The Central Orion Nebula (M42) as seen by MUSE

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The MUSE (Multi Unit Spectroscopic Explorer) instrument, an optical wide-field integral field spectrograph at the Very Large Telescope, has been operating successfully for about a year. Among the impressive sets of data collected during commissioning was a mosaic of the central Orion Nebula (M42), known as the Huygens region. During the past year, we have made the data ready for scientific use, and they are now publicly available to the community. An overview of the observations and their reduction, as well as two possible scientific applications, are presented.

The MUSE integral field spectrograph (Bacon et al., 2012) was commissioned at the Paranal Observatory in the first half of 2014. It covers a field of view of about 1 by 1 arcminute on the sky at a sampling of 0.2 arcseconds per spatial element and has a nominal wavelength range of 480 to 930 nm. An extended mode without an order-separating filter is available, which allows a contiguous data coverage down to about 460 nm. In the future, the instrument will be enhanced with an adaptive optics module and a narrow-field mode, with an eightfold increase in spatial sampling. A summary of the commissioning and Science Verification activities was presented in Bacon et al. (2014) and these activities have already amply demonstrated the instrument's capabilities for a variety of astronomical topics. In this article we highlight the Orion Nebula dataset taken during commissioning, which we have reduced and now make available as science-ready cubes[1].

The Orion Nebula

H II regions are stellar nurseries where we can study the interplay between the recently born (massive) stars and the surrounding interstellar medium. One of the best-known and closest examples, at a distance of about 440 pc, is the Orion Nebula (M42; a review is given in O'Dell [2001]). As such, it is one of the favourite targets when a new instrument needs to be validated, on account of its high surface brightness, richness in terms of structures and wealth of previous observations. The nebula was observed during the commissioning of MUSE with the main technical goals of testing offsets larger than the field of view and as a stress test for the data reduction system. The collected data: i) mapped the complete bright core (called the Huygens region) over a field of 6 by 5 arcminutes; ii) achieved a depth similar to previous studies with only 5 seconds exposure time; iii) offered a large spectral coverage ranging from approximately 460 nm to 935 nm; and iv) had reasonably good spatial and spectral resolution. Since none of the previous datasets obtained using long-slit or integral field spectrographs possessed all these properties simultaneously, it was decided to release the MUSE Orion Nebula data to the community, as a fully reduced and science-ready cube.

Data processing

Basic data processing of each individual pointing was done using the dedicated MUSE pipeline (Weilbacher et al. [2012], and publicly available for download[2]) and included bias subtraction, flat-fielding and throughput correction, wavelength calibration, geometric characterisation, application of an astrometric solution, correction for atmospheric refraction, application of the barycentric velocity offset and flux calibration. We did not attempt to remove the sky background or the telluric absorption. The 2-Micron All Sky Survey (2MASS) positions of the stars present in each pointing were used to establish the relative positioning between the individual pointings, and all the cubes were merged into a common final cube.

The dataset constitutes one of the first observations with the MUSE extended mode and thus, also one of the first

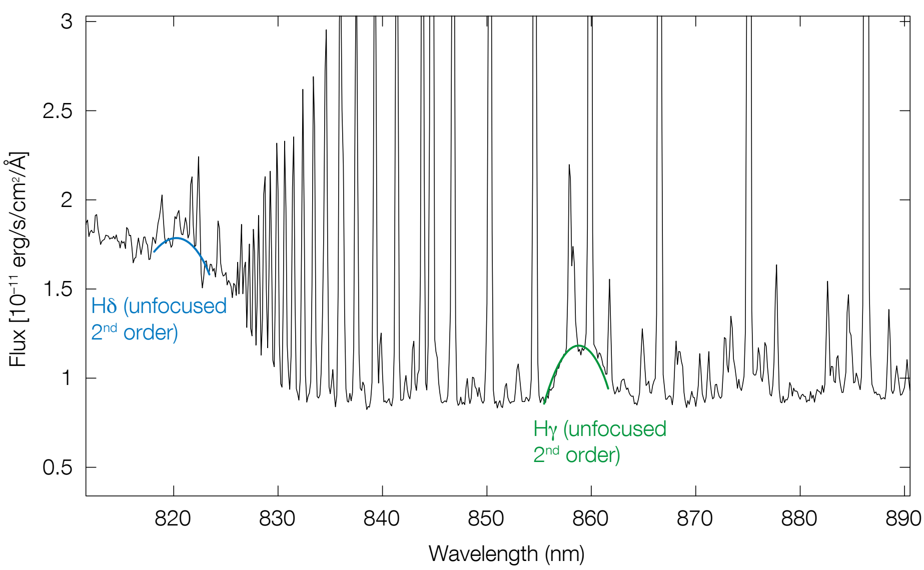


Figure 1. The red end of one Orion spectrum illustrating the contamination of the data by the broad second order. Broad bumps caused by second order contamination of Hδ and Hγ are indicated.

opportunities to evaluate the effects of second-order overlap. The central Orion Nebula shows very strong emission lines that are easy to identify, while the second order is unfocused and offset from the expected wavelength calibration. Figure 1 illustrates its appearance in the spectral direction: strong emission lines in the blue create broad bumps in the red region of the spectrum. On top of the first order spectrum, two bumps caused by the second order spectrum of Hδ and Hγ are clearly identified. These bumps can be modelled and subtracted as background, thereby minimising their effect in the estimation of the line fluxes in the reddest part of the spectra.

Data release

The released data products have a spatial size of 5.9 by 4.9 arcminutes (0.76 by 0.63 pc) at a 0.2 by 0.2 arcsecond sampling and a contiguous spectral coverage of 459.5 to 936.6 nm. They are delivered as FITS files with several extensions, including cubes for the data and the statistical variance, and reconstructed 2D images of the field of view. We provide two versions of the cube, with spectral samplings of 0.125 nm and 0.085 nm, and file sizes of 75 and 110 GB respectively. We also provide an online facility that offers the possibility of extracting only a subsection of the cubes, since by current standards these are rather large files[1].

The combined scope of the spatial and spectral directions is illustrated by the cover page and in Figure 2, which show several of the many possible three-colour composite images that can be extracted from these data. The cover page shows an image constructed from three emission lines of hydrogen: Hβ, Hα and Paschen 9 (923 nm) and another image from all three ionisation stages of oxygen that have been detected: [O I]6300 Å, [O II]7320 Å and [O III]5007 Å. As such, the change in colour in the oxygen image nicely traces the ionisation structure of the nebula. This is particularly visible in the Bright Bar, which gradually changes from red ([O III]), through green ([O II]) to blue ([O I]). Figure 2 combines maps of Hβ, [N II]6584 Å and [S II]6731 Å; the most striking features in M42 are labelled.

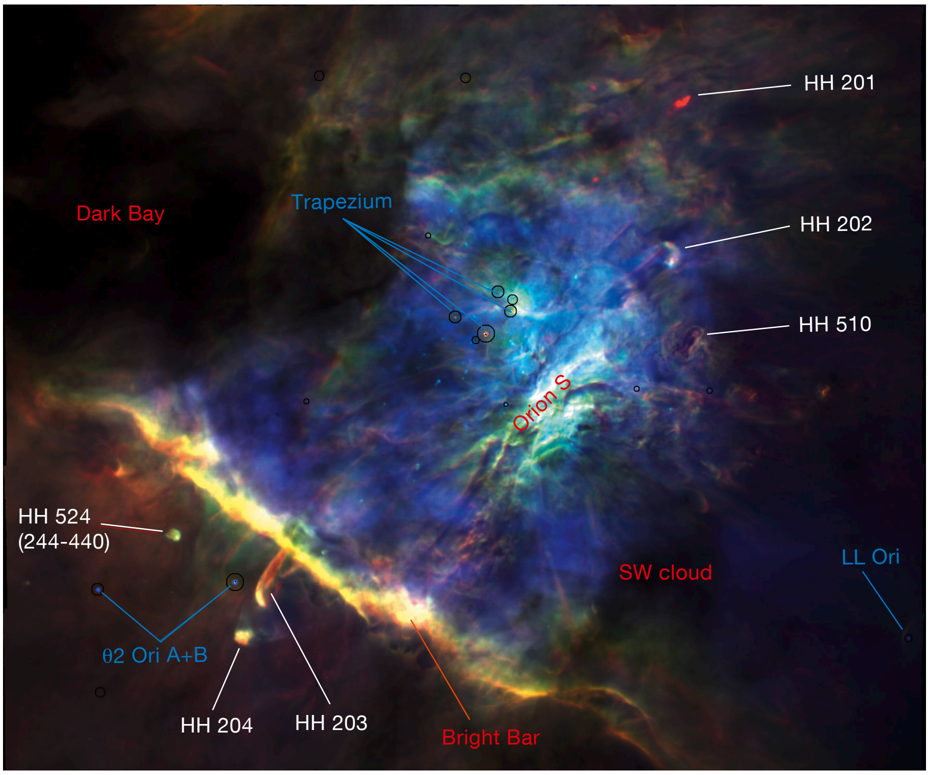


Figure 2. Colour-composite image illustrating the richness of the MUSE datacube in the spatial direction (see also the two images on the cover). [S II]6730 Å/[N II]6584 Å/Hβ (with annotated features within the image) for blue/green/red channels respectively.

These are: the Bright Bar, the Dark Bay, the Orion-S region and several shock-excited Herbig–Haro (HH) objects. The positions of the brightest stars in the field are marked as well, but the stars are not seen, as the maps are continuum subtracted.

The amount of spectral information conveyed in the cube is illustrated in Figure 3. A nebular spectrum of a bright part of M42 over the full wavelength range extracted from the MUSE data is shown. The bright H I (Hα, Hβ, Paschen series) and He I recombination lines are detected, as well as many collisionally excited lines of several metals, which can be used as diagnostics for the physical and chemical conditions of the warm ionised gas. More interestingly, we also detect many of the much fainter metal recombination lines. The faintest identified lines have fluxes on the order of 4×10^{-15} erg cm^{-2} s^{-1}.

Extinction structure

An example of the scientific possibilities offered by this set of data is presented in Figure 4, which shows the extinction map derived from the observed Hα/Hβ emission line ratio and standard assumptions for the assumed intrinsic Hα/Hβ ratio. The Dark Bay and the southwest cloud show the strongest extinction, while regions like the Bright Bar exhibit moderate reddening. This map is qualitatively similar to the reddening map derived by O'Dell & Yusef-Zadeh (2000), who use a different technique (i.e., radio-to-optical surface brightness comparison) and find an extinction peak that is higher by a factor of 1.5 in extinction c(Hβ) with respect to the one found with the MUSE data. This difference can be understood in terms of the differing capacity of both tracers to penetrate the dust, which is higher for the one involving radio emission.

Digging up proplyds by means of line ratio mapping

Although lacking the high angular resolution of Hubble Space Telescope (HST)

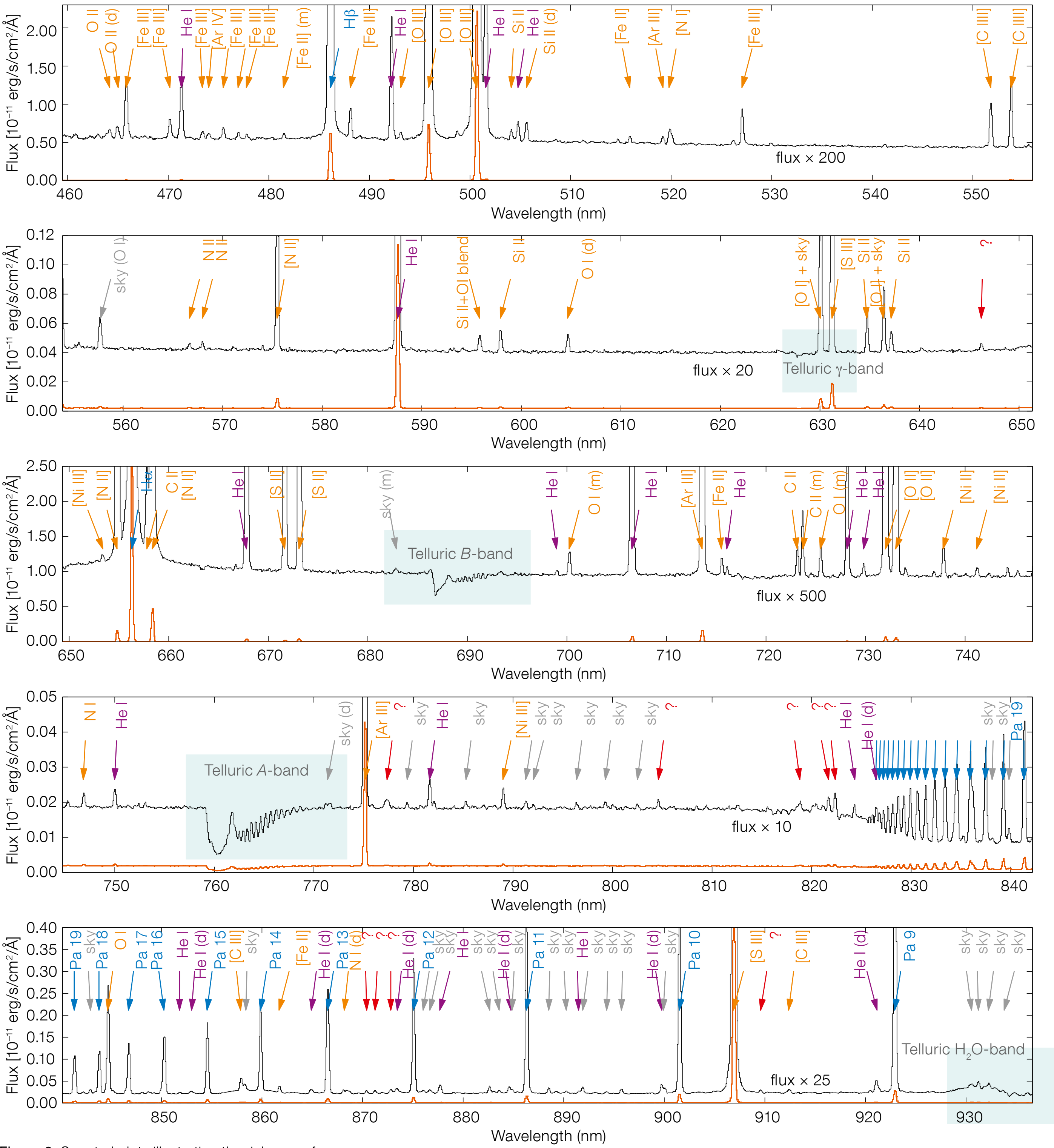


Figure 3. Spectral plots illustrating the richness of the data in the spectral direction: known hydrogen, helium, metal, and sky emission lines are marked with blue, violet, orange, and grey arrows, respectively. A few faint, unknown emission lines are marked in red. The spectrum was extracted from the location of Slit1 of Baldwin et al. (1991).

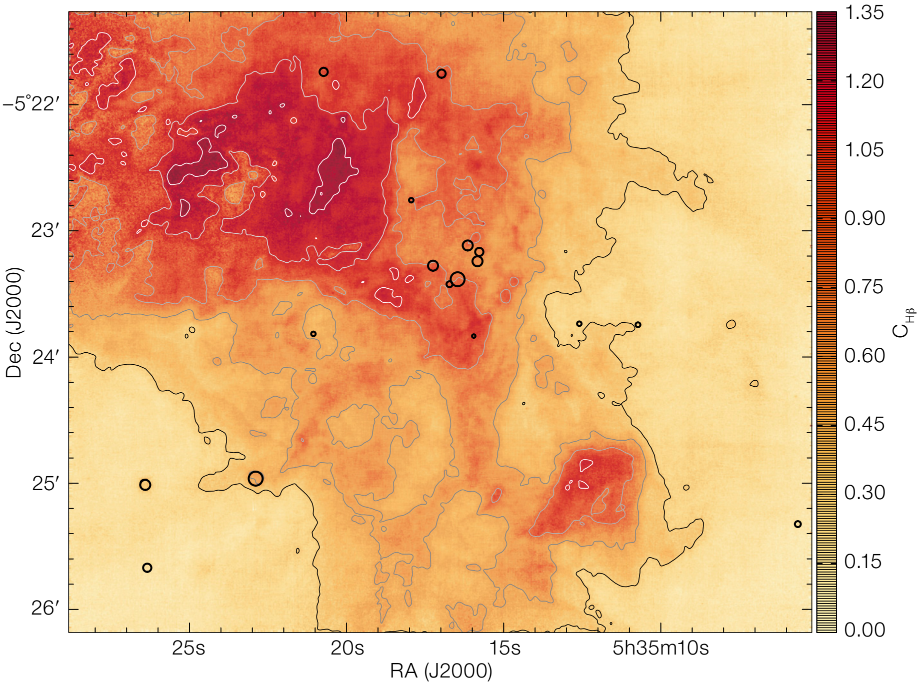


Figure 4. The extinction structure c(Hβ) over the Huygens region of M42, as traced from the Hα/Hβ emission line ratio, is shown.

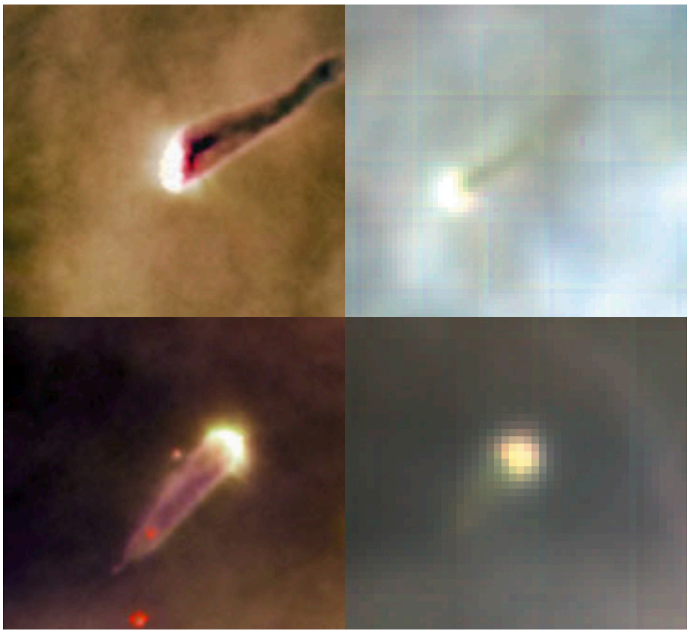


Figure 5. Two Orion proplyds (protoplanetary discs) imaged with HST (left) and MUSE (right). The top row displays object 141-301, the bottom row is 177-341 (nomenclature of O'Dell & Wen [1994]).

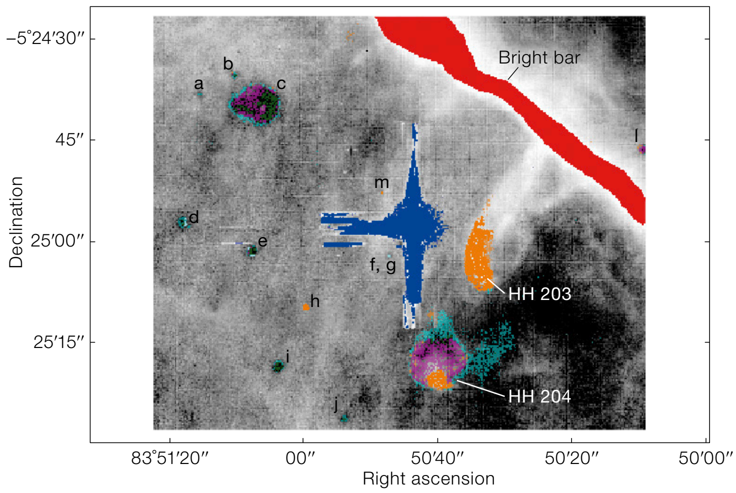
imaging, the MUSE Orion dataset can also be used to analyse various small-scale structures of the Orion Nebula, specifically HH objects and proplyds (protoplanetary discs, O'Dell & Wen [1994]). As an example of the drastic difference in spatial resolution, two Orion proplyds are shown as seen by HST (left) and by MUSE (right) in Figure 5. This analysis is based on two emission line ratios: the parameter usually called S_{23} = ([S II] + [S III])/Hβ (Vilchez & Esteban, 1996), and the indicator [O II]/[O III] representing the degree of ionisation. The parameter space for these two line ratios is shown in the lower panel of Figure 6 (of the immense full region observed with MUSE, only a small sub-region south of the Bright Bar is shown here, as this very interesting region hosts two of the major HH objects as well as several proplyds). In this figure, the data points were traced back to their spatial origin in the S_{23} map (upper panel): it is clear that the different structures and objects occupy different regions in this parameter space. This line-ratio diagram can therefore be used as an initial tool to detect these kinds of objects (proplyds and HH objects) in other star-forming regions as well.

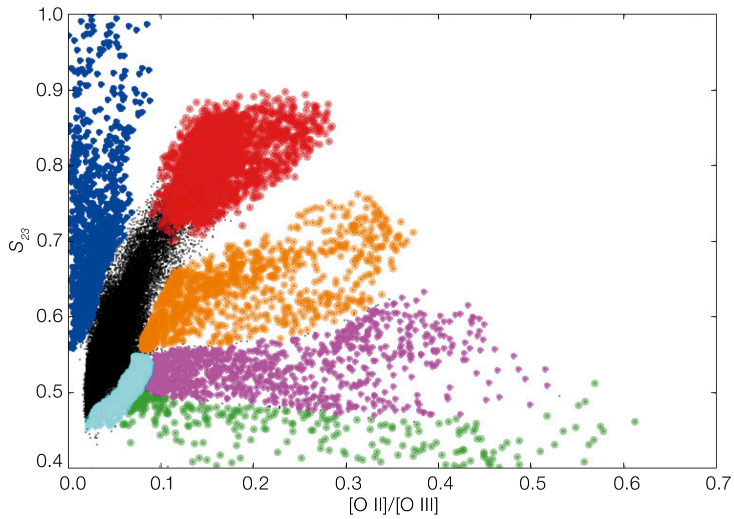
The Bright Bar (red data points in Figure 6) shows higher S_{23} values than the proplyds (their positions are drawn from Ricci et al. [2008] and marked with characters from a to m) and HH objects, while these show a wider range of degrees of ionisation. Furthermore, the HH outflows and proplyds can be separated into four classes (marked by the orange, magenta, green and cyan data points in Figure 6), depending on their S_{23} and [O II]/[O III] values. An initial, tentative, physical interpretation of this empirical finding is that the S_{23} parameter traces the relative contribution of shocks and photo-ionisation to the sulphur excitation, as the presence of shocks locally lowers the ionisation parameter, enhancing the emission of low ionisation (e.g., [S II]) over the high ionisation species (e.g., [S III]). A full discussion of this investigation will be presented in Mc Leod et al. (2015).

Future perspectives

We have released MUSE datacubes for M42[1]. This constitutes the largest integral field mosaic to date in terms of information content. We validated the data in terms of quality as apt for scientific use, and as such potentially useful to address a wide range of scientific questions. Some examples have been presented in this article as well as in Weilbacher et al. (2015) and Mc Leod et al. (2015). We hope that the astronomical community envisions many more.

Figure 6. The S_{23} parameter map of a sub-region south of the Orion Bright Bar (upper panel); the proplyds from Ricci et al. (2008) are marked with characters from a to m. The S_{23} *vs.* [O II]/ [O III] parameter space of the same region is shown in the lower panel, with the structures colour-coded as in the upper panel.





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Links

[1] Access to MUSE datacubes and sub-cube extraction tool: http://muse-vlt.eu/science/m42/
[2] MUSE pipeline: http://www.eso.org/sci/software/pipelines/muse/muse-pipe-recipes.html

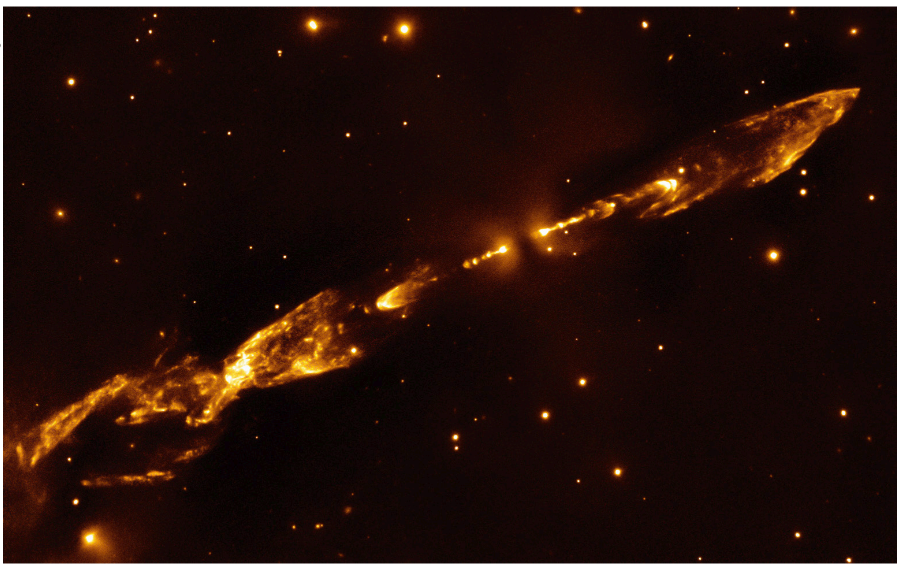

Image in the molecular hydrogen 2.12 μm line of the Herbig–Haro object HH 212 in the Orion B region obtained with the Infrared Spectrometer And Array Camera (ISAAC). The spectacular collimated bipolar outflow from the central young star shocks against the local cloud material, producing a typical emission spectrum strong in molecular hydrogen, other more complex molecules and ionised gas.