Mem. S.A.It. Suppl. Vol. 2, 131
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Memorie della
Supplementi

IR Astronomy at Dome C with a wide-field Imaging FTS

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Abstract. The interest of large-field imaging spectroscopy in the near infrared, for the detailed study of star forming regions, could be extremely amplified by the exceptional qualities of the Antarctica site. The most powerful and versatile instrument to reach this goal is an imaging FTS. The building of a replica of such an instrument under test at the Mt Megantic Telescope (Quebec) is proposed to be installed first on IRAIT. The main characteristics are: a field of view of 4.0×4.0 arcmins, a maximum resolution of 5000 at 2μm, a spectral coverage from 1 to 5μm, optimized for the 2 to 5μm range.

Key words. Star forming regions – Integral field spectroscopy – Imaging FTS

1. Main scientific driver

With the advent of bidimensionnal detectors, first in the visible (CCD) and now at almost all wavelengths, up to the millimetric range, many large photometric surveys have been undertaken, from ground and from space. The next step is a detailed study of particular regions of the sky revealed by these surveys. It can only be conducted by associating spectroscopy to imagery. This association is also called *Integral Field Spectroscopy* (IFS) since a spectrum is obtained at each point of a given field. It applied in particular to complex astronomical objects, and to specific active regions, which are characterized by emission lines. IFS represents the capability of imaging them in all their atomic and molecular species, with ideal filters, i.e. which strictly isolate a single spectral feature. Narrow-band filter imaging in most of the cases is unable to provide perfect maps of a given constituent because of the difficulty of subtracting correctly the continuum. For objects with a rich chemistry other lines are mixed coming from the wings of the filter. With IFS a spectral cube is obtained. If in addition the resolution is

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high enough, a given line corresponds to several planes of the cube. Other planes, on which it can be checked that no lines are present, make possible to define the true continuum. By direct subtraction of the two maps, without any approximative adjustment, a map of only the emitting parts of the source in an element is obtained. Then, with this technique it becomes possible to separate exactly the various regions of excitation in different species, with respect to the source of excitation, to test models of excitation. Again, if the spectral resolution is sufficient, study of the kinematics becomes feasible.

This approach is very fruitful for all the types of gaseous regions excited by a source of strong UV field and also by shocks. This includes *star forming regions* at all stages of evolution, from dense molecular clouds illuminated by nearby hot stars, to the environment of YSOs, in particular with massive young stars, in which can be studied jets, HII regions, photo-dissociation regions (PDR), to the latest stages, producing reflection nebulae. Fig. 1 gives an example of an image of the star forming region S106, obtained in the 1-0 S(1) H_2 line from a spectral cube recorded by an Integral Field Spectrometer based on an Imaging FTS called BEAR Maillard (2000a).

Near the end of stellar evolution, the *late-type stars*, up to the planetary nebula phase, show an environment with similar ingredients: jets, dust, molecular grains (PAH), ionized gas, PDR, molecular envelope. The same approach can be extended to a particular region of the Milky Way, the *Galactic Center*, where star formation is dominated by the presence of the central Black Hole (Sgr $A^\star$), with an exceptional concentration of massive stars detected in cluster (Arches, Quintuplet, Central cluster). The study of star formation in the *nearby galaxies* can also largely benefit of the same method of analysis.

Star forming regions mean deeply embedded sources which are accessible only beyond 1μm. The near-infrared domain, over the K, L and M atmospheric windows is particularly rich in spectral signatures, indicative of the various components of these regions. The main species which can be studied are listed in Table 1. The exceptional astronomical qualities of Antarctica in this spectral range (extremely low humidity, very low thermal background, good image quality) would radically amplified the analysis capabilities of an instrument able to make IFS, in particular with a field coverage wide enough. As an example, the portion of S106 presented on Fig. 1 is still too limited to obtain an overview of all the region which is dominated by a single young, massive star. Many of such instruments are only capable of a very small field (for a review of IFS capabilities at VLT see Maillard & Bacon (2002). Under seeing-limited conditions, IFS on a large field, over a useful spectral range in the infrared and with a resolution of a few thousands is possible with a long-slit grating spectrometer to the condition to adapt to the telescope a very precise field scanning. A large field coverage supposes to take a very large number of spectra (240 for a 2-arcmin field and a 0.5-arcsec slit width). The spatial resolution is defined by the slit width and not by the image quality which can be better. A tedious image reconstruction process limited by the pointing precision is required. A simpler approach is possible which is offered by an Imaging Fourier Transform Spectrometer (IFTS).

2. Instrumental solution: an Imaging FTS

An IFTS makes a direct image of the entrance field at each step of the scanning of the optical path difference (OPD). Then, the number of spatial elements is independent of the number of spectral elements, which is equivalent to a *huge multichannel advantage*. No image reconstruction is needed which preserves a precise astrometry at every wavelength. As in imagery with filter, providing the adequate image sampling, the image quality is limited only by the atmospheric turbulence on an ele-

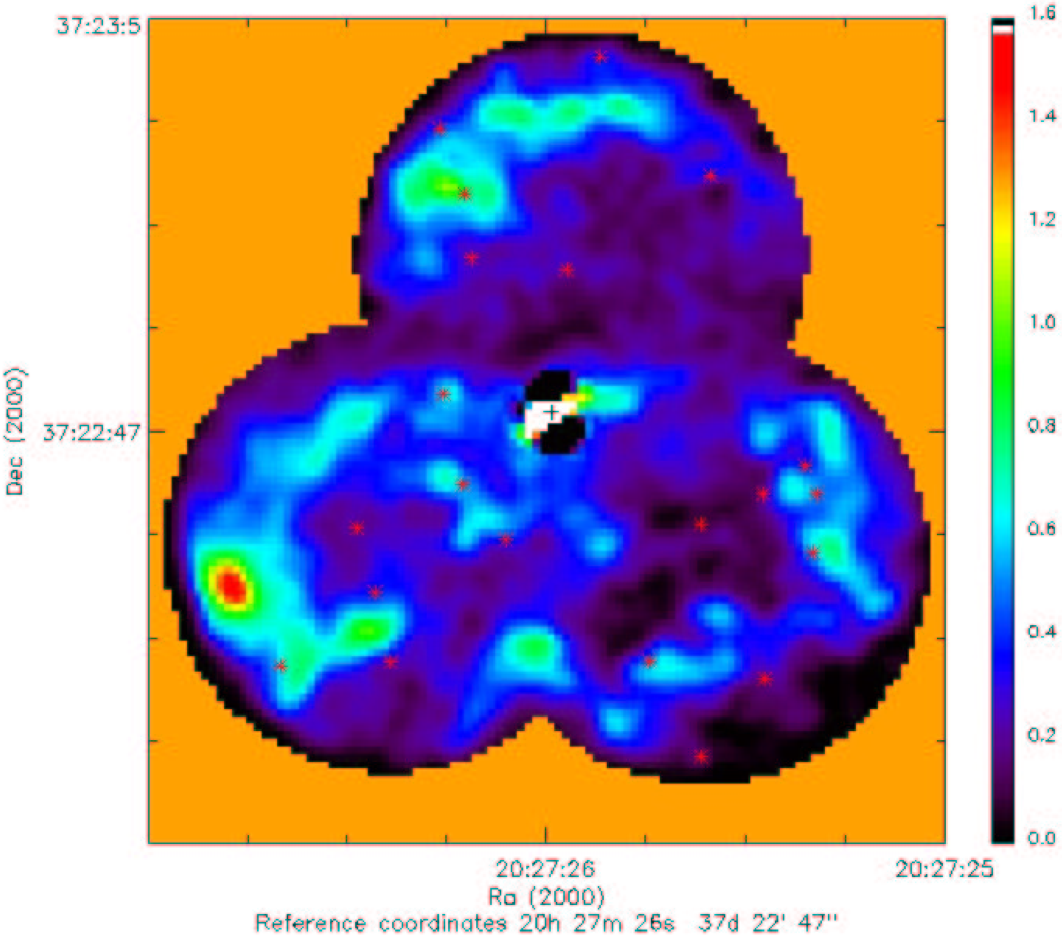

Fig. 1. YSO detection and image of the clumpy structure of H_2 in the low-mass star forming region S106 Noel et al. (2003) with the imaging FTS BEAR Maillard (2000a). As the BEAR field was only 24" in diameter 3 fields had to be merged to cover a larger field. Purely H_2 emission is obtained from integration over all the velocity field of the 1-0 S(1) H_2 line (2.12 μm) in the cube subtracted with continuum. The cross at the center of the field, in a circular black region, represents the position of the massive hot star S106-IR, a pre-main sequence O8 star Van den Ancker et al. (2002) which photo-ionizes the surrounding molecular cloud. The small crosses are the low-mass stars detected from the continuum map extracted from the same data cube.

mentary image. In the data processing, image registration makes possible to correct for guiding errors and flexures. As in any FTS a high spectral resolution is easily obtained since that is only a matter of scanning a larger OPD. Thus, the instrument can be simple and compact, particularly if a resolution of only a few thousands is

Table 1. Main atomic, molecular gas and grain tracers in star forming regions giving major spectral signatures in the 2 – 5μm region

Ionized regions, PDR

H	Brackett, Pfund series
HeI	2.058μm
H^3_+	1-0 band
HeII	2.189, 3.484μm,
[FeII]	
[FeIII]	2.145, 2.218, 2.242, 2.348μm

Molecular regions

H_2	1-0, 2-1, 3-2... S & Q lines
CO	Δv = 1, 2 gas and solid phase
H_2CO	3.57μm
HCN	ν_3 band at 3.0μm
C_2H_2	3.05μ
H_2O	3.1μm ice band
PAH	3.28, 3.4, 3.6μm bands

the goal. A maximum OPD of $\sim$1 cm is enough. However, from the multiplex properties of the instrument the photon noise is proportional to the spectral range of a spectrum, defined by the filter put on the camera. This implies to limit by cold filters the spectral domain to the region of interest and to work in low-background conditions. From this point of view, except to go to space, Antarctica is the only ground-based site to offer the optimum conditions, with a low sky background and a passive cooling of the telescope and the instrument, determining in the 2 to 5μm region. These conditions are particularly favorable to extend the use of IFTS up to the M window. The technique has been thoroughly tested with BEAR, the first astronomical IFTS, in operation on the 3.6-m CFH Telescope Maillard (2000a), result of the coupling of a step-by-step FTS and a NICMOS3 camera. Many astronomical results have been obtained with this instrument as illustrated on Fig. 1, also on pre-PNs Cox et al. (2002), on the Galactic Center Paumard (2001), at a spectral resolution of $\sim$10 km s^{-1}. However, even if the instrument was installed directly at the infrared focus of CFHT, in a high elevation site, the observations were conducted at a wavelength no longer than 2.3μm in the spectro-imaging mode, since the FTS was not a cryogenic instrument. The sum of the thermal background beyond this limit, from the sky, the telescope and the instrument (the main contribution coming for 77% from the instrument) saturated the array, preventing to work at longer wavelength. A passive cooling of the telescope and the instrument at -60°C, as it happens in winter at Dome C, would make a huge difference, making possible to extend the same technique at 4.8μm in the M band, the region of CO Δv = 1. As stressed above, the FOV of this prototype was limiting the scientific capabilities, while a strong point of the principle of IFTS is the capability of wide-field imaging. This property must drive the definition of a new instrument mainly dedicated to the exploration of the atomic and molecular content of star forming regions.

3. Strategy

On Fig. 2 is shown the optical layout of a visible IFTS developed at LLNL Wurtz et al. (2002). This instrument was first studied as a response for the call of idea for the instrumentation of NGST with other proposed IFTS Maillard (2000b). The optical design is simpler than for BEAR which is based on a dual input/dual output FTS, but with cat's eyes replacing the flat mirrors of the standard Michelson Maillard & Bacon (2002). This design was imposed by the requirement of large OPD (60 cm). If the OPD is limited to less than 1 cm, off-axis flat mirrors can be used, making possible to have access to the two complementary output beams.

In the standard flat-mirror Michelson interferometer one output beam returns toward the source, resulting in the loss of 50% of the light. With this design the instrument can be very compact. From the context discussed above, a medium resolution

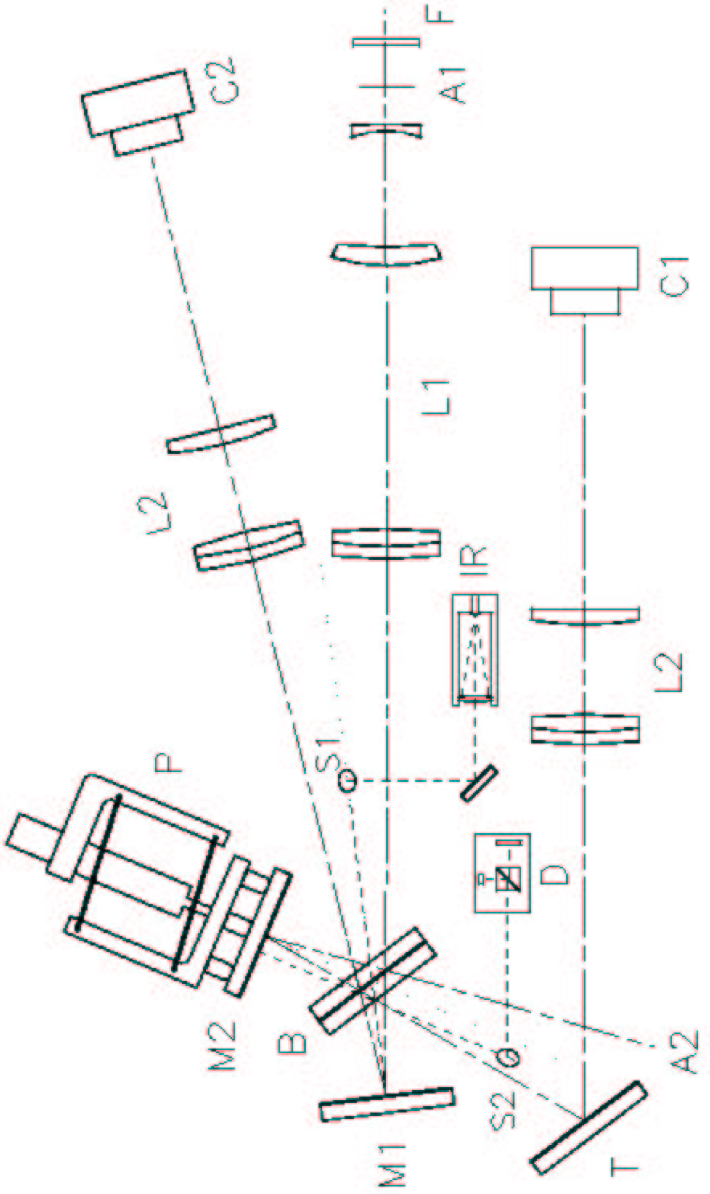

Fig. 2. Schematic diagram of a visible IFTS developed at Livermore Nat. Lab. Wurtz et al. (2002) with a dual-input/dual-output mounting; A1: focal plane of the telescope; B: the beamsplitter. The collimated beam arrives 7° off-axis to the interferometer to produce the two complementary output beams spatially separated. They are focused by the L2 systems to image the field on camera C1 and C2. The IR metrology system is in the center of the interferometer.

IFTS based on this design is proposed to be tested first on the 80-cm IRAIT Telescope. The key features of the proposed IFTS are listed below:

- entrance field 4.0×4.0 arcmins FOV
- image sampling 0.25″ *(5×10^5 spatial samples for 0.35” seeing)*
- FTS: dual-input/output *with flat mirrors (Fig. 2) - 2nd entrance blocked*
- a single beamsplitter $2-5\mu$m
- pupil image on the beamsplitter
- maximum OPD 6 mm
- maximum limit of resolution 1 cm^{-1}
- all resolutions up to R = 5× 10^3 (at 2 μm)
- optical throughput $> 60\%$
- detector on each output port Hawaii2RG 1K× 1K ($2.0-5.0\,\mu$m)
- operating temperature $\sim -60°$ C

The same design was adopted for a similar instrument called SPPIOMM, originally studied also within the NGST's call for idea, in a collaboration between the company ABB-BOMEM in Quebec and the University of Laval. This instrument is proposed to be tested on the 1.5-m Mt Megantic Telescope at the fall of 2003. To work at this site the instrument must be able to work in low temperature conditions. Even if the conditions are not as extreme as at Dome C, it will be a good test of the scanning mechanism which drives one of the flat mirror of the interferometer. Since this instrument is developed for wide-field imaging in the visible (CCD detectors) an installation of SPPIOM at Dome C or a direct copy does not present a fundamental interest. It would not benefit from the major advantages of the site. However, the same optical and mechanical design can be kept to adapt for the 2 to 5μm region. The main elements to be changed are: the beamsplitter and the two cameras (InSb). A new design has probably to be studied for the entrance and the output collimators to use mirrors instead of lenses for an achromatic instrument. Most important, the heart of the instrument which is the step-by-step mechanism, already tested in low temperature conditions will be used. This adaptation could start rapidly, offering a unique tool for preparing the use of Antarctica a major IR site.

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