Studies of pre-main-sequence stars with integral field spectrographs

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Abstract

We review the contribution of integral field spectroscopy (IFS) to pre-main-sequence star studies. These studies are mostly synoptic in nature reflecting the use of this technique in addressing difficult and complex objects. Physical diagnostics were derived from IFS data such as (atomic, molecular) gas excitation and pre-shock densities, gas morphology and spectra from close binaries. Models for the sources are directly tested: shock models (planar, bow-shock) and magneto-hydrodynamics jet models.

Future contributions to the field are addressed. Surveys of mass loss across age and mass spectrum and in the nearby Orion Nebula cluster emerge as the most scientifically promising.

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Keywords: Integral field spectroscopy; Pre-main-sequence stars; Herbig–Haro objects; Binaries.

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1. Introduction

The first ideas on integral field spectroscopy (IFS) appeared in the late 1970s, early 1980s roughly at the same time as astronomical adaptive optics. Twenty years later, mature common-user instruments combining both techniques are coming on-line (e.g., OASIS and SINFONI) and most large telescopes have integral field instrumentation.

Integral field spectrographs have been used in many astrophysical fields, more systematically in galactic dynamics studies with the SAURON key project. In the field of star formation, the kick-off took place in the mid 1990s the near-infrared with the MPE-3D integral field spectrograph studies of the “prototype” T Tauri star – T Tauri itself by Herbst et al. (1996). Since then around 20 papers have been published in this field using a wide variety of IFSs in the optical and near-infrared. In this paper these results are reviewed. We will focus only on real IFS techniques where multi-lambda information is obtained in only one exposure. We will not address Fabry–Perot scanning (Gustafsson et al., 2003; Hartigan et al., 2000) or slit scanning (Bacciotti et al., 2000). We start by introducing the integral field spectrograph concepts and the advantages/drawbacks of integral field spectroscopy. Then we review the literature presenting IFS studies of jets and Herbig–Haro objects, proplyds, reflexion nebulae and binaries. Finally we discuss

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Telescope</th>
<th>Type</th>
<th>Wavelength</th>
<th>FOV (pixels)</th>
<th>Spectral range (pixels)</th>
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</thead>
<tbody>
<tr>
<td>TIGER</td>
<td>CFHT</td>
<td>Lenslet</td>
<td>Optical</td>
<td>18 × 18</td>
<td>130</td>
</tr>
<tr>
<td>OASIS</td>
<td>CFHT/WHT</td>
<td>Lenslet + AO</td>
<td>Optical</td>
<td>28 × 40</td>
<td>350</td>
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<tr>
<td>VAGR</td>
<td>Byurakan 2.6 m</td>
<td>Lenslet</td>
<td>Optical</td>
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<td>128</td>
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<tr>
<td>GMOS-IFU</td>
<td>Gemini N</td>
<td>Lenslet + fiber bundle</td>
<td>Optical</td>
<td>25 × 18</td>
<td>6200</td>
</tr>
<tr>
<td>MPFS</td>
<td>SAO 6 m</td>
<td>Lenslet + fiber bundle</td>
<td>Optical</td>
<td>16 × 18</td>
<td>1024</td>
</tr>
<tr>
<td>GraF</td>
<td>Visitor</td>
<td>Fabry–Perot + AO</td>
<td>NIR</td>
<td>30 × 250</td>
<td>8 (48)</td>
</tr>
<tr>
<td>MPE-3D</td>
<td>Calar Alto 3.5 m</td>
<td>Image slicer + AO</td>
<td>NIR</td>
<td>16 × 16</td>
<td>240</td>
</tr>
<tr>
<td>UIST-IFU</td>
<td>UKIRT</td>
<td>Image slicer</td>
<td>NIR</td>
<td>14 × 50</td>
<td>1000</td>
</tr>
</tbody>
</table>

Decommissioned instruments in italic.
what significant advances are expected from IFS in this field either in the form of new instrumentation or new methodological uses of existing instruments.

2. Integral field spectroscopy

The need to obtain spectroscopy of morphologically complex objects is the main driver for integral field spectroscopy (IFS) – a technique that allows the simultaneous recording of two dimensional (angular) plus spectroscopic information. The end products of integral field spectrographs are datacubes, i.e., two dimensional images extended with a third (spectroscopic) dimension.

2.1. Instrumental concepts

The main difficulties in the design of an integral field spectrograph arise from the need to pack the 3D information onto a 2D detector. Several concepts have been proposed and are summarized in Table 1. In the next paragraphs these concepts are detailed in decreasing order of efficiency (in terms of CCD detector use).

2.1.1. Image slicers

In this concept of integral field spectrograph an image slicer cuts the imaging field in slices. The image slicer mirrors are slightly tilted to image the slices into a second mirror slicer. This second mirror rearranges the slices into a line. This line then feeds a slit that disperses the image onto a detector.

2.1.2. Optical fiber bundles

Here the image plane is first spatially sampled by a lenslet array that also feeds the fibers In Fig. 1 the multi-pupil fiber spectrograph (MPFS)\(^1\) concept is illustrated. The fibers are then rearranged along a slit that disperses the image onto a detector.

2.1.3. Lenslet arrays

A typical lenslet array IFS is composed of three stages (Fig. 1 middle). In the first (the imaging stage) a filter and an enlarger set the wavelength domain and plate scale. Secondly, in the pupil stage, a microlenses array samples the image plane. Each microlens is imaged onto a pupil. Finally, in the spectroscopic stage, a collimator, grism and camera disperses the pupil light onto the CCD. In order to remove spectral overlap a filter is used to truncate the wavelength domain and the dispersion direction must be tilted with respect to lenslet array axis.

2.1.4. Fabry–Perot type

In a Fabry–Perot (FP) based integral field spectrograph the image is first spectrally sampled by the FP interferometer (after passing by the imaging stage – Fig. 1, bottom). The image is therefore transmitted in the few discrete set of wavelengths sampled by the FP. Then a grism/spectrograph and camera sort the monochromatic images onto the detector. For GraF instrument (see Table 1) only 8 wavelengths are instantaneously obtained. The FP is then scanned yielding a total of 48 spectral pixels.

2.2. Pros and cons

An integral field spectrograph is considerably more complex than a classical spectrograph. From the astronomers point of view the complexity becomes evident at the data reduction stage. Compared to classical spectroscopy, 1000 times more spectra have to be analyzed. This has been the major difficulty in the field, but nowadays good data reduction packages are available (see XOA-SIS for a friendly example).

2.2.1. Slit effect

A classical spectrograph encodes spectral information in one spatial direction (of the CCD). If the slit width is larger than the source width, then a spatial shift of the source in the direction perpendicular to the slit will cause a shift of the spectral line in the CCD spatial direction, where wavelength information is encoded. The slit effect therefore biases the wavelength of the emission line. This effect is only important for slits larger than PSF\(^2\) and introduces bias of the order of


\(^2\) Usually the case in K band in low resolution spectroscopy in the NIR with adaptive optics.
\[ \delta v \sim n \Delta v, \] where \( n \) is the number of spatial pixels the PSF shifts in the slit, \( \Delta v \) the velocity resolution. The shift of the PSF in the slit can be due to intrinsic object structure (emission lines shifted from the continuum), atmospheric differential refraction\(^3\) along the object spectra and differential (wavelength) tilts between the AO reference and  

\(^3\) Atmospheric differential refraction shifts are \(~40\%\) of the diffraction core at 1 \( \mu m \) and decrease to \(~2.5\%\) 2.1 \( \mu m \).
2.2. Flatfielding

IFSs are generally compared to narrow band imaging and long slit spectroscopy. As calibrations are concerned, IFS data cubes are spectra and therefore they share with spectra the difficulties of flatfielding. Flatfielding the data cube to better than a few percent is currently extremely difficult to achieve. Notice that there are two “flatfield” components, the detector flatfield which is in practice impossible to obtain as the detector is illuminated only by the spectra, and the slit/microlenses array/fiber transmission “flatfield” which is the one generally referred in IFS contexts. This last flatfield is generally build from a combination of twilight plus lamp flats and intrinsically limited.

2.2.3. PSF effects

There are several PSF dependent effects that considerably bias spectroscopic observations (specially under adaptive optics) making the use of an IFS a good alternative. The first is the variable slit transmission caused by a variable adaptive optics correction of the turbulence. As the redder part of the star is more compact, due to a better adaptive optics correction, much more light goes into the slit. In practice this effect causes an artificial continuum slope and is quite severe in low resolution infrared adaptive optics spectroscopy (Goto, 2003). In an integral field spectrograph the complete PSF is sampled and therefore the spectra can be extracted by taking into account the wavelength dependence of the PSF. Another advantage is that when the continuum is unresolved it can be used as a PSF reference and accurate deconvolution of the emission line extended structure can be achieved. Finally, when using long slit spectroscopy with adaptive optics the sky absorption lines width depends on the size of the PSF. If the slit width is adjusted to the median PSF width, then in the redder zone of the spectrum (say K band) the PSF width will be smaller than the slit, due to a better correction of the AO. With the PSF changing with wavelength the sky absorption lines width will vary along the spectra. If the adaptive optics correction for the telluric standard is different from the science object the correct subtraction of the sky absorption becomes impossible (also slit effects can play a role in this issue).

The conclusion is that if accurate velocity field mapping is required for an object of complex morphology IFSs are clearly superior to long slit spectrographs. However IFSs do have smaller throughput and spectral resolution/coverage than long slit spectrographs. On the other hand the integral field capability has the potential for serendipity even for the relatively small fields of current IFSs. When using adaptive optics, integral field spectroscopy is a good option to long slit spectroscopy in the infrared, even for point like objects, given the wealth of bias discussed above.

3. Pre-main-sequence star studies

In this section we will review the published studies in the field of pre-main-sequence stars making use of integral field spectrographs. It is natural that most of the studies focus on diffuse extended emission as this is the big advantage brought by IFSs. Therefore most of the studies have been done on jets and Herbig–Haro objects and some on proplyds, reflection nebulae and binaries.

3.1. Jets and Herbig–Haro objects

Although jets are observed in a wide variety of environments (active galactic nuclei, γ-ray bursts, evolved stars and young stars), the detailed mechanisms by which matter is accelerated and collimated into jets remain unknown. The interest of jet observations in young stars is twofold. Firstly, it is in young stars that the jet engine has the largest angular size among all classes of astronomical objects. Secondly, jets are a critical component of the young star-disk system. Indeed, jets are believed to be launched by the disk or star-disk interaction region...
therefore affecting the inner-disk properties and the angular momentum balance of the system. Currently the angular resolution reached by Adaptive Optics or HST is unable to directly probe the jet launching region. Therefore observations center on the outer jet regions, >20 AU. Two methodologies are followed: (a) use of measurements within 100 AU of the source to infer jet launching properties (Woitas et al., 2005); (b) directly study the propagation of jets on large scale, including time variability and shock physics (Reipurth et al., 2002).

The emission in young stellar jets is typically of shock origin (i.e., line emission in contrast to continuum emission as observed in AGN jets). Therefore integral field spectroscopy in the visible and near-infrared is ideally suited to probe it. On the other hand, angular resolution is important to recover quantities as close as possible to the launching region (Woitas et al., 2002). Integral field spectroscopic studies of jets and Herbig–Haro objects have up to now been concentrated on the few brightest objects.

3.1.1. Morphology and excitation

The DG Tau jet, being the brightest jet known from an active T Tauri star, has been studied in detail by several authors (Bacciotti et al., 2000, 2002). The first integral field spectroscopic study of this jet was conducted by Lavalley et al. (1997) in the [OI]λ6300 emission line with TIGER (Bacon, 1995). The instrument configuration had a spectral sampling of 1.5 Å/pixel, a spectral coverage of 200 Å, a spatial sampling of 0.4", and an effective diameter of 8". The observations are presented in Fig. 2. The spatial morphology of the jet in the emission line was found to consist of four components: (a) an unresolved peak, (b) a blueshifted collimated jet, (c) two blueshifted knots and (d) the redshifted jet. The unresolved peak is slightly (0.17") displaced from the continuum and spectrally slightly blue-shifted (50 km/s). This asymmetry of the [OI] emission line is one of the strongest classical arguments for opaque disks surrounding these stars. The origin of this emission is still unknown, it can be both a low velocity wind emanating from the outer disk or a disk corona. The collimated jet is found to reach velocities as high as 340 km/s and transversally unresolved. The knots are suggested to be working surfaces in a time dependent outflow. The fact that shocks are at work in the outflow is further strengthened by the bow-shock morphology of one of the knots. Finally the redshifted jet is detected only 0.45" away from the star suggesting a sharp outer edge in the disk (in contrast to mil-

![Fig. 2. Upper row. Channel maps with velocity ranges (covering 2 or 3 individual TIGER spectral channels) indicated at the top of each panel. Contours increase by factors of 2, starting at 3.6 x 10^-19 W m^-2^-2 (\sim 4\sigma) – angular resolution \sim 0.75\". Bottom row. Same channels after Lucy–Richardson deconvolution by the continuum, with contours starting at 83% of the peak – angular resolution \sim 0.5\". The dotted circle shows the edge of TIGER field of view, from Lavalley et al. (1997).]
limeter observations). These authors have conducted follow-up studies of the same object with the OASIS integral field spectrograph coupled with the PUE'O adaptive optics system (Lavalley-Fouquet et al., 2000). The configurations used covered the 6210–6840 Å range where the forbidden lines of [OI]6300, [NII]6583 and [SII]6716/6731 can be found. The spectral sampling was 0.9 Å/pixel and spatial sampling of 0.16" and an effective diameter of 7". The line ratios across the jet where found to be well fitted by a series of planar stationary shocks of constant magnetic field (100 µG) and varying pre-shock densities $10^2–10^5$ cm$^{-3}$ and shock velocities 15–80 km/s. More recently Massaglia et al. (2005) were able to fit the high velocity data with a time-dependent hydromagnetic planar shock. The jet in the different velocities shows a nested spatial morphology (see Fig. 3), with the high velocity stream being transversally unresolved and the intermediate velocity clearly resolved. The low velocity component is only present at the base of the jet. This “onion-like” structure was confirmed with higher resolution STIS/HST slit scanning imaging by Bacciotti et al. (2000).

3.1.2. Kinematics

MHD models for jet launching do not predict line ratios but simply velocities and densities (as well as magnetic fields and currents). It is therefore natural to test these models using estimates of their intrinsic quantities, these are basically: (a) the diameter (Garcia et al., 2001; Dougados et al., 2000, 2003); (b) the density (Bacciotti and Eisloffel, 1999); (c) terminal velocities (Garcia et al., 2001) and; (d) rotation (Bacciotti et al., 2002; Pesenti et al., 2004; Woitas et al., 2005). We will focus on the kinematical aspects obtained with IFS (terminal velocities and rotation) for RW Aur. Dougados et al. (2003) observed this jet with the OASIS integral field spectrograph coupled to the PUE'O adaptive optics in a similar configuration to the DG Tau jet. The excitation is well explained by shocks. The kinematics allow to clearly rule out cold MHD disk winds (winds where thermal pressure gradient at the wind base is not the dominant launching force). Fig. 4 shows the comparison of the observations with the model. Clearly the terminal jet velocity is too high when compared to observations. The physical reason is that the magnetic lever arm

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**Fig. 3.** Continuum-subtracted maps of the DG Tau microjet in [OI] 6300, H, [NII] 6583, and [SII] 6731 from Lavalley-Fouquet et al. (2000). Velocity ranges are HV [−400,−250] km/s (top row), IV [−250,−100] km/s (middle row), and LV [−100,10] km/s (bottom row). Contours in units of $10^{-18}$W m$^{-2}$s$^{-1}$ start at 2.4, increasing by factors $\sqrt{2}$ for the next 4 levels and by factors of 2 for the following ones. The AO corrected angular resolution was 0.5". Note the increasing collimation at higher velocities.
necessary to launch, collimate and accelerate the wind is too effective. Lower lever arms (in the cold regime) would cause too highly collimated jets in disagreement with observations (Garcia et al., 2001; Dougados et al., 2003). When the jet rotation signatures are analyzed (Fig. 4) the situation becomes worse. Indeed cold winds predict too strong rotation signatures, incompatible with observations. These results have prompted theoreticians to develop warm disk winds (actually high mass load disk winds). In these winds a heating function is applied at the wind base, being therefore possible to eject more mass at lower magnetic lever arms. These dense jets rotate more slowly and fit the rotation observations (Pesenti et al., 2004).

3.1.3. Time variability

López-Martín et al. (2003) compared multi-epoch images of RW Aur pre-main-sequence star blueshifted and redshifted jets obtained with OASIS and STIS/HST. They where able to obtain the proper motions for both jets. Assuming that these motions are real and not waves propagating along the jet and using the line of sight velocity of the lines an inclination of $i = 46^\circ \pm 3^\circ$ was derived. Stationary knots at the very inner region of the jets ($d \lesssim 0.2-0.3^\circ$) were associated to possible recollimation shocks or temperature gradients at the jet base.

The observed knot spacing allowed the authors to rule out instabilities as the knot origin (Kelvin–Helmotz or MHD pinch instabilities) and to favor time dependent ejection velocities. The asymmetry of the blueshifted and redshifted jets in terms of velocities and excitations remains unexplained.

3.1.4. Herbig–Haro objects

The jets described in the previous paragraphs can propagate up to parsec scales. Very far from the source, the jets do not exist anymore as a continuous flow but instead as condensations (or bullets) of free flowing shocked material. The dynamical timescales become considerably large and probe the history of the outflow activity of the central object. Herbig–Haro 32 is a high excitation object consisting in a series of condensations at ~20" West of its source – the classical T Tauri star AS 353 A. Beck et al. (2004) observed the A condensation of Herbig–Haro 32 (Hartigan et al., 1986) with the GMOS integral field spectrograph. The spectral range covered 4820–7040 Å, at a spectral resolution of ~20,000. The observations consisted of a dithered pattern with a final field of 8.7" × 5.85", a fiber sampling of 0.2", under a seeing of 0.5". Although the condensation is quite complex it presents qualitative features of a bow-shock. Therefore the authors used a 1.5 dimensional

![Fig. 4. RW Aur kinematical data from OASIS integral field spectrograph. Left. Synthetic long slit spectra generated from the IFS data compared to the predictions of cold disk wind model A. Right. Transverse velocity shifts at different distances along the jet axis from Dougados et al. (2003). Observed emission line centroids for [OI]λ6300 (triangles) and [SII]λ6731 (squares). The lines are the predictions of cold disk wind model A (Pesenti et al., 2004).](image)
bow-shock model\textsuperscript{4} with a pre-shock density of 100 cm\textsuperscript{-3} and a bow-shock velocity of 350 km/s. The results are in qualitative agreement with the observations, in particular the velocity channel dependent morphology. Herbig–Haro 319 is a little-studied object moving away from the T Tauri stars FZ Tau and FY Tau. This object was observed by Magakian et al. (2002) with the MPFS integral field spectrograph at the SAO 6 m telescope. The field of view was 15\arcsec \times 16\arcsec, sampled by 1\arcsec fibers, the spectral coverage ranged 6200–6900 Å, with a spectral sampling of 60 km/s. Based on its morphology (cf. Fig. 5) the authors interpret the object as a shocked clouddlet of gas.

\textsuperscript{4} In these models the bow-shock is assumed axisymmetric and described by a 1D curve (z is a power-law of r). Then planar shocks are fitted along this curve.
3.1.5. Herbig Ae/Be stars

These stars are intermediate mass (2\(M_\odot \lesssim M \lesssim 7M_\odot\)) counterparts of the T Tauri stars. Jet activity is much weaker in these stars. R Mon is a binary Herbig Ae/Be star still embedded in a cometary nebula. Movsessian et al. (2002) conducted integral field observations of the object with MPFS and detected the jet against the strong nebula continuum background. The field of view was 15\('\times 16\)' field sampled with 1''\times 1'' fibers. The spectral range and resolution was 5650–7000 and 3\(\text{Å}\). In Fig. 6 the jet and the nebulae are depicted. The jet presents a helical wiggling structure. A velocity gradient perpendicular to its axis reaching up to 70 km/s is also evident and was interpreted as caused by jet rotation. On the other hand the authors argue that the observations trace a DNA-like helical shock filament woven around the outflow, which remains unseen. The projection effects being the cause of the observed velocity gradients.

3.1.6. High mass star jets

The current picture of high mass ejection is much less detailed than that for their lower mass counterparts. This is mainly due to a much shorter evolutionary timescale, the very high extinction and the complex cluster environment surrounding these objects. There is however mounting evidence that disk accretion and collimated mass ejection are present and scaled-up with respect to the low mass stars. IRAS 1851-1208 is a high mass object (2\(\times 10^6L_\odot\), Sridharan et al., 2002), embedded in a high density core, associated with high velocity CO emission and a highly collimated \(H_2\) jets (length to width ratio of 6, Davis et al., 2004). One of the jets is bipolar in the NW-SE direction with its axis roughly crossing IRAS 1851-1208 position, the other is roughly perpendicular, pointing to the SW. Integral field spectroscopy with UIST of the object as well as of some knots in the jets is presented by Davis et al. (2004). UIST was used in its medium resolution (\(R = 1000\)) configuration covering the HK bands, with a field of view of 3.3''\times 6.0'' sampled at a 0.24''\times 0.12'' pixel scale. Fig. 7 present IFU images of IRAS 1851-1208 in the continuum and emission lines. The K band nebulus image shows that the object is heavily embedded. Br\(\gamma\) emission (and also CO bandheads not shown) is unresolved and could arise in magnetospheric accretion (if the low mass picture holds) or in a compact HII region surrounding the object. The base of the blueshifted SE jet is seen in \(H_2\) and [FeII]. The spatial shift of this emission with respect to the central source is similar to what is observed in their lower mass counterparts. IFS observations of the knots in the large scale jets have

Fig. 7. Extracted IFU images of IRAS 1851-1208 (IRS 1) from Davis et al. (2004). (a) K-band image extracted over a wavelength range 2.03–2.37 \(\mu\)m. (b)–(d) Narrow-band images, in Br\(\gamma\), \(H_2\) 1–0 S(1) and [FeII]1.644 \(\mu\)m emission, have been extracted over 4-pixels (~0.0031 \(\mu\)m) in the dispersion direction. Adjacent continuum images have been subtracted from the three narrow-band images. Contours measure: (a) 0.5, 1, 2, 5, 10, 20, 40 mJy\(\cdot\)arcsec\(^{-2}\); (b) 3, 6, 12, 24 mJy\(\cdot\)arcsec\(^{-2}\); (c) 2, 3, 4, 5, 6 mJy\(\cdot\)arcsec\(^{-2}\); (d) 0.3, 0.5, 0.7, 0.8 mJy\(\cdot\)arcsec\(^{-2}\). In all images the pixel scale is 0.24''\times 0.12''.
found only H$_2$ emission. Excitation studies of this emission allowed the derivation of excitation temperatures in the 2200–2700 K range, an ortho-to-para ratio of ~3 (equilibrium value), and values of 1–0 S(1)/3–2 S(3) in the 14–53 range, clearly arguing for shock excitation (as in their lower mass counterparts). The H$_2$ luminosity is comparable to the mechanical luminosity of the CO outflow (Beuther et al., 2002) and at least 10 times larger than the ones observed in low mass Class I sources. In summary, the IFS observations of IRAS 1851-1208 support the view that high mass stars follow a scaled-up version of the accretion-outflow paradigm developed for low mass stars.

3.2. Proplyds

Proplyds are low mass embedded young stellar objects being photoionized by ultraviolet radiation field from nearby OB stars (Bally et al., 2000). In general these objects present a bow shaped head facing the ionization front and a tail directed away from the source. The main difficulty in the observational studies of these objects is the variable background of the HII nebula which makes difficult accurate background subtraction. The 167–317 (=LV2) proplyd was observed by Vasconcelos et al. (2005) with the GMOS-IFU. The FOV was 3.5" × 3.5" sampled with an array of 1000 lenses of 0.2". The spectral coverage was 5515–7630 Å sampled at 0.34 Å. Fig. 8 presents 167–317 in several emission lines. By accurate fitting of the emission lines Vasconcelos et al. (2005) uncover three velocity components in the object. They are associated to the photoevaporated flow, the redshifted jet and a faint blueshifted counter-jet. The derived mass loss rate for the photoevaporated proplyd is $\dot{M} = (6.2 \pm 0.6) \times 10^{-7} M_\odot/\text{yr}$ and for the redshifted jet $\dot{M} = (2.0 \pm 0.7) \times 10^{-8} M_\odot/\text{yr}$, typical of these structures.

3.3. Reflection nebulae

RNO 129 (HH 198) is a compact reflection nebulae harbouring a binary star. It was observed with the VARG integral field spectrograph by Movsessian et al. (2000). The field of view of 20" × 40" was sampled with 1.2" microlenses, the spectral resolution was 1800 and spectral coverage 75 Å, centered on the [SII] doublet. The images in Fig. 9 clearly show that the source is double. The alignment of the [SII] emission knots with the faint component argue for it as the driver.

Haro 6-10 (HH184) is a binary system of T Tauri stars embedded in a bright reflection nebulae. This object was observed by Movsessian and Magakian (1999) with the MPFS integral field spectrograph. The configuration had a field of view of 11" × 15" sampled with 1.35" fibers. The spectra covered the 6200–6800 Å range at a resolution of ~1700. These authors detect a jet at a position angle of 195° not coincident with the reflection nebula cone axis position angle at 150° (see Fig. 10). Based on the polarization observations of the system they argue that these measure the position angle of edge on disks. They then conclude that the Northern fainter and more embedded member of the binary is the jet driver. Further support for this view comes from the detection of H$_2$ only in the northern component.

3.4. Binaries

The binary properties (separation, eccentricity, period, mass ratios) of pre-main-sequence stars across the mass spectrum can be used to test their formation mechanism(s). But most of the pre-main-sequence stars form in clusters. The dynamical interaction within the cluster will play a key role in the binary distribution, therefore star formation in a cluster is a highly dynamic and chaotic process (e.g., Bate et al., 2003). In this context integral field spectroscopy can be a useful tool to probe the complex environment of binary stars as shown in the previous examples for the specific cases of jets and reflection nebulae.

3.4.1. Spectroastrometry of Z CMa

This object is a binary star composed of an FU Orionis object and a Herbig Ae/Be star (Koresko et al., 1991). The system drives a powerful jet (Poetzel et al., 1989). The separation of the binary is 0.1" making direct resolved spectroscopy in the optical

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5 An FU Orionis type object is a pre-main-sequence star presenting vigorous accretion such that its luminosity is completely dominated by the accretion disk.
impossible and therefore raising difficulties in the determination of the exact nature of the components and of the jet driver. Using the OASIS integral field spectrograph coupled to the PUE'O adaptive optics bonette Garcia et al. (1999) have imaged the binary and detected a micro-jet. The configuration used covered the 6200–6532 Å region at a resolution of 3200 (λ/Δλ). The spatial sampling

Fig. 8. Top left, HST WFPC image 167–317 in [OIII] from Bally et al. (2000). Top center and right, GMOS smoothed cubes in [NII]λ6548 and Hα, respectively. Bottom left, center and right: [NII]λ6583, [HeI]λ7065 and [ArIII]λ7135, respectively. The pixels of the IFU are slightly smaller than those depicted. The central object is the proplyd and the clump to the SE of the proplyd (seen in [NII] and Hα) is associated to the redshifted jet (Vasconcelos et al., 2005).
was 0.11\arcsec covering a 4.1\arcsec\times 3.3\arcsec field of view. A microjet was detected in the [OI]\lambda 6300 line and associated to the Herbig Ae/Be star. The binary spectra was recovered in spite of being unresolved (seeing of 0.63\arcsec). The technique to recover the components consisted in gaussian fitting the unresolved binary therefore recovering very accurate astrometry for each spectral image. The resulting spectroastrometry is shown in Fig. 11. Using the astrometric signal and the system separation and flux ration in the continuum the authors were able to derive the spectra of each component – cf. Fig. 11. Showing that the brightest object in the optical is the FU Orionis object but that the emission lines originate in the embedded Herbig Ae/Be star.

Fig. 9. RNO 129 observations by Movsessian and Magakian (2004). Left. Continuum I image. Right. VAGR integral field spectrograph (Movssesion et al., 2000) restored images. The grey scale traces the continuum, the contours the [SII] emission. The two emission knots (a) and (b) and the companion position (cross) are marked.

Fig. 10. Haro 6-10 system observations by Movsessian and Magakian (1999). Left: the contours trace the reflection nebula continuum emission, the gray scale the integrated [SII] luminosity. Center. The evolution of [SII] velocity and electronic density along the jet axis. Right. Schematic model for Haro 6-10 system. CS-1 is the circumstellar disk of the primary, CN it’s cometary nebula. CS-2 is the circumstellar disk of the secondary.
3.4.2. The T Tauri system

T Tauri stars are a class of low mass pre-main-sequence stars named after T Tauri. This object is an hierarchical triple with the southern companion (T Tau S) being a binary itself (T Tau Sa and T Tau Sb). T Tauri was first observed with an integral field spectrograph by Herbst et al. (1996) in January 1995. The MPE 3D integral field spectrograph coupled to the CHARM tip-tilt module was used (Weitzel et al., 1996). The spatial sampling was 0.52" and the field of view 8' × 8' and spectral resolution was ~1000 (λ/Δλ) in the H and K bands. Molecular hydrogen was detected in both stars. A Herbig–Haro object was detected to the NW of T Tau N in molecular hydrogen and [FeII]λ1.6 μm (Fig. 12). A faint H₂ filament to the West of the system was also detected as well as diffuse emission throughout the field (Fig. 12).

The orientations of these two extended structures associate them to the two jets present in the system. The H₂ line ratios show that molecular hydrogen is shock excited to temperatures of ~2000 K (except for the diffuse component at ~1000 K). Follow-up observations in the fall of 1999 with the ALFA adaptive optics system at an angular resolution of 0.15" were conducted by Kasper et al. (2002). The same system was used with a plate scale of 0.07", a field of view of 1" × 1" and spectral resolutions of ~1000–2100 (λ/Δλ) in the K and H band, respectively. The most striking observation of Kasper et al. (2002) is the non-detection of molecular hydrogen at the stellar positions. The authors argue that the line emission is connected to the flaring activity of T Tau S and hence variable. Atomic Hydrogen emission is detected in both stars and unresolved.
The extracted spectrum of T Tau S is heavily veiled arguing for a strong contribution from its circumstellar disk. This was further strengthened by radiative transfer modeling of T Tau S with an almost edge on disk.

3.4.3. Herbig Ae/Be stars

LkHα 225 (=V1318 Cyg) is a wide (5") binary located in a cluster of the giant star forming region 2 Cyg (at ~1 kpc). The binary was observed in the K band with MPE 3D coupled to the ALFA adap-
tive optics system at an angular resolution of 0.6′′ (Davies, 2001). The angular sampling was 0.25′′, the field of view 4′′ × 4′′ and spectral resolution of 1000 (λ/Δλ). A dusty ridge is observed to the south of the northern star (Fig. 13), its bluer color when compared to the stars argues for scattered light (or a lesser extinct region). Only the southern star presents molecular Hydrogen emission in a series of lines (Fig. 13). A fan shaped structure is observed to the NE of the southern component. Analysis of the H\textsubscript{2} lines reveals that they are redshifted at −75 km/s, quite broad (220 km/s) and cold (980 K), hinting for a disk wind origin. On the other hand the CO emission is compact and centered on the stars arguing for an accretion disk origin.

Using the Fabry–Perot based GraF integral field spectrograph (Chalabaev et al., 2002) coupled to the ADONIS adaptive optics Trouboul et al. (1999) obtained the spectral class of Herbig Ae/Be binaries by measuring the EW of metallic and molecular lines in the near-infrared. For Rossiter 3930 (1.6′′ from HR 5999) they obtain a K7-M0 spectral type which corresponds to 3920 ± 120 K (assuming luminosity class V). For HEN 3-225 (=HD 76534) companion at 0.6′′ a K5-M0 spectral class and 4060 ± 260 K effective temperature is determined.

4. Conclusions and further prospects

The studies of pre-main-sequence stars presented previously are synoptic in nature. This is caused by two main reasons: firstly the difficulties in data processing and analysis and secondly the use of IFS to study difficult and complex objects (impossible to tackle with long slit spectroscopy) and their further modeling.

However these studies have shown that quantitative astrophysics is achieved by IFS. Physical diagnostics were derived from IFS data such as gas excitation and pre-shock densities, gas morphology and spectra from close binaries. Models for the sources are directly tested: radiative transfer models, Shock models (planar, bow-shock) and magneto-hydrodynamics jet models.

New tools and paradigms for analysis and data reduction developed within the Euro3d RTN are available making IFS more user friendly.

The question to ask now is what is the future of IFS spectroscopy in the pre-main-sequence stars field with existing instrumentation, namely OASIS? Clearly synoptic studies of key objects will continue but new methodologies are required. For a significant advance in the study of the mass loss from pre-main-sequence stars, survey-type observations are clearly required. The potential of this methodology is proved by the huge (and impressive) success of SAURON. Possible projects are a snapshot survey of jet excitation and morphology across the mass spectrum and evolutionary state for one hundred objects. Follow-up studies of relevant targets at higher angular resolution could be done with OASIS+NAOMI+GLAS. The Orion trapezium cluster could be surveyed probing the wealth of phenomena occurring in the nearer high mass star forming cluster. A follow-up survey to IPHAS selected sources (Drew, 2005) is another exciting possibility.

Integral field spectroscopy is also part of future instrumentation both for existing large telescopes and planned extremely large telescopes. Two paradigms exist: (a) first the use of use detector space to increase significantly the field of view and therefore proceed to massive “blind” surveys – MUSE; (b) to sample large fields with deployable IFUs pointing to known objects – FALCON. Scientifically the serendipity potential of MUSE like IFUs is outstanding. On the other hand FALCON like surveys of relatively low density targets – essentially the spectroscopic characterization of components of star forming embedded clusters discovered in the recent years (Lada and Lada, 2003) is certainly an exciting possibility.

Integral field spectroscopy will therefore continue as key instrumentation for the forthcoming decade of astrophysics.

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