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Super-resolution Imaging of the Protoplanetary Disk HD 142527 using Sparse Modeling

Ph.D. student

Masayuki Yamaguchi[1,2] (masayuki.yamaguchi@nao.ac.jp)

K. Akiyama[2,3], A.Kataoka[2], M. Fukagawa[2], T. Tsukagoshi[2], T. Muto[4], M. Honma[2], S.Ikeda[5], H. Nagai[2], R.Kawabe[1,2]

1. University of Tokyo, 2. National Astronomical Observatory of Japan, 3. MIT Haystack Observatory, 4. Kogakuin University, 5. The Institute of Statical Mathematics

The University of Tokyo

国立天文台 NAOJ National Astronomical Observatory of Japan

1.Introduction: Toward Higher Resolution with ALMA

- High-resolution observations of protoplanetary disks with radio interferometers are crucial for understanding the planet formation process. In particular, a finer resolution providing a more detailed picture of disk structure can constrain their evolution and establish the framework of this type.
- Recent observations using Atacama Large Millimeter/submillimeter Array (ALMA) have revealed various small-scale structures in disks. In interferometric observations, images of an astronomical source I(l, m) can be obtained by two-dimensional Fourier transform of observed data V(u, v). However, in practical observation, there must be space between antennas, which causes unsampled holes in the (u, v) plane. Such an incomplete (u, v) coverage always causes "underdetermined problem" in the radio interferometer equation. Usually, this problem is solved by filling unsampled visibilities with zero. However, this process causes the resultant image to be "dirty image".
- The image reconstruction is therefore essential in obtaining the images in real space. One of the most commonly used reconstruction methods to improve the dirty image is a CLEAN technique, but there is a limitation of the angular resolution (diffraction limit) defined by the maximum length of the baseline between two telescopes.
- **A new technique using the sparse modeling approach is suggested. This technique directly solves a set of undetermined equations and has been shown to behave better resolution than the CLEAN technique based on mock observations with VLBI (Very Long Baseline Interferometry). However, it has never been applied to ALMA-like connected interferometers nor real observational data.**

What I did in this work

- **For the first time, the sparse modeling technique is applied to observational data sets taken by ALMA.**
- **We evaluate the performance of the sparse modeling by comparing the resulting images with those derived by the CLEAN (see, Figure 1).**

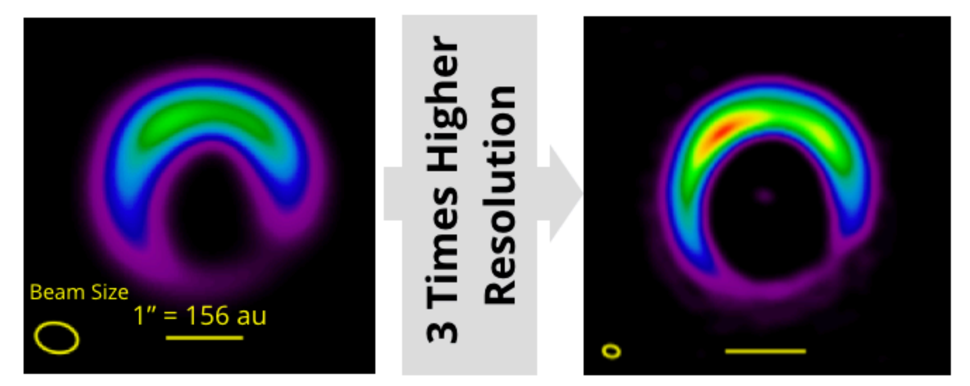

Figure 1. Reconstructed images of CLEAN and SpM.

2. Imaging Techniques for Radio Interferometer

2.1. Traditional Technique：CLEAN Algorithm

- CLEAN (Högbom 1974) is most common algorithm in radio astronomy and uses non-liner techniques effectively interpolate sample of V(u, v) into unsampled regions of the (u, v) plane.
- The algorithm

① assumes that the image consists of a number of point sources.

② is therefore to break down the intensity distribution in the dirty image into point source responses, and then replace each one with the Gaussian with a half-amplitude width equal to that of the original synthesized beam. This procedure finally provide a CLEAN image.

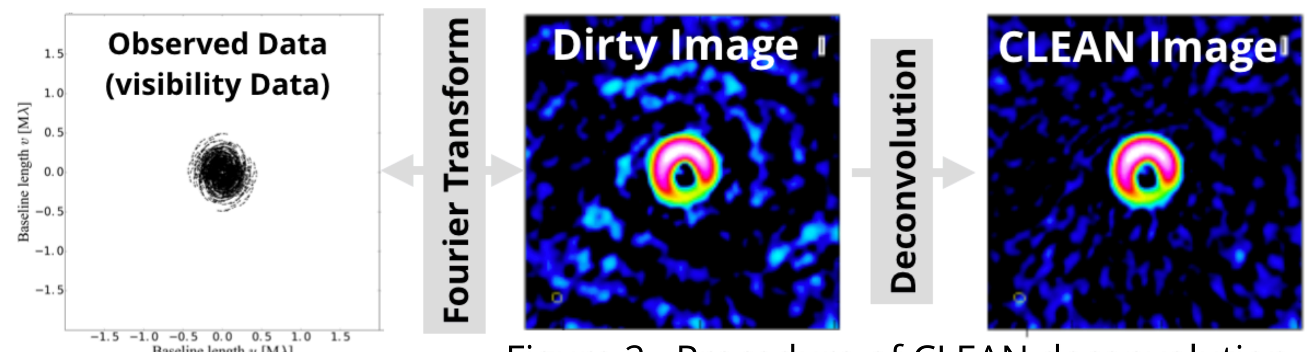

Figure 2. Procedure of CLEAN deconvolution

2.2. State-of-Art Technique : Sparse Modeling

- For the imaging equation with sparse modeling, L_1+TSV regularization (see, Kuramochi et al. 2018) is adopted as the regularization function of the image reconstruction.
- The equation

① becomes a convex optimization, guaranteeing the global convergence to a unique solution regardless of initial conditions by choosing the meaningful sparse image from the infinite number of possible solutions by introducing two regularization terms: the L_1 norm and Total Squared Variation (TSV) of the brightness distribution (see, Akiyama e al. 2017b, Kuramochi et al. 2018).

② **can achieve an optimal resolution of ~30% of the diffraction limit (~ 3 time better angular resolution) by adjusting two positive variables Λ_l and Λ_{TV} in these two regularization terms. Λ_l and Λ_{TV} can effectively be determined by evaluating goodness-fitting with 10- fold cross validation (e.g., Honma et al. 2014, Akiyama et al. 2017a,b, Kuramochi et al. 2018).**

$$\mathbf{I} = \mathrm{argmin}_{\mathbf{I}} \left(\|\mathbf{V} - \mathbf{A}\mathbf{I}\|_2^2 + \Lambda_l \|\mathbf{I}\|_1 + \Lambda_{tv} \|\mathbf{I}\|_{TSV} \right)$$

- **Deviations: Least-square fitting between the model image and observed visibilities**
- **L_1 norm: favoring sparse images**

$\mathbf{I}$: Image vector
$\mathbf{V}$: Observed visibility vector
$\mathbf{A}$: The Fourier Transformation

$$\|\mathbf{I}\|_1 = \Sigma_i \Sigma_j \mathbf{I}_{i,j} \quad (L_p \text{ norm: } \|\mathbf{x}\|_p = (\Sigma_i \|x_i\|^p)^{1/p} \text{ for } p > 0 \ )$$

- **Total Squared Variation: favoring sparse images on the gradient domain**

$$\|\mathbf{I}\|_{TSV} = \Sigma_i \Sigma_j \left(|\mathbf{I}_{i+1,j} - \mathbf{I}_{i,j}|^2 + |\mathbf{I}_{i,j+1} - \mathbf{I}_{i,j}|^2 \right)$$

3. Analysis

- We use two sets of ALMA archival data for the protoplanetary disk around HD 142527.
- Data1 is taken in the intermediate-baseline array configuration (see Kataoka et al. 2016), and Data 2 is in the longer-baseline array configuration. The image resolutions reconstructed from these data sets are different by a factor of ~ 3.
- We compare images reconstructed using sparse modeling and CLEAN.

Observed Data	Data 1 2015.100425.S (PI. A. Kataoka)	Data 2 2012.1.00631.S (PI. Fukagawa)
Observation date	March 11, 2016	July 17, 2015
Frequency	343 GHz (Band7)	322 GHz (Band7)
Longest Base length	430m (0.51"×0.44")	1570m (0.18"×0.13")

Imaging & Comparison

Data 1 Sparse Modeling	Data 1 CLEAN	Data 2 Sparse Modeling	Data 2 CLEAN

Figure 3. Analysis using ALMA data sets

4. Results & 5. Conclusion

Results. We find that the sparse modeling technique can successfully reconstruct the overall disk emission (see, Figure 4). The previously known disk structures appear on both images made by the sparse modeling and CLEAN at its angular resolutions. Remarkably, the image reconstructed from Data 1 using the sparse-modeling technique matches very well with that obtained from Data 2 using the CLEAN technique (reference image) with the accuracy of ~ 90 % on the image domain.

Conclusion. **We have shown that the sparse modeling technique is potentially useful in actual data analyses and may improve the spatial resolution by a factor of ~3.**

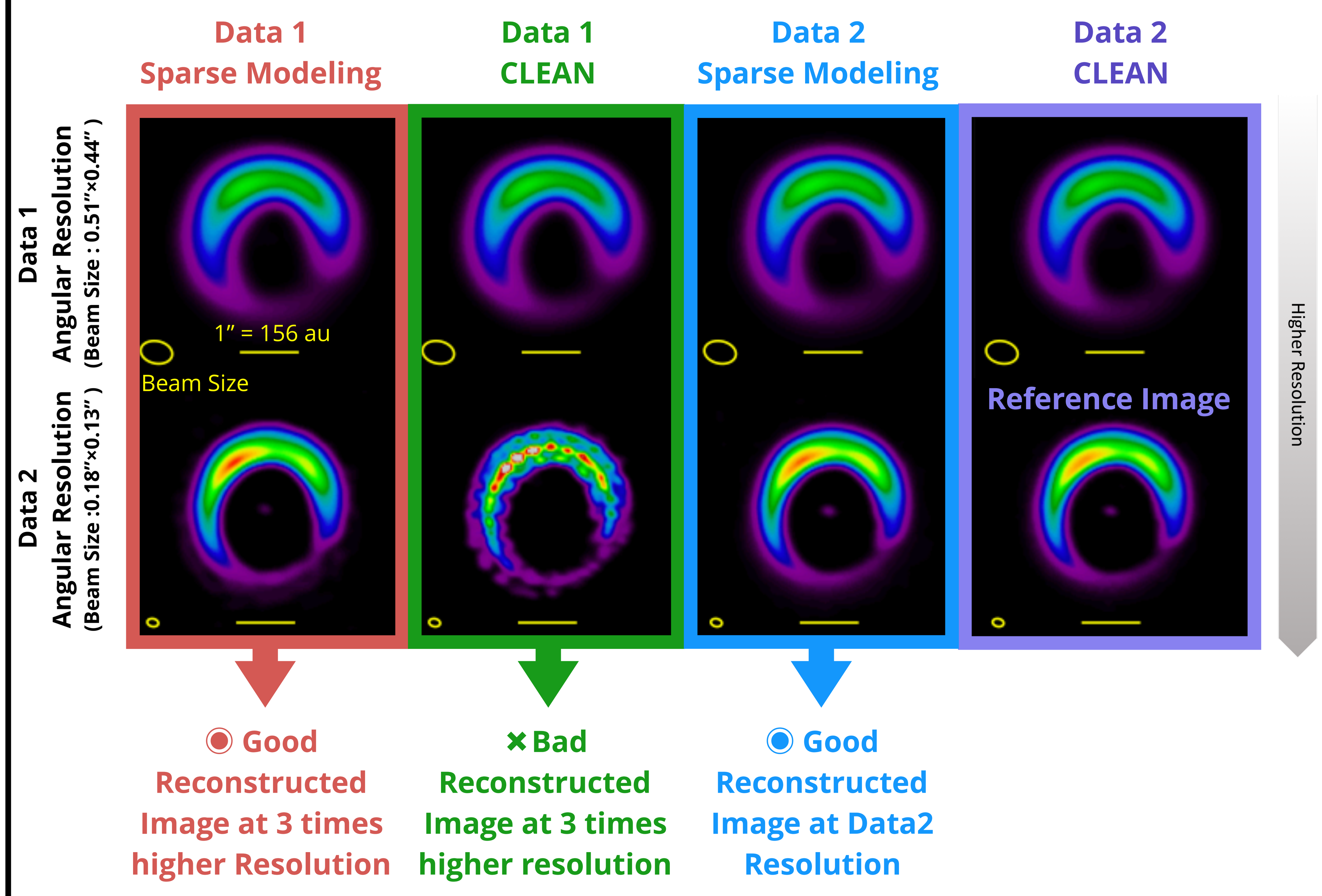

Figure 4. Images of HD 142527 from two dates of ALMA observation

6. Summary

- We present new images of the protoplanetary disk HD 142527 obtained with the ALMA using sparse modeling, which is a new high-fidelity super-resolution imaging technique for radio interferometry.
- We evaluate the performance of the sparse modeling technique with real observational data by comparison with ALMA intermediate baseline observation (Data 1) at 343 GHz (0.87 mm) and more extended baseline observation (Data 2) at 322 GHz (0.93 mm).
- Data 1 sparse modeling image achieves the spatial resolution by a factor of ~3 compared with reference image (Data2 MS-CLEAN image).

7. Future Works & 8. References

- More quantitative analysis of super-resolution imaging using Sparse modeling with ALMA data.
- Application of the sparse modeling techniques to ALMA archival data of protoplanetary disks.

Kuramochi et al. 2018, ApJ, 858, 56, Akiyama et al. 2017, ApJ, 838, 1
Akiyama et al. 2017, AJ, 153, 159, Kataoka et al. 2016, ApJ, 831, L12,
Honma et al. 2014, PASJ, 66, 95 , Högbom, J. A. 1974, A&AS, 15, 417