ADIR: Angular Differential Imaging applied to RHAPSODIE (Reconstruction of High-contrAst Polarized SOurces and Deconvolution for cIrcumstellar Environments)

How to disentangle a disk's light from its starlight

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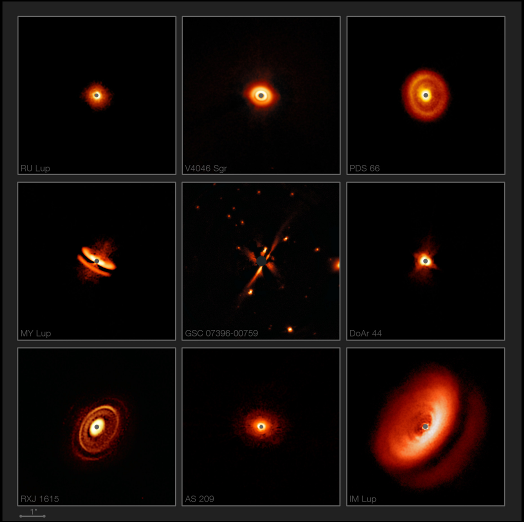
Introduction

Circumstellar Environments

- Environments surrounding young stars
- Composed with gas and dust
- Planet's cradle
- **Why is it interesting?** Helps to understand planet formation
- **Problem:** Star's light is 10k to 100k times brighter than disk's light



Credit: ESO/H. Avenhaus et al./E. Sissa et al./DARTT-S and SHINE collaborations

Differential Polarization Imaging (DPI [1])

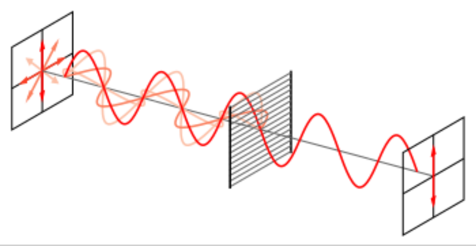


Figure 1: Scheme of polarized light

Credit: https://en.wikipedia.org/wiki/Polarizer

- Stokes Parameters : $\mathbf{S} = (\mathrm{I},\ \mathrm{Q},\ \mathrm{U})$
- $\mathrm{I} = \mathrm{Iu} + \mathrm{Ip}$
- $Iu = Iu_{star} + Ip_{disk}$
- $Ip = \sqrt{Q^2 + U^2} \iff Q = Ip\cos(2\theta) \mid U = Ip\sin(2\theta)$

Angular Differential Imaging (ADI [2])

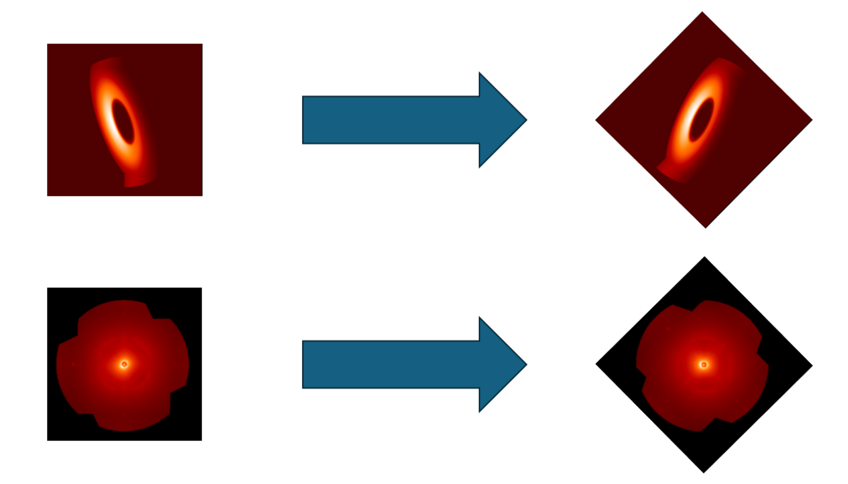


Figure 2: Scheme of ADI [2] method

State-of-the-Art

- One state-of-the-art instrument to observe circumstellar environments in dual-beam polarimetric imaging mode: **ESO/VLT SPHERE IRDIS** [3]
- State-of-the-art method to extract polarized light: **Double Difference** [4]
- **RHAPSODIE:** [5] Challenging the state-of-the-art using an inverse problem approach
  - Accounting for the statistics of the data
  - Taking into account in a direct model of the data (blur, polarization variations, translations and rotations)
- **Problem:** We only get the polarized light of the disk
- **My contribution:** Angular differential imaging (ADI) combined with differential polarization imaging (DPI)

ESO/VLT SPHERE IRDIS

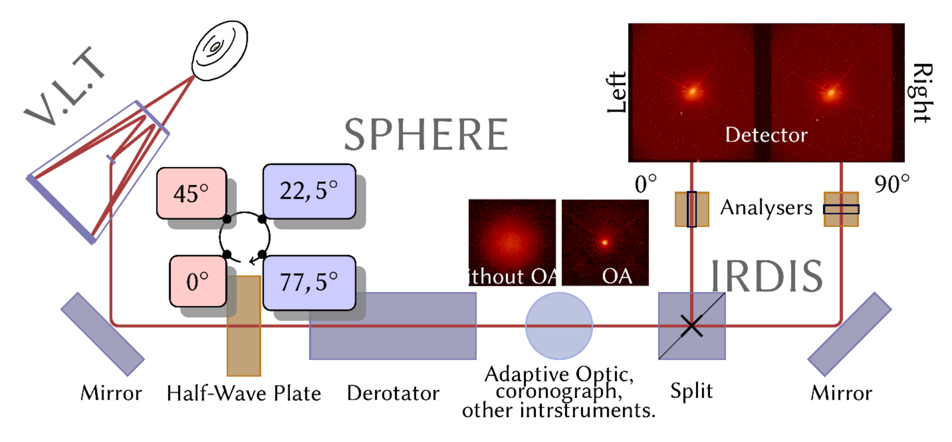
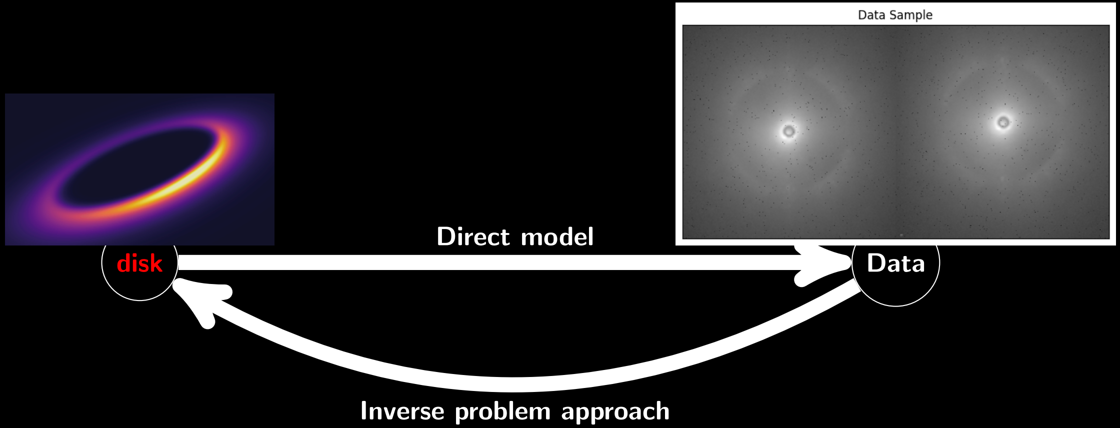


Figure 3: Scheme of the ESO/VLT SPHERE IRDIS Instrument [6]

Method

Direct Model and Inverse Problem Approach



$$\min_{\color{red}{disk}} \Big(\underbrace{distance(model(\color{red}{disk}), data) + \lambda prior(\color{red}{disk})}_{\text{Cost Function}} \Big)$$

Direct Model of One Acquisition

- $I = Iu + Ip$
- $Ip = \sqrt{Q^2 + U^2}$
- **RHAPSODIE**: $I^{det} = v_1 \mathbf{TRA} I + v_2 \mathbf{TRA} Q + v_3 \mathbf{TRA} U$
- **ADIR**: $I^{det} = v_1 (\mathbf{TRA} I_{disk} + \mathbf{T} I_{star}) + v_2 \mathbf{TRA} Q + v_3 \mathbf{TRA} U$

Data Fidelity Term

$$f_{data}(X) = \sum_{j,k} \|d_{j,k} - I_{j,k}^{det}(X)\|_{W_{j,k}}^2$$

Where:

- d: Measured data
- I_{det}: The direct model
- W: Weights
- X: (Iu_star, Iu_disk, Q, U) (Stokes parameters can be computed with a simple base change)

Regularization Terms (Prior Terms)

Two Regularizations:

- **Edge-Preserving Smoothing**: [7] $\lambda f_{prior,disk}(I^u_{disk}, Q, U) = \lambda_{disk}\sqrt{\|\Delta Q\|^2 + \|\Delta U\|^2 + c\left\|\Delta I^u_{disk}\right\|^2 + \varepsilon^2_{I^u_{disk}+I^p_{disk}}} - \varepsilon_{I^u_{disk}+I^p_{disk}}$
- **Tikhonov**: [8] $\lambda f_{prior,star} = \dfrac{\lambda_{star}}{2\varepsilon_{star}}\|\Delta Iu_{star}\|^2$

Results

Ground Truth

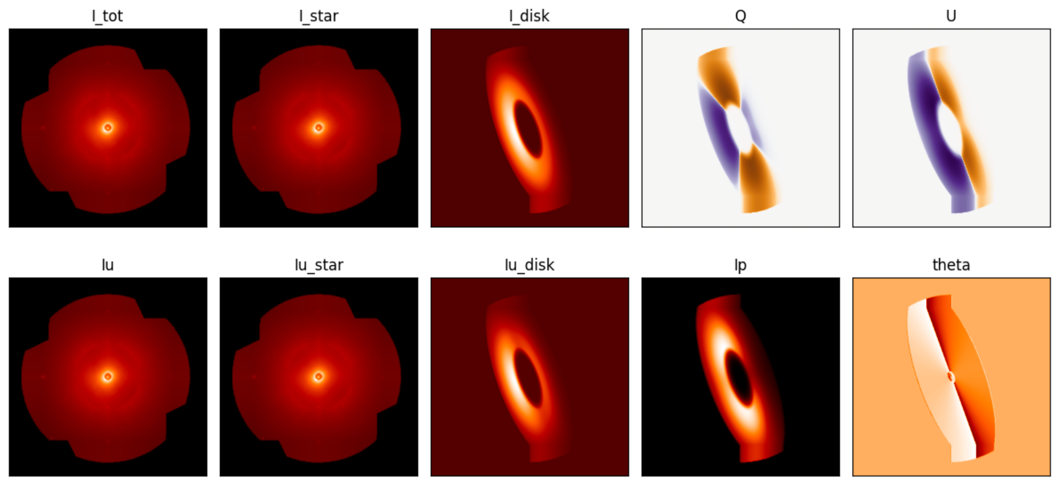


Figure 4: Ground truth simulated from DDiT[9] disk

RMSE Comparison

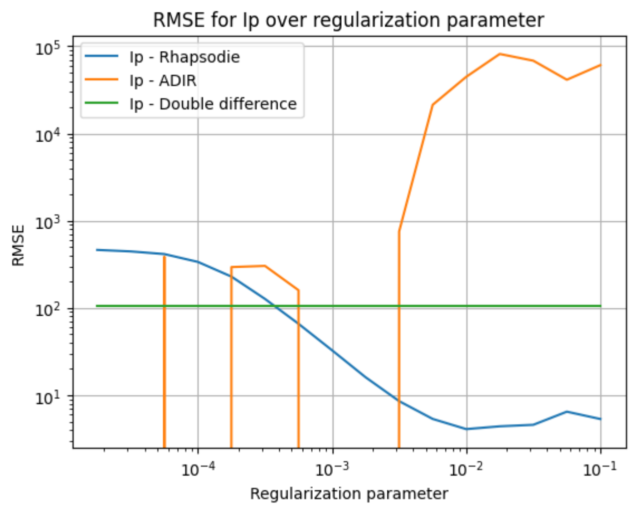
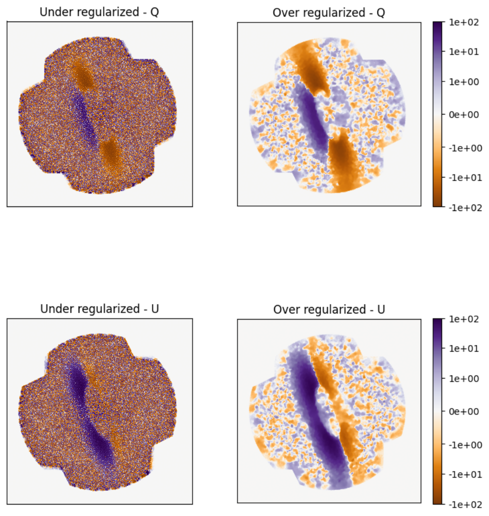
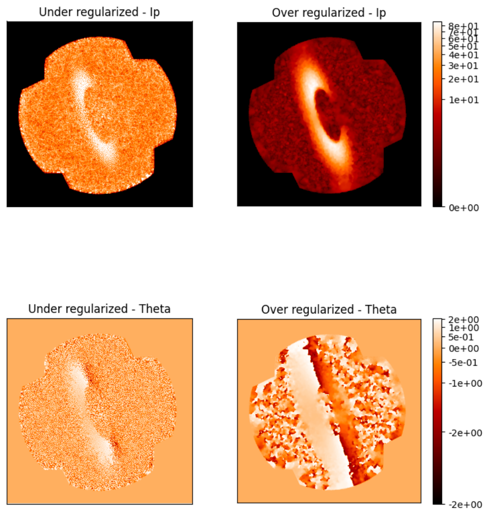


Figure 5: RMSE comparison for Ip between RHAPSODIE, ADIR and Double Difference

Under vs Over Regularization



Q and U



Ip and θ

Reconstruction Example

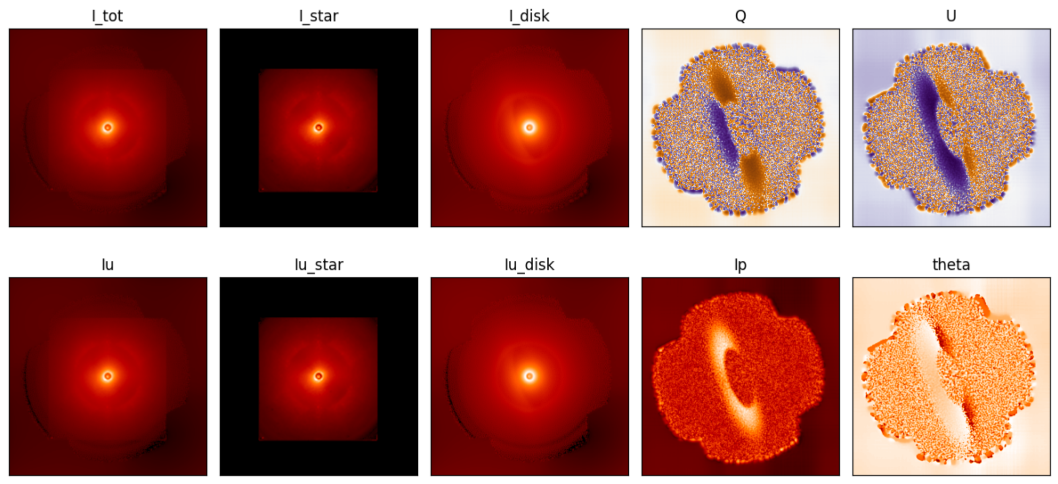


Figure 6: Reconstruction example of the ground truth

Methods Comparison on Simulated Data

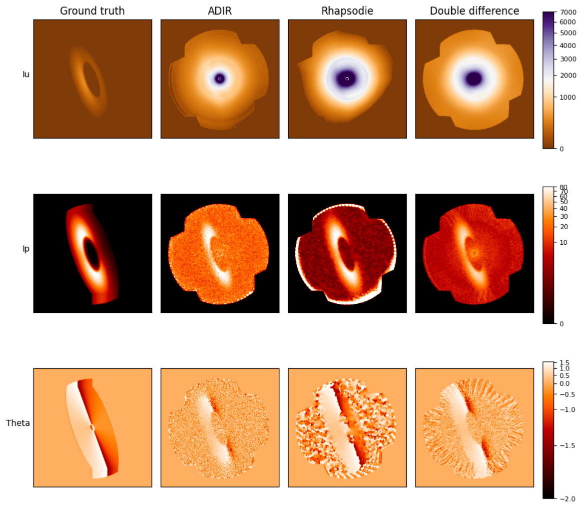


Figure 7: Comparison between state-of-the-art methods on Iu, Ip and θ

Conclusion and Perspective

Conclusion and Perspective

Conclusion:

- Promising first results on simulated images
- Been able to partially discriminize the star's light reflected on the disk from the starlight

Perspective:

- More fine tuning for different hyper parameters (Contrast, regularization parameters)
- Since we have Ip and Iu, we are now able to calculate the polarization ratio of different disks
- Application on real astronomical data

References

[1] Kim et al. DIFFERENTIAL POLARIZATION IMAGING. *Biophysical Journal*, 1987.

[2] C. Marois et al. Angular Differential Imaging: a Powerful High-Contrast Imaging Technique. *The Astrophysical Journal*, 2006.

[3] J. de Boer and M. et al Langlois. Polarimetric imaging mode of VLT/SPHERE/IRDIS: I. Description, data reduction, and observing strategy. *Astronomy amp; Astrophysics*, 633:A63, January 2020.

[4] Denis Fougère et Nicolas Jacquemet. Méthode des doubles différences (difference-in-differences). *science et bien commun*.

[5] L. Denneulin et al. RHAPSODIE: Reconstruction of High-contrAst Polarized SOurces and Deconvolution for cIrcumstellar Environments. *Astronomy Astrophysics*, 2021.

[6] Júlia Boer, Maud Langlois, R. Holstein, Julien Girard, David Mouillet, A. Vigan, Kjetil Dohlen, F. Snik, Christoph Keller, C. Ginski, D. Stam, Julien Milli, Z. Wahhaj, Mirella Kasper, H. Schmid, P. Rabou, Laurence Gluck, H. Hugot, Denis Perret, and Lizzy Weber. Polarimetric imaging mode of vlt/sphere/irdis. i. description, data reduction, and observing strategy. *Astronomy Astrophysics*, 633, 12 2019.

[7] Makoto Nagao and Takashi Matsuyama. Edge preserving smoothing. *Computer Graphics and Image Processing*, 9(4):394–407, 1979.

[8] Frank Lenzen and Otmar Scherzer. Tikhonov type regularization methods: History and recent progress. *Proceeding Eccomas*, 2004, 01 2004.

[9] DDiT Github.

Thank you for your attention!

Questions?