GriF: an infrared 3-D spectroscopic mode for KIR/PUEO

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ABSTRACT

When combined with Adaptive Optics, integral field spectroscopy , i.e. observation of a sky field simultaneously in a number of spectral passbands, is the most efficient way to perform spectro-imaging at high angular resolution. GriF will provide the CFHT community with such a capability in the near infrared K-band.

This extension will be completed by means of two simple optical devices to be installed in the KIR cryostat (the infrared camera of PUEO): a cooled grism in the filter-wheel and a cold aperture on an entrance focal plane wheel. They will be completed by a room-temperature Fabry-Perot (FP) interferometer in front of KIR. The FP selects narrow bandpass images while the grism spatially separates them, giving a 3-D spectroscopic capacity within a compact and light design.

At each exposure, several (up to 9) monochromatic images of a rectangular field of about 36 arcseconds x 4 arcseconds will be simultaneously acquired, allowing a precise substraction of continuum and background.

The cooled grism will guarantee a low background environment, thus a good sensitivity at K.

The medium spectral resolution (about 2600) will fit to a number of programs and will represent a considerable improvement on imaging with narrow-band filters.

Thus, combining high angular resolution with the spectroscopic diagnosis, GriF will allow the study of a large class of compact objects or structures, especially in the extragalactic domain where its sensitivity should be unique.

Keywords: 3-D spectroscopy, adaptive optics, Fabry-Perot interferometer, grism, near infrared

1. INTRODUCTION

Integral field spectroscopy (alias "3-D spectroscopy"), i.e. observation of a sky field simultaneously in a number of spectral passbands is the most efficient way to perform spectro-imaging at high angular resolution. When combined with Adaptive Optics, the study of a very large class of compact objects or structures, i.e. with angular dimensions smaller than one arcsecond, can be boosted by the powerful spectroscopic diagnosis. CFHT has already pioneered in this domain with PUEO/OASIS, an exceptional tool which combines high spatial and spectral resolution, but is however limited to the visible and far red spectral bands.

On the other hand, the performances reached by PUEO are outstanding in the near infrared, particularly in terms of the limiting magnitude of the source for wavefront sensing. Numerous programs in extragalactic astronomy, interstellar medium, or stellar environment and planetology have been successfully conducted up to now. However, all programs were limited so far to infrared imagery with dedicated filters. Low resolution spectro-imaging can be done with an appropriate number of narrow-band filters but has two strong limitations: it is extremely difficult to fabricate filters offering a resolution better than 100 and, as soon as a spectral coverage is needed (molecular bands, objects with various redshift, velocity measurements), much too many filters would be required. There is no infrared

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instrumental project equivalent to OASIS at CFHT, at least not in the K band. Paradoxically, this band is rich in spectroscopic features that can provide essential information on the physics of solar system objects, of the galactic and extra-galactic interstellar medium, or of stars.

In consequence, we felt that it was urgent to provide CFHT with a capability similar to OASIS at infrared wavelengths, especially in the context of intense competition that lures at the horizon (HST, 8m telescopes with AO). The Nicmos instrument on HST is not offering such a capability and therefore is not a competitor. None of the Adaptive Optics facilities on the 8-10 meter telescopes will be equipped with an infrared integral field spectroscopy capacity early in their life. As far as we know, the only decided instrument of this type is Sinfoni on the VLT with a planned date of commissioning 2002; note also the IFS project for the Keck AO system: *http://www.astro.ucla.edu/~larkin/cfao/ifu.html*. As of today, only GraF, installed on the Adonis visitor bench of the 3.6 m ESO telescope, offers to a large community, an integral field spectroscopy instrument, fed by adaptive optics. See also the progress reports (*http://www.mpe.mpg.de/www_ir/ALFA/ALFAand3D/index.html*) on the 3-D spectrograph at the German 3.5 m telescope at Calar Alto with the ALFA Adaptive Optics. GraF, developed by the Observatoire de Grenoble, being a room-temperature instrument, its performances in the K band are limited by the instrumental thermal background (i.e. a black-body at 300K with an emissivity of 1).

The instrument we propose here directly derives from the GraF concept, but would offer the advantage of a cooled instrument, i.e. with excellent performances, in terms of sensitivity, in the K band. Using a Fabry-Perot and a grism in KIR, it will provide the community with an integral field spectroscopy capability at a rather low cost and with a minimum of modifications on the instrument.

The classical mode of operation of KIR will not be compromised at all, and even, a long slit spectroscopy mode would become available, simply by selecting the grism and a slit, without any FP.

The advantages of this setup, compared with conventional monochromatic imagery or room-temperature spectro-imagers are important:

- multi-windowing (up to 9 wavelengths simultaneously);
- sky background correction (simultaneity of continuum image); the simultaneous acquisition at several wavebands turns out to be crucial when the spatial point-spread function (PSF) is subject to time variability. This is common in astronomy, even with adaptive optics (AO), in particular towards shorter wavelengths where the AO correction becomes partial. If the observed object is point-like in the continuum emission, which is a frequent case in studies of e.g. circumstellar environment, then the 3-D spectroscopic frames are self-calibrated; i.e. the continuum band images can be used as the PSF calibrator to deconvolve the images in the spectral lines, acquired simultaneously. Furthermore, the continuum windows insure the monitoring of the photometric variations from channel-to-channel frames.
- good spectral resolution (typically 2600 instead of 100);
- flexibility (fully adjustable wavelength, or scanning);
- good global transmission (not less than 50%) since very few optical elements are introduced in the beam;
- low background and thus excellent sensitivity thanks to the cold grism (the FP etalon at ambient temperature behaves as a mirror of very low emissivity);
- versatility since a) long slit spectroscopy will also become available, and b) different focal masks could be implemented on the new entrance wheel, including coronographic masks.

2. PRINCIPLES AND DESIGN OF THE INSTRUMENT

The solution we propose consists in associating a room-temperature Fabry-Perot (FP) etalon in front of the entrance window of KIR with a small cooled grism within KIR. The FP filters a small number of monochromatic images - corresponding to its transmission peaks - which are spatially separated by the grism and acquired in one single detector exposure. Compared to simple filter imaging, there is thus a multiplex gain besides a gain in resolution and the flexibility of adjusting the observed wavelength.

The FP and spatial separation by a grating was first described by Fabry[3] in 1905. Le Coarer, Georgelin and Boulesteix[5] noticed its integral field spectroscopy capacity. The simplicity and compactness of the set-up made it attractive in the context of the ESO ADONIS adaptive optics, leading to the GraF[1] spectro-imager project built and operated by LAOG. The present project will benefit from this succesfull experience, which allowed to establish the optimum observing and calibration procedures, and required the development of a comprehensive set of data reduction software, as presented by Chalabaev et al.[1] (see also *http://www-laog.obs.ujf-grenoble.fr/hra/graf/*). The Web site provides also "GraF Instrument Description" where the FP+grating set-up is discussed in more details. An example of what can be actually achieved, i.e. an angular resolution of 0.1 arcsecond combined with a spectral resolution of 10000, is given in Fig. 1

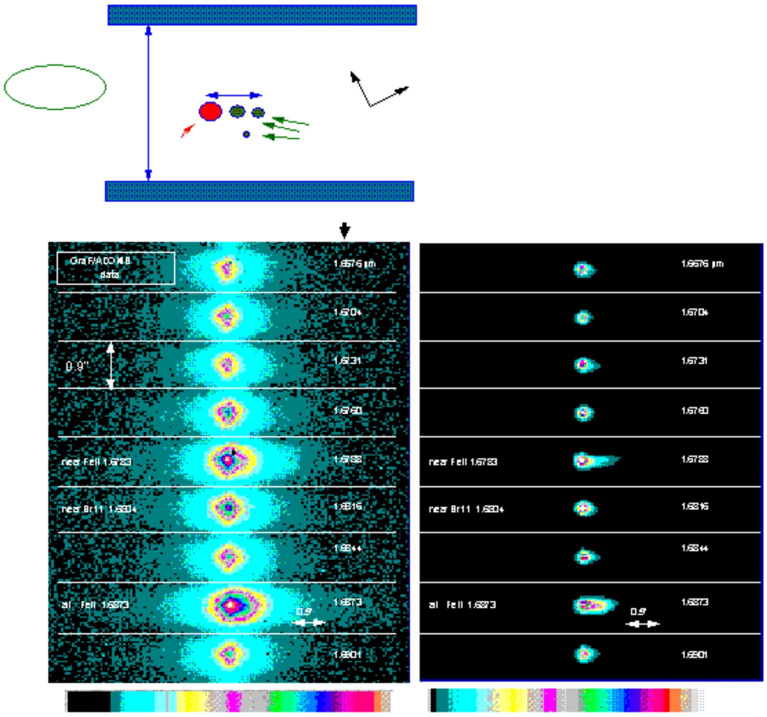

Figure 1. Example of results obtained with GraF on the massive star Eta Car. Upper left: the GraF field of view at $PA = -41°$ including the "Weigelt spots" BCD. Down left: reduced data before deconvolution. Shown here is 1 out of 48 frames taken at different spectral setting of the Fabry-Perot interferometer. The frame consists of 9 monochromatic windows of 0.9 arcseconds x 0.9 arcseconds. Down right: The frame is deconvolved (max likelihood algorithm) using the image at 1.6704 μm (continuum) as the PSF calibrator. The extented emission well seen at 1.6873 μm is in good agreement with what is expected as due to "Weigelt spots" at 0.1 arcsecond and 0.2 arcseconds. The resulting FWHM angular resolution after deconvolution is 0.1 arcsecond.

The principle of the setup for PUEO is the same as in GraF, but in the present case a more modest resolution is aimed at, which allows us to consider a far more simple optical layout and to install the grism in the cold environment. The f/20 output beam from PUEO only slightly degrades the etalon finesse, given the modest spectral resolution and thus the low gap needed.

To summarize, the optical design of GriF consists in three elements (see Fig. 2):

- the Fabry-Perot interferometer,
- the focal stop, supported by a diaphragm wheel,
- the grism block, made of a collimator lens, a K-band filter, the grism itself and an objective lens.

Each of these devices will be discussed in the present section.

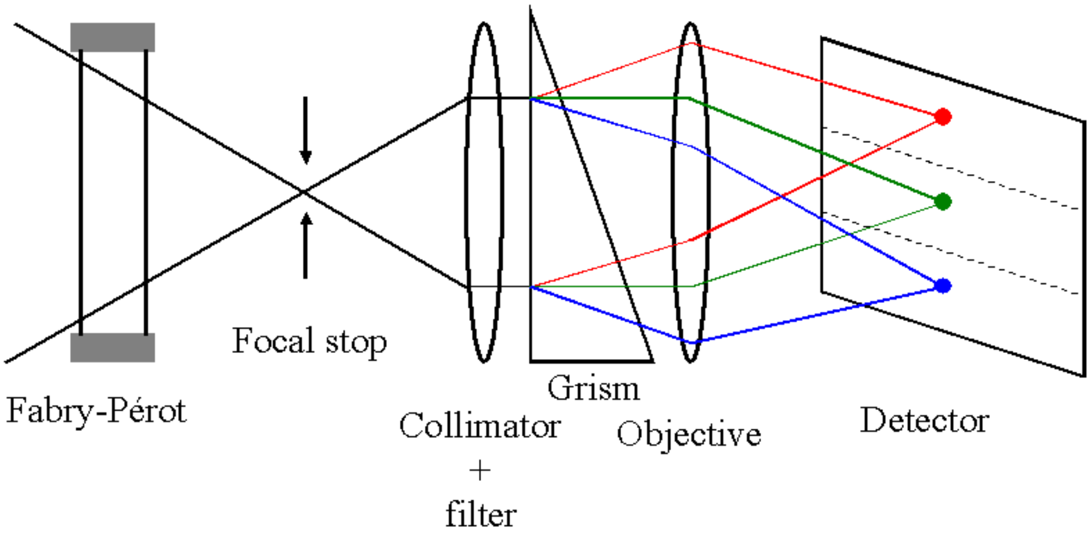

Figure 2. Conceptual design of the instrument

2.1. The Fabry-Perot interferometer

The FP etalon can be seen as a multi-passband filter (Fig. 3). The choice of the optical parameters of the interferometer is mainly a compromise between the resolution achievable and the integration time for an exposure in the scanning mode. Indeed, one main parameter is the gap between the two plates of the interferometer. Among others, this value leads to the finesse which reflects the ratio of the width between two transmission peaks (the free spectral range) by the width of a transmission peak (the spectral resolution). So, to sample an inter-channel spacing, one would need a time proportionnal to the finesse. As a consequence, the lower the finesse, the lower the integration time in scanning mode. But on the other hand, the resolving power is proportional to the finesse, so the lower the finesse, the lower the resolving power.

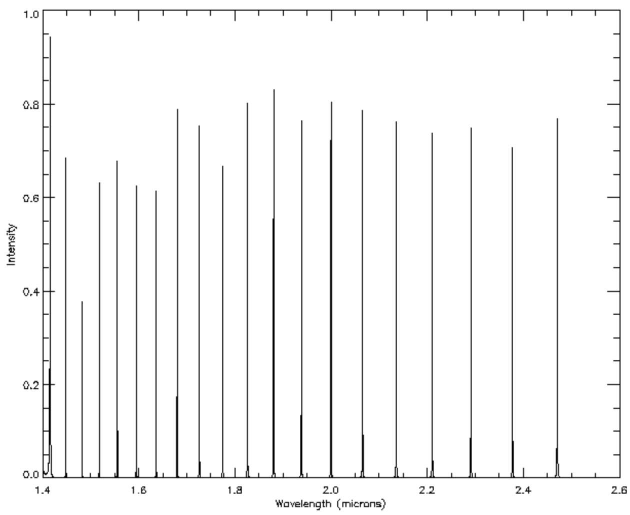

Figure 3. Theorical transmitted intensity of the Fabry-Perot etalon for a nominal gap of 31.5 μm

The paramaters choosen for the ordering to the manufacturer (Queensgate) are a gap between the two plates of 31.5 μm, a reflectance above 97% and an absorption below 0.5%. These choices lead to a resolving power around 2600 in K (Fig. 4) and a finesse between 80 and 100 in K (Fig. 5).

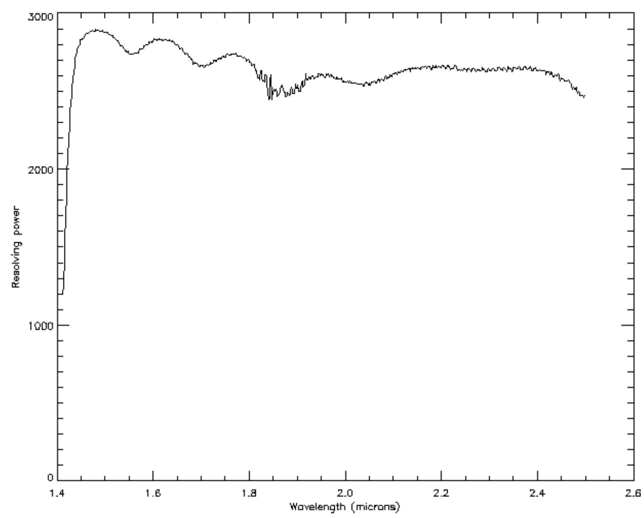

Figure 4. Resolving power of the etalon

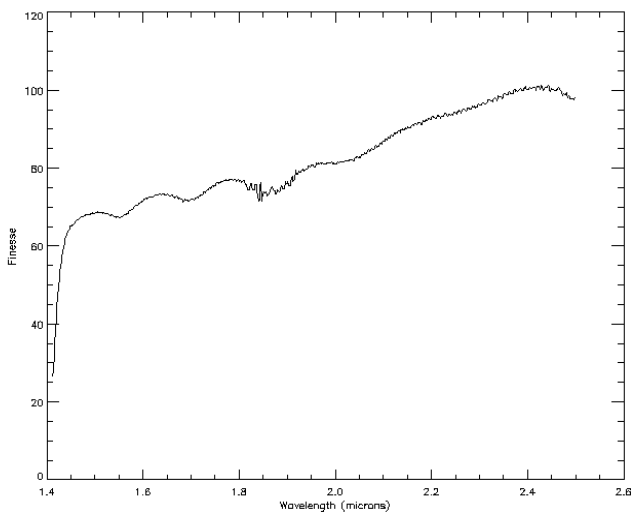

Figure 5. Total finesse of the etalon. It includes the reflection, defect and converging beam finesses.

The etalon will be located in the spacer placed between the bonnette and the camera. Then, the FP will be at room-temperature. The emissivity will not be compromised as the interferometer will be seen as a mirror at about 0°C and 90% reflectivity and then will contribute to the background at a modest level, with respect to already present mirrors.

Nevertheless, the introduction of the etalon in the optical beam will modify the focus. Indeed, the two plates are made of "water free fused silica" whose refractive index is equal to 1.43501 at 2.2 μm. Thus, the focus will be modified by 16.3 mm. To compensate this focus modification, we will make a new spacer, indentical to the former one except in its heigth, which will be extended by a length of 8.15 mm. The second half of the focus modification will be compensated thanks to the ability of the deformable mirror to move along an axis perpendicular to itself. This choice to share the focus modification between a new spacer and a shifting of the deformable mirror allows PUEO to be used with or without the FP in the optical beam without changing any mechanical part of PUEO/KIR. A simple mechanism which ensures the retractiblity of the interferometer from the optical beam will allow these two observing modes.

The Fabry-Perot interferometer has already been delivered by Queensgate.

By the publication of this article, an FTS spectrometry of the etalon would have been made to characterize more precisely its optical properties. Thus, we will be able to improve the optical design of the instrument.

2.2. The focal stop

To prevent from the overlapping of the different images transmitted by the etalon and then spatially separated by the grism, the introduction of a slit in the focal plane of KIR is necessary.

As the optimum width of the slit varies with wavelength and as the use of coronographic masks would extend the instrumental capability of GriF, we have chosen to design a diaphragm wheel which will be inserted in the KIR dewar (Fig. 6). This wheel will then support the different slits and allow us to choose the appropriate one.

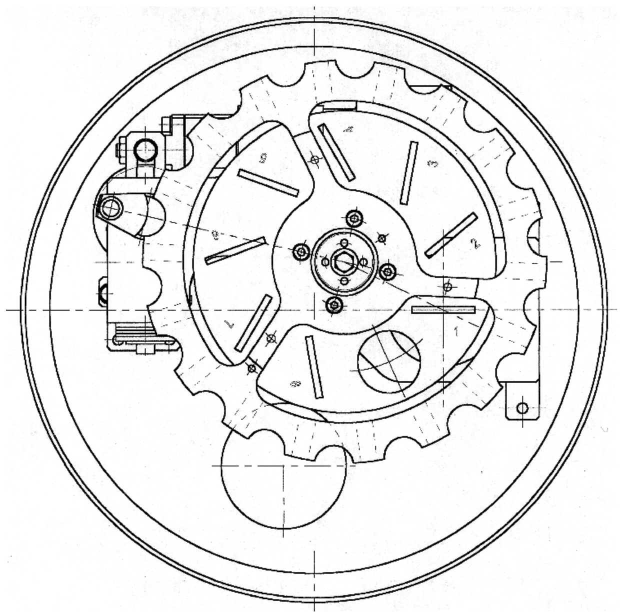

Figure 6. Top view of the diaphram wheel as it will be inserted in the cryostat. The exterior circles represent the interior surface of the cryostat and the faces of the stiffening cylinder. The lower circle partially hidden by the wheel is the filter access.

The mechanism of the wheel is based on the principle of the maltese cross. The wheel is driven by a PORTESCAP stepper motor (escap P430). The rotation of the motor axis is transmitted to a vertical axis thanks to a wheel and tangential screw mechanism whose reduction ratio value is 60. The latter axis supports a "finger" which drives the diaphram wheel itself. The maltese cross mechanism permits a good precision in the positionning of the slit. Indeed, the positions of the maltese cross are discrete and there are no "inter-positions". However, to achieve a more compact design of the diaphragm wheel - the available space in the cryostat is limited and imposed -, a slit position is encountered every other maltese cross positions.

The wheel comprises eigth slits plus a clear aperture which allows to use KIR in its classical observing mode. The mask will be engraved by laser with the LAMA equipment of the CFHT.

The integration of the mechanism in the dewar will require a new radiation field baffle, shorter than the existing one. The main difficulty of the integration will be to precisely align the slit with the pixels of the detector.

This diaphragm wheel has been already manufactured and tests at room temperature successfully undertaken. An important step still has to be got over: tests at cryogenic temperatures. By the time of the redaction of this article, they are in a setting phase.

2.3. The grism block

After their selection by the Fabry-Perot interferometer, the different transmitted wavelengths have to be separated on the detector. This role is fulfilled by a grism.

This optical device will be located in the filter wheel of KIR, and thus will be fully removable from the optical path. Then, the retractable etalon in the spacer, the circle aperture on the diaphragm wheel and the removable grism will ensure the operability of KIR in its already existing classical mode.

Being located in the filter wheel in a pupil plane, the grism will be submitted to cryogenic temperatures. KRS-5 appears to be the material well adapted to this constraint and able to resist to several thermal cycling. Our grism will be directly ruled. Different experiences had already used (or will use) KRS-5 grisms at such nitrogen temperatures (or even at lower temperatures): NIRI[4] at Gemini, TIMMI 2[7] at ESO, NSFCAM[6] at IRTF, 3D[8] at MPE, ...

The grism has been ordered to Carl Zeiss Jena. Its foreseen charateristics and design are:

- groove number: 164.0 mm^{-1},
- blaze and prism angle: 15.05 deg,
- light entrance face: 8.5 x 15 mm^2,
- diffracting area: 12 x19 mm^2,
- anti reflection coating on the entrance face,
- direct-vision wavelengh: 2.20 μm.

Actually, one should note that the grism will be inserted in the filter wheel with a K filter, a collimator and a objective lens (Fig. 7). The spot-diagrams corresponding to this design are displayed on the Fig 8.

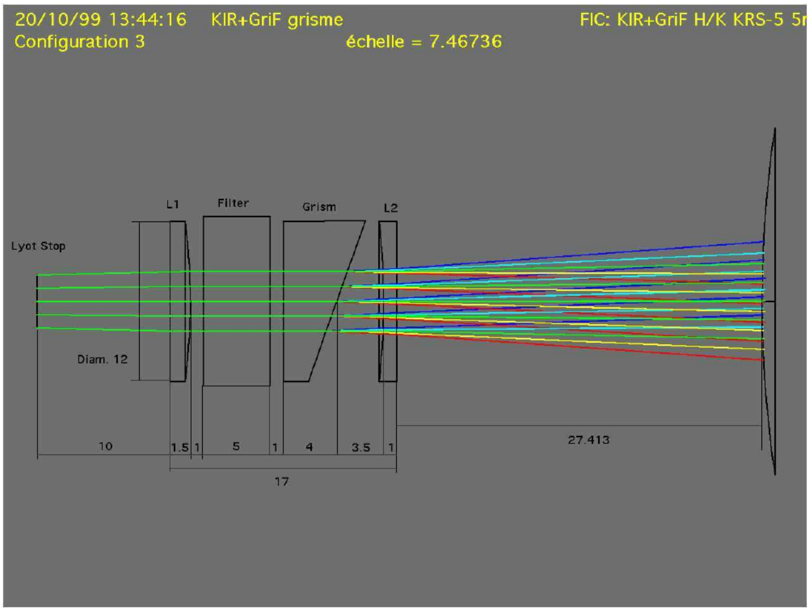

Figure 7. Optical layout of the grism block

Since different articles[6,8] have reported an alteration in the KRS-5 transmission due to mechanical constraints, a peculiar attention will be given to the mechanical holder.

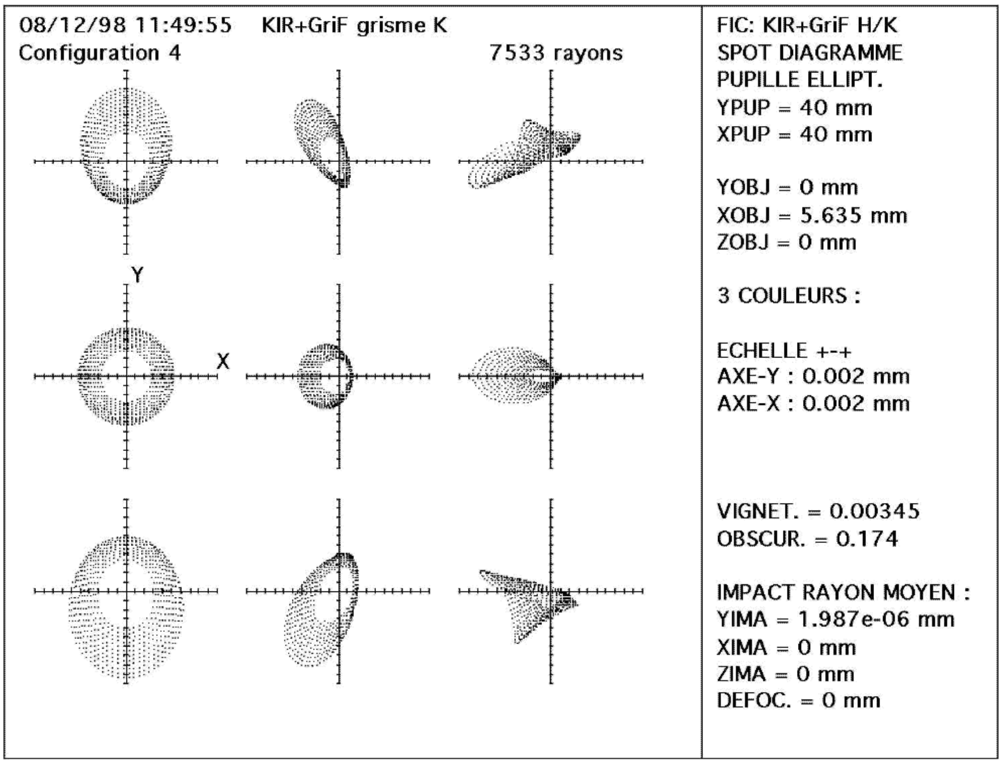

Figure 8. Spot-diagrams corresponding to the design of GriF

2.4. Observing modes

In addition to the KIR classical imaging mode, which will remain fully operable just as before, the new observing modes available on KIR with GriF will be:

- Line imaging mode: to simultaneously observe one line of interest plus the continuum; it will accessible simply by choosing the appropriate etalon gap.
- Scanning mode: to observe several atomic lines or a large molecular band; it will be achieved by a step by step change of the etalon gap.
- Long slit spectroscopy: accessible simply by removing the Fabry-Perot from the optical path.

3. SOFTWARE

3.1. Control software

The Fabry-Perot etalon is controlled by means of the standard Queensgate controller already available at CFHT. The controller is connected to the main computer which harbours the proper control sofware layers to operate the etalon either in line imaging mode or in scanning mode:

- level 0: communication hardware dependant routines (RS232 control),
- level 1: Queensgate protocol handling,
- level 2: optical to physical units (encoder values) conversion,
- level 3: higher level routines such as error handling, test procedures, interface with observatory general software.

This package includes all the facilities for calibration, tuning and communication tests.

Synchronization with KIR image acquisition system is achieved, as the human interface, by general CFHT observing software facilities.

3.2. Data analysis

In terms of the data analysis, a software package was developed for the GraF instrument in order to recover data cubes properly aligned and calibrated. This package will be adapted to GriF.

This package, available as functions coded in C++, will be made fully compatible with an IDL environment. Thus, an IDL pipe-line will produce a workable data cube (x,y,λ) shortly after the acquisition of the set of exposures.

4. SCIENCE CASE

The spectroscopic diagnosis is the only one that really allows astrophysicists to derive a quantitative information and constraints on the physical processes at work in the variety of objects they are studying. Spectroscopy is an unescapable phase after imaging. On the other hand, the richness of the 2-D information offered by an image should still be available when spectroscopy is performed: this is why integral field spectroscopy is becoming more and more popular, especially when one is interested in compact objects where the overall amount of 3-D data is still reasonnable. When coupled to adaptive optics, then the gain of 3-D spectroscopy becomes obvious. A recent result obtained by Chalabaev et al.[2] using GraF, is shown on Fig. 1 to illustrate such a gain (see also PUEO/OASIS publications).

The near-infrared range is rich in spectroscopic signatures of molecules, atoms, ions, and solids that give direct physical information on stellar population, interstellar medium or planet atmospheres or grounds. For instance, in the case of the interstellar medium, important features are the quadrupolar lines of molecular hydrogen (H_2 v=1-0 s(1), ...) and the Brackett γ line tracing ionized hydrogen. Regarding the stellar population, CO bandhead (2.3-2.4 μm), indicative of Giants and Supergiants, and the helium line at 2.05 μm, are among the most important ones. Atmospheres and mineral surfaces of objects in the solar system can also be probed in lines or bands such as those of methane (2.0 μm) or broad organic bands such as those at 2.07 and 2.27 μm.

The infrared range has the additional advantage of being much less absorbed by the interstellar dust than the visible where opacity can be a very limiting factor, precisely in compact objects where dust is often highly concentrated (protostars, YSOs, circumstellar envelopes around AGB and post-AGB stars, starbursters, AGN, ...).

The spectral resolution that can be aimed at, within the present compact concept, is about 2600: this value is well adapted to a wide set of programs, including velocity measurements in the field of extragalactic astrophysics. Regarding this last field, one notes that a characteristic that makes PUEO/KIR practically unique is the good sensitivity of the wavefront sensor which authorises to observe external galaxies, using the nucleus as the reference source.

A non-exhaustive list of science programs that should directly benefit from the new capacity provided by GriF is given in the following:

- Gas and stellar clusters towards the Galactic Center
- Accurate spectral classification of tight binary systems among young stellar objects (Herbig and T Tau stars) - clues for the formation of stellar and planetary systems, stellar mass function
- Search and accurate classification of brown dwarf stars, due to improved separation and/or relative radial velocities measurements
- Embedded very young stellar or protostellar sources (e.g. BN/KL cluster in OMC1)
- Circumstellar envelopes and flows around evolved stars (post-AGB, LBVs, Planetary nebulæ)
- Small scale structures of the ISM
- Gas kinematics in the nuclear region of nearby and distant galaxies
- Starbursters, ultra-luminous galaxies
- Dusty/gaseous torus in AGNs, micro-spiral structures

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