Integral field spectroscopy of protoplanetary disks in Orion with VLT FLAMES

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Summary. We discuss integral field spectroscopy of proplyds in M42 using the FLAMES Argus unit and report the first detection of recombination lines of C\textsuperscript{II} and O\textsuperscript{II} from the archetypical LV2 object. These lines can provide important new diagnostics of the physical conditions in proplyds. We also draw attention to the future capabilities of the MUSE spectrograph in relation to similar studies.

1 Rationale

This contribution focuses on optical integral field spectrophotometry (IFS) of protoplanetary disks (proplyds) in M42 taken with the Argus unit of VLT FLAMES. The proplyds in M42 are partially ionized, low-mass embedded young stellar objects immersed in the extreme UV radiation field of the Trapezium cluster \cite{1}. They represent a unique nearby environment for the study of ongoing star formation in a region dominated by main sequence OB-type stars. At optical wavelengths proplyds usually present a photoionized skin facing the Trapezium, giving way to a neutral dusty envelope which is shielded from the ionizing photons and is often shaped into ‘cometary’ radiation-bounded tails. IFS mapping of the proplyds and their immediate surroundings can yield new insight on the influence of small-scale ‘inhomogeneities’ on integrated spectra of distant galactic and extragalactic H\textsuperscript{II} regions.

With this programme we specifically aimed at recording the faint optical recombination line (ORL) spectra of carbon (C\textsuperscript{II}) and oxygen (O\textsuperscript{II}) ions and use them, for the first time, as abundance diagnostics of the photoionized surfaces of the proplyds and their outflows. Simultaneous coverage of the strong collisionally excited lines (CELS) of [O\textsuperscript{III}] would allow us to obtain a separate estimate of the oxygen abundances across the field and thus study the ‘abundance discrepancy problem’, whereby heavy element abundances, relative to
H, from ORLs are found to be higher than the corresponding CEL-based abundances for classic H II regions such as M42 and 30 Doradus, by factors of up to \( \sim 2 \) [2]. The resolution of this problem is of high priority as it casts uncertainty on classic CEL-based methods of abundance determinations for local and distant nebulae and galaxies. It has been proposed that temperature fluctuations [3], density fluctuations, or zones of hydrogen-deficient plasma [4] within the nebulae may contribute to the ‘ORL vs. CEL’ problem. Our observations were aimed at discriminating between the various possibilities.

2 Observations and data reduction method

Argus is a rectangular array of 22×14 microlenses fed by optical fibres: we used the small configuration which provides a sampling of 0.30 arcsec\(^2\)/microlens and projects 6.6×4.2 arcsec\(^2\) on the sky, yielding 297 positional spectra per field of view. The targets were three relatively bright proplyds, including the archetypical object LV2 (167-317; [5]), and were selected from HST WFPC2 H\(\alpha\) and [O III] images of the nebula. The spectra were taken in service mode, and in sub-arcsec seeing, with the LR1–5 and HR1, 3, 4, 6, 8, 14B grating set-ups of the Giraffe spectrograph at resolving powers of \( \sim 10\,000 – 46\,000 \). For LV2 the total exposure time in the LR/HR modes was 3000 and 590 sec respectively; similar times were allocated to the other two targets. The data reduction was done with the girBLDRS pipeline developed by the Geneva Observatory. Custom-made IRAF scripts allowed us to construct data cubes and spectral line maps, and a dedicated \( \chi^2 \) minimization routine was used to automatically fit Gaussians to the emission lines.

3 First results

At the time of writing preliminary monochromatic maps have been obtained for LV2. We succeeded in detecting the C II \( \lambda4267 \) and O II \( \lambda4649 \) ORLs from the head of the proplyd, and imaged the proplyd head and outflow in the light of H\(\alpha\), and the [O III] \( \lambda\lambda4363, 4959, \) [Ar IV] \( \lambda\lambda4711, 4740, \) and [S II] \( \lambda\lambda6716, 6731 \) CELs. The [O III] line ratio yielded an electron temperature \( (T_e) \) map and the [Ar IV] and [S II] ratios yielded electron density \( (N_e) \) maps. In Fig. 1 spectra of LV2 are shown extracted over the proplyd’s tip (\( \sim 9 \) spaxels). The C II \( \lambda4267 \) 3d–4f line is well detected in the LR2 setting, as are the numerous O II V1 multiplet 3s–3p lines around 465.0 nm in the HR6 setting. All these lines are useful abundance diagnostics [6], and the intramultiplet relative intensities of O II V1 lines are a \( N_e \) diagnostic of their emitting regions too [7].

In Fig. 1b the O II lines appear single peaked meaning that they mostly arise at the LV2 rest frame velocity; in contrast, the [Fe III] \( \lambda4658 \) line exhibits...
two additional velocity components associated with the proplyd’s bipolar outflow; further detections of [Fe III] lines, which are good tracers of shocked gas, will allow us to measure the electron density in the outflow. Analysis of the [O III] λ5007 line substructure at a spectral resolution of 9 km s\(^{-1}\) pix\(^{-1}\) indicates that the lobes of the bipolar jet emanating from the embedded protostar have line of sight velocities of approximately \(-100\) and \(+80\) km s\(^{-1}\) (see Fig. 2). It is likely, however, that the velocity structure will differ amongst various ionic species; a detailed kinematical analysis of emission lines from the numerous Giraffe HR settings will clarify this. The velocity resolution of this dataset at H\(\alpha\) is a factor of 2.3 higher compared to a Gemini-S GMOS IFU analysis [8] (which focused only on the red part of the optical spectrum and did not go deep enough to detect any heavy element ORLs).

In Fig. 3 we show a \(T_e([\text{O III}])\) map of LV2 and its immediate vicinity based on the \(\lambda\)4363/\(\lambda\)4959 ratio with the corresponding O\(^{2+}\)/H\(^+\) CEL abundance map based on the \(\lambda\)4959 line. Notably, the electron temperature over the proplyd appears to be as high as 15,000 K whereas the background temperature is only \(~8500\) K. This is mainly due to collisional suppression of
Fig. 2. LV2 (167-317) Argus spectrum showing the [O III] λ5007 line taken with the HR8 setting (at 9 km s$^{-1}$ pix$^{-1}$); note the blue- and red-shifted components arising from the proplyd’s outflow and which are absent in the background nebula.

the relatively low critical density λ4959 line over the dense proplyd (at $N_e > 7 \times 10^5$ cm$^{-3}$). As a direct result of such pseudo-$T_e$ fluctuations, the O$^{2+}$/H$^+$ CEL abundance (Fig. 3 right) in the close vicinity of LV2 appears to be about a factor of 3 lower than in the background nebula.

An intricate combination of pseudo-variations in CEL-based abundances coupled with enhanced ‘metallic’ ORL emission from dense proplyds, and similar types of condensations, could at last provide a factual explanation to the long-standing abundance discrepancy problem in H II regions. Detailed studies with VLT FLAMES can improve our understanding of the protoplanetary disks themselves and help elucidate the influence of such objects on integrated nebular spectra.

In conclusion, we note that the planned second generation VLT instrumentation will include MUSE, an adaptive optics assisted IFU spectrograph, which in wide field mode (1×1 arcmin$^2$) will be able to take integral field spectra of the whole central Orion region (and of distant giant H II regions), and to sample simultaneously the entire proplyd population with 0.2$''$×0.2$''$ spatial pixels. In narrow field AO-assisted mode the spatial resolution of 0.025$''$×0.025$''$ will allow unprecedented views of individual proplyds and protostellar outflows. It is unfortunate, however, that the currently planned wavelength coverage of MUSE is only 465.0 – 930.0 nm; this will miss the brightest optical
recombination lines from C II, C III, N II, N III, O II, Ne II species (< 465.0 nm) which have in recent years opened an exciting new window to the chemistry and astrophysics of nebulae.

Fig. 3. LV2 (167-317) and M42 background physical conditions: (Left) The electron temperature map based on the [O III] auroral to nebular line ratio; (Right) The corresponding forbidden-line doubly ionized oxygen abundance map.

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