Fusion of high-dimensional astronomical data

– Ph.D. proposal in statistical signal/image processing –

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Abstract

High-dimensional hyperspectral data have become the norm in astrophysics and, most of the time, these acquisitions are coupled with high spatial resolution multispectral data. In order to take advantage of all the (spatial and spectral) information provided by these data, an innovative approach developed within the framework of a collaboration between IRIT and IRAP consists in fusing these data sets [5, 4]. The developed methodology has been tested on synthetic data, using classical regularizations and is currently being tested on data from the James Webb Space Telescope (JWST). The objective of this project is to consolidate this collaboration between astrophysics, data analysis and image processing, in order to develop data fusion methods that will allow information to be extracted from large-scale data sets from current and future missions in astrophysics.

Context

The James Webb Space Telescope (referred to as JWST or Webb hereafter) is the largest telescope (6.5m diameter) ever sent into space, coupled with 4 scientific instruments, allowing both imaging and spectroscopy, in the near and mid-infrared range ($0.6 - 28\mu$m). The large mirror size as well as the passive (and active for the MIRI instrument) cooling of the telescope and instruments allows Webb to provide unparalleled sensitivity and spatial resolution in the infrared. The mission is planned to last up to 20 years, so it is an instrument that will be central to astrophysics in the coming decades. In order to study "photodissociation regions" (PDRs), Olivier Berné, leader of this PhD project, was at the origin of an "Early Release Science" (ERS) program on JWST, in collaboration with Emilie Habart (Institut d'Astrophysique Spatiale) and Els Peeters (Univ. Western Ontario). The objective of ERS programs is to provide, from 2022, observations and analyzes demonstrating the scientific potential of the mission to the international community. Thirteen ERS programs were selected after an international call for projects, including this project, entitled PDRs4all, which brings together more than 100 scientists in from countries [2]. This program is based in particular on three of Webb instruments:

- the NIRCam imager, in the $1 - 5\mu$m range, to obtain high spatial resolution and wide field images of the area in up to 17 spectral bands,
- the NIRSpec spectrometer, in the $1 - 5\mu$m range, in integral field unit (IFU) mode with a spectral resolution of R$\sim$ 3000, to obtain a mosaic of hyperspectral cubes along a cut through the Orion Bar and detect AIBs and gas emission,
- the MIRI spectrometer and imager, in the $5 - 28\mu$m range, to obtain a mosaic of hyperspectral cubes (spectral resolution of R 3000) across the bar, to detect AIBs, gas lines, and grain emission at thermal equilibrium

Images with NIRCam and MIRI instruments as well as NIRSpec hyperspectral data were obtained in September 2022, while the MIRI hyperspectral observations have been obtained in Febuary 2023.

Objectives

We therefore have a multispectral dataset (NIRCam) with high spatial resolution and low spectral resolution, and a hyperspectral dataset (NIRSPec), with high spectral resolution and low spatial resolution. In order to take advantage of all the (spatial and spectral) information in these data, an innovative approach developed since 2018 as part of a collaboration between IRIT and IRAP consists in fusing these datasets. For this, we have proposed mathematical instrument models for the NIRCam camera and the NIRSpec spectro-imager (IFU mode) of the JWST. These models made it possible to produce synthetic but realistic observations of the JWST [5] from a simulated astrophysical scene of the Orion bar by exploiting existing data from this region and spectra extracted by [3]. These models can then be leveraged to formulate the fusion problem between NIRspec and NIRCam data by solving an inverse problem. The major obstacles that arise are then the large dimensionality of the data and the models of the instruments (convolution operators) which are spectrally variant. The resolution of this inverse problem regularized by a conventional Tikhonov term is then conducted in a low-dimensional spectral subspace to efficiently deal

Figure 1: NIRCam image of the Orion bar obtained as part of the ERS PDRs4All program (composite image). Credit: NASA, ESA, CSA, Data reduction and analysis: ERS PDRs4All team; graphic processing S. Fuenmayor.

with convolution operators as well as the high dimensionality of the data [4]. This method has been successfully tested on the synthetic data mentioned above, allowing a gain in spatial resolution of hyperspectral data by a factor of ~ 3. We are currently testing the application of this fusion method on the real data obtained with the JWST last September. We also plan to complete this dataset with new NIRSpec observations in 2023 as part of the second call for observations for the JWST.

The current challenge is to show that the method developed is applicable to real data. However, there are still several challenges to be tackled. This thesis will focus in particular on four specific objectives:

- The first objective consists in fusing real data by applying the method developed by IRAP and IRIT not only to the scene observed in Orion (which is an ongoing project between IRAP and IRIT), but more generally within the framework of the JWST mission. The genericity of the developed approach will also be validated by extending it to other application contexts in astrophysics, i.e., with data obtained by instruments other than Webb.
- The second objective will aim to go beyond the quadratic regularizations currently implemented. It was indeed shown that these have a limited ability to accurately describe astrophysical scenes, whose content is rich and statistically complex. The solutions developed can rely on the statistical properties that can be learned from images, for example by mobilizing recently developed models to capture the spatial structure of astrophysical images [1]. More generally, learning data-driven regularizations using deep generative models represents a promising alternative to model-based regularizations.
- The third objective will have as its ambition the design of so-called "task oriented? fusion methods, i.e. making it possible to directly obtain interpretable results at the physical level, going beyond a sequential processing chain (fusion then interpretation) which remains sub-optimal.
- Finally, the last objective is to make these tools as ergonomic as possible, so that the astrophysical community can use them as widely as possible.

Scientific environment

The Ph.D. candidate will be a member of the FUSIONJWST project, funded by CNRS under the 80—PRIME program. He/she will become a member of the Toulouse JWST Team and of the international ERS program as an extended core team member. The two main teams involved in this Ph.D. project located in Toulouse are the MICMAC group from IRAP and Signal & Communications (SC) group from IRIT. The MICMAC group is interested in physics and chemistry of the interstellar medium, star and planet formation. The SC group brings its expertise in the development of state-of-the-art statistical signal & image processing methods, in particular for multivalued images for various applications (medical imaging, remote sensing, microscopy).

The Ph.D. student will benefit from a scientifically rich environment and will be able to acquire a solid background on the most recent advances in statistical signal & image processing for astrophysics and astronomy. He/she will be mainly co-advised by

- Olivier Berné, CNRS Research Director within the MICMAC group at IRAP;
- Thomas Oberlin, Professor within the DISC department at ISAE-Supaero and associated member with the SC group at IRIT;
- Nicolas Dobigeon, Professor within the SC group at IRIT.

Funding

This position is fully funded by the CNRS 80—PRIME program. This includes salary with benefits and additional funding for research related expenses (travelling, computer, etc.).

Period

The Ph.D. shall start in 2023, with a duration of 3 years. The precise starting date can be adjusted according to the availability of the selected candidate.

Keywords

Infrared astronomy, inverse problems, hyperspectral imaging, JWST.

Profile & requirements

Graduate students with major in applied mathematics, computer science or electrical engineering. The knowledge needed for this work includes a strong background in **signal & image processing** and **optimization**. Knowledge of machine learning is a plus. Experience and/or interests in astrophysics and astronomy will be appreciated.

Contact & application procedure

Applicants are also invited to send (as pdf files)

- a detailed curriculum,
- official transcripts from each institution you have attended (in French or English).

to the co-advisors

- Olivier Berné, olivier.berne@irap.omp.eu
- Thomas Oberlin, thomas.oberlin@isae-supaero.fr
- Nicolas Dobigeon, nicolas.dobigeon@irit.fr

You will be contacted if your profile meets the expectations. Review of applications will be closed when the position is filled.

References

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