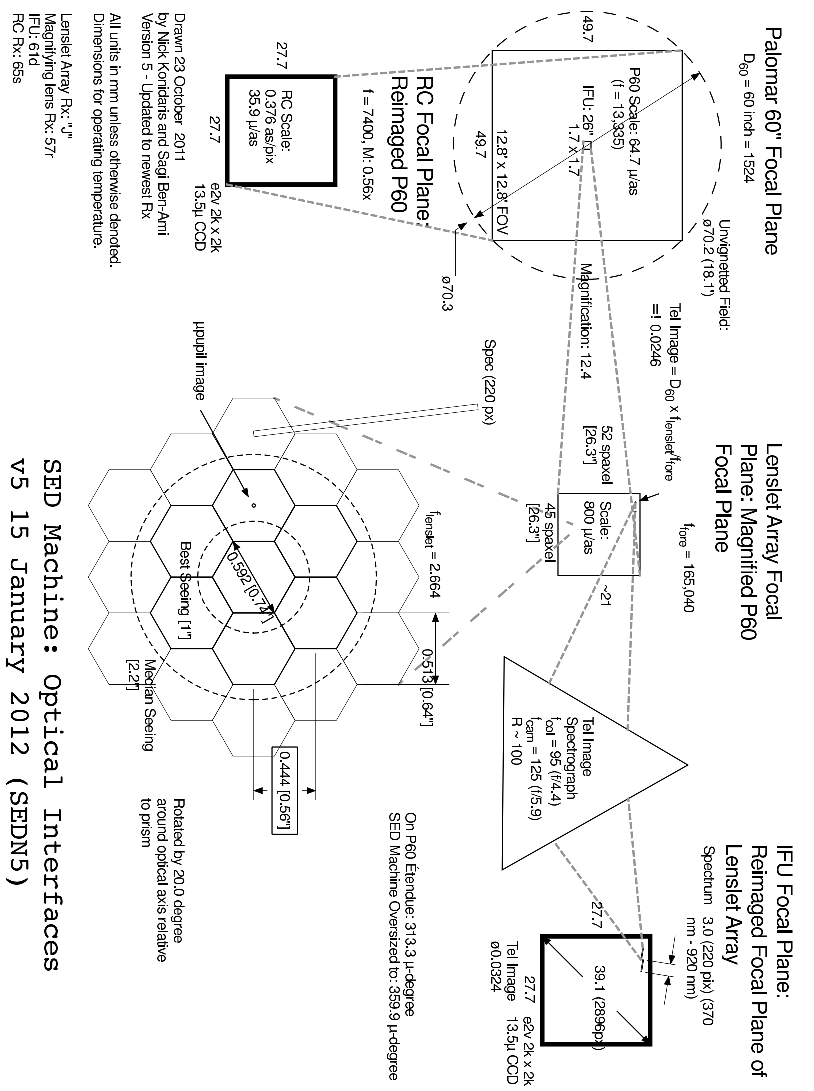

Figure 2. Sketch of the optical interfaces in the SED Machine. The focal plane is shared by the RC and the IFU. To maximise the throughput, no traditional beam splitter is used. Instead a small prism is utilised to redirect a small portion of the light perpendicularly into the IFU. The majority of the light continues as it came on, through a rainbow filter into the RC optics. The RC has a FoV of $12.8' \times 12.8'$, divided to 4 different bands. Each pixel covers $0.376''$on the sky. The IFU features an array of 52×45 hexagonal lenslets, each lenslet covering $0.74''$on the sky. The light then passes through the collimator into a triple prism (providing a nearly constant resolution of $R \approx 100$ over the whole wavelength range 360–980 nm) into the IFU camera. Both instruments are equipped with an E2V 2k $\times$ 2k camera with 13.5μ pixels.

ters a lenslet array with 52×45 hexagonal lenslets, each lenslet covering $0.74''$on the sky. The lenslet array is mounted together with 6 other optics in the collimator barrel. Upon exiting the collimator, the beam enters a triple prism that provides nearly constant resolution ($R \approx 100$) over the whole wavelength range ($\lambda \approx$ 360-980 nm). The camera barrel is simpler than its collimator counterpart, but has its own complexities in that is has to be able to translate along the optical beam by $\approx$1 mm for focusing reasons. Finally, the beam enters through a field flattener into the detector which is of the same type as the RC detector.

3.3. Data Reduction

The Data Reduction Pipeline (DRP) for the SED Machine RC was written in the Python scripting language. It includes various python modules such as numpy, scipy, pyRAF and pyFITS. The first step in the RC pipeline is to create a master flat-field image based on a list of input flats, at which these flat images are split into four sub-images and combined separately. The raw scientific images are then reduced with sub-routines in pyRAF in a standard manner, including overscan subtraction and flat-fielding. Source detections on the reduced images are performed using SExtractor (Bertin *et al.*, 1996), followed by astrometric refinement with a suite of codes from astrometry.net (Lang *et al.*, 2010). Photometry of the detected sources is extracted using the APPHOT subroutine from pyRAF. Finally, detected sources are matched to the SDSS catalog in order to derive the relative zero-points for the ugri filters in a given image.

The DRP for the SED Machine IFU is based on the STELLA pipeline (Ritter, Washuettl 2004). It consists of a number of C/C++ programs encapsulated by IRAF (Valdes, 1984) scripts. After overscan and bias subtraction, the spectra are automatically identified and traced using a scattered-light subtracted flat-field. The DRP then performs the flat-fielding and extracts all spectra using simple-sum extraction. These extracted spectra are then used to re-construct an image of the sky as seen by the lenslet array for the (so far manual) identification of the object and surrounding sky spectra. The object and sky spectra are then optimally extracted assuming Gaussian profiles plus a constant background, making use of the cmpfit[1] library. The big advantage of the cmpfit library is that one can put limits on each fitting parameter, making sure that these parameters have reasonable values. Cross-talk between the spectra is dealt with by fitting multiple Gaussians to the data values. During the optimal extraction cosmic-ray hits are automatically identified and removed. After wavelength calibration and re-binning to a common wavelength, the median of the sky spectra is subtracted from the object spectra. The object spectra are then summed up, weighted with their signal-to-noise ratio. Finally, the object

[1] http://www.physics.wisc.edu/~craigm/idl/cmpfit.html

spectra are flux calibrated. Further details of the DRPs will be given elsewhere in the near future.

3.4. Current Status of the SED Machine

The SED Machine I is finished and currently in the commissioning phase at the P60 telescope at Palomar Observatory. So far 11 nights have been observed with the instrument mounted to the telescope. The observations are being used to measure the throughput of the RC and IFU, the instrument stability, focus, and flexure, as well as to test the DRPs for the RC and the IFU.

3.5. Outlook

The SED Machine I will enter science operation in late 2013 / early 2014. The DRPs will get further improved, e.g. the optimal-extraction algorithm by Piskunov & Valenti (2002), which was re-implemented in C++ by Ritter *et al.* (2013, submitted), will be used for the calculation of the spatial profile of the IFU spectra to replace the assumption of Gaussian profiles. SED Machine II will be installed on a 2 m telescope at Lulin Observatory in Taiwan. More SED Machines are planed.

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