Towards a 3D characterisation of X-ray extended sources

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Context: With deep X-ray mega-second observations with XMM-Newton and Chandra (containing up to 100 millions photons), very high spectral resolution data from the Hitomi telescope and the XRISM and Athena satellites on the horizon, X-ray data are getting scientifically richer but increasingly complex to analyse. With a strong implication from the French community, the X-IFU instrument onboard the Athena telescope will combine high spectral and spatial resolution and will be a game changer in the X-ray spectro-imaging domain. Despite this huge improvement in instrumental performances, the development of the analysis methods have stalled in the last decades and are not ready to reveal the true wealth of information encoded in these rich datasets. Current methods are limited to 1D spectra or 2D images, and do not exploit the multi-dimensional nature (position, energy, and time being recorded for each event, see Fig. 1) of the X-ray data. In addition they are not efficient at correcting from geometrical projections effects and the disentangling of multiple physical components.

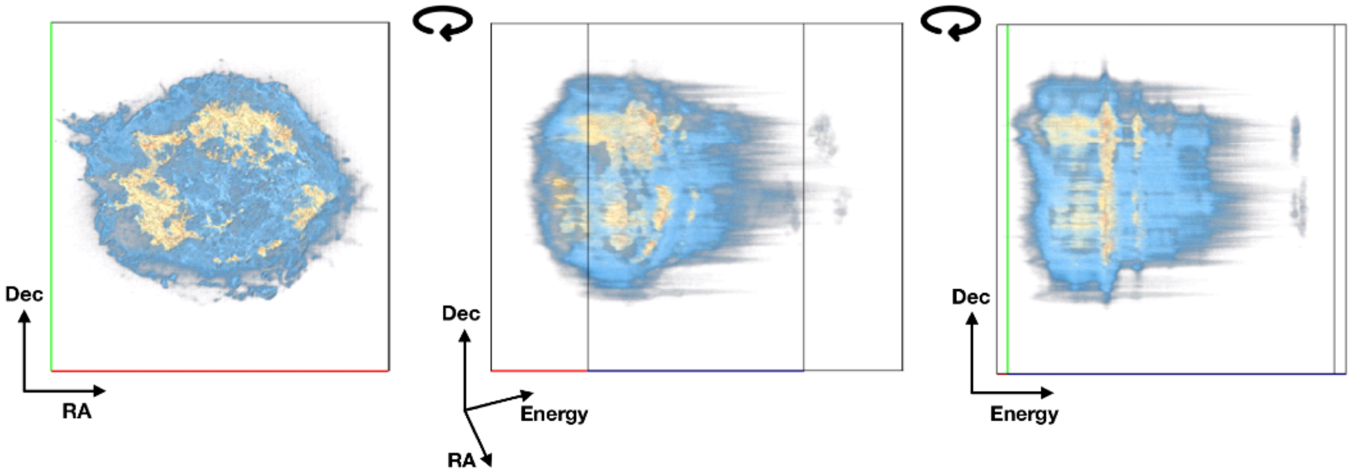

Figure 1: volume rendering of the supernova remnant Cassiopeia A X-ray data cube (RA, Dec, Energy). The colours indicate a higher density of X-ray photons. The face-on image (left panel) shows the spatial distribution of the X-ray emission and is comparable to classical images. Looking at the cube edge-on reveals a different facet of the object showing the distribution of heavy elements (Mg, Si, S, Fe, etc) via their line emission. Our new analysis tools takes advantage of the multi-dimensional nature of the data to separate the physical components at stake.

Description of the project: we propose to transform the way X-ray data are analysed by capitalising on the expertise developed by the applied mathematics group in our laboratory; in particular in the blind source separation algorithms initially developed to separate the CMB map from the foregrounds in the Planck data. The method jointly exploits the morphological and spectral diversity of the data in the wavelet domain to separate the different astrophysical components and map their properties.

These new techniques allow to identify and characterise new, potentially unexpected, physical components in extended sources. A new branch of the method is currently being developed with an implementation of physically motivated models within a machine learning context (i.e. feature learning). This opens the possibility to disentangle the physical components and deconvolve from projection effects at the same time. This allows mapping of quantities such as the velocity distribution of heavy elements in supernova remnants, or the temperature and abundances of the hot gas in clusters of galaxies in 3D (x, y, z).

In supernova remnants those new tools will be used by the PhD candidate to investigate what fingerprints supernovae leave in their remnant. The explosion mechanisms of Type Ia and core-collapse supernovae are still unclear but each explosion scenario has a specific ejecta fingerprint.
In this project, we will revisit the nature of the progenitors (core-collapse or Type Ia supernova) and the explosion mechanism via a detailed morphological analysis by mapping the 3D structures of the heavy elements in the remnants (see Fig. 2) and comparison with numerical supernova explosion.
From a technical point of view, the PhD candidate will develop and apply these advanced techniques to data of increasing complexity. First we will test these methods on the archival data (XMM-Newton) to fully extract the scientific potential of these data. This part exploits the morphological diversity visible in current X-ray satellite imaging data, in conjunction with moderate spectral resolution.
The second part will explore how to leverage high spectral resolution data provided by Hitomi, possibly XRISM and Athena X-IFU, in conjunction with moderate resolution imaging data. This will be achieved by applying a modified algorithm, focusing on the spectral diversity, to synthetic Athena observations built from numerical simulations of supernova remnants. This project will enhance the French scientific contribution to the Athena mission and in particular to its ground segment by building new analysis tools.

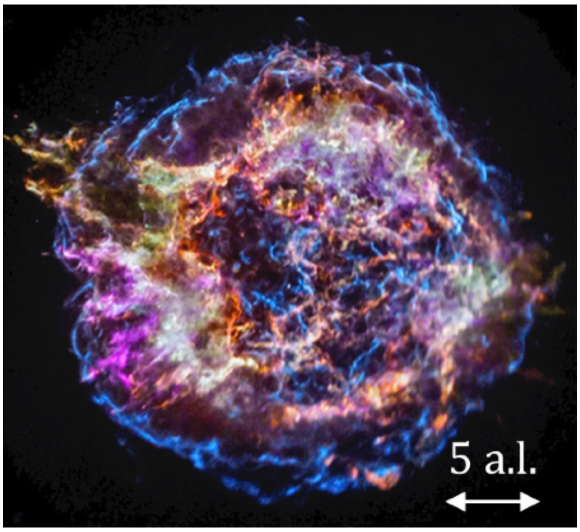

*Figure 2: Cassiopeia A, the 340 years old remnant of a core-collapse supernova. Red, yellow, green and orange colours indicate the spatial distribution of the ejected heavy elements. We propose to **build a 3D view** of the ejecta distribution.*

Comparison with previous works: the adaptation of the blind source separation technique to X-ray data of supernova remnants has already been proven to be successful and allowed a better reconstruction of physical components that any other methods (Picquenot et al., 2019). This project will now focus on the implementation of prior physical knowledge via the feature learning of a library of spectral templates using algorithms presented in Bobin et al. 2020. This will be applied to archival XMM-Newton observations and mock Athena X-IFU observations generated using numerical simulations of supernova remnants.

High-resolution spectroscopy in France: While French teams are heavily involved in the construction of the X-IFU instrument, the development of new analysis tools and the expertise specific to the high-resolution spectroscopy need to be consolidated in the French community. This project will contribute to develop new ways to analyse data cubes (as part of the X-IFU ground segment) and build up the French expertise by training a new generation of students on those specific aspects. In addition, the analysis of XRISM data (via a call for external collaborators on specific targets) expected to launch in 2022, could serve as a path finder towards the interpretation of high-resolution spectroscopic data.
We also note that both proposers are members of the Athena X-IFU Science Advisory Team (XSAT).

References:
Cosmic microwave background reconstruction from WMAP and Planck PR2 data; Bobin et al., 2016
Novel method for component separation of extended sources in X-ray astronomy; Picquenot, Acero, Bobin, Maggi, Ballet & Pratt, 2019.
Metric learning for semi-supervised source separation with spectral examples; Bobin, Acero, Picquenot, 2020

Topics: X-ray astronomy, XMM-Newton, Athena, signal processing, blind source separation, physically motivated machine-learning clusters of galaxies, supernova remnants.