The ORION-B project: molecular clouds in the era of wide-field hyper-spectral imaging

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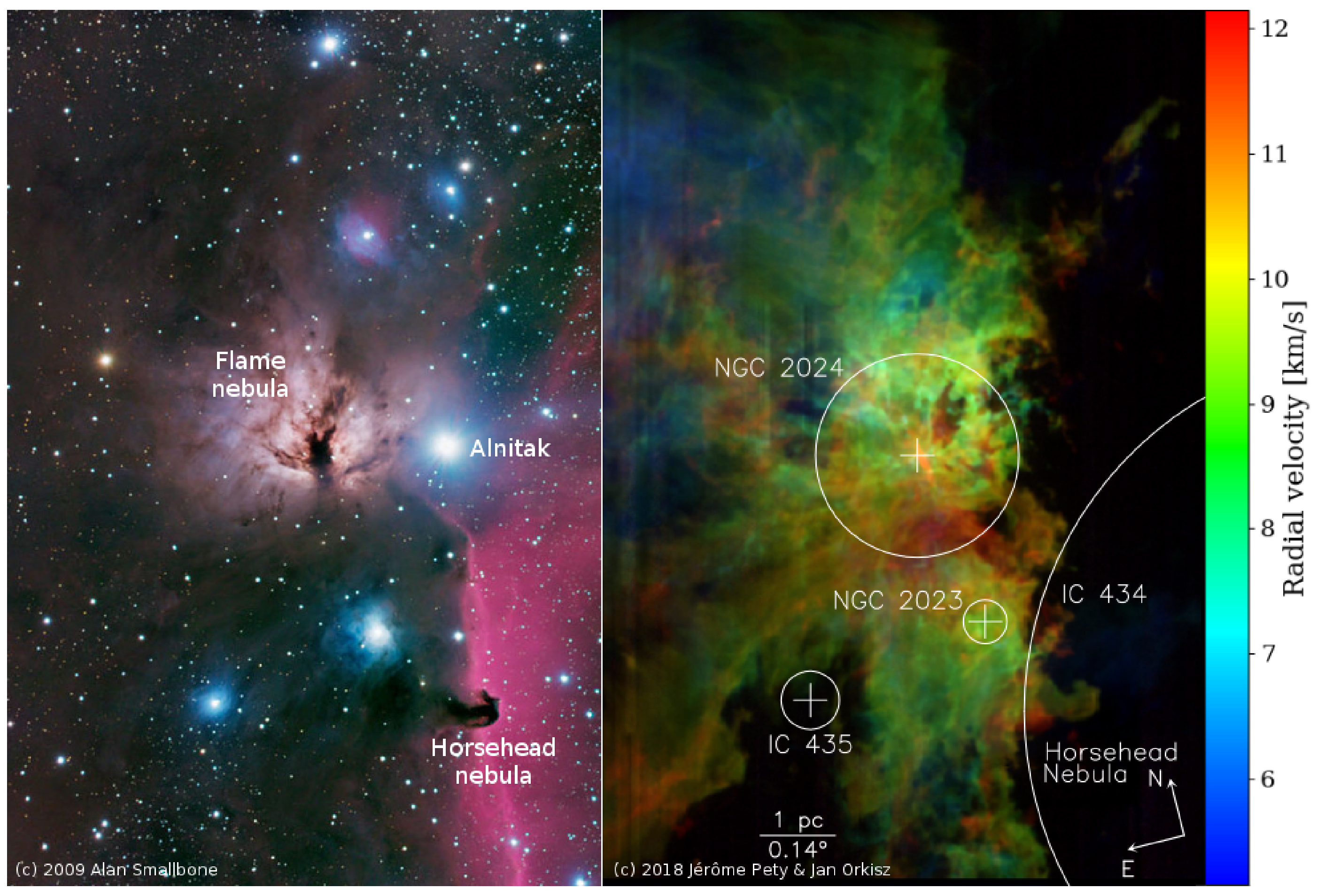


Optical (*left*) and radio (*right*) image of the Orion B molecular cloud. The radio image displays the velocity structure of the cloud detected by the ^{12}CO($J = 1-0$), each velocity channel being directly encoded as a hue.

The ORION-B project (**Outstanding Radio-Imaging of OrioN B**, PIs: Jérôme Pety and Maryvonne Gerin) aims at mapping a large fraction of the Orion B giant molecular cloud in an unbiased spectral survey in the **3 mm band** using the **IRAM-30m** telescope. In addition to providing a remarkable dataset for studying **GMC physics**, the project aims at providing **benchmarks for extragalactic studies** and testing statistical analysis methods for the **new generation of wide-bandwidth receivers**. Orion B has the advantage of being one of the closest (400 pc) star-forming regions. It hosts varied environments, with regions that are dense or diffuse, warm or cold, illuminated or dark, implying **a wealth of different chemistries**.

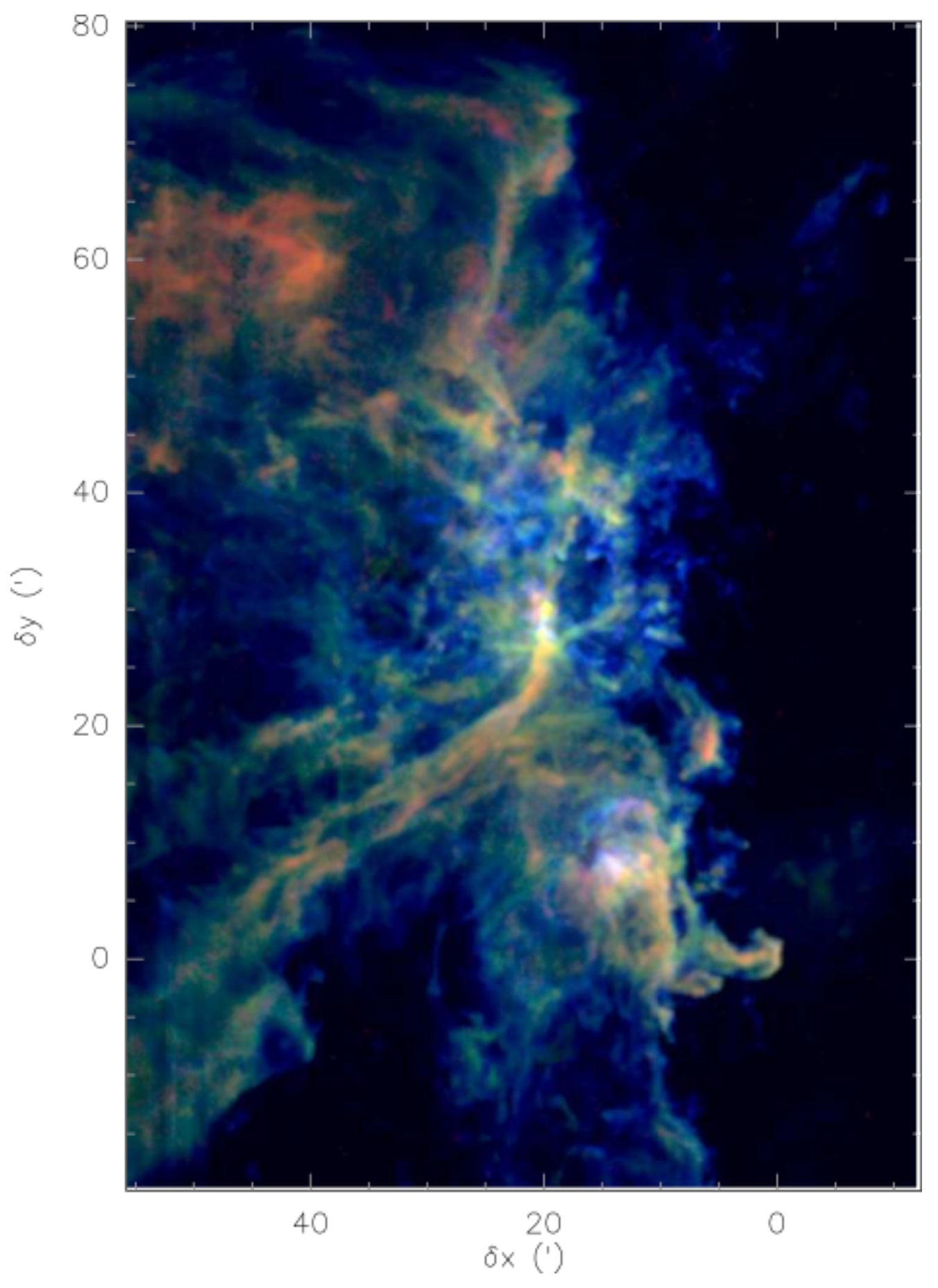
The ORION-B project in numbers:

- **850 hours** of observations
- 40 GHz bandwidth (from 72 to 116 GHz)
- 200 kHz resolution (0.4 – 0.7 km/s)
- 0.1 – 0.5 K sensitivity
- 8 TB of raw data
- 5 square degree field of view
- 22" to 36" (~60 mpc) resolution
- **completion due in 2019**

The presented results cover just a fraction (between 0.9 and 1.5 square degree) of the entire dataset... which means that many more exciting results are still ahead of us!

A first look at Orion B molecular line maps

Pety et al. (2017) have analysed the spatial distribution of the emission from various detected tracers (^{12}CO, ^{13}CO, C^{18}O, C^{17}O, HCN, HNC, ^{12}CN, C_2H, HCO$^+$, N_2H^+ to name a few) and correlated them with one another, with column density (extinction) and with UV illumination (temperature), highlighting how line intensities depend on sensitivity, excitation, and, above all, chemistry.



$J = 1-0$ lines of CO isotopologues (^{12}CO in blue, ^{13}CO in green and C^{18}O in red) tracing different column density regimes.

Because of the intense UV illumination, the gas temperature is higher than average and **the CO emission is overluminous** as compared to the standard $X_{\rm CO}$ factor.

The reliability of tracers of gas density and UV illumination was reassessed with a unbiased statistical approach. **N_2H^+ is the only reliable tracer of dense gas**, while usual "high density" tracers (HCO$^+$ or HCN) were detected at densities as low as ~ 500 H_2 cm^{-3}. **The best tracers of A_V are C^{18}O and HNC**, in terms of the range and linearity of the relationship. **CN and C_2H** appear to be the tracers **most sensitive to UV illumination**.

Line ratios were computed and compared to those observed in nearby galaxies. **N_2H^+/^{12}CO and C_2H/^{13}CO** are very good tracers of the fraction of dense gas and UV illumination respectively.

Star formation and dynamics

Turbulence forcing vs. star-formation efficiency

Orkisz et al. (2017) have determined the fraction R of solenoidal motions in the 3D velocity field of ^{13}CO($J = 1-0$) using properties of the map of its projection. We expect **$R = 2/3$** in the case of equipartition.

$$0.72 < R < 1$$

for the entire field of view. This implies that **solenoidal motions** dominate the cloud, in agreement with its remarkably **low star-formation efficiency**.

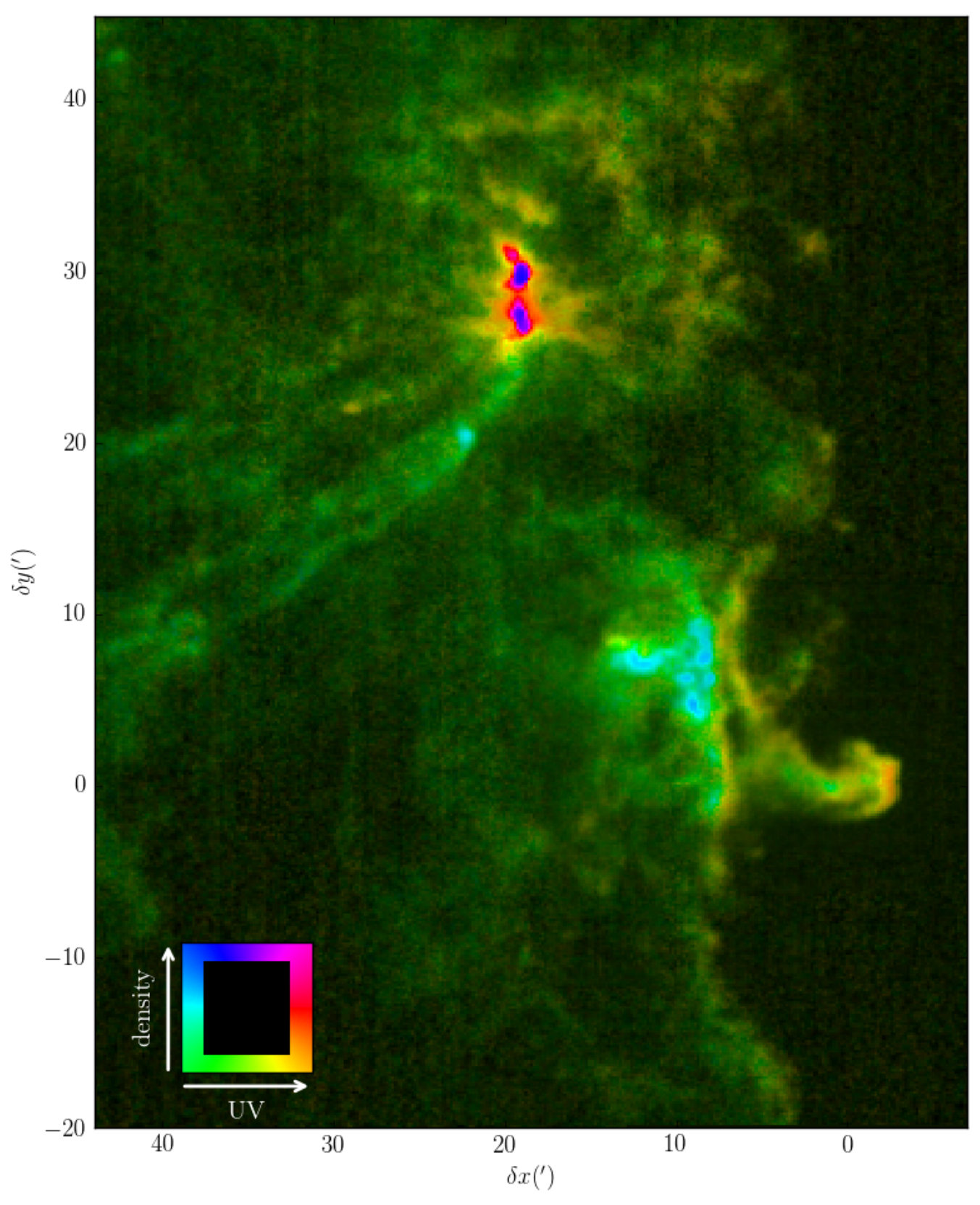
However when zooming into the star-forming regions NGC 2023 and NGC 2024, we see **strongly compressive motions** (obtaining R values as low as 0.3). This is consistent with **recent and/or on-going star formation activity**, e.g. in the presence of a young, expanding HII region.

Quiet filaments

The statistical analysis of the filamentary network in Orion B shows an overwhelming majority of filaments **stable against gravity**. The velocity field suggests the presence of quiescent **fibres** in the filaments, but we identify at least one case of periodic **longitudinal fragmentation** (Orkisz et al., submitted).

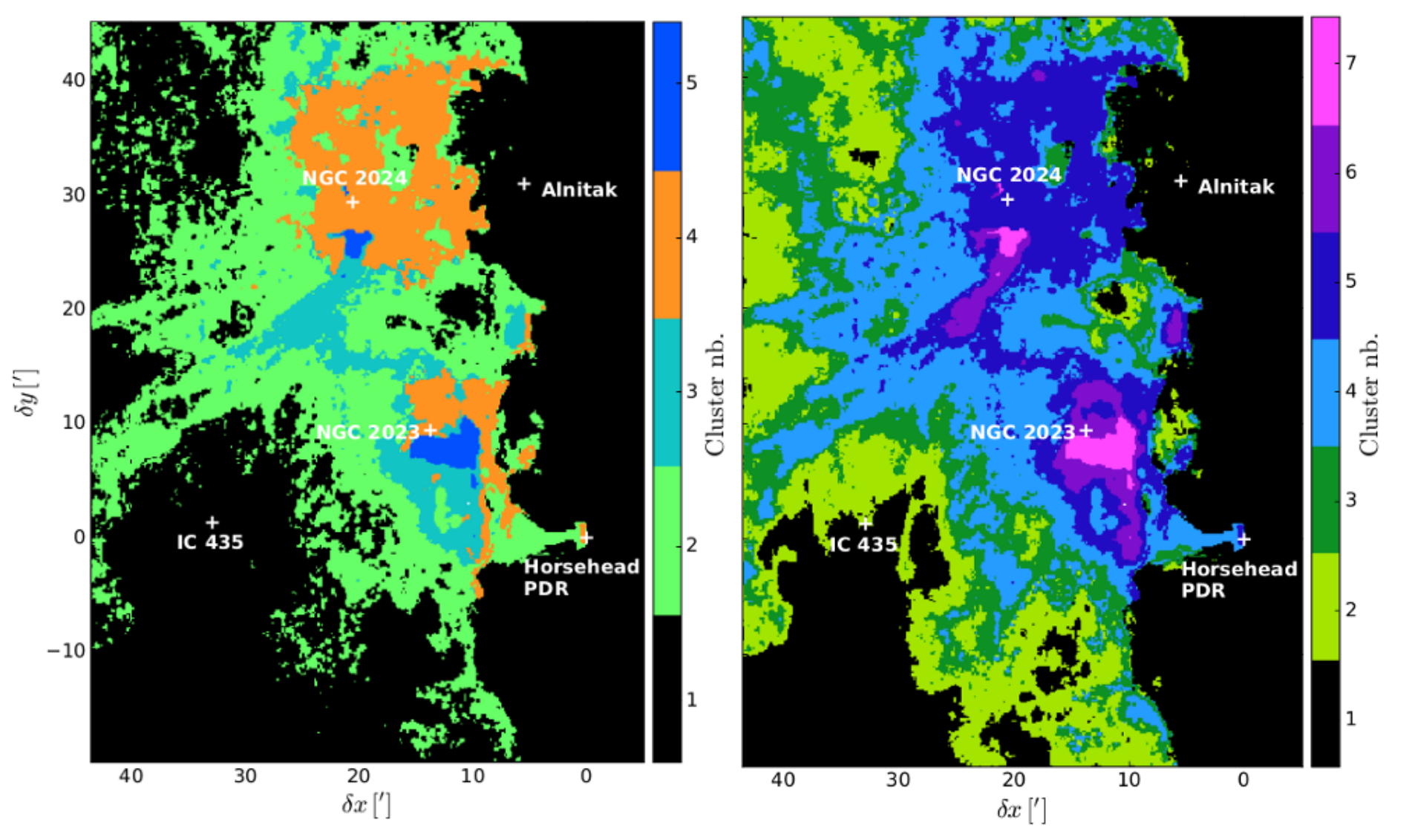
Multi-tracer statistical analysis

The amount of data produced by a modern spectral survey such as ORION-B requires **machine learning** methods to take advantage of all the information hidden in the joint variations of the detected tracers.



The brightness is encoded by the column density (PC1), and the hue by volume density and UV illumination (PC2 and PC3).

Principal Component Analysis is the simplest multivariate analysis method. It identifies the main axes of correlation of a N-dimensional dataset, and thus provides a new N-dimensional basis in which the data can be recast more efficiently. Using the integrated intensities from **12 molecular tracers**, Gratier et al. (2017) have shown that 78% of the variance is contained in **just 3 components** (linear combinations of lines), which can in turn be correlated to **column density, volume density and UV illumination**. This provides a **synthetic view** of the molecular cloud that reveals its physical properties rather than molecular emission.



Left: dense and dark regions (blue) vs. dense PDRs (orange). *Right:* Nested clusters of increasing densities.

A **spatial segmentation** of the cloud has been achieved by Bron et al. (2018) by applying the **Mean-shift clustering** algorithm to intensities of CO isotopologues, CN and HCO$^+$. This method allows us to distinguish between different regions of the cloud based on their chemical properties. When the obtained clusters are regrouped based on their CN intensity, they reveal the clear difference between **dark and illuminated dense regions**. When regrouped based on their HCO$^+$ intensity, they reveal a **nested pattern of increasing densities** up to 10^5 H cm^{-3}.

In both methods, the analysis returns **spatially coherent structures** which purely result from the **molecular emission** of the cloud, since no spatial information is initially provided to the algorithms.

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