Beyond the appearances:

The anatomy of the Orion Jedi revealed by radio-astronomy

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Au-delà des apparences :

L'anatomie du Jedi d'Orion révélée par la radio-astronomie

À l'aide du radio-télescope de 30 mètres de l'IRAM, dans la Sierra Nevada espagnole, une équipe internationale d'astronomes, menée par Jérôme Pety (IRAM & Observatoire de Paris) et dont font partie Maryvonne Gerin et François Levrier (Laboratoire de radioastronomie, département de physique de l'ENS, LERMA & CNRS), a obtenu la carte la plus complète de l'émission radio du nuage d'Orion B, célèbre pour deux de ses nébuleuses, la Tête de Cheval et la Flamme. Tirant parti du fait que les molécules du gaz froid brillent dans le domaine radio, et en utilisant des techniques de "machine learning" adaptées à ces données, l'équipe a révélé l'anatomie cachée du nuage d'Orion B. Un découpage minutieux du nuage en régions de compositions moléculaires différentes offre un éclairage inédit sur le processus par lequel de nouvelles étoiles naissent au cœur des parties les plus froides du nuage. A l'image des anciennes civilisations associant des personnages mythologiques aux structures du ciel nocturne, la carte radio d'Orion B semble nous montrer le squelette d'un Jedi, sabre laser à la main!

Using the IRAM 30 meter radio-telescope in Sierra Nevada (Spain), the ORION-B (Outstanding Radio-Imaging of OrionN B) project, an international scientific program led by Jérôme Pety (IRAM & Observatoire de Paris), has achieved the most complete observations in the radio domain of the Orion B giant molecular cloud (GMC), a huge reservoir of interstellar matter in the Orion nebula, containing about 70,000 times the mass of the Sun in gas and dust. Pety, astronomer at IRAM, explains: "Focused on a field around the well-known Horsehead and Flame nebulae, the ORION-B observations deliver a data set that amounts to about 160,000 images of 325 x 435 pixels, enough to make a movie of 1h50m at 24 frames per second. However, only 1% of these frames -1 minute of the movie- deliver a clear signal, including emission from molecules such as carbon monoxide, carbon monosulfide, cyanides, methanol, small hydrocarbons, and the like. Detecting these molecules is crucial, since molecular hydrogen, which make up about 75% of interstellar gas, is invisible in cold molecular clouds. Molecular emission thus enables a radiography of clouds that are otherwise invisible to the unaided eye (see Fig. 1)."

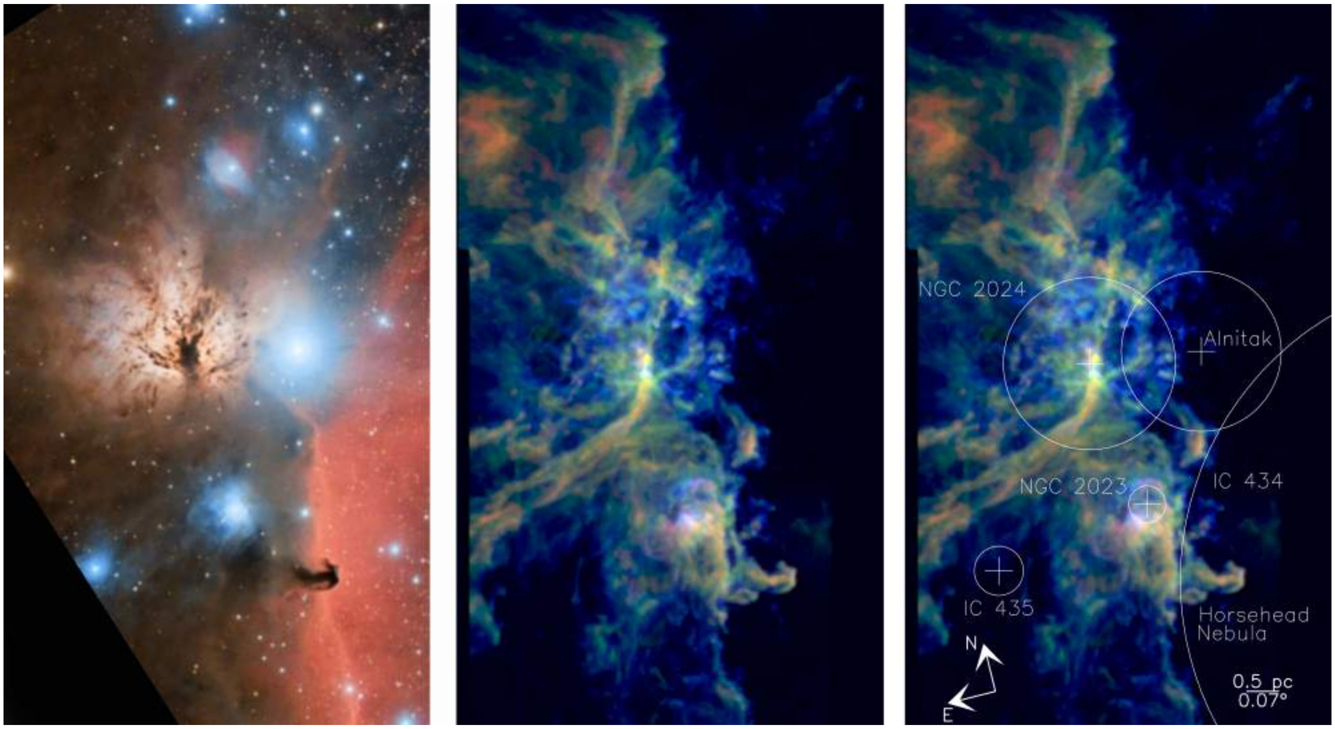

Figure 1: The same region of the Orion B Giant Molecular Cloud seen in optical (left panel: I*mage credit & copyright* Sergi Verdugo Martínez) and as a composition of three radio lines observed by the ORION-B Collaboration (middle and right panels: *Image credit & copyright* J. Pety, the ORION-B Collaboration & IRAM). Positions and areas of influence of the main stars illuminating Orion B are shown in the right panel. The ionized hydrogen shines in bright red in the optical, while radio observations reveal the intrinsic structure of the dense molecular gas in the middle and at the right.

The ORION-B project provides breathtaking images of a part of the sky that is only seen as a dark region in the visible. Moreover, the wealth of data opens the possibility to classify the different kinds of gas in GMCs based on the molecules they contain. It is truly a dive into the inner anatomy of the Orion B cloud. “Diffuse gas, filaments, and dense cores could be the equivalent of muscles, bones, and vital organs, respectively. And the images of different molecular lines enable to radiography different parts of Giant Molecular Clouds, like Magnetic Resonance Imaging (MRI) enables to reveal the interior of the human body” says Jan Orkisz, PhD student. Audrey Pety, pursuing design studies, comments: "I immediately saw the skeleton of a Jedi knight when first discovering this image. This reminded me that constellations are human interpretation of the stellar patterns on the sky and that Orion is a hunter (Fig. 2). And I ended up drawing my own modern constellation on this image (Fig. 3).”

Figure 2: The Orion constellation annotated in an optical image obtained by Rogelio Bernal Andreo. The Orion nebula, located in the Orion constellation is one of the best known and most observed celestial objects. The Orion B cloud lies just below the stars (Alnitak, Alnilam, and Mintaka) that form the Hunter's Belt. It hosts the Horsehead nebula and the Flame nebula, which are among the most popular targets for amateur astronomers. Orion is also extensively studied by professional astronomers: at about 1300 light-years away, it is the region closest to Earth where massive stars are forming, as shown by the brightly illuminated

interstellar gas.

In the series of 3 articles, the team explains how molecular lines are sensitive to the physical state of the gas, notably, its density, temperature, and the far ultraviolet illumination it is exposed to. This study confirms that the potential places of star formation, namely the dense cores, are exclusively traced by specific molecular tracers, like the diazenylium ion (N_2H^+). Another important result is the discovery of a clear relationship between the kind of turbulent motions (shocks or vortices) and the local star formation activity. This pioneering work involving the simultaneous statistical analysis of many molecular tracers will provide the needed tools and experience to characterize star formation in the interstellar medium. It brings radio-astronomy into the era of big data!

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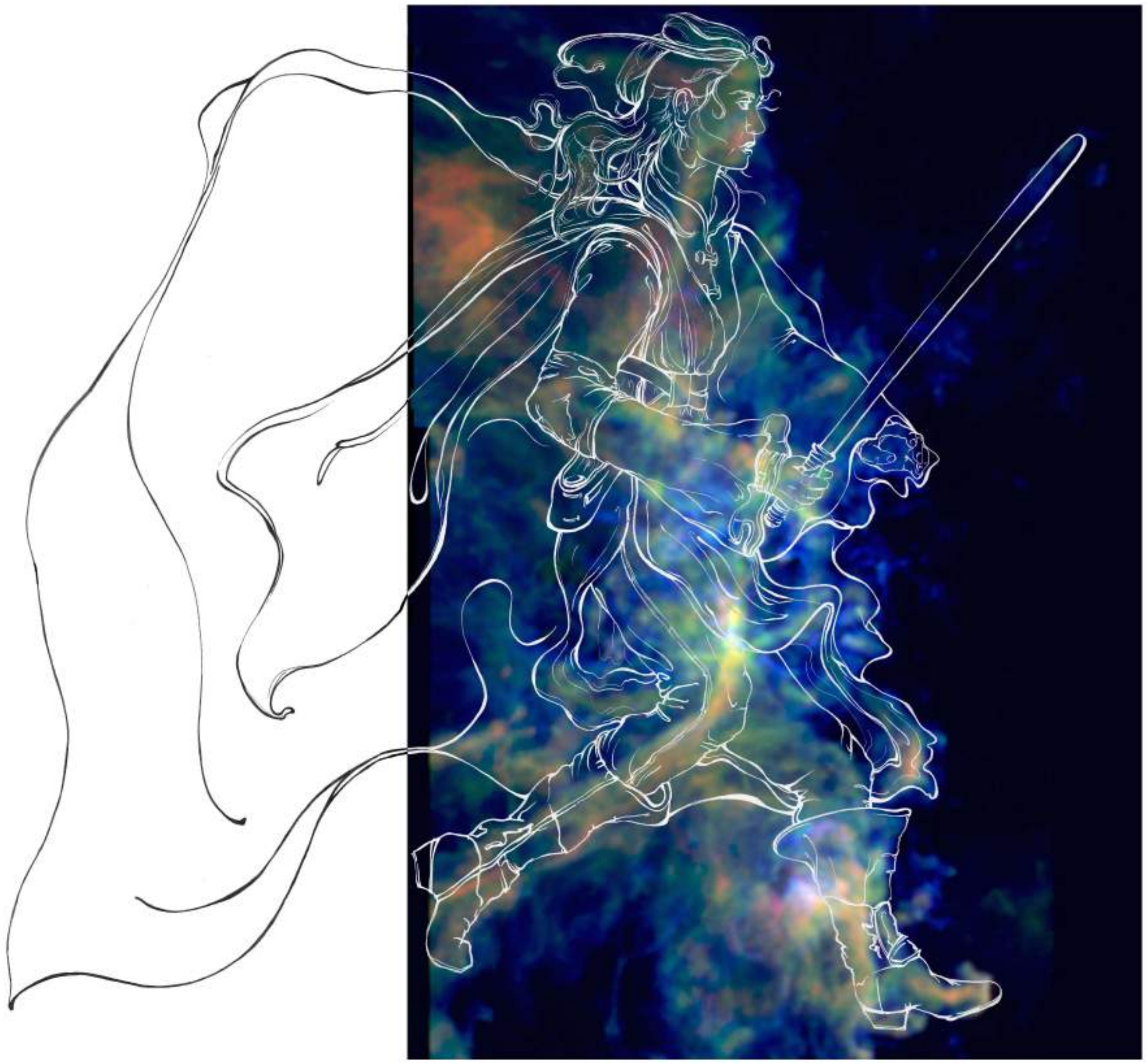

Figure 3: Artistic view of a Jedi knight overlaid on part of the ORION-B project data (*Image Credit & Copyright:* Audrey Pety).

References

1. Jérôme Pety, Viviana V. Guzmán, Jan H. Orkisz, Harvey S. Liszt, Maryvonne Gerin, Emeric Bron, Sébastien Bardeau, Javier R. Goicoechea, Pierre Gratier, Franck Le Petit, François Levrier, Karin I. Oberg, Evelyne Roueff, Albrecht Sievers. "*The anatomy of the Orion B Giant Molecular Cloud: A local template for studies of nearby galaxies*". **doi:**
2. Pierre Gratier, Emeric Bron, Maryvonne Gerin, Jérôme Pety, Viviana V. Guzman, Jan Orkisz, Sébastien Bardeau, Javier R. Goicoechea, Franck Le Petit, Harvey Liszt, Karin Öberg, Nicolas Peretto, Evelyne Roueff, Albrecht Sievers, Pascal Tremblin. "*Dissecting the molecular structure of the Orion B cloud: Insight from Principal Component Analysis*". **doi:**
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Additional information

How molecular lines are sensitive to the state of the gas

Pety et al. discuss the three parameters that control the brightness associated with each molecular line: 1) the efficiency with which thermal excitation is converted into light, 2) the quantity of hydrogen molecules along the line of sight, and 3) how other molecules chemically trace the presence of molecular hydrogen. They show that chemistry plays the dominant role among these three causes. Viviana Guzman, a post-doctoral fellow at the ALMA observatory in Chile, explains: “The spatial distribution of the emission of molecules like HCO^+ and N_2H^+ is incredibly different, even though these molecules have similar excitation requirements: HCO^+ mostly traces the diffuse GMC gas where atomic hydrogen turns into molecules. In contrast, N_2H^+ only traces dense cores, the very places of star formation, at least 100 times denser than the diffuse gas. While the diffuse and turbulent phase occupies most of the GMC volume, the dense cores represent only a few percent. In between, the gas is collected through filaments.” In the middle and right panels of Fig. 1, the diffuse gas is shown in blue, the dense cores lie inside the pink regions and the filaments are shown in green. This access to the molecular structure of the cloud through many chemical probes helps understanding the formation, evolution, and dispersal of GMCs, which is the least understood stage on the long way from diluted and ionized gas of the interstellar medium to the formation of stars and planetary systems. This wide-field, wide-bandwidth mapping of Orion B is also key for defining chemical probes of the star formation activity in more distant galactic clouds and in external galaxies, near and far.

Powerful statistical techniques applied to radio-astronomy big data

Gratier et al. obtain information on the physical structure of the interstellar medium through a statistical analysis of many molecular lines from different species without any a priori selection or interpretation. Pierre Gratier, astronomer at LAB in Bordeaux, explains "We applied one of the simplest techniques of statistical analysis, namely the Principal Component Analysis (PCA). This allowed us to decompose the observed signals into 3 components that are good proxies i) for the quantity of matter along the line of sight, ii) for the local density of the gas, and iii) for the intensity of UV radiation produced by nearby massive young stars. Figure 4 that results from this analysis is a composite image where the brightness codes the quantity of matter and the colors the density and UV illumination."

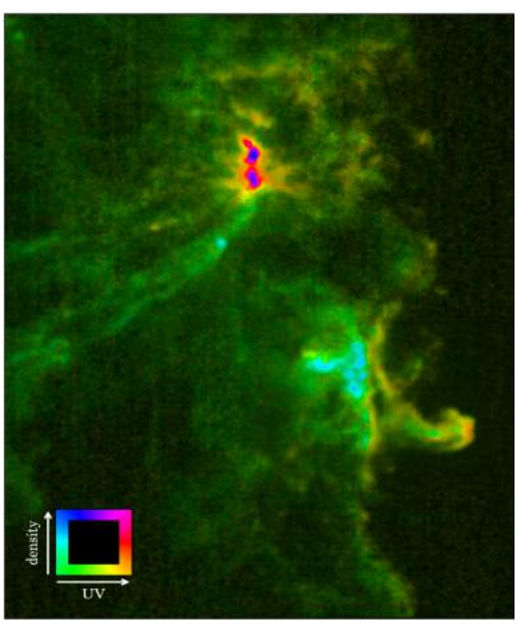

Figure 4: Synthetic view of the Orion B molecular cloud. In this image, the brightness of each pixel encodes the quantity of matter along each line of sight, and the colors encodes the gas density and its UV radiation field, according to the pattern displayed at the bottom left corner.

Star formation efficiency and turbulent motions

One of the key question of modern astrophysics is why Giant Molecular Clouds are so inefficient at forming stars. Gravity should condense the matter of the cloud to form dense cores and stars, however, at most of few percent of the GMC mass is forming stars. What are then the key parameters that control the star formation efficiency? Maryvonne Gerin from CNRS states: "One possibility is the nature of the motions of the gas in GMCs: compressive motions can trigger the collapse of cores while rotational motions offer an effective resistance to gravitational collapse." In the third paper of the ORION-B Collaboration, led by Jan Orkisz, the team quantifies for the first time the fraction of compressive motion that is injected in the Orion B cloud. Jan Orkisz, PhD student, summarizes the results: "The cloud's motions are on average mostly injected through vortices. This is consistent with the fact that Orion B is the local GMC with the lowest star formation efficiency. This study shows that, while the overall fraction of compressive motion is low, it increases greatly when zooming into the Flame nebula that is known to host most of the current star formation in Orion B."

Project history

The ORION-B project results from 10 years of research. It was made possible by the advent of a new generation of wide bandwidth receivers combined with high resolution spectrometers at the IRAM 30 meter telescope, and builds on long experience in radio-astronomy by the team members. Jérôme Pety explains: "Using the IRAM 30 meter telescope, we undertook in 2011 a systematic survey of the chemical content of the Horsehead's mane, during a project named Horsehead WHISPER. This allowed us to discover in 2012 a new molecule in the interstellar medium, the propynylidyne ion (C_3H^+) that is a member of the hydrocarbon family. Building on this success, we decided to generalize these observations, i.e., to observe one hundred thousand positions in Orion B instead of a single one towards the Horsehead nebula, each direction delivering information at 160,000 different frequencies!" Harvey Liszt, astronomer at NRAO, adds: "It's flabbergasting to see how this field has grown tremendously. During my PhD, I tuned a precursor millimeter receiver to obtain the first noisy detection of carbon monoxide towards one direction in Orion B, together with Nobel prize winner Bob Wilson. And only 45 years later, we easily gets such wide maps for so many molecules over the whole cloud!" No doubt that the future will offer even faster and wider observations for radio-astronomers. When that happens, the pioneering statistical approach of the ORION-B project will provide the needed tools and experience to handle bigger and bigger datasets.