SEMINAIRE DE PROSPECTIVE SCIENTIFIQUE 2014

APPEL A IDEES

A1. RENSEIGNEMENTS GENERAUX

INTITULE DU PROJET

BATMAN flies: a compact spectro-imager for Space and Earth Observation

THEMATIQUE PRINCIPALE A LAQUELLE SE RATTACHE LA PROPOSITION

- **Astronomie et astrophysique, y compris cosmologie, physique stellaire et planètes extrasolaires**
- **Planètes et petits corps du système solaire**

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ABSTRACT

BATMAN flies: a compact spectro-imager for Space and Earth Observation

Multi-Object Spectrographs (MOS) are the major instruments for studying simultaneously numerous astronomical sources in a single exposure. Current object selection systems are limited and/or difficult to implement in next generation MOS for space. A promising solution is the use of micro-opto-electro-mechanical systems (MOEMS) such as micromirror arrays which allow the remote control of the reflective multi-slit configuration in real time.

We are developing MOEMS - based spectrograph called BATMAN. As we want to access the largest FOV with the highest contrast, we have selected the largest Digital Micromirror Device (DMD) from Texas Instruments in 2048 x 1080 mirrors format, with a pitch of 13.68µm. Our optical design is a compact spectro-imager with two arms in parallel, the DMD feeding one arm or the other. An all-reflective spectrograph design has been selected with F/4 on the DMD component and robust 1:1 Offner relays. The wavelength range is 0.85 – 1.7 µm and the spectral resolution is 500 – 1000.

Our proposal is a deep multi-survey mission in the infrared with a multi-object spectrograph based on a reconfigurable slit mask. 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
- 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)

In Earth Observation, oceans and coastal line exploration will benefit from programmable slits for removing bright objects like clouds from the scene, and optimize the signal to noise ratio according to the observed field of view. Another promising instrument is a wide field programmable spectrograph where both spatial and spectral features of the scene are addressed.

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.

RESUME

BATMAN vole : un spectro-imageur compact pour l'Observation de l'Univers et de la Terre

Les spectrographes multi-objets (MOS) sont des instruments clés pour étudier un grand nombre de sources astronomiques simultanément en une seule pose. Actuellement les systèmes de sélection d'objets sont limités et/ou difficiles à mettre en place dans la prochaine génération de MOS. Une solution prometteuse est d'utiliser des systèmes micro-opto-électro-mécaniques (MOEMS) comme les matrices de micro-miroirs qui permettent de contrôler à distance la configuration des micro-miroirs et ainsi de créer en temps réel le masque de fentes.

Nous développons un spectrographe nommé BATMAN basé sur un composant MOEMS. Voulant observer le plus grand champ de vue possible avec le meilleur contraste, nous avons choisi le plus grand composant Digital Micromiroir Device (DMD) de Texas Instruments, dans un format 2048x1080 miroirs avec un pas de 13.68µm. Notre design optique est un spectro-imageur compact avec deux bras en parallèle, le DMD adressant l'un ou l'autre bras. Nous avons choisi un design entièrement en réflexion avec une ouverture sur les DMD de F/4 et un design robuste de type relais Offner 1:1. La bande de longueur d'onde est 0.85 - 1.7 µm et la résolution spectrale est 500 - 1000.

Notre proposition couvre plusieurs sondages profonds dans l'infra-rouge à l'aide d'un spectrographe multi-objets basé sur un masque reconfigurable. Des cas scientifiques uniques seront adressés par cet instrument :

- Sondage profond de galaxies lointaines : grand échantillon de 200 000 galaxies jusqu'à H=25 sur 5 deg^2
- Sondage profond de galaxies proches : caractérisation de l'IMF sur plusieurs milliers d'amas d'étoiles sur un grand échantillon de galaxies proches.
- Sondage profond de la Ceinture de Kuiper : sondage spectroscopique de **tous** les objets connus jusqu'à H=22 (700 objets, échantillon actuel multiplié par 10)

En Observation de la Terre, pour l'exploration des océans ou des zones côtières, nous utiliserons les fentes programmables pour supprimer les objets brillants comme les nuages des sites observés et ainsi optimiser le rapport signal à bruit dans le champ de vue. Un autre instrument très prometteur pourrait être un spectrographe programmable où les deux composantes, spatiale et spectroscopique, seraient traitées simultanément.

Le chemin de BATMAN vers l'Espace est tracé : grâce à des études passées et présentes financées par le CNES et l'ESA, nous avons pu étudier en profondeur les composants MOEMS et leur intégration dans des missions spatiales pour l'exploration de l'Univers et de la Terre. Les DMD ont été testés avec succès dans un environnement spatial. ROBIN, un démonstrateur sur banc de BATMAN, a été construit et produit déjà des images et des spectres en parallèle, nous permettant de valider toutes les performances attendues. Enfin, BATMAN est prévu pour être testé sur le ciel dans l'année à venir sur un télescope de la classe des 4 mètres.

Puis, nous espérons que BATMAN volera.

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) (Burg 1998, Zamkotsian 1999, Robberto 2009) or micro-shutter arrays (MSA) (Li 2010). 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) (Waldis 2008, Canonica 2010). 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 (Zamkotsian 2011).

We are presenting in this proposal 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 presented in this document, from high-z galaxies to nearby galaxies and Trans-Neptunian Objects of Kuiper Belt. Ocean and costal line observation would also benefit from this type of instrument.

Preliminary observation strategy, readiness level and collaborations are also presented.

INTRUMENTATION

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) (Zamkotsian 2012).

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.

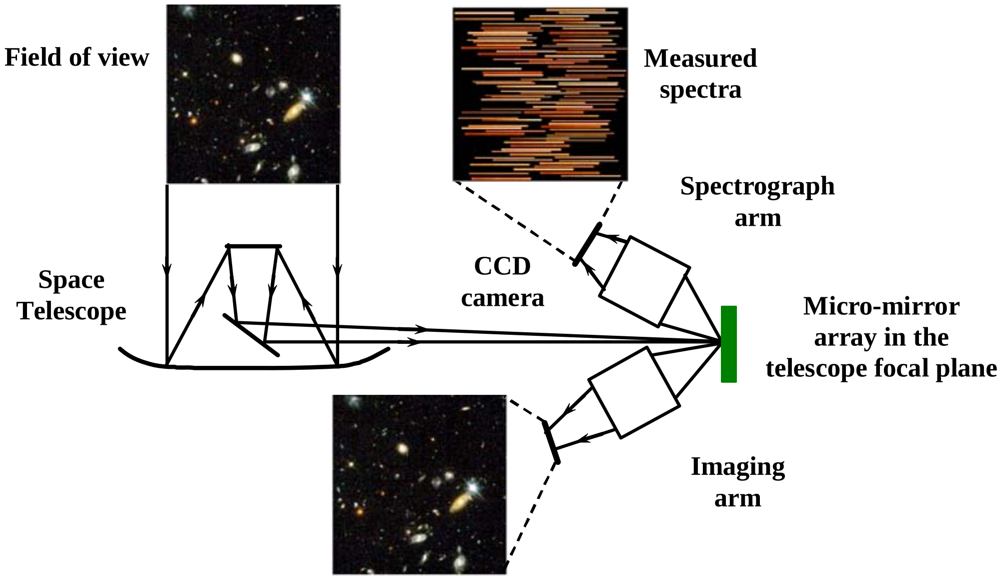

Fig. 1: Principle of BATMAN spectro-imager

Even if complex, we succeeded to design such a system, developing ideas proposed many years ago for the JWST near-infrared multi-object spectrograph (Zamkotsian 1999). 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

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** (Zamkotsian, 2011)**.**

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. On a longer time scale, these arrays could be used in BATMAN concept.

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).

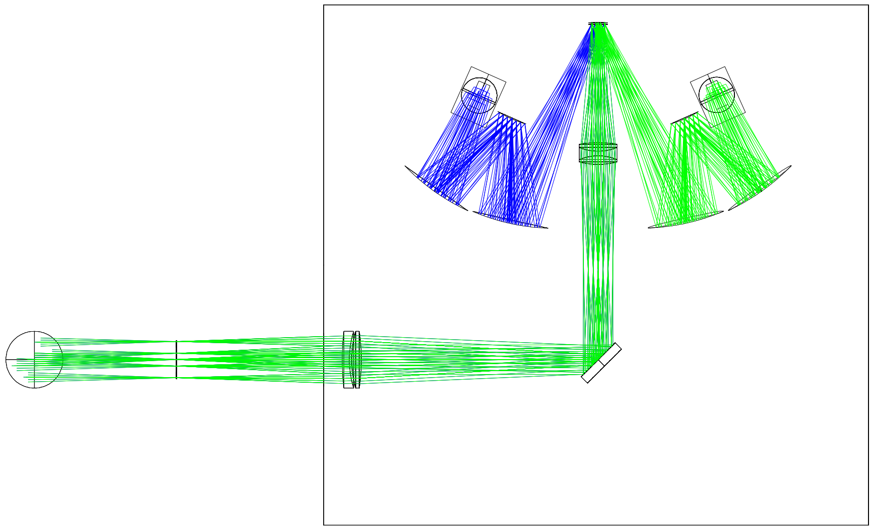

Fig. 2: Optical layout of BATMAN. Light coming from the telescope is split by the DMD into 2 arms, a spectrograph arm and an imaging arm (both are Offner relays).

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.

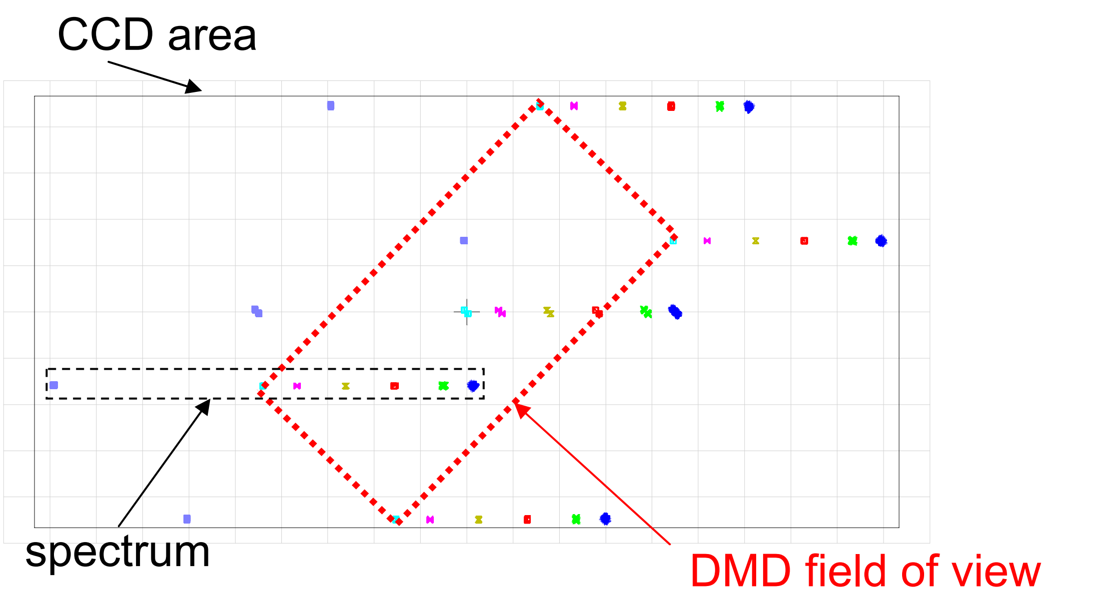

Fig. 3: Spectroscopic channel; simulated spectra on the detector.

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).

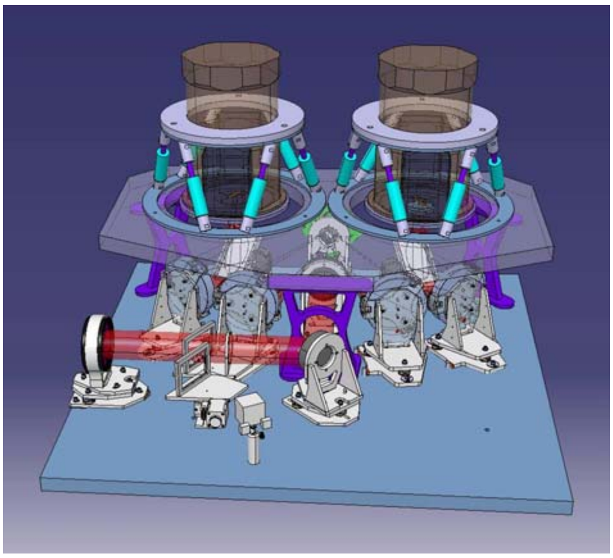

Fig. 4: BATMAN opto-mechanical design.

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).

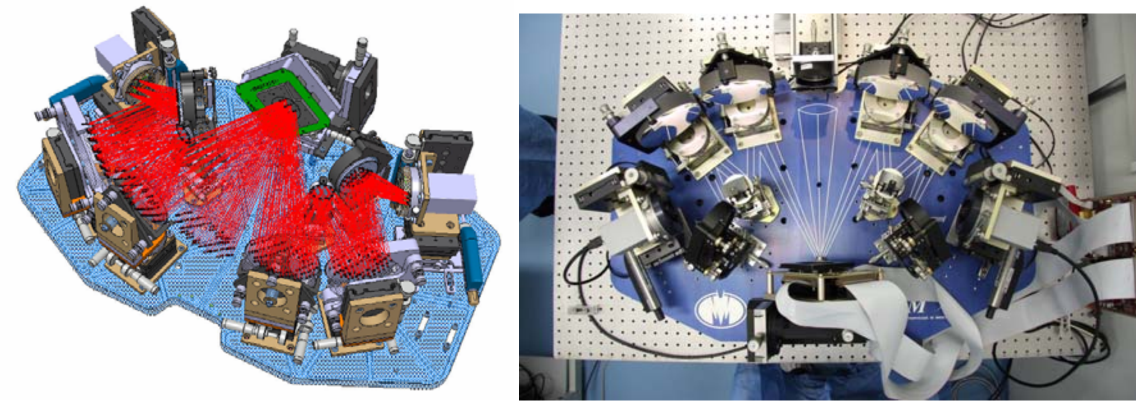

Fig. 5: (a) 3D general design view of ROBIN (in red, beam propagation in the demonstrator)
(b) integrated ROBIN picture

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 first spectra have been recorded (Fig. 6). A serial of slits, 5 micromirrors wide and 15 micromirrors long are set on the DMD: in the imaging arm, they appear in black as the light located on these slits is sent towards the spectrograph; in the spectroscopic arm, the slits generate spectra for each of them, and all spectra are aligned on the detector, due to the dispersion orientation of the grating. For demonstration purpose, the incoming beam has been limited to the 450 – 650 nm range in order to fit the limited size of the detector.

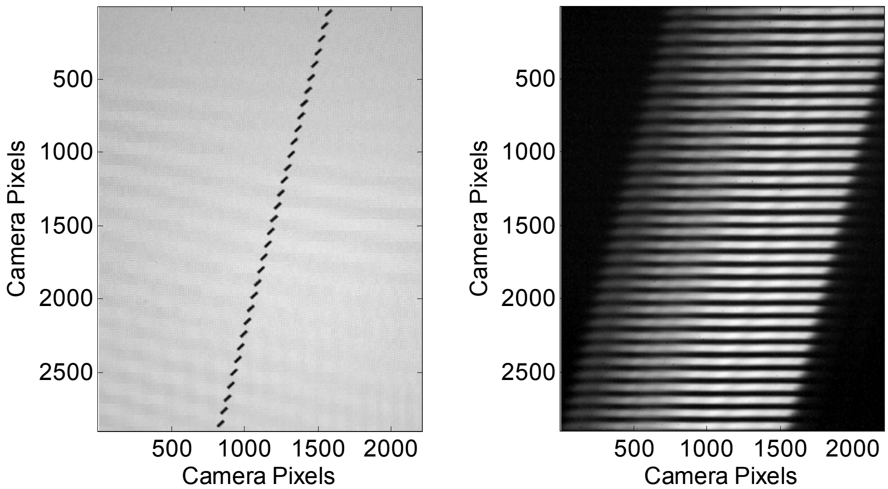

Fig. 6: Image of the slit mask in the imaging channel
and the corresponding spectra in the spectral channel

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. 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 the end 2013 – beginning 2014 (Zamkotsian 2012).

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 two SNR value, SNR=3 and SNR=5. The case of SNR=3 is relevant of the detection capabilities and the case 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 and flux limit of an emission line source at 1.2μm. 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 (Apostolakos et al. 2012). 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. The results are summarized in table 2.

Exposure time	3600s	50 x 3600s	150 x 3600s
Magnitude limit (H) @ SNR=5	22.8	25.0	25.3
Magnitude limit (H) @ SNR=3	23.4	25.6	25.9
Flux limit @ SNR=5	2.0 10^{-17} erg/s/cm^2	3.0 10^{-18} erg/s/cm^2	1.5 10^{-18} erg/s/cm^2
Flux limit @ SNR=3	1.0 10^{-17} erg/s/cm^2	2.0 10^{-18} erg/s/cm^2	1.0 10^{-18} erg/s/cm^2

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

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 (Kuemmel et al. 2007). This code was designed to simulated HST images in slitless spectroscopy. The code was modified to able us to include a DMD in the optical path of simulated instruments.

The simulated galaxies come from the COSMOS Mock Catalog (Jouvel et al 2009). We simulated the observations a strategy of 150 exposures of 3600s and a zodiacal light sky background (Aldering 2001). Fig. 7 shows the resulting co-added image and two examples of extracted spectra. The first spectrum is a bright elliptical galaxy at redshift 2.0 with a magnitude of 22.4 in J band and 21.6 in H band. The high signal to noise ratio enables to identify easily the 4000Å break and several absorption lines. The second spectrum is a star burst galaxy with bright emission lines at redshift 1.5. In that case the main properties of the spectrum which able the characterization of the galaxy are the [OII] line, 2 10^{-17} erg/s/cm² at 9311A and the [OIII] doublet of 1.5 10^{-17} erg/s/cm² at 12390 Å and 12510 Å.

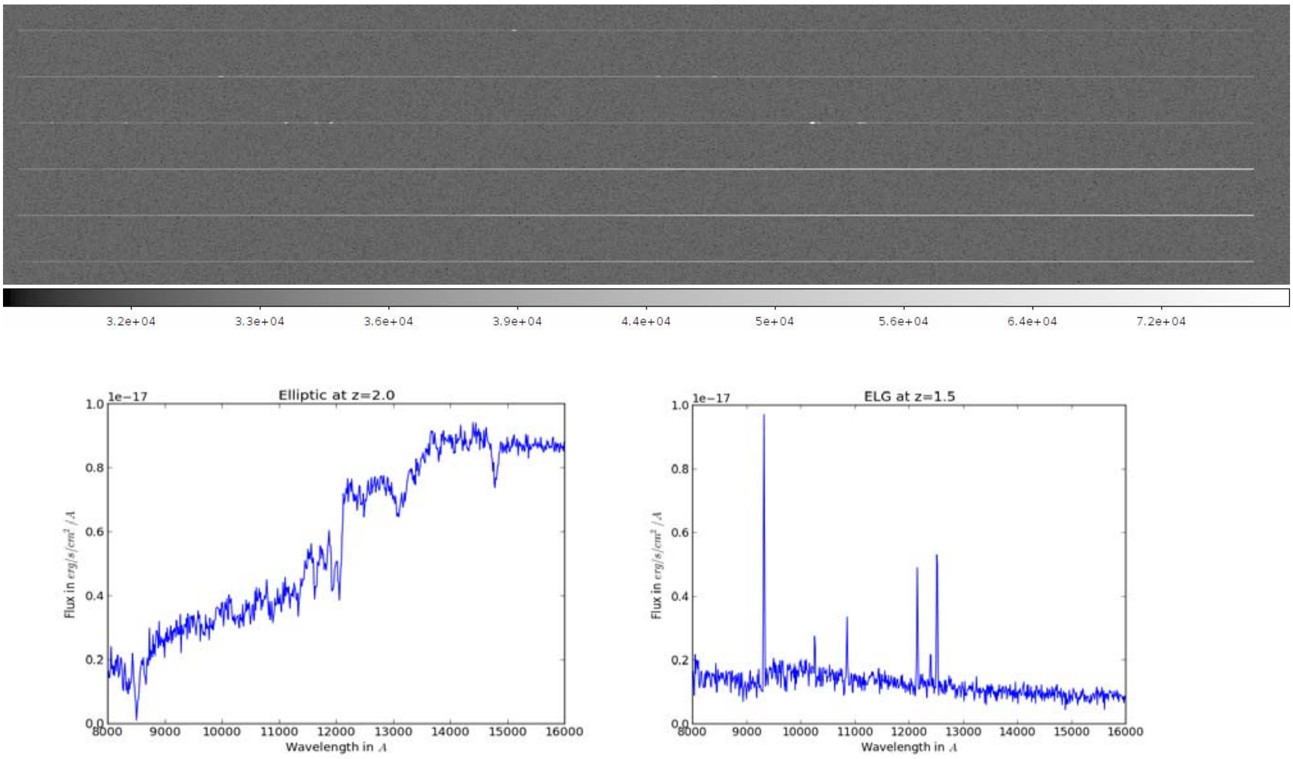

Fig. 7: Pixel simulation; Top: spectra recorded on CCD ; bottom: 1D spectra extracted from the image, at left elliptical galaxy at redshift 2, at right emiision lines galaxy et redshift 1.5

SURVEY OF FAINT GALAXIES

In the last five years, an incredible amount of effort was dedicated to assemble large and deep photometric NIR surveys in order to study the galaxy formation at z>1. But such dedicated effort hasn't been conducted yet for NIR spectroscopic surveys. NIR spectroscopic surveys are still extremely parse and currently limited to few dozens of galaxies (mainly using MOIRCS and FMOS on the Subaru telescope, and the WFC3 slitless spectrometer). In the next years, KMOS on VLT and MOSFIRE on Keck will efficiently gather NIR spectra. But even with these instruments, we will not be able to assemble galaxy samples with more than few thousand galaxies to study the high-z Universe.

The next decade will see real progresses. Large and deep spectroscopic NIR surveys will be conducted with the EUCLID and JWST space telescopes. We propose an approach which brings the gap between the expected EUCLID and JWST surveys, in term of sensitivity and field-of-view. In a 3 years mission, we could:

1. **cover a large field of view of 5 deg^2**, which is far beyond the area possibly covered by JWST. We propose to observe the common deep fields, i.e. COSMOS, UDS, GOODS and the future HCS deep fields, which will have the required depth in NIR photometry to preselect our targets.
2. **detect the continuum of H<25 sources** (see ETC paragraph with the configuration considering a 50 x 3600s exposure time), far beyond the planned EUCLID Deep survey (H<23-24 for emission lines and star-forming galaxies).
3. **gather a sample of 200,000 galaxies in NIR spectroscopy** considering 3 years missions with 500 spectra per pointing, which is 2 order of magnitude larger than what will be done with KMOS or MOSFIRE. We note that the survey strategy could be easily tuned to increase significantly this number (a fraction of micro-mirrors could be dedicated to brighter objects with a smaller exposure time, i.e. a constant SNR survey).

Such survey will be ideal to bring some definitive answers on crucial aspect of galaxy formation and evolution, as detailed below.

A detailed analysis of the 1<z<3 Universe

The redshift range 1<z<3 (the Universe was between 2 and 5 Gyr old) corresponds to the most active period in the galaxy evolution: the global star formation rate in galaxies peaks at z~2 (Cucciati et al. 2012); 60% of the stellar populations in elliptical galaxies are assembled at this period (Ilbert et al. 2010); the merger rate reaches a maximum at this period (Lopez-Sanjuan et al. 2012, Conselice et al. 2013). But all the studies at 1<z<3 are extremely uncertain since they rely almost exclusively on the photometry, without reliable distance measurements. Few of these studies rely on small spectroscopic samples (<1000 sources), which are highly biased toward star-forming and massive galaxies. We need a large, deep and representative spectroscopic survey at 1.3<z<3 if we want to study the Universe in one of its most interesting phase. The challenge is to get NIR spectroscopy since most of the spectral features are redshifted at λ>0.8μm. Such survey can be only done with an efficient NIR spectrograph, i.e. using a dedicated space telescope.

The largest deep spectroscopic sample obtained with powerful visible Multi-Object Spectrograph VIMOS contain 10^5 galaxies at intermediate redshift 0.2<z<1.2 (e.g. Guzzo et al., in prep). Our proposed NIR spectroscopic survey will contain 200,000 galaxies over 5 deg^2. Therefore, **we will be able to build a sample at 1.3<z<3 which is equivalent to the best survey currently done at 0.3<z<1.3.**

With our proposed survey, we will:

1. create a mass limited sample reaching 10^9Msol at z<3.2 (the OII line still observable)to study how the stellar populations are assembled into galaxies**.**

2. The OIII lines will be visible out to z=2.2. Therefore, we will be able to establish standard diagnostic like the metallicity, or the age of the stellar populations for 10^5 galaxies out to z=2.2. This is crucial to understand the interplay between the galaxies and their interstellar medium.
3. We will get spectra for 50% of the galaxies at H<25. With such coverage, we will be able to reconstruct the large-scale structures, and understand the link between the galaxies and their environment in the early Universe.

Primordial galaxies

In the last few years, a huge amount of work has been dedicated in finding 6<z<10 primordial galaxies. Through the detection and characterization of these galaxies in the first billion year of the Universe, we can constrain the accretion rate of gas onto galaxies at early times and the growth of the early generations of galaxies. We can also infer how their emitted UV radiations contribute to the reionization of the Universe.

The detection of primordial galaxies is based on the Lyman_α emission lines or/and the Lyman break identification. The z>6 galaxies selected today in photometry by the Lyman break selection technique show a H band magnitude fainter than H>28 (McLure et al. 2013). Therefore, we will not be able to get the continuum for this population. But we should be able to get the Lyman_α emission lines. With our wavelength covered range [0.8-1.6 μm], we will detect this feature from redshift 6 to redshift 12. Vanzella et al. (2011) confirmed spectroscopically two z~7 galaxies which have a lyman_α flux of $2*10^{-17}$ erg/s/cm^2. Such emission lines will be easily detected with our exposure time, which allow us to detect 10 time fainter emission lines. Numerous possible z>6 candidate already exist in our field. We will target the possible primordial galaxies. **Our goal is to build a Lyman alpha luminosity function at z>6 and put some constrain on its shape.**

Galaxy-AGN co-evolution and formation of the elliptical galaxies

The masses of the black hole correlate extremely well with the bulge masses of their host galaxy. Moreover, powerful energetic sources are required to shut down the star formation into massive galaxies in "state-of-art" simulations (e.g. Bower et al. 2006, Croton et al. 2006). One of the most popular scenario explaining the elliptical galaxy formation is based on the galaxy-AGN co-evolution: a major merger triggers a huge starburst with a star-formation >1000 Msol/yr ; then, a massive black hole will be fed at the galaxy center and powerful jets will shut down the star-formation ; it will result a "quiescent" massive galaxies with an elliptical morphology (see the figure below from Hopkins et al. 2009).This scenario is extremely interesting because it creates an evolutionary link between the most interesting sources in the Universe. This scenario could explain the properties of the "today" massive elliptical galaxies.

But such scenario is extremely challenging to demonstrate observationally. "BATMAN flies" is a powerful telescope to tackle this problem. Indeed, the micro-mirror can be oriented toward the most interesting sources, which are extremely faint.

Our proposed survey is probably the unique way to assemble the required samples to validate this scenario:

1. Being extremely sensitive in NIR, we will obtain spectra for all the elliptical galaxies at 0<z<3 with M>10^9Msol, by observing the Balmer break. Such study requires to observe the NIR continuum of the sources, that we will obtain with our telescope.
2. We will obtain the redshift of sub-millimeter galaxies (the "starburst" phase in the scenario). Less than a hundred of such sources are know today. We will also be able to follow future ALMA sources.

3. because of the good resolution of the spectra, and the large covered wavelength range, we will observe OIII out to z<2.5. We will be able to apply standard diagnostic to isolate the AGN (PBT diagram, Kewley et al.) at z<2.5.
4. we will target all the possible galaxy pairs in the field to confirm their physical association, which will be used to compute the merger based on galaxy pairs statistic.

Therefore, we will link the merger rate, and the density evolution of the elliptical galaxies, starbursting galaxies and AGN. With such dataset, we will be able to establish a link between the redshift evolution of these populations and validate/infirm the scenario "merger ➔ starburst ➔ AGN ➔ quenching ➔ elliptical" (Fig. 8).

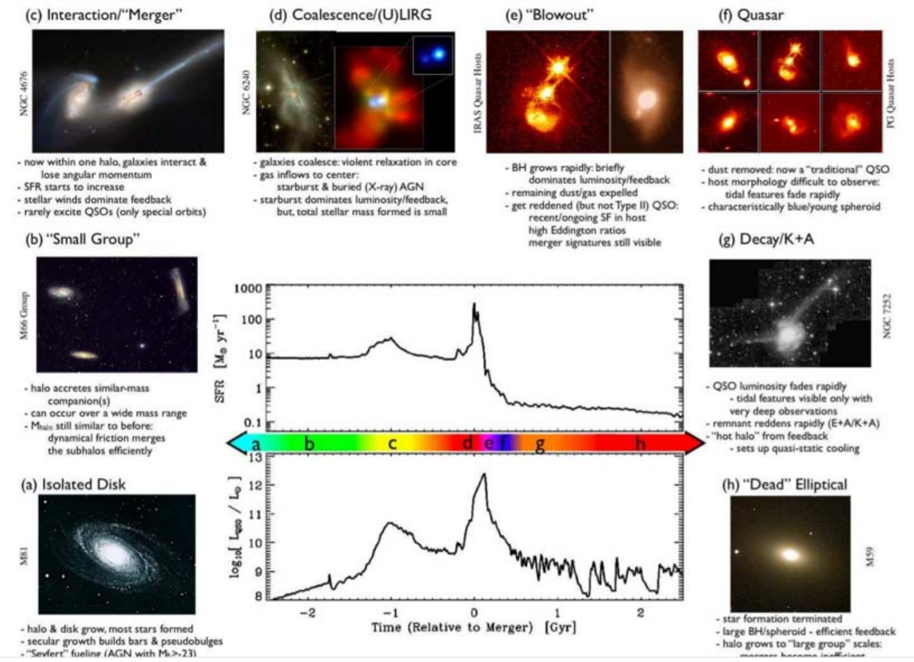

Fig. 8: galaxy evolution scenario "merger ➔ starburst ➔ AGN ➔ quenching ➔ elliptical"
(simulation by Hopkins et al. 2009)

IR SURVEY OF STELLAR CLUSTERS IN NEARBY XUV GALAXIES

GALEX has discovered extended UV emission around otherwise normal nearby galaxies (Gil de Paz et al. 2005, Thilker et al. 2005, 2007, Boissier et al. 2007). 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 (e.g. Koda et al. 2012) but a difficulty is the intrinsic variability in the SFR history in such diffuse regions (see e.g. Boissier et al. 2008 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 if 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 Figure 9: 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 (Fouesneau & Lançon 2010). 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.

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 (e.g. Koda et al. 2012). 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 Thilker et al. (2007), 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. 10 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. 2012 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 a 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.

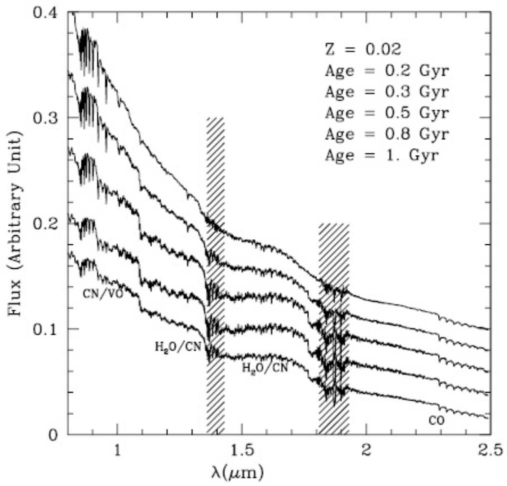

Figure 9: Evolution of the NIR spectra of a stellar cluster (Fig 13 of Mouhcine & Lancon 2002)

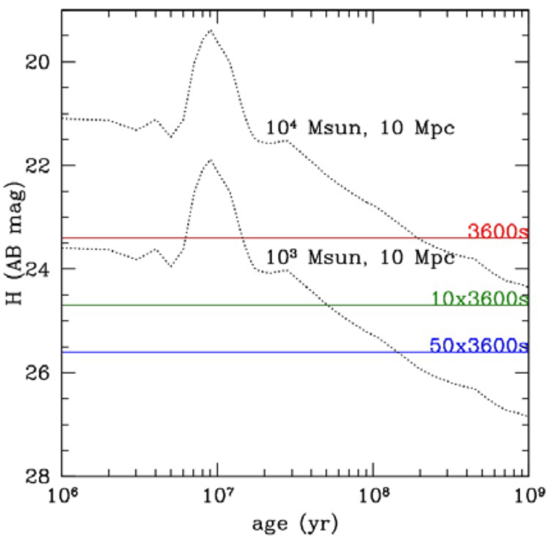

Figure 10: H-band magnitude of 10^3 or 10^4 stellar clusters as a function of time, with horizontal limits of our surveys, for a galaxy at 10 Mpc and a variable number (1,10,50) of "unit" exposures (3600 sec).

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 (Jewitt & Luu 1993); 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.

A complex dynamical sculpting

After a few years only, several dynamical classes were identified (see Gladman et al 2008 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, Malhotra 1995, the Nice Model, see Morbidelli et al. 2008, the "Grand tack" model by Walsh & Morbidelli 2011)

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 Doressoundiram et al 2008 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 (Barucci et al, 2011), 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, see Fig. 11, 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.

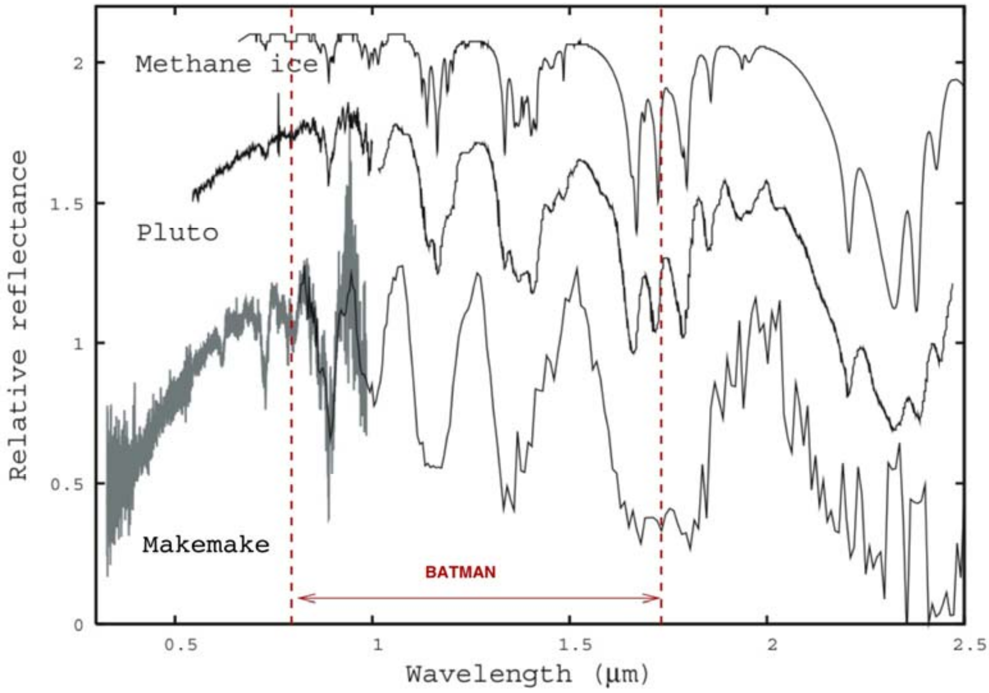

Figure 11: a visible-NIR spectrum of two methane-rich objects: Pluto and Makemake. Various absorption bands are measured in the 1-2.5 micron range. The vertical dotted lines show the interval that will be explored with BATMAN, at a much higher SNR and for 700 objects (instead of the current 70). Adapted from Licandro et al. 2006

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” 2008 book, for a review).

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 (Schaller & Brown, 2007). 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?

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 matrix 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.

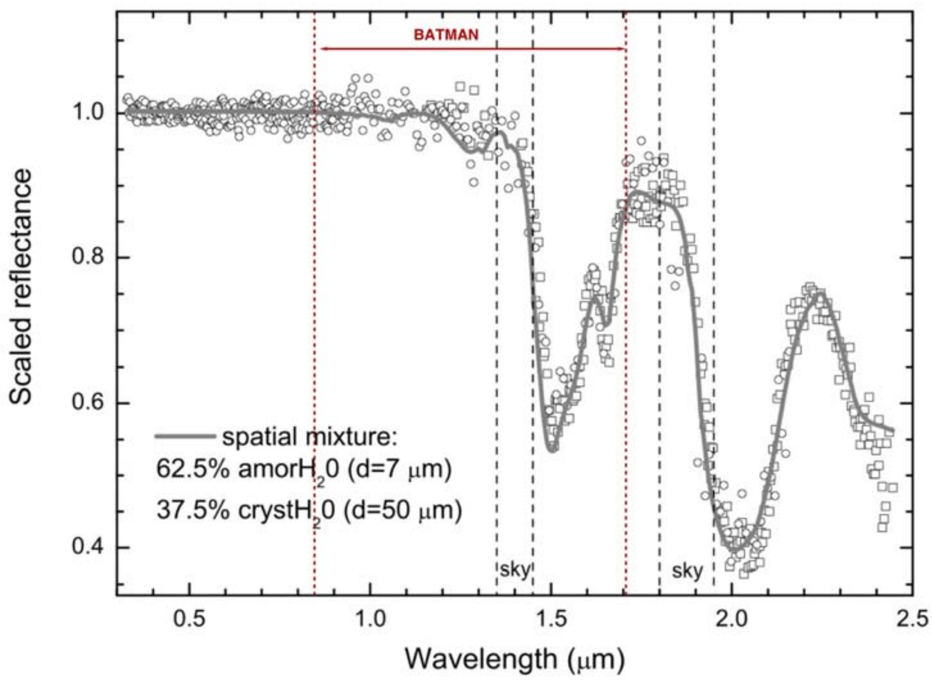

Fig. 12: visible-NIR spectrum of dwarf planet Haumea, showing large absorption bands of water ice. The vertical dotted lines show the interval that will be explored with BATMAN, at a much higher SNR and for 700 objects (instead of the current 70). Adapted from Pinilla-Alonso et al. 2009

Water ice displays a large absorption feature at 1.5 microns, with a ~0.2 micron width (see the example of Haumea, Fig. 12), 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 (Merlin et al. 2009, see also Fig. 11). 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)

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

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

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 operations.**

EARTH OBSERVATION SCIENCE CASES

In Earth Observation, oceans and coastal line exploration will benefit from programmable slits for removing bright objects like clouds from the scene, and optimize the signal to noise ratio according to the observed field of view. Another promising instrument is a wide field programmable spectrograph where both spatial and spectral features of the scene are addressed.

Contacts with Earth Science researchers have been established and scientific cases are under construction.

LA COMMUNAUTE SCIENTIFIQUE IMPLIQUEE EN FRANCE

The Science Group will be built in the coming weeks. The developed science cases (galaxy formation and evolution, nearby galaxies, outer solar system) represent the interests of a large part of the astronomical French community.

SCENARIO DE MISSION

The proposed mission is scheduled for 4.5 years with dedicated survey times:

3 years for faint galaxies

1 year for nearby galaxies

0.5 year for Trans-Neptunian Objects of Kuiper Belt

CONTEXTE ET COLLABORATIONS

Our proposal addresses a new type of space instrument with unique performances. Our robust design is based on high TRL components able to be implemented in a short period of time.

Our team has a strong background on MOEMS-based MOS instruments, being involved in numerous CNES and ESA studies, both on components side as well as instrument side, including micromirror arrays studies, programmable diffraction gratings studies, JWST-NIRSpec and EUCLID-NIS.

Our team is involved in on-going CNES and ESA studies on MOEMS-based instruments for Space and Earth Observation. NASA has begun studies on DMD-based space instruments (Robberto) and may be associated at some stage.

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