Revisiting the ejecta asymmetries in Cassiopeia A with a novel method for component separation in X-ray astronomy

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• Supernova remnants in X-rays
• Traditional analysis methods of spectro-imaging instruments
• An introduction to the Generalized Morphological Components Analysis
• Benchmarking the method with SNR Cassiopeia A Toy models
• Application to real data of Cassiopeia A
Core Collapse Supernovas

Simulation, SXS project

Cassiopeia A seen by Chandra

Asymmetries in the explosion proved necessary in the simulations.
Ejecta can trace the explosion mechanisms.
Supernova Remnants in X-rays

Cassiopeia A data cube ($x, y, E$)

Chandra data, visualized with vaex
Supernova Remnants in X-rays

- Elements: Fe, Si, S, Ar, Ca, Mg, Ne
- Redshift: -4000 km/s
- Blueshift: +4000 km/s
Supernova Remnants in X-rays

- Thermal emission continuum
- Synchrotron emission continuum
- Line emissions

How to obtain a clear image of those components?
Decomposition is made on the spectra retrieved from particular places defined on the images, without leveraging Chandra's great spatial resolution.
Analogy with the CMB

Planck survey of the sky
Blind Source Separation algorithm: The aim is to retrieve $n$ images $(x, y)$ and spectra $(E)$ from the initial $(E, x, y)$ data set without prior instrumental or physical knowledge.

$X = AS + N = \sum_{i=1}^{n} A_i S_i + N$

GMCA

Generalized Morphological Components Analysis (Bobin et al. 2016)
Without any information on $A$ and $S$, this problem is ill-posed.

\[ X = AS + N = \sum_{i=1}^{n} A_i S_i + N \]

How can we add a constraint that will help disentangling?
**The concept of sparsity**

Analogy with 1-D:

The Fourier transform allows to describe periodic signals with only a few non-zero coefficients.

It makes the different components easier to disentangle by diminishing the overlapping.
In 2-D:

Wavelet transforms give sparse representations of images. In particular, Starlets are well adapted for astrophysical images.

Starlet transform of the Fe structure in Cassiopeia A
The concept of sparsity

In 2-D:

Starlet transform third scale coefficients of gaussians of different sizes
A grid of small gaussians with a constant spectrum

A large gaussian with a gaussian spectrum

Noise
Without any information on $A$ and $S$, this problem is ill-posed.
With a sparsity constraint term:

\[
X = AS + N = \sum_{i=1}^{n} A_i S_i + N
\]

\[
\min_{A,S} \sum_{i=1}^{n} \lambda_i \|S_i\|_p + \|X - AS\|_F^2
\]
The algorithm is iterative, each iteration containing two steps:

- Step 1: Estimation of $S$ for fixed $A$, by simultaneously minimizing $\|X - AS\|_F$ and the term enforcing sparsity in the Wavelet domain;
- Step 2: Estimation of $A$ for fixed $S$ by minimizing $\|X - AS\|_F$. 

$$\min_{A,S} \sum_{i=1}^{n} \lambda_i \|S_i\|_p + \|X - AS\|_F^2$$
Our two toy models have two components:

The first component is a synchrotron emission, the second one is either a thermal emission or a line emission. We generate Poisson noise.
Test on toy models

Both components are entangled in our toy model
Test on toy models

Components disentangled by GMCA
Reconstructed image accuracy

SSIM coefficients of the images of the retrieved second component in both toy models

Examples of SSIM coefficients associated with the corresponding images
Spectral accuracy

Spectra of second component retrieved by GMCA in both toy models. The dashed lines represent theoretical models. On the right, we can see important deviations in high energy from the model.
Spectral accuracy

After a fitting in Xspec.

Retrieved $kT$: 2 keV
Application on real data

Application between 5 and 8 keV:

- Synchrotron
- Red-shifted Fe structure
- Blue-shifted Fe structure
- Noise
Application on real data

Application around each major line emission:

- Interpolation
- GMCA

- Si
- S
- Ar
- Ca
- Fe
Conclusion

• GMCA retrieves morphologically and spectrally accurate components.
• The performances of the algorithm are very case-specific.
• Bootstrap resamplings give accurate error bars.
• First applications on real data are very promising, offering a lot of new information to do science!

The methodology paper has been submitted.
Perspectives

• The method will be developed to take into account mosaic-like data (for example on RXJ 1713).
• Dictionary of physical spectral shapes, to «help» the algorithm with further information.
• HESS / CTA: Feasible, but in need of an energy dependent PSF handling.
• A promising method for Athena:

Toy model of Athena X-IFU data (2eV of resolution, vs. 120 eV for Chandra) of Cassiopeia A (100ks) around the Fe line.