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An Integral Field Spectrograph for SNAP

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ABSTRACT

A well-adapted visible and infrared spectrograph has been developed for the SNAP (SuperNova/Acceleration Probe) experiment proposed for JDEM. The primary goal of this instrument is to ensure the control of Type Ia supernovae. The spectrograph is also a key element for calibration and is able to measure redshift of some thousands of galaxy spectra both in visible and IR.
An instrument based on an integral field method with the powerful concept of imager slicing has been designed and is presented. We present the current design and expected performances. We show that with the current optimization and the proposed technology, we expect the most sensitive instrument proposed on this kind of mission. We recall the readiness of the concept and of the slicer technology thanks to large prototyping efforts performed in France which validate the proposition. This work is supported in France by CNRS/INSU, CNRS/IN2P3 and by the French spatial agency (CNES).

Keywords: SNAP, Supernovae, Integral field, Spectrograph, Image slicer

1. Introduction

The SNAP satellite is designed to measure very precisely the cosmological parameters and to determine the nature of the dark energy. The mission is based on the measurement of some 2000 supernovae (SNe) of Type Ia up to a redshift of *z*=1.7. Details of the mission and the expected physics results can be founded in [(1)] Spectroscopy of each candidate supernova near maximum light is required to identify and control intrinsic variations through spectral features. The spectrograph can also measure redshift of galaxies up to redshift of 3 and is very well calibrated to transfer the standard stars to the imager. After a short summary of the science drivers, we will review the developed concept and gives an overview of the expected performances and technological readiness.

2. Science Drivers

To achieve the primary goals of selecting Type Ia supernovae and of controlling for intrinsic physical variations, a spectrum of each candidate must be acquired near maximum light. Operating in space has clear advantages for such a mission as it allows following supernovae in the infrared region. The main limitation is the flux of faint objects (up to magnitude 25). Space helps compared to ground to lower exposure time, thanks to reduction of background to the level of the zodiacal light. Anyway the efficiency of the instrument should be keep as high as possible.

Property	**IR**
Wavelength coverage (μm)	0.4-1.70
Field of view	3.0" × 3.0"
Spatial resolution element (arc sec)	0.15
Spectral resolution, $\lambda/\delta\lambda$	100
Cumulative optical throughput	55%

Table 1: Spectrograph main specifications.

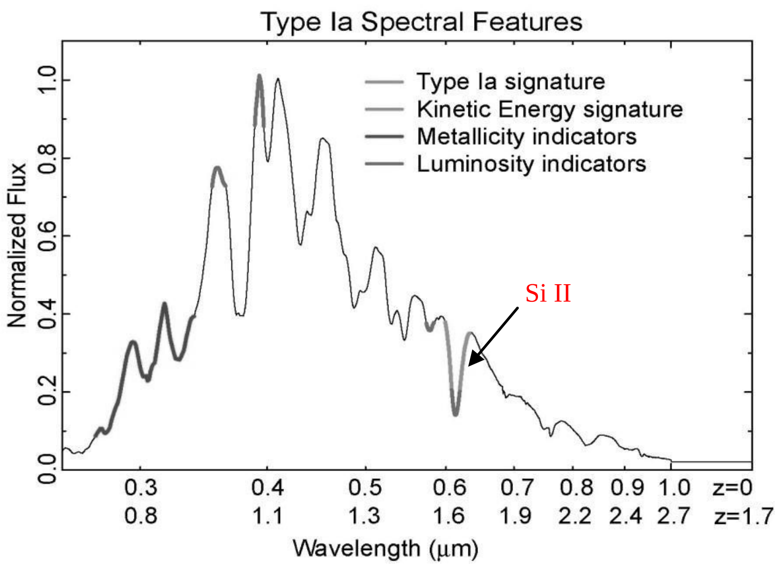

Figure 1: Typical spectrum of SN Ia.

Spectral identification and sub-classification requires spectra from restframe UV (where the iron lines vary) through the red (where the SiII (610 nm) is used to confirm it as Type Ia.) (See Fig 1). The broadness of these features and the non-negligible detector noise contribution for the faintest objects make a low-resolution spectrograph optimal. The spectrograph should also measure the host galaxy redshift at a precision of 0.005(1+z) up to z=1.7.

Specifications

The instrument should be well adapted to space environment (small, compact, light). To see faint supernovae and galaxies, a low spectral resolution ($\delta\lambda/\lambda$~100) covering the visible and the near infrared range, with very high optical and detector performances (the main limitation is the telescope diameter) and a constant resolving power in the 0.6-1.7µm range, is required to keep the S/N optimized for all redshifts The Supernovae and host galaxies should be taken together to minimize exposure time. To facilitate galaxy background subtraction the spectrograph employs an integral field unit to simultaneously obtain spectra of the SN and the galaxy and to ensure that underlying host-galaxy light does not bias SiII velocity measurements. The main specifications are summarized in Table 1

Finally, to achieve the required precision on supernovae measurements and on redshift determination, a calibration at the percent level is needed. The spectrograph is also a key component of the calibration procedure. The spectrograph will be used to transfer the calibration of fundamental standard stars to primary standards in the range m_V= 12-18 mag where the imager cannot reach the needed sensitivity. This requires a spectro-photometric calibration at 1% accuracy.

3. Instrument Concept

Given the science drivers and specifications, we have conducted a trade-off study to choose the best instrument concept. The requirement for simultaneous acquisition of SN and host spectra, and the high object acquisition precision that would be needed for a traditional long slit spectrograph, lead us to prefer a 3D spectrograph. The presented concept is then based on a classical spectrograph with a prism for constant and low resolution ($\delta\lambda/\lambda$~100) and high efficiency. To increase its efficiency in the IR, the configuration is under-sampled.

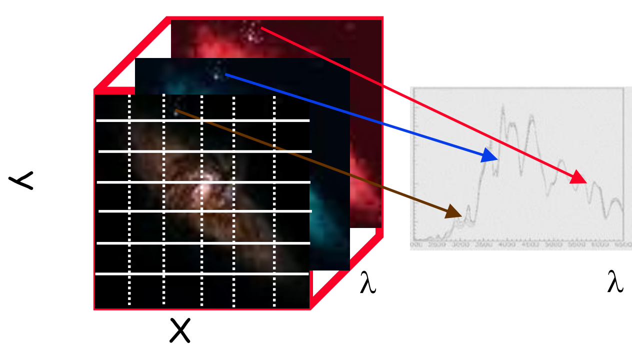

Figure 2: 3D spectroscopy illustration.

3D spectrograph and image slicers

A 3D spectrograph reconstructs the data cube including the two spatial directions X and Y plus the wavelength direction. For each spatial pixel, the spectrum is reconstructed. Thanks to the large field of view, the pointing requirements are relaxed. The image slicers minimize optical losses and improve the efficiency and the compactness of the system. Figure 3 shows the principle of this technique. The field of view is sliced along *N* (for SNAP *N*=40) strips on a "slicing mirror". Each of *N* slices re-images the telescope pupil, creating *N* telescope pupil images in the pupil plane. Thanks to a tilt adapted to each individual slice, the *N* pupil images lie along a line. These images are arranged along a line and form a "pseudo-slit."

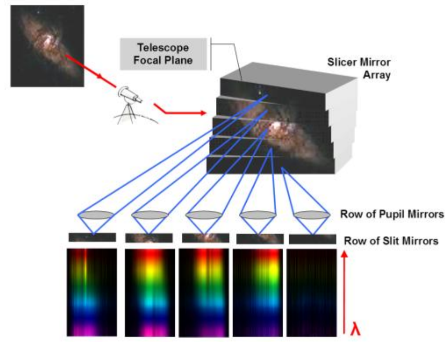

Figure 3: Image slicer principle

The final choice after our trade-off is the image slicer technique. This technique, developed since 1938 in order to minimize slit losses, is very powerful[2,3,4,5]. The new generation of image slicers improves the efficiency and the compactness of the system.

3.1. Instrument Concept System requirements

The system requirements for each sub element are summarized on Table 2. To avoid single-point failure in the spectrograph, detectors will be duplicated. The field of view is enlarged to 3"× 6" and is displayed on 40 slices along the larger dimension.
The Table 2 summarizes the technical requirements for the SNAP instrument.

3.2. Functional Description

The instrument is the assembly of four major blocks:

- The fore optics: This optics will relay the image from the telescope to the slicer unit. The plate scale adaptation will be also done in this unit
- The Integral field unit: This optical unit will slice the field in 40 sub-slits and re-arrange them along a long entrance slit to the spectrograph
- The Spectrograph: This unit will dispersed the beam in the perpendicular direction of the slit
- The Detector unit: This unit composed in two HgCdTe detectors will convert the photons in electron and after in digital datas

	requirement	**System description**
Spatial resolution (arcsec)2	0.15	2x20 Slices (0.5 x 10 mm)
Field-of-View (arc second)	3 x3	3x6 for detector redundancy
Wavelength (µm)	0.4-1.7	
Spectral Resolution range	70-100	Prism
Detector Size	2kx2k	800 x 200 useful, 2 booted detectors
Pixel size	18µm	Camera F/D=12
Detector Temp (K)	140	Passive cooling

Table 2: system specifications

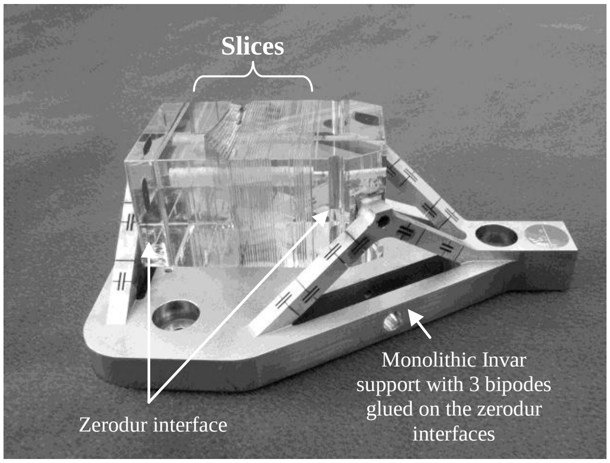

Figure 4: image of a block of slicers

3.3. Relay optics

This unit is the interface between the telescope beam and the instrument. The optical solution is highly dependent on the implementation of the instrument. The definition of this optical system requires knowledge of the spectrograph position with respect to the telescope focal plane. The beam can be picked off wherever it is most convenient for the overall instrument. It will be beneficial to correct some telescope aberrations within this optical system. A simple, easily conceived three-mirror configuration (one sphere and two flat folding mirrors) should be sufficient to satisfy these requirements.

3.4. Slicer unit

The slicer unit acts as a field reformatting system. As described above, the principle is to slice a 2D field of view into long strips and optically align all the strips to form a long spectrograph entrance slit. The slicing mirror is comprised of a stack of slicers. Each slice has an optically active spherical surface on one edge. The physical dimension of each slices are 0.5x20mm. The Figure 4 shows the accommodation selected for SNAP. At the two extremity of the 40 slices stack, two interfaces in zerodur are optically bounded. These two interfaces will be glued on the invar structure.
The invar structure is a monolithic piece. This piece is machined to accommodate three bipods. Each one are glued of the zerodur assembly using the DP490 from 3M fabrics.
This assembly is qualified to the GEVS NASA standard.
The manufacturing of the slices stack is described in Vivès & al[7]. The mechanical design, analysis and qualification tests are describe in Pamplona & al.[9].

3.5. Optical bench

Thanks to the moderate beam aperture and field of view, the spectrograph optics will be straightforward. The baseline is a classical spectrograph: The optical beam reaches a BK7 prism with its back face coated with a mirror. The BK7 prism is used in double pass to reach the required spectral dispersion with a smaller prism. Then the beam hits the camera which images the spectrum on the detector. Figure 5 shows a schematic view of the optical bench.

The IFU plus fore-optics are encapsulated in the first rectangular box (bottom of the figure). Beam (in red) is going to the collimator then the prism and is refocussed by the camera mirror after the last folding mirror on the focal plane unit (in brown). This focal plane unit is set with two adjacent 2kx2k HgCdTe detectors.

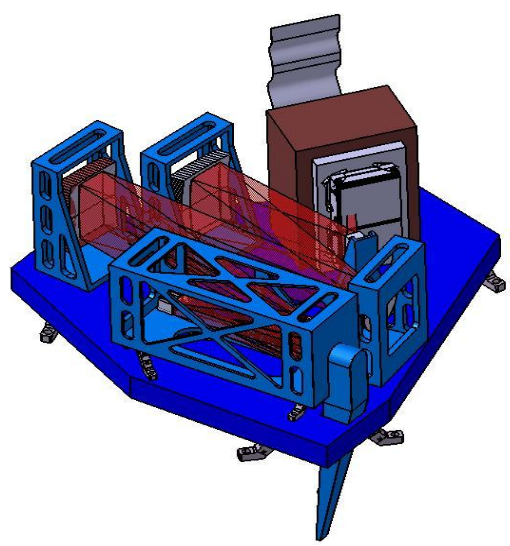

Figure 5: schematic view of the optical bench

3.6. Detectors optimisation

The choice of the detector set was optimized between three candidates: EEV CCD, LBL CCD, and HgCdTe. During long times, we privileged the couple LBL CCD, HgCdTe. This couple was the most appropriate in terms of QE when we want to emphases the red part of the visible. Nevertheless, the effort of Teledyne on the performance of the HgCdTe detectors gave impressive results in term of QE in visible (see Figure 6).

	EEV	LBL CCD	IR
Detector size	2kx2k	2k × 2k	2k × 2k
Pixel size	9 µm	9 µm	18 µm
Detector temperature (K)	140	140	130
Read noise(e) per individual exposure	4	4	5

Table 3: detector specifications

This optimization effort in QE was followed by an important improvement of the detector noise. The current performances for the total noise of this detector are better than 8e$^-$ per exposure using the appropriate multiple read-out scheme.

After exposure time simulation effort, we can see, than the visible detectors provide a shorter exposure time at low redshift (<0.5) but the exposure time law is mainly driven by the high redshift SNIa. The gain in time on low redshift SN1a (z< 0.5) is small (few ten of second compared to 10ks) compared to the complexity of a two arm instrument. Then, from a cost, risk and complexity analysis, a single technology detector spectrograph configuration is the optimal and has been chosen as the baseline.

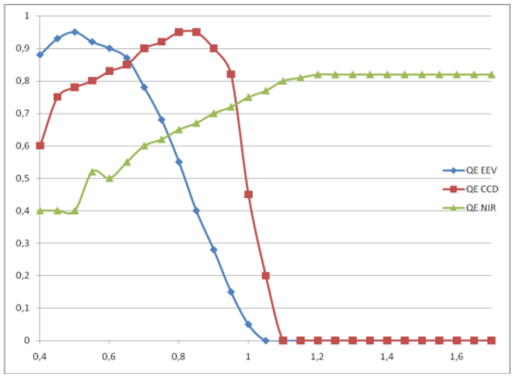

Figure 6: QE of the different detector candidates

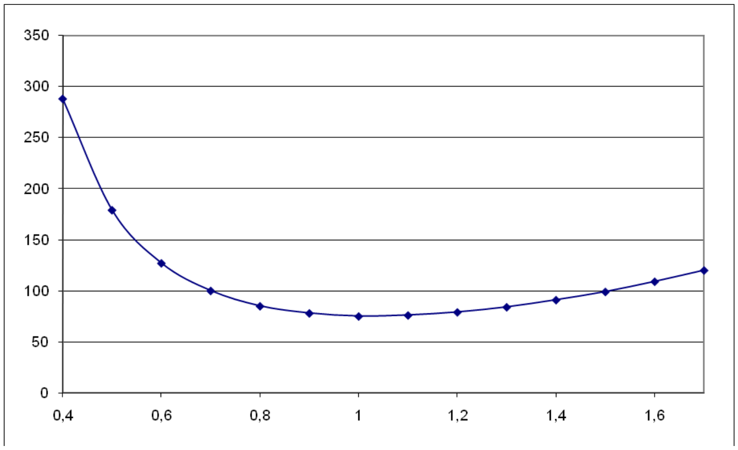

Figure 7: spectral resolution in the visible and IR

4. Performances

4.1. Spectral resolution

The spectral resolution is shown on Figure 8 and has been optimized to be maintained as flat as possible, privileging lower values in the IR region. The detailed simulation has been used to confirm this resolution.
This result is given by the prism used in double pass. The spectral resolution is well constant around 100 in the range 0.6 to 1.7µm. The bluer region will be more dispersed decreasing a bit the overall performance in this range.

4.2. Throughput

The estimated throughput of the instrument is given on Figure 9. Thanks to the good throughput of the reflective silver coated optic and to the slicer performance, the expected total throughput of the instrument is 3 to 4 time higher than the HST-STIS one. The effect of the slicer diffraction in the larger wavelength is added in our model.
The discussion on the detector optimization (see 3.6) demonstrate that even with the none optimal performance in visible (compared to the case of CCD detector), the proposed configuration is optimized to be

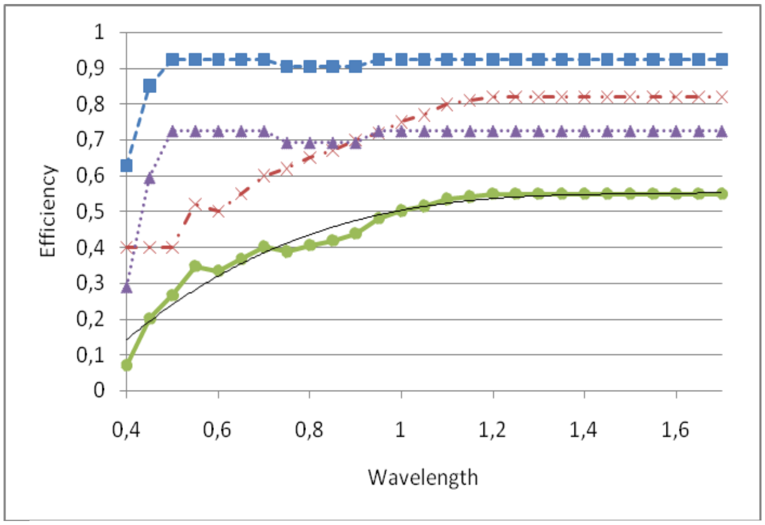

Figure 8: instrument efficiency estimation (square: telescope throughput; triangle: spectrograph throughput; crosses HgCdTe QE; round overall efficiency)

5. Readiness, R&D and qualification efforts:

A large prototyping effort has been done in Marseille both on the performances and on the slicer technology readiness. Three main efforts have allowed to test the optical performance of the concept by a complete SNAP demonstrator, to develop a full simulation that reproduce well the instrument response and to bring the slicer technology at a TRL6 level required to be fly qualified.

5.1. Performance demonstration:

An intensive effort of performance demonstration is pursued. The main development was done through the construction of an optical demonstrator. The optical demonstrator was built during the three last years and tested during 2007. Description of the instrument and first results are presented in two papers(8),(11) in this conference and first results show that the optical configuration we are proposing is fulfilling the top level requirement for the spectrograph listed in 1 and in particular than slicer optical properties are well under control.
A further validation has been done by the development of a complete simulation that reproduce well the demonstrator results , showing, than even with a low knowledge of the detector performances, the control of the instrument can be achieve and well understood.

5.2. Image slicer qualification:

Since 8 years, LAM is developing the glass slicer technology. The readiness level 6 is required to be "space qualified." In 2004, a full slicer stack of 30 zerodur slices was manufactured and maintained with spring. This prototype has been tested under JWST specifications. The slicer block passed successfully vibration tests at 24 Grms at 50 K but the vibration load has demonstrated that the mounting configuration was difficult to optimize and a weak in the opto-mechanical mount was enlighten in this study. The R&D effort necessary to optimize the opto mechanical concept for a TRL6 assessment has been conducted from 2005 to 2007 at LAM in the scope of the SNAP studies to provide a full qualification of the components for a space environment. In 2006, a new mounting development of a dummy zerodur slicer based on a glued concept has been tested and has passed successfully a vibration test of 10.5 Grms(8). In 2007, a configuration of 60 zerodur slices has been manufactured at the SNAP specifications. The current mechanical concept of the slicer support is based on three bipods maintaining by glue the stack of 60 slices in-between two interfaces in

zerodur. A notch has been made on one of the zerodur blocks to limit the stress propagation on the first slice, thus optimizing the optical bonding. This mounting has survived [9] to the specification given in documentation (NASA: General Environmental Verification Specification for STS & ELV: Payloads, subsystems and components; and SNAP environmental condition requirement). Tests on this configuration were conducted on the three axes to 14.1Grms specified and to 8 thermal cycling (100-303K). The system keeps the optical alignment within the specifications. This configuration can be considered as qualified to the specification needed for SNAP. Some more manufacturing with 4à slices are undergoing with a consolidation of procedures. In mean time, the bipod manufacturing is also under mitigation by further manufacturing tests.
Therefore, we consider that this technology is on the final road to be qualified at the level 6.

6. Conclusion

We are proposing an optimized configuration for the SNAP spectrograph. This configuration is based on a classical opto-mechanical bench with an integral field unit added. This new technology had been demonstrated to deliver the performance needed for SNAP, to be easily manufactured (see Vivès & al [7]) and qualified to the SNAP environmental requirement Pamplona & Al. [9]
The expected performances for this instrument are similar to JWST, the outstanding instrument, available at that time for the SN1a science case. The SNAP configuration (2m class telescope, large focal plane plus an integral field spectrograph) will be the best price complexity optimized instrument to answer to the dark energy science case.

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