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BEAR Imaging FTS: High Resolution Spectroscopy in Infrared Emission Lines

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Abstract. An imaging FTS makes 3D spectroscopy possible at high resolution in the infrared. The coupling of the step-scan FTS of the CFH Telescope, to a NICMOS3-type array has been realized to exploit this concept in the 1 to 2.5 μm domain. Any spectral resolution up to $\sim 30,000$, in a spectral range within these limits, is possible. The most appropriate applications are the studies of the physical conditions and the kinematics of various gaseous media through their emission lines (like Brγ, H_2 2.12 μm, HeI 2.06 μm ...). Hence, young stellar objects interacting with their molecular clouds, planetary nebulae at different phases of evolution, as well as the inner region of the Galactic Center, are suitable targets.

1. Properties of an IFTS

The main characteristics of an astronomical Imaging FTS (IFTS) can be summarized as follows (Maillard 1995):

- the entrance field is imaged on a 2-D array through a Michelson-type interferometer. Each pixel acts as a detector matched to the corresponding point on the sky. The pixel size must be adapted to the seeing disk (or the diffraction pattern) to correctly sample it. An IFTS makes it possible Integral Field Spectroscopy (IFS) over a field, the size of which is limited only by the pixels number and the pixel scale.

- data acquisition is only compatible with a step-by-step scanning of the path difference. An image is recorded at each step.

- spectral resolution is continously adaptable, up to a maximum value which depends on the beam diameter, the field and the pixel size. However, the overhead time associated with the recording of each image, which must be as short as possible, imposes a practical limit.

- the spectral coverage can in theory be as wide as wanted. However, since the noise increases with the bandpass, filters selecting spectral domains of interest are preferable.

- by applying a FT to the interferogram for each spatial element, the spectral data cube is directly produced. Each plane is a monochromatic image of the field. Imaging through the equivalent of an ideal square filter is obtained, by summing on slices of the cube.

Despite these constraints, when compared to any other spectro-imaging devices, an imaging FTS offers the maximum flexibility , in the choice of spectral resolution and spectral coverage, and over a sizeable field.

2. Presentation of the BEAR instrument

The facility FTS installed at the infrared f/35 focus of the CFH Telescope, currently used for high-resolution spectroscopy (60 cm max path difference), with InSb mono-detectors in the 1 – 5.4 μm range (Maillard and Michel 1982) has been coupled to a 256 × 256 HgCdTe near-infrared camera (Simons *et al.* 1994, Maillard 1995). Since it is a step-scan instrument, the data acquisition was directly adapted to work in imaging mode. The interferometer uses cat's eye retroreflectors in each arm to provide the symmetric and asymmetric outputs. The field of view of 24" is determined by the size of the secondary mirror of the cat's eyes. An interface box provides a means of bringing the two images of the telescope's focal plane produced by the FTS onto a single array. The final scale on the detector is 0.35 arcsec/pixel (4 pixels in the core of a stellar image). The dead time to read and store a frame is currently of 2.5 s. To limit the total overhead time of a scan to no more than $\simeq$ 40 min, the number of frames in a raw data cube must be limited to $\sim$ 1000. Thus, if a high resolution is needed (large path difference), the spectral coverage must be limited, which permits an increase of the step size and hence, a total number of frames not higher. These considerations determine the optimum use of the instrument. In practice, a minimum of two hours and $\sim$ 1000 frames devoted to one scan is needed, to obtain an efficiency better than 50%. Allowing for source acquisition, four cubes can be recorded in one night. Resolutions of $\sim$ 3000 for a $\Delta\lambda/\lambda \simeq 15\%$ filter (e.g. a K' filter), and of $\sim 30,000$ for a 1.5% filter (e.g. a 2.12 μm filter for H_2) are typical values for data cubes acquired with BEAR. At $\sim$ 10 km s^{-1} resolution, through a narrow filter, line fluxes in H_2 1-0 S(1) as faint as 10^{-19} W m^{-2}/arcsec^2 are detected.

2.1. BEAR software

Specialized software, (all written in IDL), is also part of the BEAR development effort. The available procedures are :
– *bearprocess* : generates the spectral cube from the raw data cube ($\sim$ 1000 frames of 128×256 pixels). This two-part package, first, conducts standard image processing (flat-fielding, dark subtraction, correction for bad pixels), flipping of one image about the Y-axis and spatial registration with respect to the other image to insure the complementarity of all the points in image pairs, registration of all the frames with respect to the first one to correct for guiding errors and flexure drifts. Secondly, the prepared cube is scanned in X and Y to extract the interferogram from each pair of complementary points. The zero path difference is then determined in order to obtain the spectrum directly as the real part of the interferogram FT, and restore the optimum spectral resolution of the data.
– *psubcub* : extracts a sub-cube from the main cube, limited to a spectral region of interest (e.g. a line profile), in which the original channel width (determined from the Shannon's criterion) is divided into an equal number of intervals. It results in a local oversampling, making it possible, without generating too large

a cube, to apply the correction of the natural phase error present throughout the field and, to dispose of the full line position precision.
– *merge_cube* : merges two cubes (original cube or sub-cube) recorded to increase the spatial coverage of an extended object. It assumes a stellar-like object in the common area (e.g. Fig. 1).
– *bear_calib* : provides the absolute calibration of spectral cubes, by using a spectrum extracted from a similar cube recorded on a reference star.
– *cubeview* : permits inspection of any spectral cube. Monochromatic images can be displayed and the spectrum of any point of an image extracted through an adjustable square aperture, to be shown and stored with the scale in wavenumber, wavelength or velocity (e.g. Fig. 1 and 2).

2.2. Scientific programs

IFS on emission-line objects at high spectral resolution in the near infrared, are the most appropriate and unique programs for BEAR. This choice is dictated by the desire to obtain the optimal sensitivity, with the highest possible spectral resolution. As the CFHT-FTS is a room-temperature instrument, spectro-imaging beyond 2.5 μm is excluded. With narrow-band filters, the background emission can be limited and for emission-line objects the mean energy within a filter is low, all of which contribute optimizing the S/N ratio. The 1 to 2.5 μm range provides access to many common spectroscopic indicators including, atomic hydrogen (in particular Brγ 4616.6 cm^{-1}), molecular hydrogen (1 - 0 S(1) 4712.9 cm^{-1}), HeI (4857.5 cm^{-1}) and also FeII and CO (Δv = 2) lines. Young stellar objects, late type stars in the planetary nebula phase, star clusters and starburst galaxies, less than 1 arcmin in size, are suitable targets for BEAR. Brief reviews of some programs are given below.

3. The inner region of the Galactic Center

Observations of the central parsec of the Galaxy have been undertaken with BEAR, with a filter isolating the Brγ line, first by Simon and Maillard (1996), and more recently by Morris and Maillard (2000, this volume). With a spectral resolution of 32 km s^{-1}, the kinematics of the main components of the mini-spiral traced by this line have been modelled in the context of the gravity field created by the 2.6×10^6 M$_\odot$ black hole. Observations have also been conducted with a 2.058 μm filter to reanalyze the HeI star cluster (Krabbe *et al.* 1995) detected in the IRS16 region. The profile of this line in the HeI stars has been obtained with a resolution of 40 km s^{-1}, which is superfluous for profiles 1000 km s^{-1} wide. However, with this resolution it has been possible to detect, for the first time, helium streamers, with a linewidth of $\sim$ 50 km s^{-1}.

This gas must originate from the mass loss of the HeI stars. It was possible to separate this contribution from the emission of the stars and to eliminate those which were improperly identified as HeI stars. The comparison of the velocity field of the ionized gas in these two tracers (Brγ and 2.058 μm HeI), which extends over 700 km s^{-1} will improve our understanding of the complex kinematics in the vicinity of the central black hole.

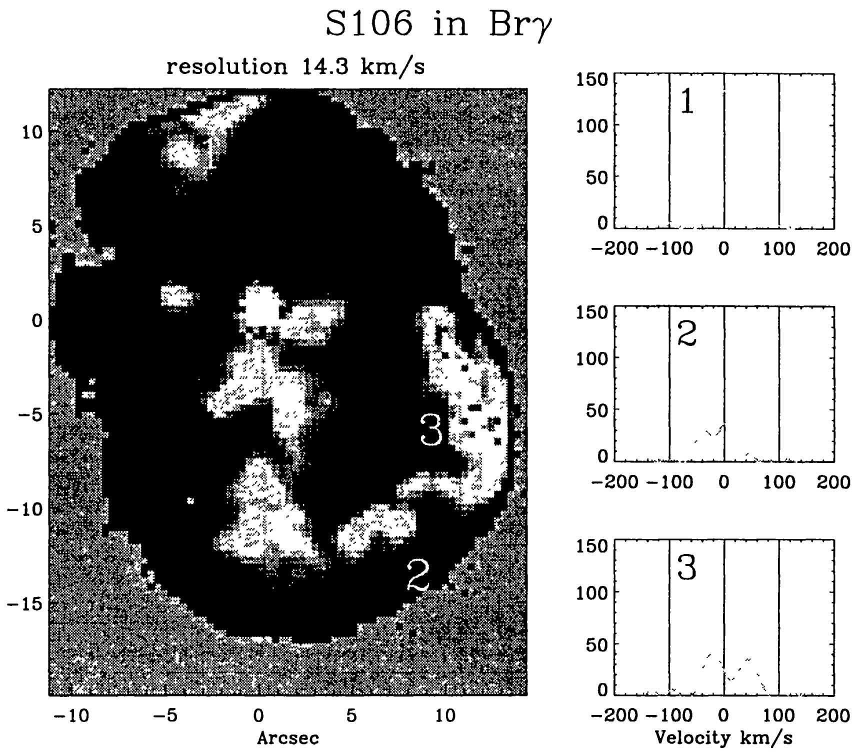

Figure 1. Image in the Vel = 0 km s^{-1} plane, showing the patchy structure of the flows and, line profiles in different points (Maillard *et al.* 2000). The bright spot at [0,0] is the young source S106-IR.

4. The environment of young stellar objects

The massive young stellar objects (YSOs) are hot stars (O type or early B). In their early phases they are still embedded in their parent molecular cloud, and are thus only accessible in the infrared. They contribute efficiently to the dispersion of their dusty and gaseous environment. Mapping the velocity of the gas, in order to study the turbulent conditions in the vicinity of the hot central star is a unique capability provided by BEAR. In this case, the maximum resolution (up to 10 km s^{-1}) is attempted as the lines are narrow, which requires the use of a narrow-band filter isolating a single line. Brγ was used to study the ionized regions, and the 1 - 0 S(1) and 2 - 1 S(1) H_2 lines to derive line ratios to test the excitation conditions of the molecular cloud. A selection of high-mass YSOs has been observed, which represents a sequence of evolution from a deeply embedded YSO to its visible stage. Complementary data have also been obtained in the mid-IR with the ISO satellite. The current ground-based observations provide a ten times better spatial resolution but on a smaller field. Typical objects are :
– GL2591 : an object in a very early phase. A HII region has not yet developed. The surrounding H_2 is relatively undisturbed by the central object.
– S106 : in contrast presents a very developed HII region with a broad bipolar structure (Fig. 1). Information on the 3-D structure of the flows in H and H_2 can be extracted from the data, with a study of their interaction and also with PAH grains, by comparison with 10-micron maps (Maillard *et al.* 2000).

– LkHα 234 : an YSO in a more evolved state with deflected jets.
– NGC 7023 : a prototypical reflection nebula. The hot star is no longer enshrouded. Remnants of the parent molecular cloud remain in filaments excited by the UV field of the star. Excitation conditions, densities, velocity fields are deduced from the data (Lemaire *et al.* 1999).

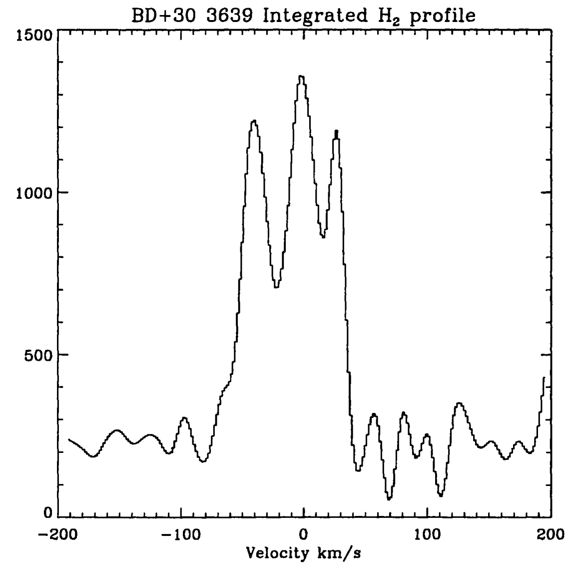

Figure 2. Velocity profile of the 1–0 S(1) H_2 line in the PN BD+30°3639, extracted with *cubeview* (see text) from the 15 km s^{-1} resolution cube with a square aperture covering the full field. Several velocity components are seen, representative of distinct ejection events.

5. Study of planetary nebulae

The planetary nebulae (PN) represent the final stages of evolution of 1 to $8M_\odot$ stars. Generally, the remnant of the red giant circumstellar envelope forms an outer molecular shell surrounding the ionized region excited by the central white dwarf. The integrated spectrum in the infrared shows a rich variety of emission lines from neutral and ionized atoms, and molecular hydrogen as well. A K' filter covering simultaneously several H_2 lines, Bγ, HeI and HeII lines was used, making it possible a clear separation of the regions of excitation of each species. Complementary studies were made at high resolution (up to 10 km s^{-1}) through narrow-band filters to study the velocity field in the prominent emission lines. Different PNs which form a sequence of evolution, were observed. Depending on their stage of evolution and the UV-field intensity, these lines are more or less intense :
– CRL 2688 and CRL 618 : two examples of pre-PN. The H_2 envelope is well developed with a bipolar structure while Brγ is not detected (Cox *et al.* 1997).
– NGC 7027 : the prototype of a young PN with an almost spherical, hollow, ionized region, inside a symetrical H_2 envelope (Cox *et al.* 1997).
– BD+30°3639 : a young PN slightly more evolved. With the K' filter, the ionized region (with Brγ and 2.058 μm HeI) of same shape than in NGC 7027, and the H_2 envelope, still with a general bipolar shape but very irregular, were

detected. From a high resolution study with a filter isolating the 2.12 μm line, the molecular envelope appears with a complex velocity field (Fig. 2).

6. Conclusion

The results reviewed above show that the combination of high spectral resolution with 3D spectroscopy provides a unique diagnosis for complex sources. This capability is provided by spectro-imaging made with an IFTS. However, the BEAR instrument does not represent the last word for this method. Further developments are possible. It would be tempting to extend the same technique toward the mid-infrared. Because of the increasing thermal background, the sensitivity is degraded on ground-based telescopes. On the contrary, this extension is promising in space and is proposed for an IFTS on the NGST (Graham 1998, Maillard & Renault 2000) with the extremely low background environment it offers. The combination of high spectral resolution with large spectral coverage is also a feature of an FTS. In the imaging mode, the quantity of data to store would rapidly become a limiting factor. In the NGST application, a rationale completely different than for an instrument like BEAR is adopted : very low spectral resolution ($\sim$ 100), on a very large spectral domain (1 to 5 μm) and a field of several arcmins. Spectro-imaging at the diffraction limit of an 8m telescope would become possible. Note that could be already feasible on a small field with an IFTS behind an adaptive optics system. Finally, the optical simplicity of an IFTS, even with a large field, is a property which should be exploited for a spaceborn instrument.

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