

ScatteringOptics.jl: An Interstellar Scattering Framework in the Julia Programming Language

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Summary

ScatteringOptics.jl is an astronomy software package developed in the Julia programming language (Bezanson et al., 2017). It implements physical models for the anisotropic scattering of radio waves, which arise from turbulence in the ionized interstellar medium. This toolkit excels in simulating and modeling the temporal, spatial, and spectral effects of interstellar scintillation in the strong scattering regime, taking advantage of Julia's speed and composability. The package provides essential functionalities for modeling, analyzing, and interpreting the images of the Galactic Center's supermassive black hole, Sagittarius A*, especially with the Event Horizon Telescope (EHT), as well as the images of extremely high brightness temperature emissions in active galactic nuclei using space very long baseline interferometry.

Statement of Need

Scintillation is a well-known phenomenon in astronomy. In radio wavelengths, electron density fluctuations in the ionized interstellar plasma cause scattering of radio waves, resulting in the scintillation of compact radio sources in the sky (Narayan, 1992; Rickett, 1990). The interstellar scintillation produces temporal and spectral modulations (i.e., twinkling) in the brightness of objects, as well as distortion of the source images. Interstellar scattering of radio emission typically occurs in the strong scattering regime, dominated by two distinct effects: diffractive and refractive scattering. Diffractive scattering, arising from small-scale fluctuations, typically causes angular broadening of the source image. Conversely, refractive scattering, resulting from large-scale fluctuations, introduces 'refractive substructures' into the observed image (Goodman & Narayan, 1989; Johnson & Gwinn, 2015; Narayan & Goodman, 1989).

Scattering has become increasingly important in high-angular-resolution studies of compact radio sources at micro-arcsecond scales using very long baseline interferometry (VLBI). Notable examples include event-horizon-scale imaging of the Milky Way's supermassive black hole, Sagittarius A* (Sgr A*), with the EHT (Event Horizon Telescope Collaboration et al., 2022a, 2022c, 2022d), and studies of extremely high brightness temperature emissions in active galactic nuclei (AGNs) using space VLBI, exemplified by projects like RadioAstron (Johnson et al., 2016). In both scenarios, the observed interferometric data is influenced by both diffractive and refractive scattering effects. This has driven the development of a theoretical framework (Johnson, 2016; Johnson et al., 2018; Johnson & Narayan, 2016; Psaltis et al., 2018) that can model, simulate, and assess these effects on both the sky images and the interferometric measurements.

ScatteringOptics.jl implements physical models for anisotropic interstellar scattering, based on the fast 'stochastic optics' framework, using a single thin-phase screen (Johnson & Gwinn, 2015; Johnson & Narayan, 2016). The package offers capabilities to simulate diffractive and

refractive scattering effects on sky images and interferometric measurements. It provides reference implementations of three different analytic, probabilistic models for the phase screen, as introduced in Psaltis et al. (2018) and widely used in the community. Additionally, `ScatteringOptics.jl` includes a set of abstract types that enable users to define other phase screen models. Designed for seamless integration, the package natively works with sky models and interferometric data types from the advanced Bayesian radio interferometric modeling package `Comrade.jl` (Tiede, 2022). This integration allows for the incorporation of advanced scattering models into radio interferometric imaging of Sgr A* and other AGNs using the EHT and other VLBI arrays.

The package leverages the strengths of the Julia programming language, which is designed for high-performance computing. A major advantage of Julia is its speed. Programs written in Julia are compiled into efficient native machine code, offering speed comparable to optimized C/C++ or Fortran, and often achieving performance more than a hundred times faster than Python. This speed provides a factor of 10-100 acceleration compared to the current standard implementation of scattering models in Python. This acceleration significantly enhances current state-of-the-art techniques for deriving the maximum posteriori estimate of joint models, including the sky model and phase screens (Johnson, 2016), and also enables the utilization of novel Bayesian inference techniques (available in `Comrade.jl` and related libraries) for deriving full posterior distributions of scattering parameters.

Mathematics

`ScatteringOptics.jl` implements a single thin-screen scattering model described in Johnson et al. (2018) and Psaltis et al. (2018) that simulates both diffractive and refractive scattering. In many instances, the properties of the interstellar scattering can be well described by a single, thin phase-changing screen $\phi(r)$, where r is a two-dimensional transverse coordinate on the screen. The statistical characteristics of scattering can be described by those of the phase screen through its spatial structure function $D_\phi(r)$.

Diffractive scattering causes the angular broadening of the source image. The diffractively scattered image $I_{ea}(r)$ is mathematically given by the convolution of the source image $I_{src}(r)$ with a blurring scattering kernel, $G(r)$,

$$I_{ea}(r) = I_{src}(r) * G(r),$$

In radio interferometry, each set of measurements, so-called visibilities, obtained with a pair of antennas at different time and frequency segments, samples a Fourier component of the sky image. The source visibilities, $V_{src}(b)$, are related to the diffractively scattered visibilities, $V_{ea}(b)$, by

$$V_{ea}(b) = V_{src}(b) \exp \left[-\frac{1}{2} D_\phi \left(\frac{b}{1+M} \right) \right],$$

in which b is the baseline vector between observing stations. The magnification $M = D/R$ is the ratio of Earth-scattering distance D (i.e., the distance between Earth and the scattering material) to scattering-source distance R . While convolution is performed through the above equation in Fourier space, where the kernel is analytically described, `Comrade.jl` provides a toolkit to compute the kernel on the image domain through FFT, and blur arbitrary sky models with this kernel.

Refractive scattering further introduces compact substructures on the diffractively-scattered, angular-broadened images. The compact substructures arise from phase gradients on the scattering screen $\nabla\phi(r)$. The refractively scattered image $I_a(r)$ is given by

$$I_a(r) \approx I_{ea}(r + r_F^2 \nabla \phi(r)),$$

84 in which the Fresnel scale,

$$r_F = \sqrt{\frac{DR}{D+R} \frac{\lambda}{2\pi}}$$

85 is dependent on the observing wavelength λ (Johnson & Narayan, 2016).

86 ScatteringOptics.jl implements three analytic probabilistic models for the phase screen
 87 $\phi(r)$, named Dipole, Periodic Boxcar, and Von Mises models in Psaltis et al. (2018), providing
 88 the corresponding semi-analytic descriptions of the phase structure function $D_\phi(r)$. The
 89 default model is the Dipole model, known to be consistent with multi-frequency measurements
 90 of Sgr A* (Johnson et al., 2018) and being used as the standard model in the Event Horizon
 91 Telescope Collaboration (Event Horizon Telescope Collaboration et al., 2022b, 2022c, 2022d).

92 Example Usage

93 This example code segment uses ScatteringOptics.jl to simulate interstellar scattering on
 94 an input sky model of Comrade.jl (Tiede, 2022). More detailed tutorials are available in the
 95 software documentation.

```

96 using CairoMakie
97 using ScatteringOptics
98 using StableRNGs
99 using VLBI_Sky_Models

100
101 # Load a image model from an image FITS file
102 # This FITS file is available in the tutorial pages of the
103 # software documentation.
104 im = load_fits("data/jason_mad_eofn.fits", IntensityMap)
105
106 # Plot source image
107 imageviz(im, size=(600, 500), colormap=:afmhot)
```

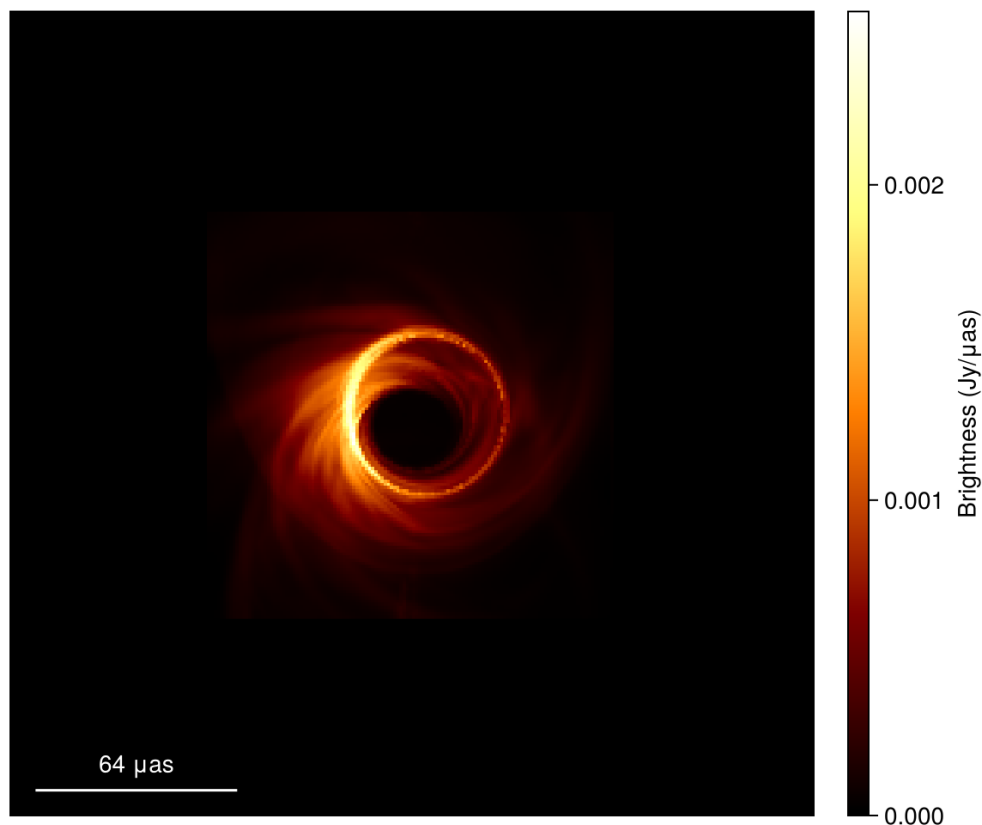


Figure 1: Output of above code plotting an example unscattered source image (obtained from [Dexter, 2014](#)).

```

108 # Initialize a scattering model (the default is a Dipole model)
109 # The default model is a Dipole model with the best-fit parameters
110 # for the Milky Way supermassive black hole Sgr A*
111 sm = ScatteringModel()
112
113 # Here using StableRNG for the reproducibility
114 rng = StableRNG(123)
115
116 # Create a refractive phase screen model from scattering model
117 # and image dimensions
118 # Produce the scattered image
119 im_sc = scatter_image(sm, im; rng=rng)
120
121 # Plot source image
122 imageviz(im_sc, size=(600, 500), colormap=:afmhot)

```

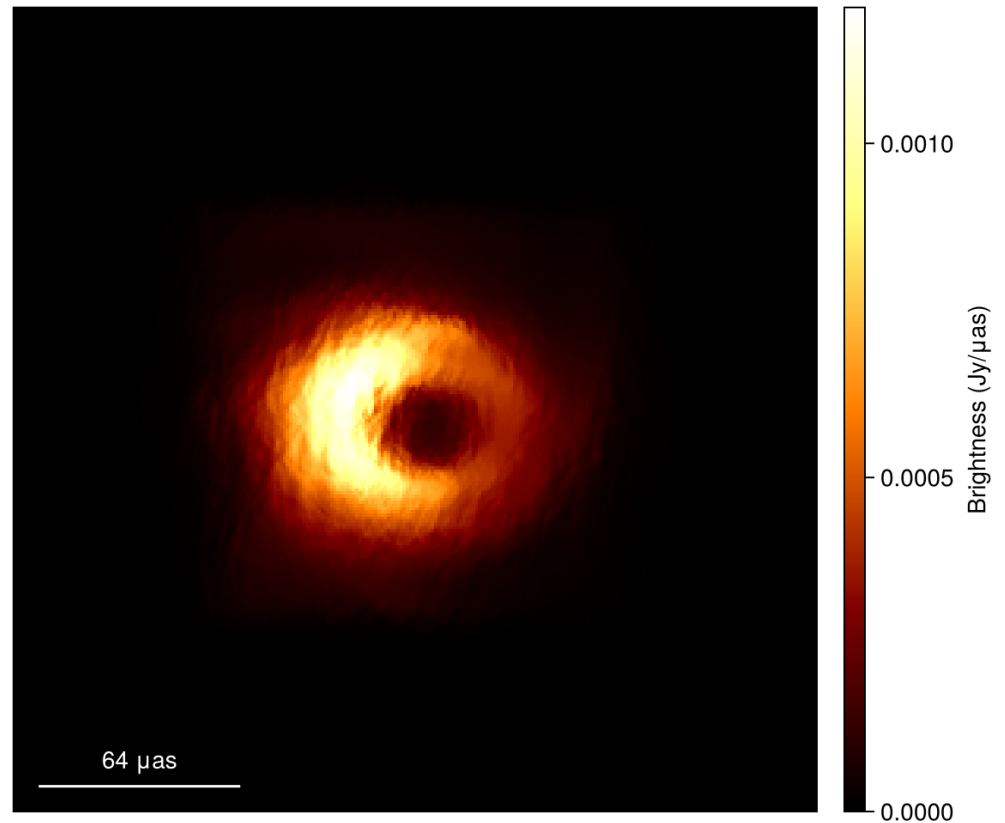


Figure 2: Output of above code plotting the output scattered image.

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References

- Bezanson, J., Edelman, A., Karpinski, S., & Shah, V. B. (2017). Julia: A fresh approach to numerical computing. *SIAM Review*, 59(1), 65–98. <https://doi.org/10.1137/141000671>
- Dexter, J. (2014). Event horizon scale emission models for Sagittarius A*. In L. O. Sjouwerman, C. C. Lang, & J. Ott (Eds.), *The Galactic Center: Feeding and feedback in a normal galactic nucleus* (Vol. 303, pp. 298–302). <https://doi.org/10.1017/S1743921314000775>
- Event Horizon Telescope Collaboration et al. (2022a). First Sagittarius A* Event Horizon Telescope results. I. The shadow of the supermassive black hole in the center of the Milky Way. *The Astrophysical Journal Letters*, 930(2), L12. <https://doi.org/10.3847/2041-8213/ac6674>
- Event Horizon Telescope Collaboration et al. (2022b). First Sagittarius A* Event Horizon Telescope results. II. EHT and multiwavelength observations, data processing, and calibra-

- tion. *The Astrophysical Journal Letters*, 930(2), L13. <https://doi.org/10.3847/2041-8213/ac6675>
- Event Horizon Telescope Collaboration et al. (2022c). First Sagittarius A* Event Horizon Telescope results. III. Imaging of the Galactic Center supermassive black hole. *The Astrophysical Journal Letters*, 930(2), L14. <https://doi.org/10.3847/2041-8213/ac6429>
- Event Horizon Telescope Collaboration et al. (2022d). First Sagittarius A* Event Horizon Telescope results. IV. Variability, morphology, and black hole mass. *The Astrophysical Journal Letters*, 930(2), L15. <https://doi.org/10.3847/2041-8213/ac6736>
- Goodman, J., & Narayan, R. (1989). The shape of a scatter-broadened image - II. Interferometric visibilities. *Monthly Notices of the Royal Astronomical Society*, 238, 995. <https://doi.org/10.1093/mnras/238.3.995>
- Johnson, M. D. (2016). Stochastic optics: A scattering mitigation framework for radio interferometric imaging. *The Astrophysical Journal*, 833(1), 74. <https://doi.org/10.3847/1538-4357/833/1/74>
- Johnson, M. D., & Gwinn, C. R. (2015). Theory and simulations of refractive substructure in resolved scatter-broadened images. *The Astrophysical Journal*, 805(2), 180. <https://doi.org/10.1088/0004-637X/805/2/180>
- Johnson, M. D., Kovalev, Y. Y., Gwinn, C. R., Gurvits, L. I., Narayan, R., Macquart, J.-P., Jauncey, D. L., Voitsik, P. A., Anderson, J. M., Sokolovsky, K. V., & Lisakov, M. M. (2016). Extreme brightness temperatures and refractive substructure in 3C273 with RadioAstron. *The Astrophysical Journal Letters*, 820(1), L10. <https://doi.org/10.3847/2041-8205/820/1/L10>
- Johnson, M. D., & Narayan, R. (2016). The optics of refractive substructure. *The Astrophysical Journal*, 826(2), 170. <https://doi.org/10.3847/0004-637X/826/2/170>
- Johnson, M. D., Narayan, R., Psaltis, D., Blackburn, L., Kovalev, Y. Y., Gwinn, C. R., Zhao, G.-Y., Bower, G. C., Moran, J. M., Kino, M., Kramer, M., Akiyama, K., Dexter, J., Broderick, A. E., & Sironi, L. (2018). The scattering and intrinsic structure of Sagittarius A* at radio wavelengths. *The Astrophysical Journal*, 865(2), 104. <https://doi.org/10.3847/1538-4357/aadcff>
- Narayan, R. (1992). The physics of pulsar scintillation. *Philosophical Transactions of the Royal Society of London Series A*, 341(1660), 151–165. <https://doi.org/10.1098/rsta.1992.0090>
- Narayan, R., & Goodman, J. (1989). The shape of a scatter-broadened image. - I. Numerical simulations and physical principles. *Monthly Notices of the Royal Astronomical Society*, 238, 963–1028. <https://doi.org/10.1093/mnras/238.3.963>
- Psaltis, D., Johnson, M., Narayan, R., Medeiros, L., Blackburn, L., & Bower, G. (2018). A model for anisotropic interstellar scattering and its application to Sgr A*. <https://arxiv.org/abs/1805.01242>
- Rickett, B. J. (1990). Radio propagation through the turbulent interstellar plasma. *Annual Review of Astronomy and Astrophysics*, 28, 561–605. <https://doi.org/10.1146/annurev.aa.28.090190.003021>
- Tiede, P. (2022). Comrade: Composable modeling of radio emission. *Journal of Open Source Software*, 7(76), 4457. <https://doi.org/10.21105/joss.04457>