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Nuevo Espectrómetro Fabry-Perot de Extrema Resolución

A High Resolution Wide Field 2D Spectroscopic Module for OSIRIS on the GTC

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NEFER

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Fig. 1 Members of the developing team at the GTC observer’s room.

NEFER

SUMMARY

We are presenting to the GTC community a new module, NEFER, incorporated into the OSIRIS tunable filter (TF) on the GTC which supplies OSIRIS with a Fabry-Perot (FP) scanning mode, effectively converting it into a 2D high resolution spectrograph. NEFER, which will act as a “visiting module” fully supported by the proposers, giving the GTC unique capability among telescopes of its class to perform a powerful range of combined observations of the kinematics, dynamics, and metallicity of extended objects, notably complete galaxies from the local universe to the epoch of galaxy formation. This document describes the science drivers, the coupling of the module to the GTC, and the results found from the observations done during the commissioning.

NEFER reach a spectral resolution close to 10,000, initially in two principal spectral ranges: 6300 to 7,000 Angstrom and 8,000-9,000 angstrom, over a free spectral range covering some 500 km/s at the Hα wavelength of 6563 Angstroms and fit into the unvignetted field of OSIRIS (7 x 7 arcmin) with seeing-limited spectral resolution over a pixel size of 0.124 arcsec..

The module has been implemented on the GTC in its first phase last December 2017. In the first phase the FP etalon (from the IA-UNAM) was incorporated into OSIRIS, using the existing detector and adapting its own controller system.

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1. Theory of Fabry-Perot Interferometers

A Fabry-Perot interferometer (FP) is a system of two parallel, semi-reflecting glass plates that produces interference rings of extended emission line sources such as spiral galaxies and nebulae. If the gap between the two plates remains fixed it is called “FP etalon”, otherwise is a FP interferometer.

The relevant geometry is depicted in Figures 2 and 3 where it is appreciated the one-to-one correspondence of the points corresponding to the extended source and the interference rings. That is why a FP system is an “imaging” system providing point-to-point spectra of the extended source.

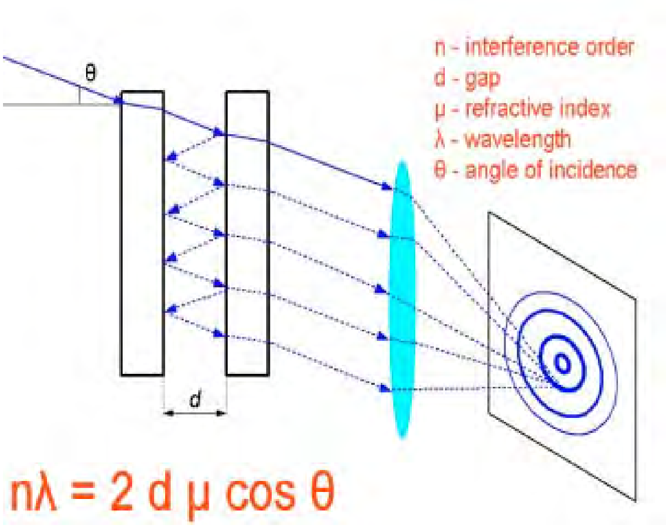

Fig. 2 A FP system and the relevant formula of maximum of interference rings.

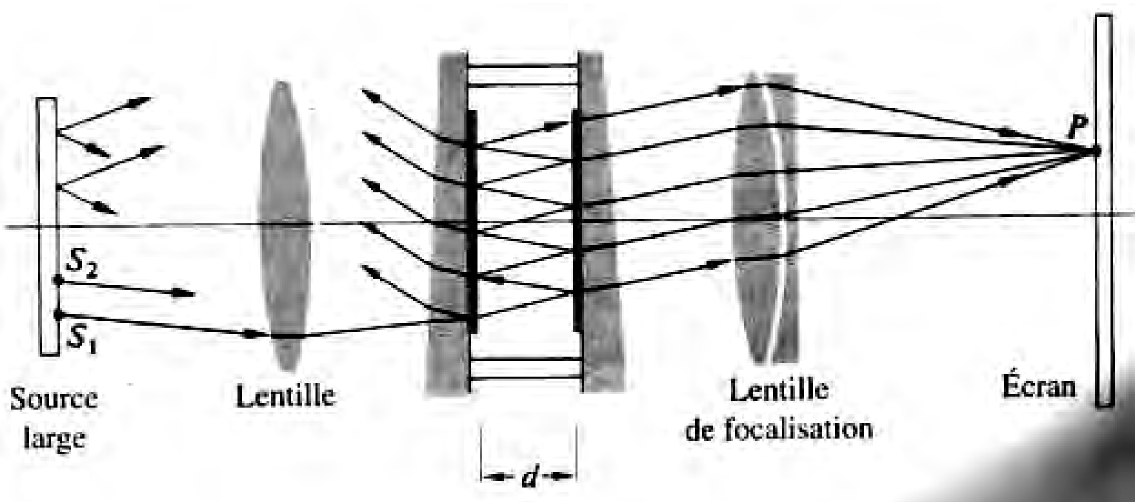

Figure 9.43 Étalon Fabry-Pérot.

Fig. 3 A specific optical design (after Georges Courtès) of a FP etalon.

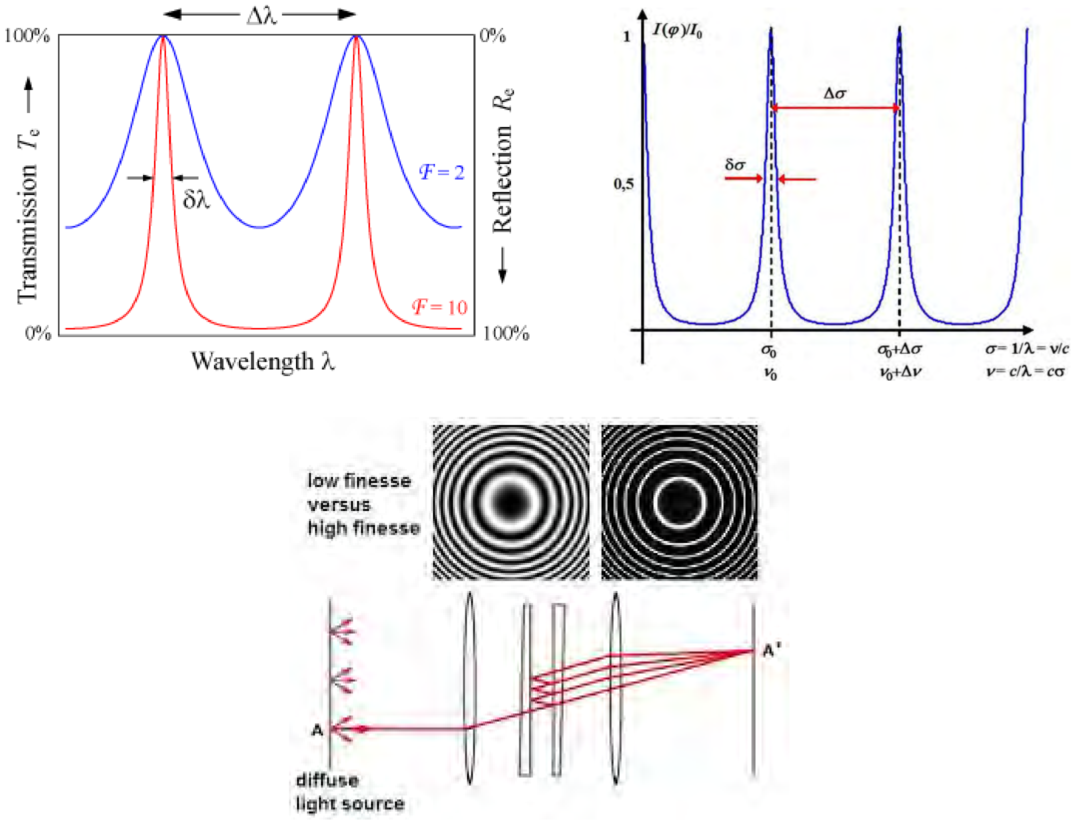

Fig. 4 Illustration of the main parameters of a FP etalon: The Finesse $\mathscr{F}$, and the Free Spectral Range Δλ.

Where the Reflective Finesse, Resolution and Free Spectral Range are given by:

$$\mathscr{F} = \Delta\lambda/\delta\lambda = \Delta\sigma/\delta\varsigma \qquad (1)$$

$$\mathscr{F} = \pi R^{1/2} / (1 - R) \qquad (2)$$

$$\Delta\lambda = \lambda / n \qquad (3)$$

$$\mathscr{R} = n\, \mathscr{F} \qquad (4)$$

Where R is the reflection coefficient of the semi-reflecting plates. From the figures we see that the larger is the reflection coefficient, the sharper is the interference ring system.

The interference pattern (i.e., the rings) is given by the Airy Function:

$$I(\lambda) = \frac{1}{1 + \frac{4R}{(1-R)^2} \cdot \sin^2\left(\frac{2\pi}{\lambda} \cdot n_{cavité} \cdot e\right)}$$

Being here $n_{cavité} = \mu$ (the refraction index between the semi-reflectant plates) and e = d (the gap separation).

Very important:

I is maximum when $\sin(2\pi\, d\cos\theta/\lambda) = 0$, then $I = I_0$, i.e., the light is fully transmitted even if the reflection coefficient R approaches 100 %!!!

For a bright ring:

$$2\ \mu\ d \cos\theta = n\lambda \qquad (5)$$

Thus all the light is concentrated on those interference maxima.

2. The Scanning Fabry-Perot Interferometer

A fixed-gap FP interferometer or etalon has its limitations because it does not cover the whole 2D field of the extended source; instead it acts like a strainer "straining" only the rings corresponding to the interference maxima (however it is still more advantageous than a long-slit spectrometer!).

In order to get the information for the whole extended source the plate separation or gap, d, should vary by scanning a very small quantity corresponding to a Free Spectral Range (Eq. 3). This is achieved by introducing piezoelectric separators between the plates.

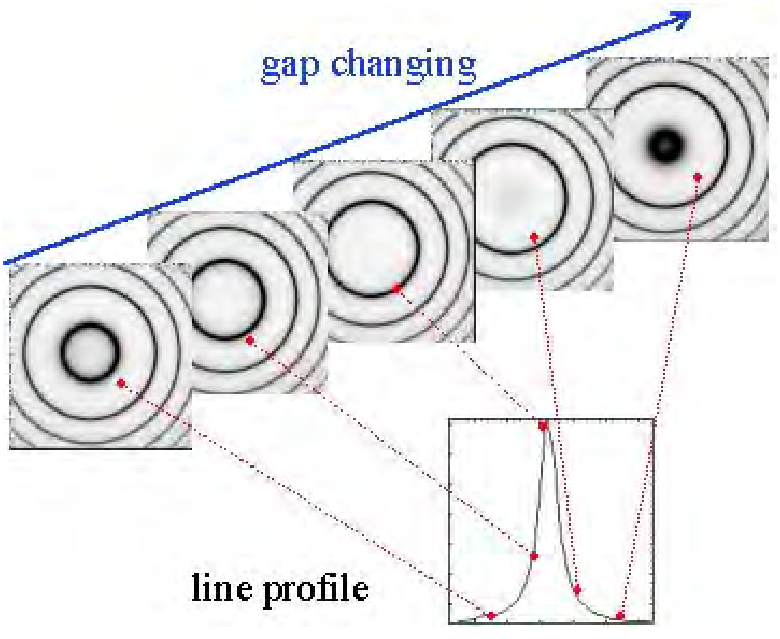

Fig. 5 Scanning the gap in a scanning FP interferometer.

In Figures 5 and 6 it is illustrated how acts a scanning FP interferometer in building an emission line profile for every (x, y) point in the 2D field of an extended source. Also, it is seen how a data cube is built.

Fig.
6

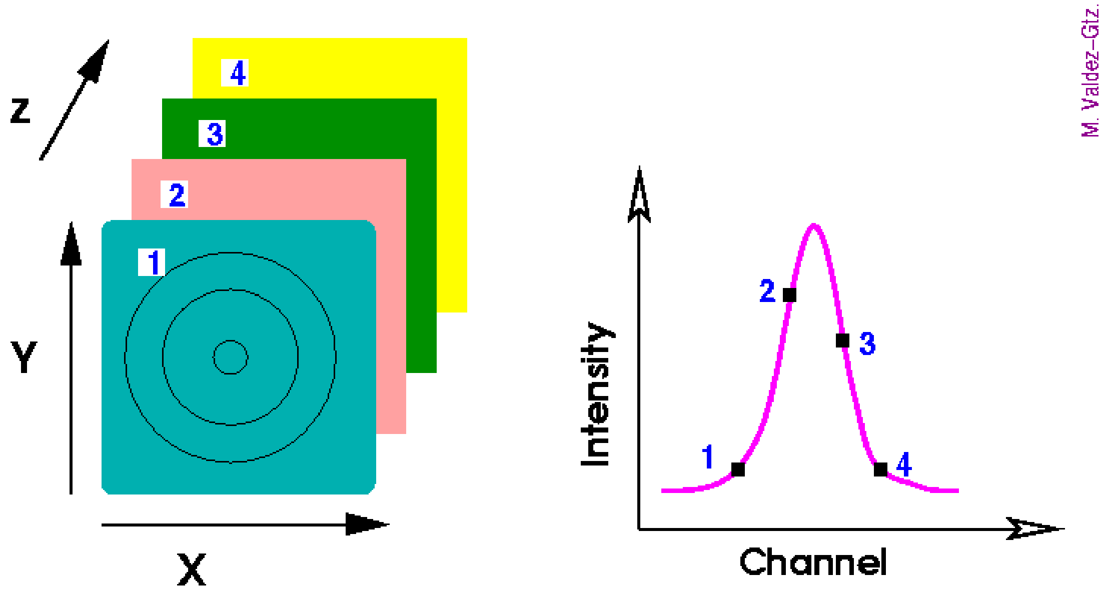

Fig. 6 The scanning FP principle and the construction of an “interference” or data cube.

The FP scans across the whole Free Spectral Range with a regular step given by: Number of channels = 2 $\mathscr{F}$ (taking into account Shanon’s rule). In this way an object or data cube is produced consisting of x, y, the CCD coordinates and z (the gap spacing related to the wavelength and, by the Doppler Effect with the velocity).

The steps followed to produce a velocity cube are the following:

1. First it is necessary to get a calibration cube (Fig. 7). This is done using a calibration lamp (for example Neon) illuminating an extended diffuse and uniform screen passing through the same optical path as the object and scanned in the same way too.
2. The calibration cube allows us to produce a Phase Map (Fig. 8) which is a 2D image where each pixel value corresponds to the shift in wavelength (or velocity) of the emission line center in the calibration data cube due to the geometry.
3. The data cube, consisting of the scanned interferograms of the object (Fig. 9) is thus callibrated in wavelength using the Phase Map and a Velocity cube (also called lambda-maps) is produced (Fig. 10).

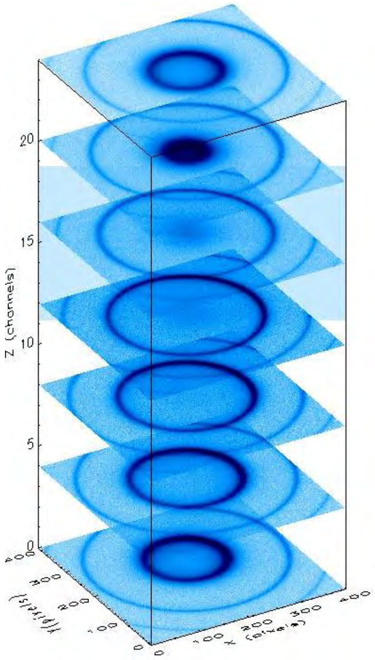

Fig. 7 Calibration cube.

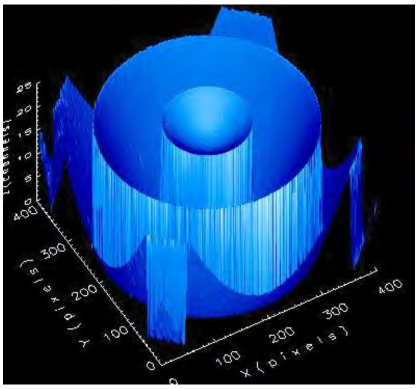

Fig. 8 Phase map.

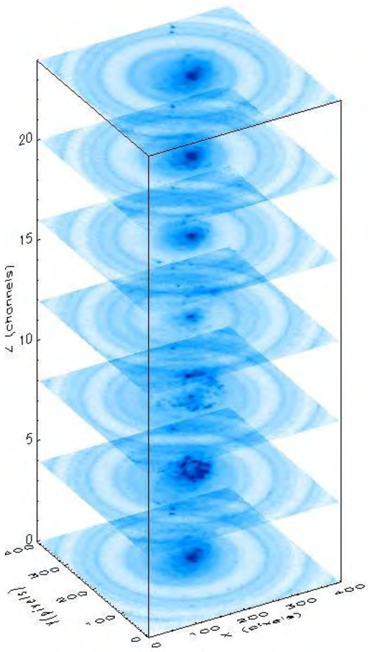

Fig. 9 Original data or interferogram cube

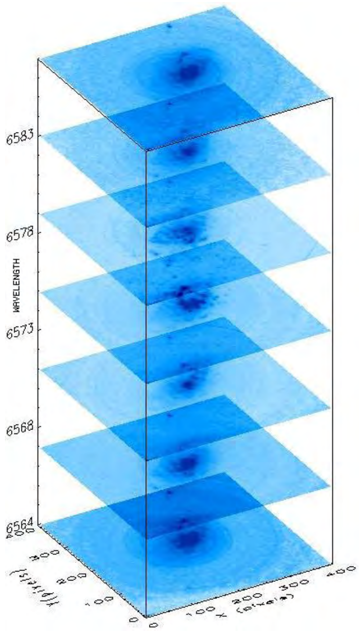

Fig. 10 Velocity cube.

Further information on scanning FP can be find in Plana et al. http://haro.astrossp.unam.mx/indexspm.html or A. Moiseev (see the link https://www.sao.ru/hq/lsfvo/devices/scorpio/ifp/cubes.html).

FP Spectroscopy: A High Spectral Resolution Profile for Each Pixel

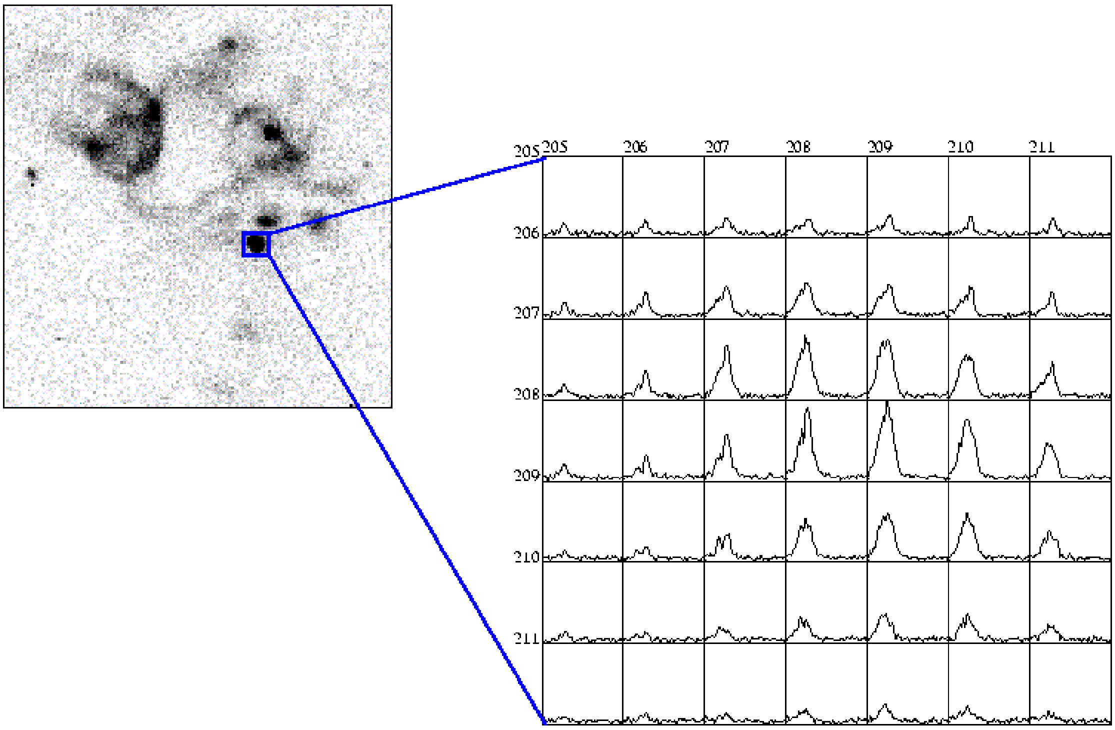

Fig. 11 Left: Part of the PUMA's field of view of a velocity channel of the irregular galaxy IC 1613 showing a complex of superbubbles (Valdez-Gutiérrez et al. 2001). Right: Pixel per pixel Hα line profiles of the supernova remnant marked by a blue square in the image to the left. Note the complex internal motions revealed by the velocity profiles.

3. Science Goals

General.

NEFER is essentially directed at problems in astrophysics which can be solved using gas dynamics. This covers a very wide range of subjects, ranging from the phenomena associated with star formation to the phenomena related to late stellar stages (supernovae, planetary nebulae, pulsar's bow-shocks) studied in detail within nearby galaxies, to the galaxy-wide feedback processes which govern the formation and evolution of galaxies on cosmological timescales. It is important to insist that the results from NEFER should be taken in a context normally assigned to radioastronomy, and should not be confused with data from IFU-based spectrometers, which are aimed principally at the stellar components of galaxies. NEFER performs, for the ionized gas the same tasks as ALMA for molecular gas, and the VLA and SKA for neutral gas. Indeed one of its most powerful assets is direct comparison and combined use of data from all these instruments for the three principal components of the interstellar and intergalactic media. We give a brief overview here of some key types of observations.

Low redshift galaxies.
To understand galaxy evolution it is just as important to study nearby galaxies as to go to high redshift (<u>though with NEFER we aim at both</u>). This is because the high linear resolution obtained locally is the only way to explore and quantify the mechanisms which have governed all the evolutionary processes from the earliest times, but are beyond our observable reach at high z. Among the most important, and still only partly understood processes are massive star formation and feedback, and the equilibrium between them which has governed the stability of galaxies since their birth.
The areas in the local universe where NEFER will ensure strong progress include,

Galaxy-wide problems:
Quantification of the resonant structure of galaxies which governs the build-up of their structures (discs, bars, bulges, and pseudo-bulges),
Measurement of gas flow along bars towards galaxy centres, and in the circumnuclear zones towards the supermassive black holes,
Observations of gas interchange and inflow induced by mergers, both major and minor, during the evolution of galaxies,
Observations of outflow, from the circumnuclear zones of galaxies, notably those with AGN, and from the full discs of galaxies, which enrich the intergalactic medium (IGM) with metals,
Combination of AGN excitation and ionization diagnostics with gas kinematics,
Observations of the distribution functions in mass, luminosity, radius, and velocity dispersion of gas clouds (in the ionized, neutral, and molecular phases) yielding key information about the parameters which govern the initial mass function of stars, and its variability in space and time These observations can also yield new ways of measuring cosmic distance.

Understanding key physics:
Kinematic detection of superbubbles around OB associations, their interaction with the surrounding disc ISM, and halo ISM. The latter leading to an understanding of how gas inflow to halos from outside a galaxy can maintain star formation over cosmic timescales.
Physical diagnostics of supernova remnants, and their role in accelerating cosmic rays.
The dynamics of the gas flow in planetary nebulae at high resolution.
Gas flows and turbulence in individual HII regions.
These detailed studies at high linear resolution will be made with Local Group galaxies and even occasionally in the Milky Way itself. All of them need the 2D field at high spatial and spectral resolution with the depth needed to separate out multiple component line systems, a key feature of FP's such as NEFER.

Intermediate redshift galaxies
Investigating mass assembly in galaxies is now possible with 10m class telescopes.
Much of the work on galaxy assembly has been carried out on gas poor galaxies with old stellar populations, partly because the observations are less complex and partly because it is often assumed that these galaxies have done less to destroy the imprints of their construction. With NEFER we can take powerful steps towards incorporating gas rich galaxies into the evolutionary structure, which is in practice vital to understand processes. This entails studying gas and stellar kinematics, dynamics and chemistry of intermediate redshift galaxies in different environments,(clusters, groups, field). This means studying inflows and outflows of baryons in the circumgalactic medium, the gas rich region around galaxies, inside their dark matter halos, at scales between 10 kpc and 200 kpc using e.g. absorption lines, such as those detectable in faint objects which have typical velocity dispersions of 10-20 km/s and which show multiple components requiring high spectral resolution and high sensitivity to separate them. The large field of view of NEFER matches cluster sizes and will allow us to observe tens or even hundreds of targets per field.

High redshift galaxies
One fundamental type of observations would put NEFER into a leading position for high redshift galaxy work. Weak Lyman-α emission lines are expected to be emitted by the progenitors of most types of normal galaxies. At low spectral resolution even an instrument on a 10m class telescope is sky limited in the optical range, while the resolution permitted by NEFER allows us to resolve and eliminate the relatively bright night sky lines, and fully exploit the ability of a large telescope to detect sources with faint, extended emission. The range of

predicted detectable Ly-α emitters per arcmin per resolved range in redshift δz lies between 0.5 and 5, so that a very sensitive 2D spectrometer with a field of view of over 50 $arcmin^2$ should make major progress. Very deep high resolution observations on preselected dense Lyman-α fields will be needed to study the complex dynamics of this resonance line, and hence the behaviour of the populations of these distant galaxies.

4. Module design

The module design is especially simple, because OSIRIS is being used in the same configuration as the existing Tunable Filter (TF) mode. The only difference with NEFER is the substitution of the TF etalon with a scanning FP etalon, and the substitution of the existing filters with narrow band blocking filters to define the uncontaminated free spectral range. The FP controller, known as CS 100 is inserted in the rack of OSIRIS controllers. The control of the FP scans in order to acquire the data and calibration cubes are given by means of an added software commanded by the GTC technical staff. The team has purchased one scanning FP interferometer, one CS 100 controller and several narrow band interference filters. These items are described in the following but it is important to take into account that other scanning FP and/or filters could be acquired in the future.

In this phase of the module development NEFER uses the OSIRIS CCD detectors.

The scanning FP interferometer
This is inserted in OSIRIS at the place of the blue TF.
Manufacturer: ICOS (UK) (formerly Queensgate Ltd.) which is the manufacturer of the existing TF's in OSIRIS.
Model: ET100, the in the same range as the TF, and ***has the same mechanical envelope*** as the OSIRIS TF's.
Clear aperture: 10 cm
Wavelength range: optimized for 6570 A through 8500 A

Fig. 12 Introducing NEFER scanning FP into OSIRIs wheels.

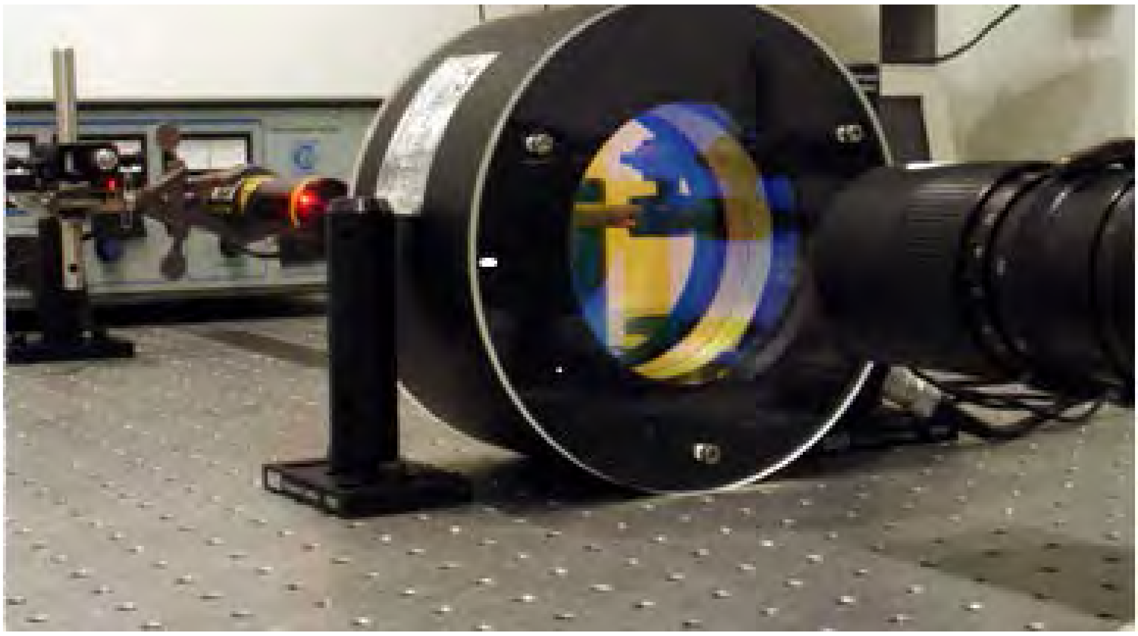

Fig. 13 NEFER’s scanning Fabry-Perot.

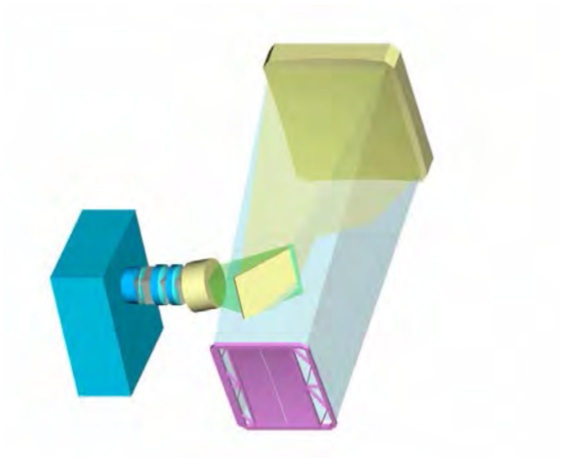

Fig. 14 The blue TF is replaced by the scanning FP into the collimated beam. Order sorters are placed in the filter wheels.

The interference filters
These are required to isolate the individual orders of interference of the FP (blocking filters). A subset has been purchased with mechanical specifications already designed to fit the OSIRIS filter wheel, and these are shown in Table 1.

Line	**$\lambda_{central}$**	**(z)**	**δλ**	**Diameter**	**Transmission**
Hα and [NII]	6570 A	0	50 A	14 cm	82%
[SII] or Hα redshifted	6716 A	0.02	78 A	14 cm	92%
Hα redshifted	6615 A	0.01	76 A	14 cm	92%
Hα redshifted	6665 A	0.015	78 A	14 cm	91%
Hα redshifted	8600 A	0.3	50 A	14 cm	91%
Hα redshifted	9200 A	0.4	50A	14 cm	91%

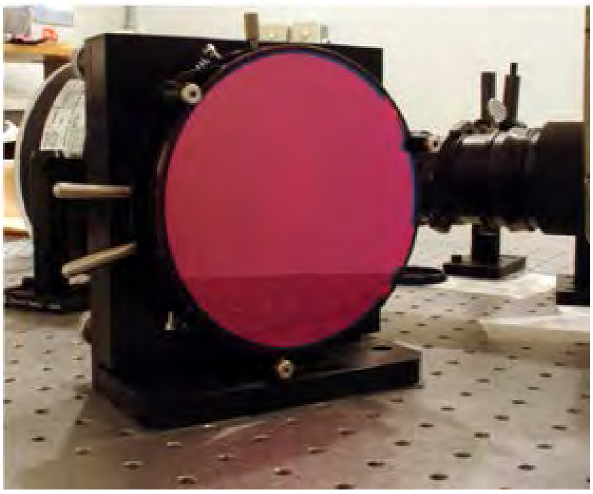

Fig. 15 One of the NEFER's narrow band filters.

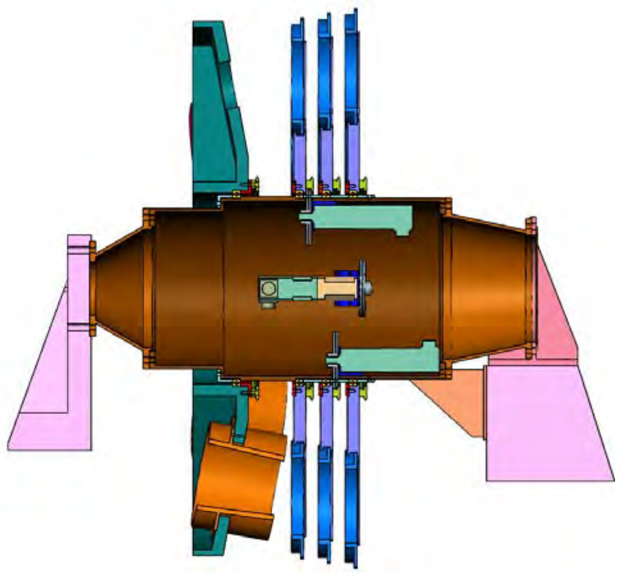

Fig. 16 Location of the OSIRIS filter wheels (blue components) relative to the wheel where the TFs and grisms are placed (yellow component). As it can be seen, the filter wheels are inclined 10 degrees relative to the TF (or scanning FP interferometer) location.

5. Calibration

As can be noted from Fig. 14, there is an inclination of 10.5 degrees between the filter wheel where the narrow band interference filters are placed and the location where the NEFER scanning FP interferometer is located. This inclination between isolating filter and FP has as effect a gradient in the filter central wavelength along the FOV of the detectors.

We have studied this shift in wavelength for all the filters listed in Table 1 by obtaining long-slit Ne spectra along the FOV using the OSIRIS grism of R=2500R.
We find that the gradient in central wavelengths is such that OSIRIS CCD1 runs from redshifts to blueshifts for CCD2. Thus, at the moment of pointing with the telescope the object of interest it is important to have a previous knowledge (if possible) of the velocity field in order to orientate the object in such a way that redshifted wavelengths fall in CCD1 whereas blueshifted lambdas fall in CCD2. This, of course, if the object is so extended that occupies the entire FOV.
For each of the filters it is possible to get a Ne calibration cube because in CCD1 it is possible to identify a Ne line to do the calibration.
The following table gives the Ne wavelengths of the calibration lines:

Filter	Ne calibration Line
6570 A	6598.9528 A
6716 A	6717.0430 A
6615 A	6678.2766 A (in all the FOV)
6665 A	6678.2766 A (in all the FOV)
8600 A	8591.2583 A (in all the FOV)
9200 A	9220.0598 A (in all the FOV)

6. Instrument Performance

Thorough tests of the components (filters and scanning Fabry-Perot) have been already done. In Rosado et al. (2008; Proc. of SPIE Vol. 7014 70145M-1) and in Bernal et al., Proceedings of the SPIE, Volume 7735, id. 77354M (2010) we give the description.

At the telescope we have had allocated some diurnal and nocturnal time in December 2017 and March 2018. During the commissioning we determined the remaining main parameters of the NEFER´s scanning FP interferometer wich we can list in the following table:

NEFER parameters

- **Manufacturer: ICOS (Queensgate,Ltd.)**
- **Model ET100**
- **Clear Aperture 100 mm**
- **Wavelength Range 630 to 930 nm**
- **Resolution R = 9552 at Hα**
- **Interference Order 595 at Hα**
- **Measured Finesse 16 at Hα**
- **FP scanning steps 32**
- **Sampling spectral resolution 16 km s^{-1}**
- **Spectral Resolution 0.6894 Å**
- **Free Spectral Range 11.03 Å (504 km s^{-1})**
- **Velocity Accuracy ±3 km s^{-1}**
- **Queensgate Constant 9.2943**
- **Measured Cavity Spacing 195 micrometers**
- **Cavity Scan Range ±2.6 micrometers**
- **Detector 2 CCD 2048x4096 (OSIRIS)**
- **Field of View 7.8 x 7.8 $arcmin^2$**
- **Plate scale 0.254 arcsec pix^{-1} (binned 2)**
- **Filters See Table 1**
- **Calibration line [a]) Ne (6598.95, 6678.28, 6717.04,**
- **8591.26, 9220.06 AA)**
-

! Note that with this velocity resolution the narrow spectral lines typical of the ISM can be separated in complex sources with an effective accuracy better than 3 km/s (exact value S:N dependent).

Limiting sensitivity

- NEFER as a scanning FP interferometer is expected to be a quite sensitive instrument making use of the interference properties described in Sect. 1, Eq. 5 where we note that the intensity transmitted by a FP interferometer could reach the incident intensity even if the reflection coefficient approaches 100% because all the secondary beams reflected inside the gap are in phase and interfere positively.
- Furthermore, the high spectral resolution provided by NEFER separates the night-sky lines from the nebular lines. Thus, NEFER can detect (and obtain the kinematics) even faint nebular emission below the values of the night-sky lines.
- Fig. 18 shows in the right panel the monochromatic image of the galaxy M 82 obtained in March 2018 during the commissioning. It has been obtained from a data cube of 32 channels with exposure time of 60 s per channel. The square depicts a faint zone of the emission with velocity profiles with S/N > 3. In the right panel it is shown an Hα image published in Lehnert et al. (1999). The contours correspond to X-ray emission. The faintest Hα surface brightness corresponds to **3.3 x 10^{-17} ergs s^{-1} cm^{-2} $arcsec^{-2}$**. We see that the monochromatic emission detected by NEFER covers at least that faint emission reported so that we can preliminarily say that NEFER limiting sensitivity is **3.3 x 10^{-17} ergs s^{-1} cm^{-2} $arcsec^{-2}$** for an exposure time of 60s per channel.

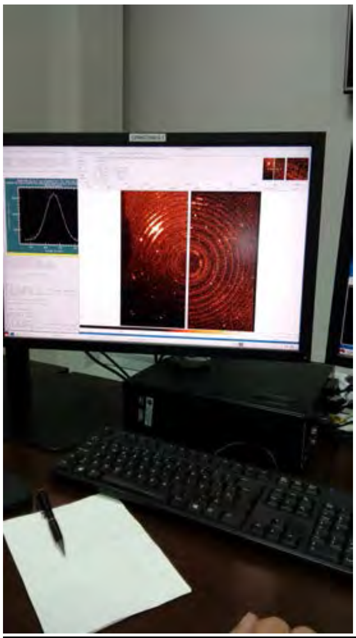

Fig. 17 Screen of the computer during NEFER's first light. Note the two OSIRIS CCDs separated by a central strip and the interference rings for one of the channels.

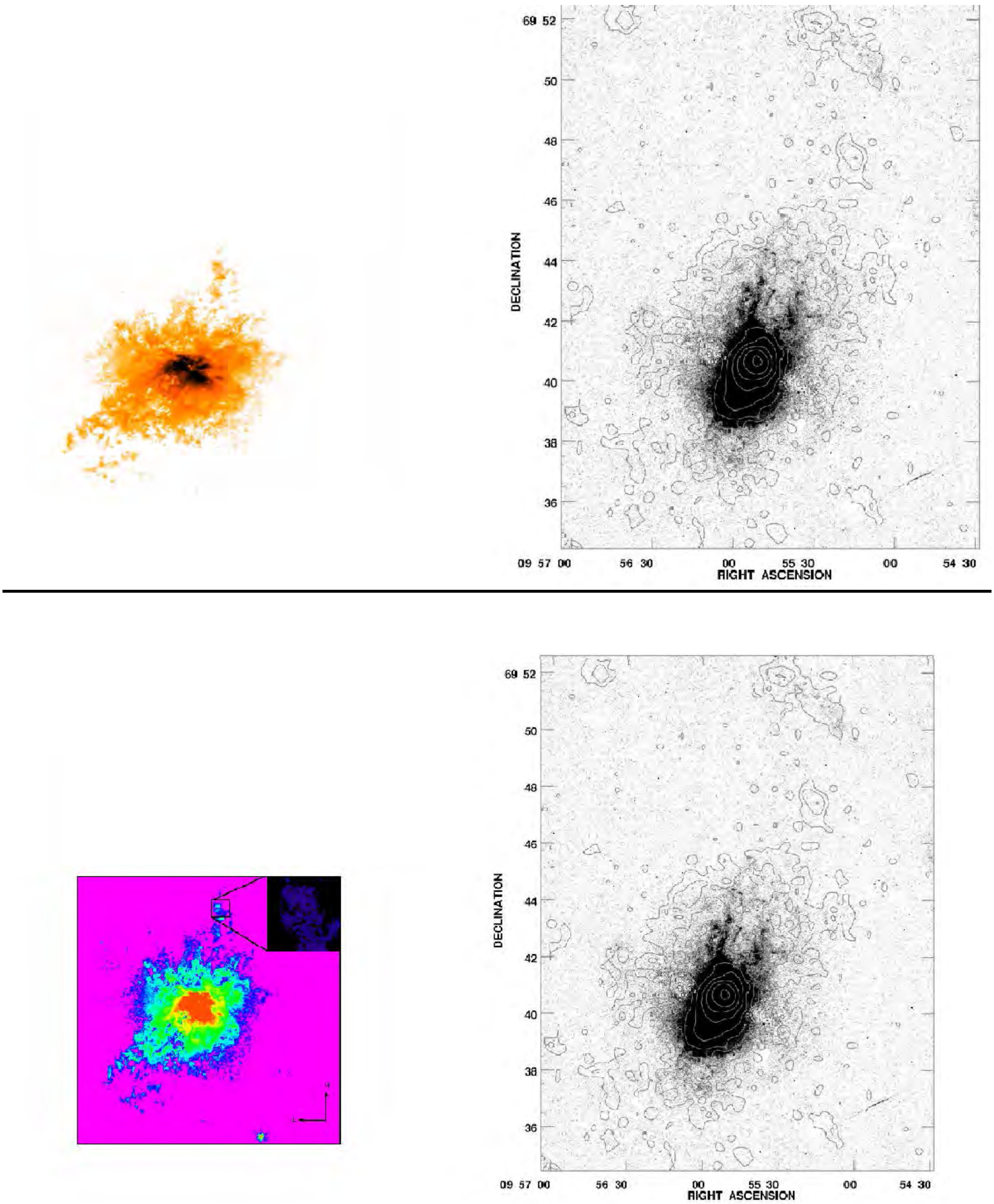

Fig. 18 Left: NEFER's monochromatic image of M 82. The square shows the faintest emission detected with velocity profiles with S/N >3. Right: Lehnert et al. (1999) Fig. 1 showing the Hα emission and the X-ray contours.

7. Observational Routine

As deduced from the values of the instrument performance, the data cubes consist of cubes of 32 channels of the 2 x 2028 x 4096 CCDs dimensions. The central strip between the CCDs should remain. Bias and flat fields should be obtained during the evening. It is also important to ensure that both the calibration cube and the data cube are taken with about the same rotator angle in order to suppress possible gravity effects.

The observer should select the filter among the filters listed in Table 1, according with the redshift of the object. Regarding the calibration, it is recommended to calibrate using the same filter as the observation (in order to reduce phase effects) and using the information about Ne lines passing through the filter as reported in Sect. 5.

NEFER´s team has developed a way to scan properly the Free Spectral Range for each wavelength. The calibration cube could be acquired in the evening before the observation or in the morning after. Data cubes are taken during the observing run and typical values for them are 30s, 60s, 90s and even 120s per channel, ensuring blocks of observing time typical in the GTC.

8. Data handling (reduction software)

Although most of the data reduction can be done using IRAF standard tasks, specific packages are required for the wavelength calibration. There are several software packages developed by the participants in this project for data reduction of Fabry-Perot data cubes. These are: CIGALE (developed by the LAM and U. Grenoble, France), ADHOCw (developed by the LAM, France), packages in IDL and Python (developed by the LAM and U. Montreal) that are of public use, well documented, and thoroughly tested in years of observational projects at the telescope.

Links to retrieve some of the mentioned packages are:

1. http://www.astro.umontreal.ca/~odaigle/reduction/index.html [1]
2. ftp://ftp.oamp.fr/pub/pamram/ADHOCw.zip

The header of each of the cube's channels is of the type of this example:

```
SIMPLE   = T
BITPIX   = 16
NAXIS    = 3
NAXIS1   = 2098
NAXIS2   = 2051
NAXIS3   = 32
ORIGX   = 0
ORIGY   = 0
BINNING= 2
BSCALE   = 1.
BZERO    = 0.
INSTRUME= ' NEFER '
```

```
OBJECT  = M82/HALFA
OBSERVER= MR
OBSERVAT= GTC
CHAMPS  = 12.4587
CDELT1  = 0.000202778
CDELT2  = 0.000202778
MASKX1  = 10
MASKY1  = 10
MASKX2  = 2000
MASKY2  = 2000
COFACT  = 0.9
MOFACT  = 0.7
MINVIS  = 250
MAXVIS  = 1000
REDSOL  = -9.26
CORAPEX = -16.75
VELOCITY= 0
ETA-BEG = Sat Mar 24 01:04:03 2018
OBS-BEG = Sat Mar 24 02:53:21 2018
OBS-END = Sat Mar 24 02:53:31 2018
ITPCAN  = ???
NTPCAN  = ???
NTOT    = ???
NCYCLES = ???
P_INTERF= 595.0
ORIGIN  = NEFER
P_XBASE = -353.0
P_STEP  = 22.0
P_CSTE  = 9.2943
WAVE_ETA= 6598.95
WAVE_BAL= 6562.78
WAVE_NEB= 6562.78
X_CENTR = ???
Y_CENTR = ???
ELLIPS  = ???
ALPHA   = 09.5553
DELTA   = +69.4046
EPOQUE  = 2000
TEL_NAME= GTC
LATITUDE= 28 45 24
LONGITUD= 17 53 31
SUFFIX  = ' p160 '
ETA_FILT= 657/5
NEB_FILT= 657/5
TEMPERAT= 3 C
CAMERA  = CCD_TEK
DECA_PHA= 0.000000
DECA_PHA= 0.000000
END
```

The team is seeking to put the right p_step and the right z of the scan into the header of each channel.

The observed data will be supplied to the user in the same way than OSIRIS TF data, but with the addition of the calibration cube. Wavelength calibration can be done by the user using one of the packages mentioned above. The NEFER team is committed to ensuring that these tasks can be well accomplished and will give the users the relevant assistance until they have become fully practiced in data reduction and calibration. This mode of operation will be normal as the OSIRIS-NEFER mode is considered a visitor instrument. However if at some future date it is considered desirable the Team could develop a GTC compliant pipeline integrated into the OSIRIS one, as well as a data reduction standalone system that could be implemented in GTC observer's workstations or laptops.