BATMAN flies: a compact spectro-imager for space observation

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ABSTRACT

BATMAN flies is a compact spectro-imager based on MOEMS for generating reconfigurable slit masks, and feeding two arms in parallel. The FOV is 25 x 12 arcmin^2 for a 1m telescope, in infrared (0.85–1.7µm) and 500-1000 spectral resolution.
Unique science cases for Space Observation are reachable with this deep spectroscopic multi-survey instrument: deep survey of high-z galaxies down to H=25 on 5 deg^2 with continuum detection and all z>7 candidates at H=26.2 over 5 deg^2; deep survey of young stellar clusters in nearby galaxies; deep survey of the Kuiper Belt of ALL known objects down to H=22.
Pathfinder towards BATMAN in space is already running with ground-based demonstrators.

Keywords: astronomical instrumentation, MOEMS, multi-object spectroscopy, cryogenic.

1. INTRODUCTION

Multi-object spectroscopy (MOS) is a key technique for large field of view surveys. MOEMS programmable slit masks could be next-generation devices for selecting objects in future infrared astronomical instrumentation for space telescopes. MOS is used extensively to investigate astronomical objects by optimizing the Signal-to-Noise Ratio (SNR): high precision spectra are obtained and the problem of spectral confusion and background level occurring in slitless spectroscopy is cancelled. Fainter limiting fluxes are reached and the scientific return is maximized both in cosmology and in legacy science. Major telescopes around the world are equipped with MOS in order to simultaneously record several hundred spectra in a single observation run. Next generation MOS for space like the Near Infrared Multi-Object Spectrograph (NIRSpec) for the James Webb Space Telescope (JWST) require a programmable multi-slit mask. Conventional masks or complex fiber-optics-based mechanisms are not attractive for space. The programmable multi-slit mask requires remote control of the multi-slit configuration in real time. During the early-phase studies of the European Space Agency (ESA) EUCLID mission, a MOS instrument based on a MOEMS device has been assessed. Due to complexity and cost reasons, slitless spectroscopy was chosen for EUCLID, despite a much higher efficiency with slit spectroscopy.

A promising possible solution is the use of MOEMS devices such as micromirror arrays (MMA) [1,2,3] or micro-shutter arrays (MSA) [4]. MMAs are designed for generating reflecting slits, while MSAs generate transmissive slits. In Europe an effort is currently under way to develop single-crystalline silicon micromirror arrays for future generation infrared multi-object spectroscopy (collaboration LAM / EPFL-CSEM) [5,6]. By placing the programmable slit mask in the focal plane of the telescope, the light from selected objects is directed toward the spectrograph, while the light from other objects and from the sky background is blocked. To get more than 2 millions independent micromirrors, the only available component is a Digital Micromirror Device (DMD) chip from Texas Instruments (TI) that features 2048 x 1080 mirrors and a 13.68µm pixel pitch. DMDs have been tested in space environment (-40°C, vacuum, radiations) by LAM and no showstopper has been revealed [7].

We are presenting in this paper a DMD-based spectrograph called BATMAN, including two arms, one spectroscopic channel and one imaging channel. This instrument is designed for getting breakthrough results in several science cases, from high-z galaxies to nearby galaxies and Trans-Neptunian Objects of Kuiper Belt.

2. INSTRUMENTATION

2.1 BATMAN concept

BATMAN is a compact spectro-imager with two arms in parallel: a spectroscopic channel and an imaging channel. Both arms are fed by using the two DMD mirrors stable positions (Fig. 1) [8].

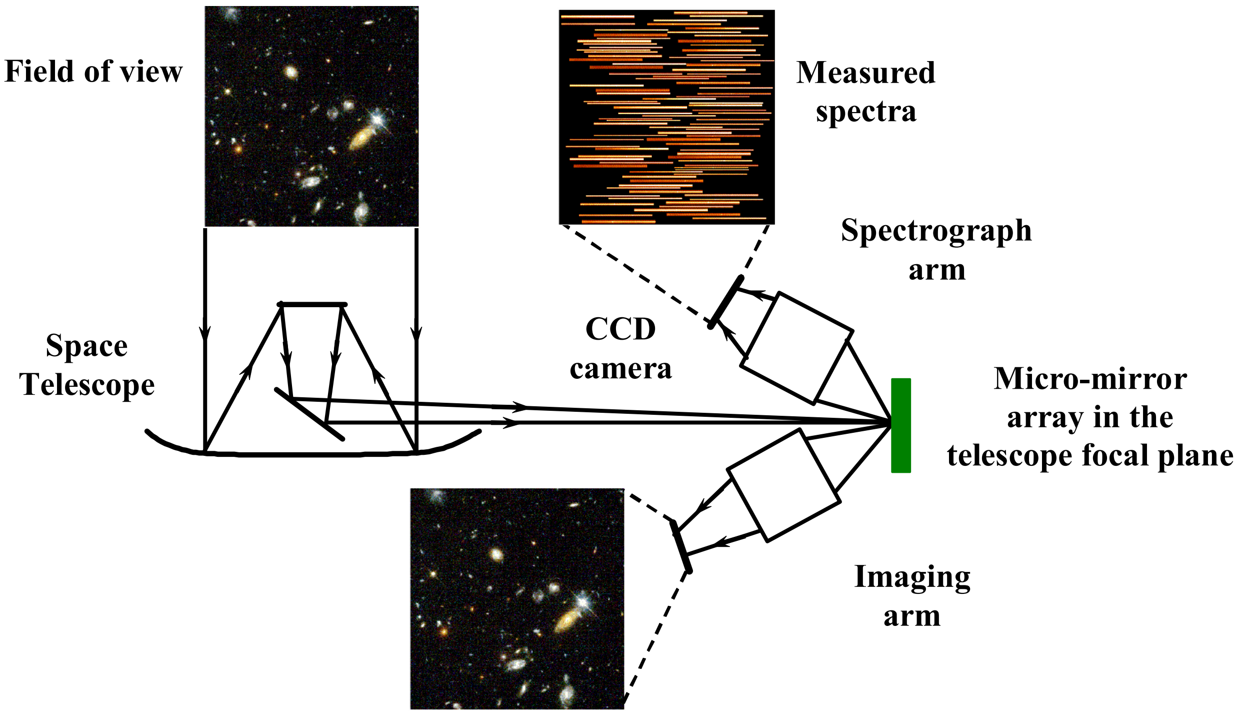

Fig. 1: Principle of BATMAN spectro-imager

Our goal is to make a robust and efficient instrument for a space mission. Selecting a good starting point was really important. Previous works have been based onto smaller DMD chip areas and larger focal ratios, covering relatively smaller field of view. Here we concentrated to meet larger areas, still with simple optical layouts. In order to simplify as much as possible the optical layout of the system, we fixed some constraints:
(a) focal ratios feeding DMD should be close to F/4, thus allowing relatively easy decoupling from the incoming an outcoming beams on the DMD surface;
(b) incoming beam must hit DMD surface at normal incidence, everywhere on the DMD chip, translating into a simpler relay system not introducing tilted image planes and being telecentric;
(c) both spectroscopy and imaging modes could be available, using the two ON/OFF state mode of micromirrors;
(d) all optical components should lie in plane, for easy integration and alignment;
(e) use as much as possible only plano and spherical optics, to reduce cost and delivery time.

Even if complex, we succeeded to design such a system, developing ideas proposed many years ago for the JWST near-infrared multi-object spectrograph [2]. BATMAN baseline is resumed in Table 1.

Primary mirror diameter	1 m
Obscuration	10 %
Objects selector	DMD with 2048 – 1080 micro-mirrors
Micro mirror scale	0.75 arcsec
Field of View	25 x 12 $arcmin^2$
Wavelength range	[0.85-1.7] µm
Two arms instrument	One imaging and one spectroscopic channels
Spectral resolution	500 - 1000
Optical transmission (total)	0.6
Detectors size	Two 2k x 4k detectors
Pixel scale	0.75 arcsec
Readout noise	9 electron/pixel
Dark current	0.1 electron/pixel/second
Quantum efficiency	0.75

Table 1: Baseline of DMD-based instrument

2.2 Slit generator

Digital Micromirror Devices (DMD) from Texas Instruments could act as objects selection reconfigurable mask. The largest DMD chip developed by TI features 2048 x 1080 mirrors on a 13.68µm pitch, where each mirror can be independently switched between an ON (+12°) position and an OFF (-12°) position. This component has been extensively studied in the framework of an ESA technical assessment of using this DMD component (2048 x 1080 mirrors) for space applications (for example in EUCLID mission). Specialized driving electronics and a cold temperature test set-up have been developed. Our tests reveal that the DMD remains fully operational at -40°C and in vacuum. A 1038 hours life test in space survey conditions (-40°C and vacuum) has been successfully completed. Total Ionizing Dose (TID) radiation tests, thermal cycling (over 500 cycles between room temperature and cold temperature, on a non-operating device) and vibration and shock tests have also been done; no degradation is observed from the optical measurements. **These results do not reveal any concerns regarding the ability of the DMD to meet environmental space requirements** [7]**.**

In Europe an effort is currently under way to develop single-crystalline silicon micromirror arrays for future generation infrared multi-object spectroscopy (collaboration LAM / EPFL-CSEM). First arrays with 2048 micro-mirrors have been successfully designed, realized and tested at 160K [6]. On a longer time scale, these arrays could be used in BATMAN concept.

2.3 BATMAN optical design

The entrance beam is adapted in F-number by the fore optics and is split by the DMD into 2 arms, a spectrograph arm and an imaging arm (Fig. 2). BATMAN is based on a double Offner relay system with a 1:1 magnification between the DMD pixels and the detector pixels. DMD orientation is at 45° (rotation around z-axis) with respect to the bench, due to the fact that the micromirrors are tilting along their diagonal. A simple spectrograph layout has been set up, based on two identical spherical mirrors acting as collimator and camera, and a low density convex grating to disperse light. The two identical spherical mirrors have a diameter of 160mm and a radius of curvature of 438mm. The most critical component of the system, the convex grating, has a 224mm radius of curvature with about 200 l/mm line density, leading to a spectral resolution of 500-1000 according to the slit size (one or two micro-mirrors).

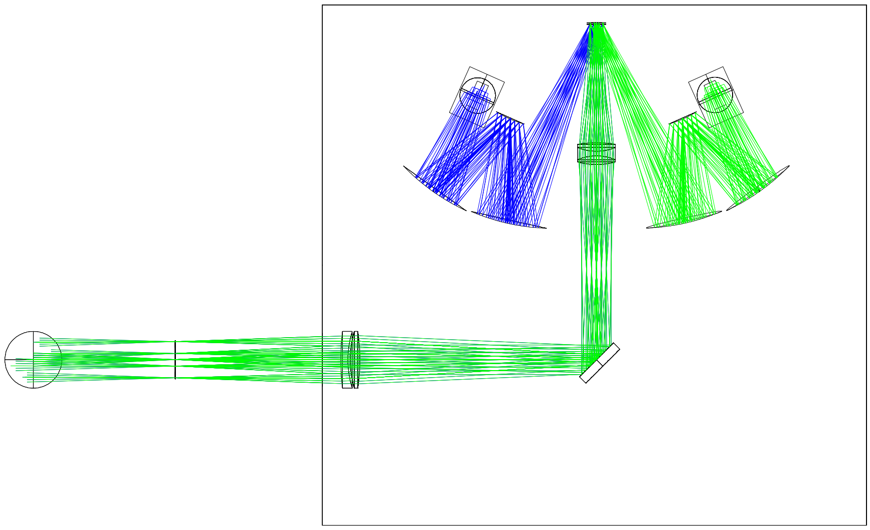

Fig. 2: Optical layout of BATMAN. Light coming from the telescope is split by the DMD into 2 arms, a spectrograph arm and an imaging arm (both are Offner relays).

This will make the system simple and efficient. Additionally it will not suffer from chromatic aberrations. Delivered image quality onto the detector is high enough to not degrade resolving power and spatial resolution, too. Typical monochromatic spot diameters are <0.8 arcsec over the whole FOV for whole wavelength range. Simulated spectra are shown in Fig. 3.

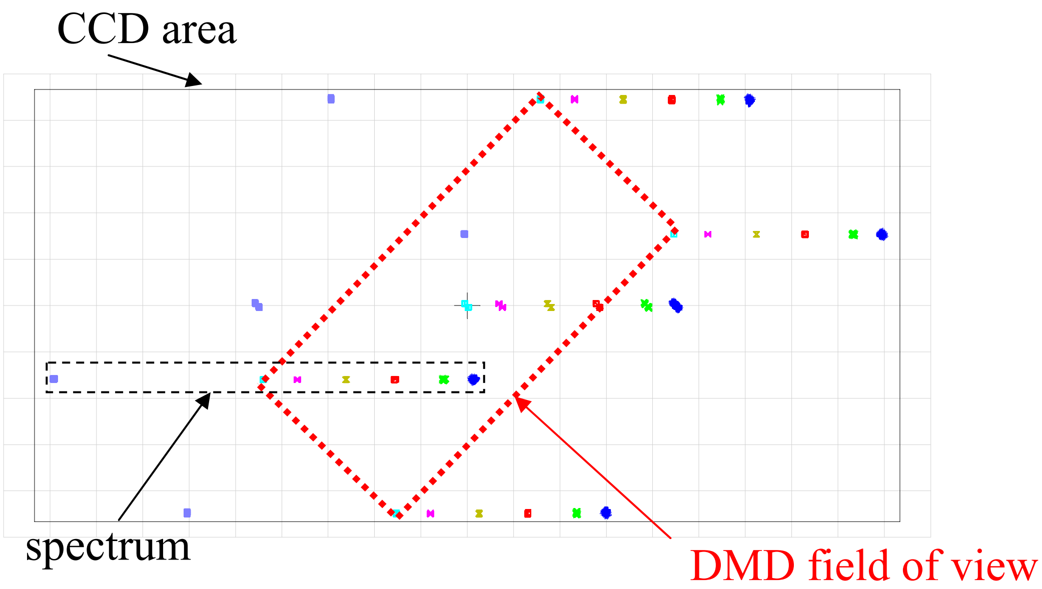

Fig. 3: Spectroscopic channel; simulated spectra on the detector.

2.4 BATMAN opto-mechanical design

The general mechanical design of BATMAN consists of a main optical bench supporting all optical elements except the detectors mounted on a second bench over the first one and attached to the main bench thanks to two hexapods for an individual alignment of the detector housings (Fig. 4).

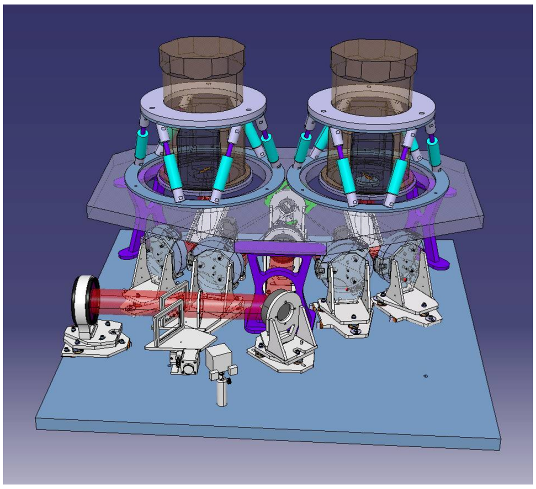

Fig. 4: BATMAN opto-mechanical design.

2.5 Mission pathfinder: ROBIN, a BATMAN demonstrator

Before developing BATMAN, we have built a demonstrator named ROBIN, for characterizing the actual performance of this new family of instruments, as well as investigating the operational procedures on astronomical objects. The design of the demonstrator is identical to the instrument design for being fully representative, with a global reduced size, on mirrors as well as on the grating. The general mechanical design of ROBIN consists of a main optical bench supporting 2 arms: a spectrograph arm and an imaging arm. The detectors are located on both sides of the bench. Opto-mechanical design is shown in Fig. 5 (a).

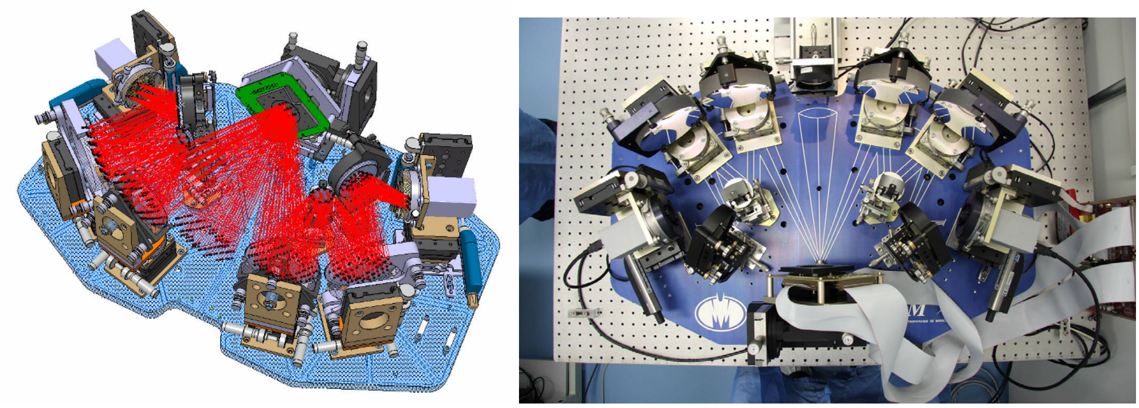

Fig. 5: (a) 3D general design view of ROBIN (in red, beam propagation in the demonstrator); (b) integrated ROBIN picture

ROBIN has been integrated and aligned (Fig. 5 (b)). The optical beam is entering from the top center; the DMD is located at the bottom center and both arms are fed, on the right hand side is the imaging arm and on the left hand side is the spectroscopic arm. Both arms are fully identical except the convex mirror being replaced by the convex grating in the spectroscopic arm. Images and spectra are recorded by two CCD cameras located on both sides (left and right).

First images and spectra have been obtained and measured. In the imaging arm, typical slit mask patterns are recorded (Fig. 6a); the optical quality is good enough for imaging each individual micromirror. In the spectroscopic arm, typical spot diameters are within 1.5 detector pixels, and spectra generated by one micro-mirror slits are displayed with this optical quality over the whole visible wavelength range (Fig. 6b).

We have tested the instrument abilities in terms of variable spatial bin and variable spectral resolution, and any combination of the above modes over the whole FOV; in particular, MOS and IFU-like (scanning slit) modes have been studied, with any slit mask configurations (any shape, including long slit) as well as real time reconfiguration.

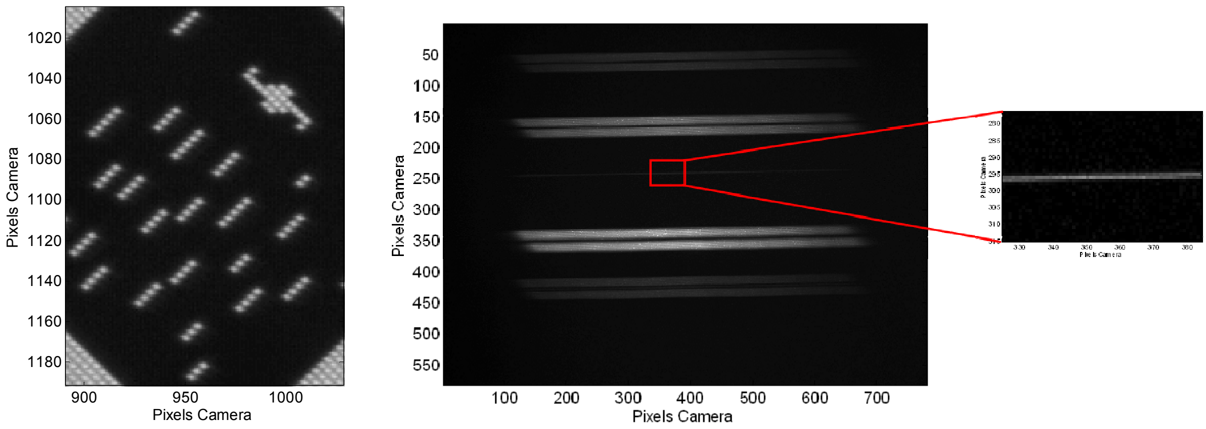

Fig. 6: (a) Image of a typical slit mask in the imaging channel; (b) spectra in the spectral channel, including a single micromirror slit (close view of the spectrum generated by the one-micromirror slit)

2.6 BATMAN: on-sky demonstration

BATMAN on the sky is of prime importance for characterizing the actual performance of this new family of MOS instruments, as well as investigating the operational procedures on astronomical objects [8]. Thanks to a French-Italian collaboration, this instrument will be placed on the Telescopio Nazionale Galileo 3.6-m telescope, at the Nasmyth focus, by mid-2015.

3. PRELIMINARY SIMULATIONS

To explore the instrument capabilities for astrophysics applications, we based our work on a signal to noise ratio (SNR) analysis. The SNR is relevant of both the detection efficiency and the measurement accuracy. Such study is used to estimate the instrument performances independently to any data processing and then able us to determine the scope of the project very early in its development. For this preliminary study, we based our result on an Exposure Time Calculator (ETC) to keep it simple and focus our analysis on the main noise contributions. We already start to develop tools for the next studies based on a pixel simulator to include in the simulation nonlinear effects.

We limited ourself to study the case of a telescope concept and an observation strategy designed for a very deep survey in spectroscopy channel. We assumed a 1m telescope optimized in near infrared. The micro mirror scale was choose as a compromise between the sky resolution needed to resolve far galaxies and the size which maximize the single source flux collected by a single micro mirror. For the image acquisition we simulate a typical NIR detector based on HgCdTe matrix. All the instrument model parameters are described in table 1.

We focus our analysis on the sensitivity for an exposure time of 3600s. We derived the sensitivity for SNR=5. The case of SNR=5 is relevant of the measurement capabilities. We also declined the sensitivity in term of magnitude limit of the source continuum in H band. The source continuum used is a black body at 5870°K and the emission line source is a gaussian. The source was supposed punctual. The computation itself was released with the ETC 42 software [9]. We choose this ETC mainly because it was designed to be highly modulable and then able us to simulate a DMD based instrument without any further development. We did these simulations for several telescope diameters in order to find the minimum diameter for reaching our science goals. The results are summarized in table 2.

Telescope diameter (m)	Exposure time: 3600s	Exposure time: 50 x 3600s	Exposure time: 100 x 3600s	Exposure time: 200 x 3600s	Exposure time: 400 x 3600s
0.5	21.0	23.1	23.5	24.0	24.4
1	22.8	25.0	25.3	25.7	26.2
2	24.0	26.1	26.6	27.0	27.4

Table 2: Magnitude limit reachable by our DMD-based instrument

A 0.5m diameter telescope is too small for reaching our scientific goals. **The nominal BATMAN telescope diameter is then set to 1m.**

This preliminary study demonstrates the power of a DMD-based instrument for spectroscopic observations, as it will be developed in the science cases paragraphs. In our further works, we plan to improve and validate these predictions using a pixel simulator of the DMD instrument. First work on the pixel simulations was realized using the aXeSIM software [10]. This code was designed to simulated HST images in slitless spectroscopy. The code was modified for including a DMD in the optical path of simulated instruments.

4. SURVEY OF FAINT GALAXIES

4.1 Primordial galaxies

One of the most exciting objectives of our telescope would be the study of the first galaxies in the primordial Universe. We will provide a cencus of the most massive galaxies at z>6 over 5 deg^2, including thousand of spectra. These galaxies are the first ones to be formed. We will get their Lyman alpha emission as well as their continuum. Such sample is unique to constrain the epoch of formation of the first galaxies. We will study their spatial distribution, depending on the presence or not of the Lyman alpha emission line, which is crucial to understand the source of the reionisation.

Based on the millenium simulation by Wang et al. [11], we expect 40 (300) galaxies at z>7 (z>6) for which we will get a spectra using our standard survey configuration (50h of observation). Since we are observing 8 times the same fields, we can get up to 400h of integration for a number of selected targets of interest. Therefore, we can get the continuum of sources as faint as H=26.2. Our simulation shows that we expect almost 500 (3000) galaxies at z>7 (z>6) with such magnitude limit. If we dedicate ~20 micro-mirrors per pointing to such sources, **we could observe ALL the z>7 candidates at H<26.2 over 5 deg2 and even detect their continuum (Fig. 7). This strategy does not affect our main survey.**

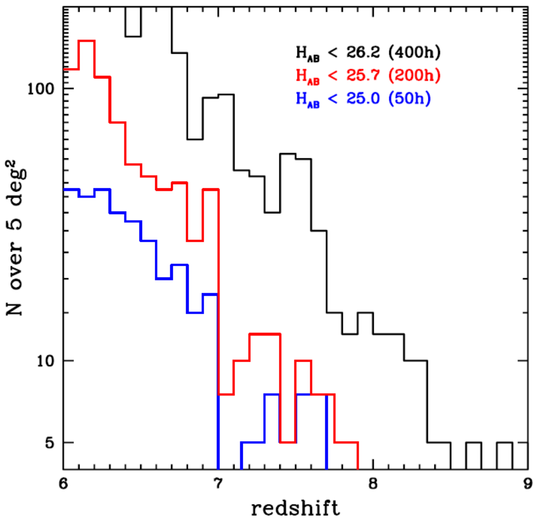

Fig. 7: Number of galaxies in BATMAN survey total field of view with respect to the redshift

Using a smaller telescope (e.g. 50cm), we would detect only 40 galaxies above z>6 and no galaxy above z>7. It becomes impossible to study the primordial galaxies. A comparable mission called Chronos has just been proposed at ESA to study the primordial galaxies [12]. They propose a telescope of 2.5m with similar scientific objective than us. **By increasing the exposure time at 400h for the few thousand of primordial galaxy candidates, we believe that we can reach a similar scientific objective with a 1m telescope.**

Getting the spectra of the primordial galaxies is one of the main objectives of the E-ELT/TMT and JWST. While JWST could reach the same sensitivity than us (H~26.2) in few hours, the field of view of NIRSPEC is limited to 9 arcmin^2. Therefore, this telescope will be really efficient to observe the faintest primordial galaxies on field of view limited to tens arcmin^2. Our strategies are complementary: while the JWST will observe the faint-end of the luminosity function of z>7 galaxies over small fields, we will target all the brightest galaxies of the luminosity function over few square degrees. The formation of the brightest and most massive galaxies takes place early on in the history of the Universe and has to be studied at z>7. Therefore, this is a key population to study if we want to understand how galaxies formed. As JWST, the next generation of giant telescopes (E-ELT and TMT) will also propose NIR multi-object spectrograph but with a limited field of view (2 arcmin^2 for the Infra- Red Imaging Spectrograph on the Thirty Meter Telescope).

We also underline that such study is absolutely impossible using EUCLID which is not designed to reach such faint level in the continuum. While Lyman alpha could be detected for few tens of sources at z>6 in EUCLID, the continuum will not be reached even in EUCLID Deep, and few galaxies are expected at z>7. However, the deep photometry provided by EUCLID on the calibration fields will be crucial to preselect our targets.

4.2 Galaxies 1.5<z<4

Local spectroscopic surveys like the SDSS or GAMA provide an incredibly detailed picture of the current-day Universe. We want to characterize the rate at which the structures that we observe today have been established, and which physical processes govern galaxy evolution on cosmic scales. At which rate galaxy groups and clusters appeared? How does the environment impact galaxy evolution? Which processes are able to stop the star formation in the most massive galaxies? How related are these quenching processes to the elliptical morphology of galaxies? How galaxies with hundred of billions of star were able to grow? What is the importance of merger in galaxy formation? The extensive surveys performed with current optical spectrograph have shown that the Universe at z~1 is already quite similar to our local Universe. Most of the galaxy evolution seems to occur at z>1, which is now the epoch on which we need to focus: the density of the galaxies with a quenched star formation increases extremely rapidly between 1<z<4 [13, 14, 15], the peak of the star formation activity seems also to occur at 1<z<4 [16], the peak of the merger rate could also occur at the same period.

The survey that we propose is unique to study the evolution of galaxy properties at z>1.5 at the peak of their activity, and trace the growth of the structures:
1) We will gather a representative sample of 200 000 mass selected galaxies at z>1.5. Our survey will provide the equivalent of surveys performed today at 0.5<z<1.2 with optical spectrograph (e.g. VIPERS) but at 1.5<z<6. Since we want to study the Universe at z>1.5, we need to use a spectrograph sensitive in NIR, which is much more efficient using space observations.
2) The good S/N on the continuum that we will get is crucial for detailed analysis of the galaxy physical properties using Stellar Population Synthesis Code. It will allow detailed analysis of the galaxy metallicities, SFR, and star-formation history.
3) We will assemble a sample of 200 000 galaxies with a sampling rate of 50%: we will be able to trace the large scale structures at z>1.5 with the same quality as what is currently done with VIPERS at 0.5<z<1. We will systematically identify the first proto-clusters over 5 deg^2. This is the key to understand the impact of environment on the evolution of galaxy properties.

The survey that we propose is unique. EUCLID Deep will also gather a large spectroscopic sample in this redshift range but EUCLID is not designed to reach the spectra continuum. Therefore, only the most star- forming galaxies will be observed in EUCLID which make difficult the study of the quenching at z>2. Detailed analysis of the spectral properties will also be challenging. JWST or the next giant telescopes have a too small field of view to cover 5 deg^2 and will unlikely be used as a survey machine. eBOSS or MS-DESI will operate in optical and select bright emission line galaxies, which makes them inefficient for such studies. Their target sampling rate will be so low that they will not be able to reconstruct the environment.

4.3 IFU mode with BATMAN

The spatial sampling of BATMAN is 0.75 arcsec and a single micro-mirror will probably select the whole object for primordial as well as intermediate redshifted galaxies.

However, if the size of the galaxy (or its irregular shape) is larger than 0.75 arcsec we could use the pseudo IFU mode of BATMAN by sequentially moving the slit along the object and record the local spectra. Since all fields are visited several times, we could get the whole information without using extra time.

4.4 Comparison of BATMAN and EUCLID-deep survey

The EUCLID mission is tuned to survey a huge area of the sky. The near infrared spectroscopy is optimized to detect a maximum of emission line galaxies up to redshift 2. The instrument is based on slitless spectroscopy which allows to observe all the sources in the field of view but the slitless spectroscopy have a very high sky background and the spectra of neighbour sources could overlap. The observation strategy and the data analysis must take into account some decontamination methods. The EUCLID deep survey will combine 40 observations of the same fields to ensure a sensitivity up to 5e-17 erg/s/cm² on 40deg² and a very efficient decontamination of the spectra crowding.

To compare the BATMAN and EUCLID spectroscopy, we simulated a Emission Line Galaxy from a model of a COSMOS galaxy [13]. This galaxy is at redshift 2.5 and at magnitude H 24. The flux in the OII line is 1.0e-16 erg/s/cm². For the BATMAN simulation we used the same instrument model than in the proposal. We made a EUCLID-like instrument model using the EUCLID definition study [17]. The image simulation for both instruments is based on the aXeSIM software [18]. For the BATMAN simulation, we simulate the shortest version of the observation strategy, 50 exposures of 3600s. For the EUCLID-like simulation, we simulate a deep survey with 40 exposures of 560s as defined in the reference document. We performed a very simple extraction (not optimal) and we binned the 2D spectra of each exposure to reconstruct the 1D spectra.

Figure 8 compares the input spectrum, the simulation of BATMAN observation and our EUCLID-like simulation. The BATMAN spectrum is at very high signal to noise ratio and allow a very deep analysis of the galaxy properties. We can clearly identify two emission lines. The EUCLID spectra allow clearly to detect and measure the OII line but the fainter lines and the continuum are in the noise fluctuations. This example illustrates that the two instruments and the two missions goal are very different. The EUCLID mission is optimized to survey a very large part of the sky and to study the statistical properties of the universe. **The BATMAN proposition will study fainter sources on a restricted area compared to EUCLID.**

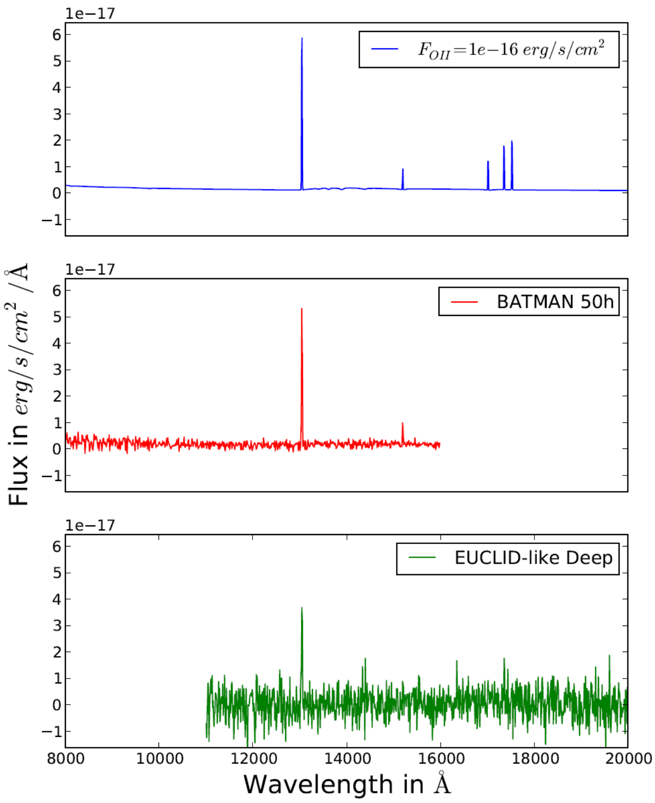

Fig. 8: Comparison of BATMAN and EUCLID-deep survey
The spectrum, in blue, at the top, is the input spectra of the simulation. This is a spectrum from COSMOS galaxy [13] at redshift at z=2.5, magnitude H 24 and with a flux the OII line of 1e-16erg/s/cm2. The red spectrum is the expected observation with BATMAN with 50 exposures of 1h.The green spectrum, at the bottom, is the expected observation with a EUCLID-like deep survey.

Figure 9 shows the simulation of a Lyman Break Galaxy from the composite spectrum of Shapley et al. [19]. We redshifted this rest-frame spectrum at z=7 and we scaled it in order to have a flux in the Lyman alpha line of 1.0e-18 erg/s/cm² and a magnitude H of 26. The spectra in red are the simulation result in four cases, 50, 100, 200 and 400 exposures of 1h. Even if the extraction was not performed in an optimal way, we see that below 200h of observation the identification of the galaxy would be difficult. The 200h of integration, allow to measure the Ly alpha line and by the way the redshift. To access to the continuum analysis, 400h of integration are required.

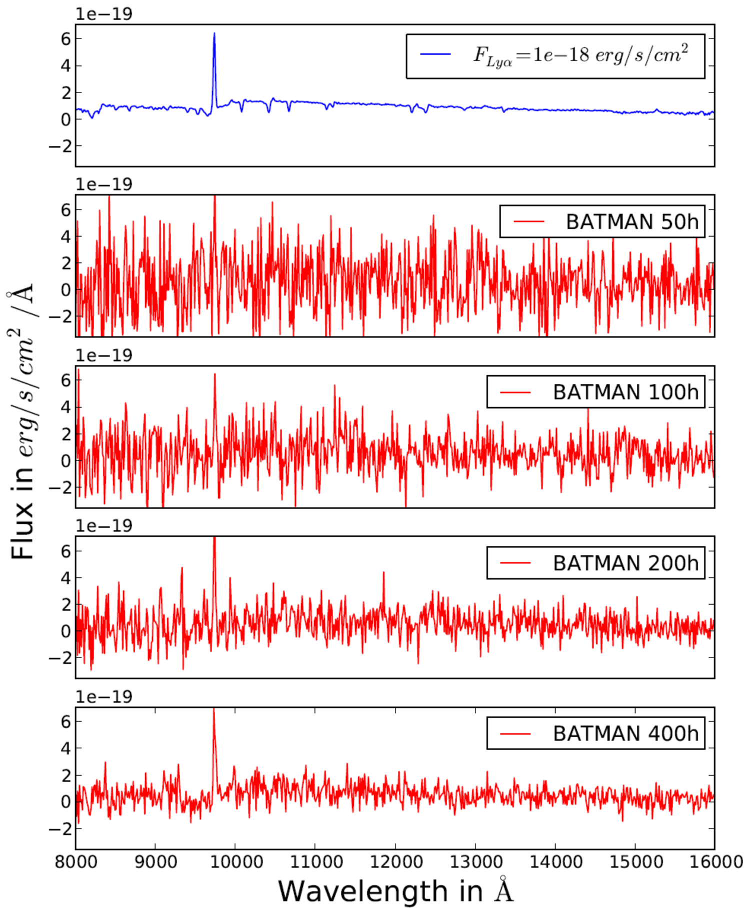

Fig. 9: Simulation of a Lyman Break Galaxy observation with BATMAN
The spectrum, in blue, at the top, is the input spectra of the simulation. It is a composite spectrum from Shapley et al. [19], redshifted at z=7 and scale in order to have 1e-18erg/s/cm2 in the Ly alpha line and a continuum at magnitude 26 in H band. The others spectra, in red, are the expected observations with BATMAN with 4 exposure times, 50h, 100h, 200h and 400h.

5. UNVEILING THE OUTSKIRTS OF OUR SOLAR SYSTEM:

PROBING THE KUIPER BELT OBJECTS SURFACE ORIGINS

The outer region of our Solar System is populated by thousands of minor bodies that are the less altered remnants of the period of formation of our planetary system. Their physical and dynamical properties provide strong constraints on the timing and formation scenario of the giant planets and on the conditions than prevailed in the early Solar System disk. The study of the trans-Neptunian of Kuiper Belt is therefore crucial to understand the Solar System history as a whole. The first object was detected only in 1992 [20]; more than 1600 are known today with estimated diameters from 50 to ~3000km. Their large distance from the Sun and relatively small size make them faint, moving and challenging targets to study, with typical visible magnitudes in the V > 21 range.

5.1 A complex dynamical sculpting

After a few years only, several dynamical classes were identified (see [21] for a review), completely discarding our initial vision of a thin disk of planetesimals on a circular orbit, as expected from a proto-planetary disk in rotation. The classical belt, that is believed to be a primordial feature consists of objects with quasi-circular orbits with semi-major axis in the 42-48 UA range and a relatively low inclination with respect to the ecliptic (also called the "cold" classical belt). But astonishingly, several other classes exist, that were (or still are) dynamically processed since 4.5 Myr: the “hot” classical Belt, with median orbital inclination of 15°, the objects in mean motion resonance with Neptune (as the most famous of them, dwarf planet Pluto at 39.5 AU), the Centaurs (semi-major axis a < 30 AU, wandering in the giant planets region) and scattered objects (a > 30 AU, with large eccentricities and inclinations) on unstable orbits due to past or recent interactions with Neptune. More extreme orbits exist, with the "detached objects" whose semi-major axis can be above 100 AU (500 AU for Sedna), and which are completely free from the giant planets gravitational influence.

The dynamical sculpting of the current Kuiper Belt has deep implications on the Solar System history: planetary migration has to be invoked (which gives strong constraints on where and when the giant planet formed), as well as complex interactions between the giant planets and the initial planetesimal disk. Several models describe quite consistently the current architecture of the Kuiper Belt, although some key questions remains about the precise origin of the different dynamical populations (see the planetary migration model [22], the Nice Model [23], the “Grand tack” model by Walsh & Morbidelli [24]).

5.2 Surface and physical properties

From the ground, only very general properties can be inferred even with the largest 10m-class telescopes: bulk color properties are inferred from broadband unresolved photometry surveys in the 0.4 – 2.5 micron range, and give only a general hint on the spectral continuum of the planetesimals. From the various surveys conducted (see [25] for a review), it appeared that Kuiper Belt Objects (KBOs) exhibit a wide range of surface colors from neutral (solar reflected light) to extremely red (redder than the surface of Mars), illustrating a wide range of surface composition and properties.

But the key tool to thoroughly explore surface composition is spectroscopy. Among the 1600 objects discovered since 1992 in the Kuiper Belt, only 75 of them have meaningful surface reflectance spectra available [26], and this is almost the limit that can be reached with current state-of-the-art instruments available. Currently, surfaces are classified into:

1. methane-rich (the largest objects, like Pluto, Makemake (Fig. 10), Eris, Sedna, which might also host nitrogen)
2. water-rich (about 30 objects) with some possible traces of methane or ammonia
3. spectrally featureless. The latter class is suspected to host carbon-rich, chemically evolved compounds, although the lack of signal to noise in the data might actually hide features from chemical components of interest.

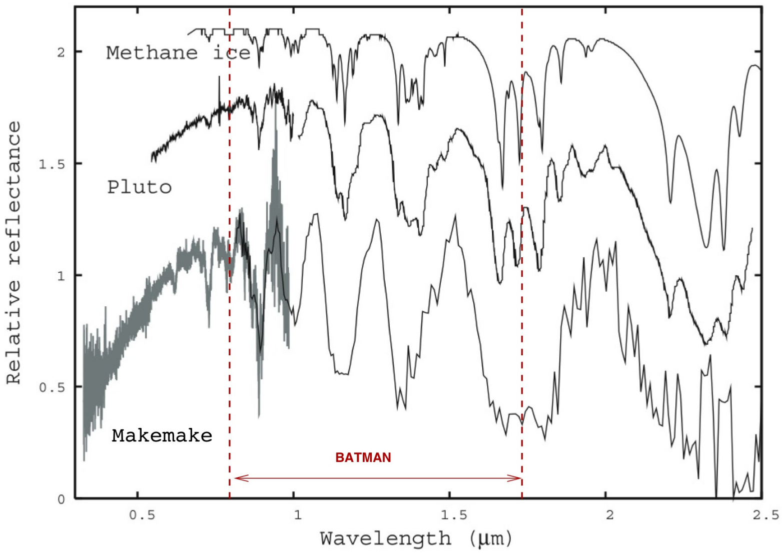

Figure 10: a visible-NIR spectrum of two methane-rich objects: Pluto and Makemake. Various absorption bands are measured in the 1-2.5 micron range. The vertical dotted lines show the interval that will be explored with BATMAN, at a much higher SNR and for 700 objects (instead of the current 70). Adapted from [27].

5.3 BATMAN and the new paradigm

There is no obvious link between the surface composition and dynamical properties and history nor heliocentric distances, which makes the global interpretation of the Kuiper belt surface properties and evolution scenario very difficult despite the huge observational efforts provided by our community since 20 years (see the "Solar System beyond Neptune" book, for a review, [28]).

Recent theoretical studies pointed that the ability for an object to retain a primordial inventory of ices (such as methane or nitrogen for instance) can be related to the size and surface temperature history of the object [29]. A new paradigm is now emerging: is the current surface composition "nature" (e.g. primordial) or "nurture" (e.g the result of evolution processes)? Unfortunately, the low quality of the current data available from the ground (due to sensitivity effects in the NIR) prevents us from addressing this question properly.

The main issue is the available sample size, but most importantly the limited signal-to-noise ratio (SNR) reached from current spectroscopy. **BATMAN provides a unique opportunity to obtain excellent SNR** (from 20 to above 100) low resolution spectra **on 700 objects** (with H mag > 17) in the 0.85-1.7 microns region where some ices of cosmogonic interest have their absorption bands (in particular water and methane). **This huge sample will simply open a new era in the Kuiper Belt properties and origins studies, that is not reachable by any other observatory.**

The key questions that will be addressed through the BATMAN Kuiper Belt spectroscopy survey in the 0.8-1.7 micron region on 700 KBOs are: is water ubiquitous in the outer solar system? What is the fraction of methane and water-bearing objects and is the surface content related to size and surface temperature? What is the physical state of methane? What physical processes can be identified? Is the current composition "nature or nurture": what is the primordial surface inventory heritage, what is the evolution scenario of the remaining components? What primordial proto-planetary disk constraints and physical processes can be derived?

5.4 The unique contribution of BATMAN

Despite the large telescope diameters (8-10m) available from the ground, the limiting magnitude that is generally reached in the H band spectroscopy (H=18 for a SNR of 10 in a few hours of exposure) allows us to only access ~100 objects over the 1600 known and with generally a poor quality. This is a hardware limit that can be beaten only by enlarging the collecting area by a *significant* fraction, or by going to space to boost the sensitivity in the NIR domain. Another issue is the ability for the instrument to follow an object moving at non-sidereal rate, while acquiring spectroscopy.

BATMAN provides a unique solution for our community, with enhanced spectroscopy capabilities in a spectral domain where water ice and methane, our main molecules of interest, sign. Most KBOs lies in the H mag > 18 region, with the bulk know population in the 19-22 area. Simulations showed that in spectroscopy mode, for R=500, a SNR of 100 is reached in 1h exposure for H=18 and SNR=10 for H=22. This means that we can perform a spectroscopic survey of all objects down to H=22, and with outstanding SNR ratio for the brightest objects.
Another key feature from BATMAN is the capability to move the spectroscopy slit across the array of micro-mirrors with simple activation of the corresponding mirrors, following the motion of the object in real time. The main limitation with classical instrumentation is to properly maintain the moving KBO through the spectroscopic slit during the exposure time needed.

Water ice displays a large absorption feature at 1.5 microns, with a ~0.2 micron width (see the example of Haumea, Fig. 11), and a shallower band around 1.25 microns. Pure methane ice at KBO surface temperature displays 10 absorption bands in the studied range (0.73, 0.79, 0.87, 0.89, 1.13, 1.16, 1.20, 1.33, 1.48, 1.67 microns), with depths varying from 7 to 80% and width from 0.05 to 0.2 microns ([31], see also Fig. 10). A resolution of 50-100 is highly sufficient to detect all of the corresponding absorption bands if they are present: we will be able to spectrally rebin the original R=500 data by a factor up to 5, to boost the SNR for the faint end of the distribution.

Table3 presents the performances of BATMAN in R=500 spectroscopy mode, for a point source with a continuum following a Solar-type black body profile (e.g. our ETC simulation for a KBO).

Table 4 presents the frequency of known KBOs per bin of 1 mag, the corresponding exposure time and SNR planned.

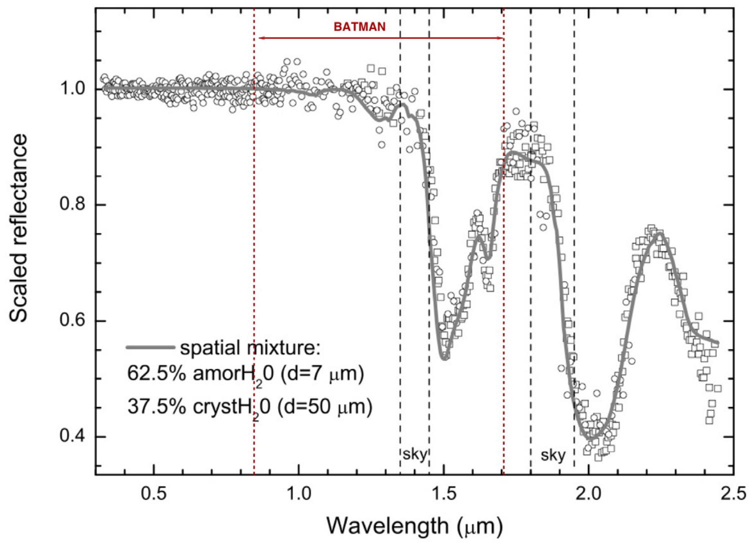

Fig. 11: visible-NIR spectrum of dwarf planet Haumea, showing large absorption bands of water ice. The vertical dotted lines show the interval that will be explored with BATMAN, at a much higher SNR and for 700 objects (instead of the current 70).
Adapted from [30]

H magnitude	**SNR for a 3600s exposure**
18	100
19	60
20	35
21	19
22	10

Table 3: performances of BATMAN in R=500 spectroscopy mode, for a point source with a continuum following a Solar-type black body profile

H magnitude	**Number of known objects**	**Exposure time per object (h)**	**SNR**	**Total exposure time (h)**
17-18	14	0.5	~90	7
18-19	52	0.8	~90	41,6
19-20	116	1	~60	116
20-21	169	3	~60	507
21-22	336	5	~30	1680
Total	**687**			**2351,6**

Table 4: the frequency of known KBOs per bin of 1 mag, the corresponding exposure time and SNR planned

These SNR ratios do not take into account the possibility to spectrally rebin the data, which can almost double the final SNR. If we count that 40% of the operation time is dedicated to overheads, the complete survey will take about 4000h, e.g. 6 months.

The calculations above show that **BATMAN will be able to survey in spectroscopy all known KBOs down to H mag = 22 (700 objects) with outstanding SNR in 6 months of operation.**

6. IR SURVEY OF STELLAR CLUSTERS IN NEARBY XUV GALAXIES

GALEX has discovered extended UV emission around otherwise normal nearby galaxies [32, 33, 34, 35]. This emission has been interpreted as the sign of wide-spread star formation. The stellar clusters found in external regions are the subject of studies to determine e.g. if the IMF is normal in these regions [36] but a difficulty is the intrinsic variability in the SFR history in such diffuse regions (see e.g. [37] in LSB galaxies). Some of these methods rely simply on counting regions of different ages (e.g. UV emitting vs H-alpha emitting regions). The determination of ages is difficult from broad band images. The NIR part of the spectra includes features (variable slopes, and breaks) due to AGB stars that can be used to date stellar clusters, or test the presence of AGB stars (see Fig. 12: the features due to AGB stars can be dated from 0 to 1 Gyr with ~ 100 Myr resolution). With a "constant" IMF, NIR spectra of stellar clusters would thus allow us to verify if the spectra are consistent with a normal IMF or not (comparing predictions of fig GP1 with observations), to determine the age of the stellar clusters (if the IMF is indeed normal), to determine their mass. However the situation is more complex because the stochastic sampling of the IMF will affect the properties of individual clusters [38]. The comparison of many clusters with the same mass should demonstrate this effect. Moreover, the methods developed in this paper will be applied to the spectroscopic features (a paper on the method for spectral features is in preparation), what will allow us to put constraints on the age and mass of the clusters in a statistic sense, taking into account these stochastic effects.

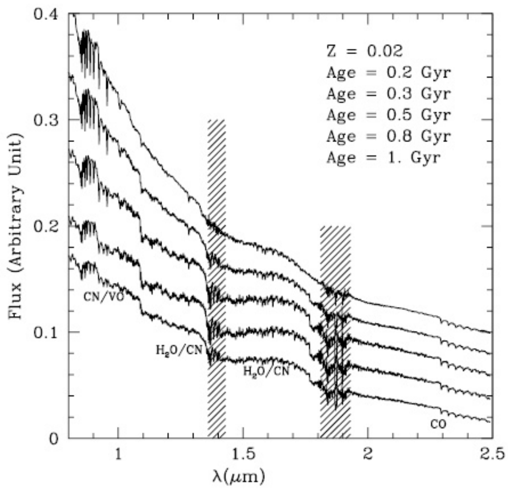

Fig. 12: Evolution of the NIR spectra of a stellar cluster (Fig 13 of [39])

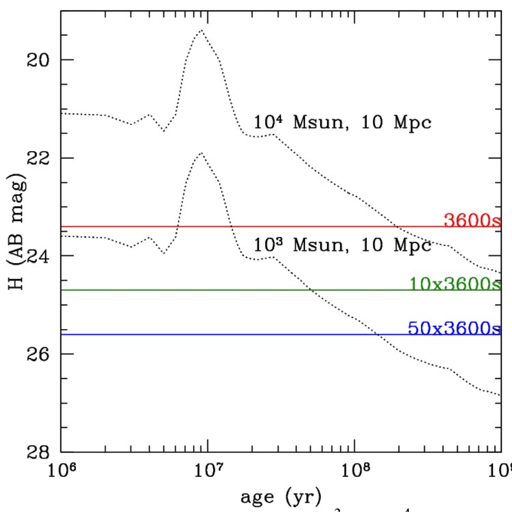

Fig. 13: H-band magnitude of 10^3 or 10^4 stellar clusters as a function of time, with horizontal limits of our surveys, for a galaxy at 10 Mpc and a variable number (1, 10, 50) of "unit" exposures (3600 sec).

NIR spectra will then allow us **to simultaneously test in the extreme outer disks of nearby galaxies: the shape of the IMF, its stochastic sampling, and to estimate the variability of the SFR history**, what is not possible with current data allowing only much more simpler approaches [36]. This study will help us to get a better understanding in star formation, and especially in the possible variations of the IMF, a subject of high importance for all extra-galactic astronomy.

We propose for the first year of the mission to observe the 54 XUV galaxies identified in [33], at typical distances of ~10 Mpc, with sizes fitting our field of view for many galaxies. The few larger galaxies will be covered by a mosaic. Other nearby galaxies of interest may be added to this core sample. To be conservative, we assume we will need about 100 pointing for the full sample. We will use slits on the centroids of the GALEX UV sources in the outer disks. Fig. 13 shows that we should be obtain useful data for clusters with stellar mass above 10^4 M_{sun} with 3600s. We thus propose to observe each pointing for one orbit during the first year. This will provide us with enough data to perform a first scientific analysis. The following years, we will progressively revisit the same fields in order to achieve by the end of the mission at least 50x3600s exposure, largely sufficient to scientifically analyze 10^3 M_{sun} clusters over the full range of ages of interest. In accumulated time, this survey will then take about 1 year of the mission.

The results would be totally unprecedented. For comparison, the analysis of the clusters in the outer disk of M83 by Koda et al. [36] reach ~ 10^3 M_{sun} for FUV-NUV<0 and analyze about 100 clusters. On-going ground-based programs (accepted, on Subaru and CFHT) aim at performing a similar analysis in less than 10 galaxies. **Our survey will produce data for more than five times these numbers, resulting in the study of several thousands of young stellar clusters.** Moreover it will allow a totally original and new method (based on IR spectroscopy) that promise to be much more performant (less information is available in broad-band images, not allowing to derive such precise ages for the clusters).

Such IR spectral survey would be impossible to perform from the ground:
1) because of the amount of time needed
2) because many of the spectral features would be affected by the atmosphere.

7. CONCLUSION

Our proposal is a deep multi-survey mission in the infrared with a multi-object spectrograph based on a reconfigurable slit mask, using MOEMS devices. Unique science cases Space Observation are reachable with this instrument:

- Deep survey of high-z galaxies: large sample of 200 000 galaxies down to H=25 on 5 deg^2, and all z>7 candidates at H=26.2 over 5 deg^2
- Deep survey of nearby galaxies: characterization of the IMF in several thousands of young stellar clusters in a large sample of nearby galaxies
- Deep survey of the Kuiper Belt: spectroscopic survey of **all** known objects down to H=22 (700 objects, current sample multiplied by 10).

Pathfinder towards BATMAN in space is already running: thanks to CNES and ESA former and on-going studies, MOEMS devices are considered for integration in space missions both for Space and Earth Observation. DMDs have been tested in space environment and no showstopper has been revealed. ROBIN, a BATMAN demonstrator on an optical bench, has been built and delivers already images and spectra in parallel, allowing us to validate all expected performances. Finally, BATMAN is scheduled to be mounted for an on-sky demonstration in the coming year on a ground-based 4m-class telescope.

And then, hopefully, BATMAN will fly.

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