Ray-Tracing in Relativistic Magnetohydrodynamic Jet Simulations

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Introduction

- We simulate relativistic magnetohydrodynamic (RMHD) non-axisymmetric jet flows in 3D with Cartesian coordinates using the *PLUTO* code [1]. As a post-process step, we use the *RADMC-3D* code to perform ray-tracing and radiative transfer calculations [2].
- The three panels to the right (Fig. 1) present the various stages of our imaging pipeline: Panel (1) displays a 2D slice through jet's density in dimensionless grid units. Panels (2)/(3) illustrate zoomed-in ray-traced total intensity maps of the resulting synchrotron emission when the jet is imaged without/with a jet tracer to exclude the ambient medium. The red box highlights the location of a strong recollimation shock within the jet flow.
- We run three different jet simulations in which the jet carries a: (i) poloidal, (ii) helical, and (iii) toroidal magnetic field (from top to bottom in Figs. 2 & 3).

Mapping the non-Thermal from the Thermal

We explore three different emission recipes [3] for mapping from the thermal fluid variables to the non-thermal electron power-law distributions (see Equations 1, 2, and 3). The resulting ray-traced Stokes I, linear polarized intensity, and Stokes V maps for each simulation/recipe are presented in Figures 2 & 3. We use a jet tracer to exclude the ambient medium/jet cocoon from our ray-tracing calculations.

- Recipe 1 We assume that the electron power-law distribution $n(\gamma) = n_0 \left(\frac{\gamma}{\gamma_{\min}}\right)^{-s}$ is proportional to the fluid's density ρ:

$$\int_{\gamma_{\min}}^{\gamma_{\max}} \mathrm{d}\gamma n_e(\gamma) = \frac{\rho}{m_p} \quad (1)$$

- Recipe 2 We assume that the electron power-law distribution is proportional to the fluid's internal energy density via a relativistic equation-of-state (*p* is the fluid's thermal pressure and $\hat{\gamma}$ is an adiabatic index):

$$\int_{\gamma_{\min}}^{\gamma_{\max}} \mathrm{d}\gamma n_e(\gamma) m_e c^2 = \frac{p}{(\hat{\gamma}-1)} \quad (2)$$

- Recipe 3 We assume that the electron power-law distribution is proportional to the fluid's magnetic energy density:

$$\int_{\gamma_{\min}}^{\gamma_{\max}} \mathrm{d}\gamma n_e(\gamma) \gamma m_e c^2 = \epsilon_B \frac{B^2}{8\pi \cdot (\hat{\gamma}-1)} \quad (3)$$

Stokes V Images, i=5°

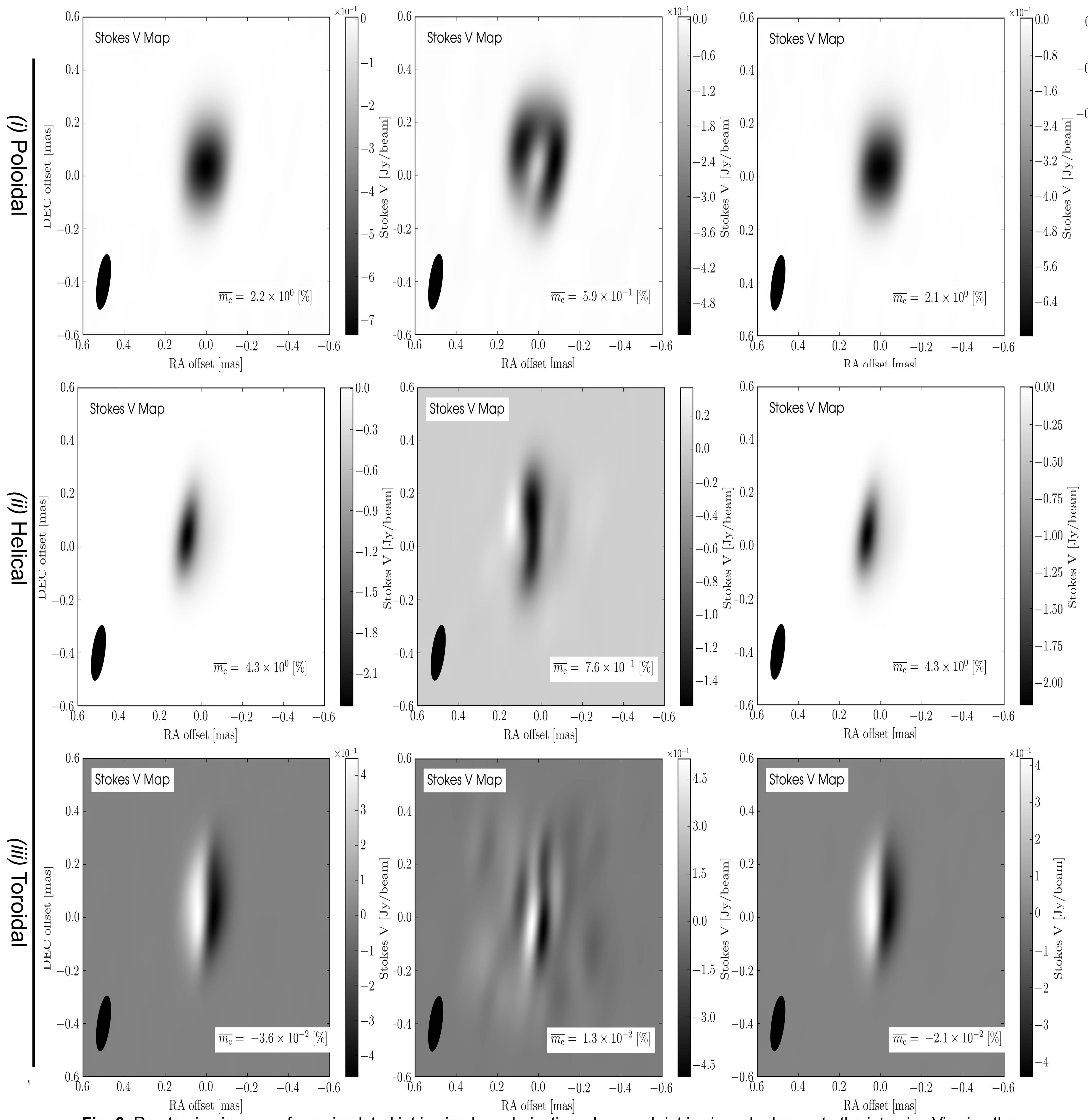

Fig. 3: Ray-tracing images of our simulated jet in circular polarization when each jet is viewed edge-on to the jet-axis. Viewing three different recipes for mapping from the thermal to the non-thermal (see equations 1-3).

$(1)\ n(\gamma) \propto \rho$ $(2)\ n(\gamma) \propto p$ $(3)\ n(\gamma) \propto B^2$

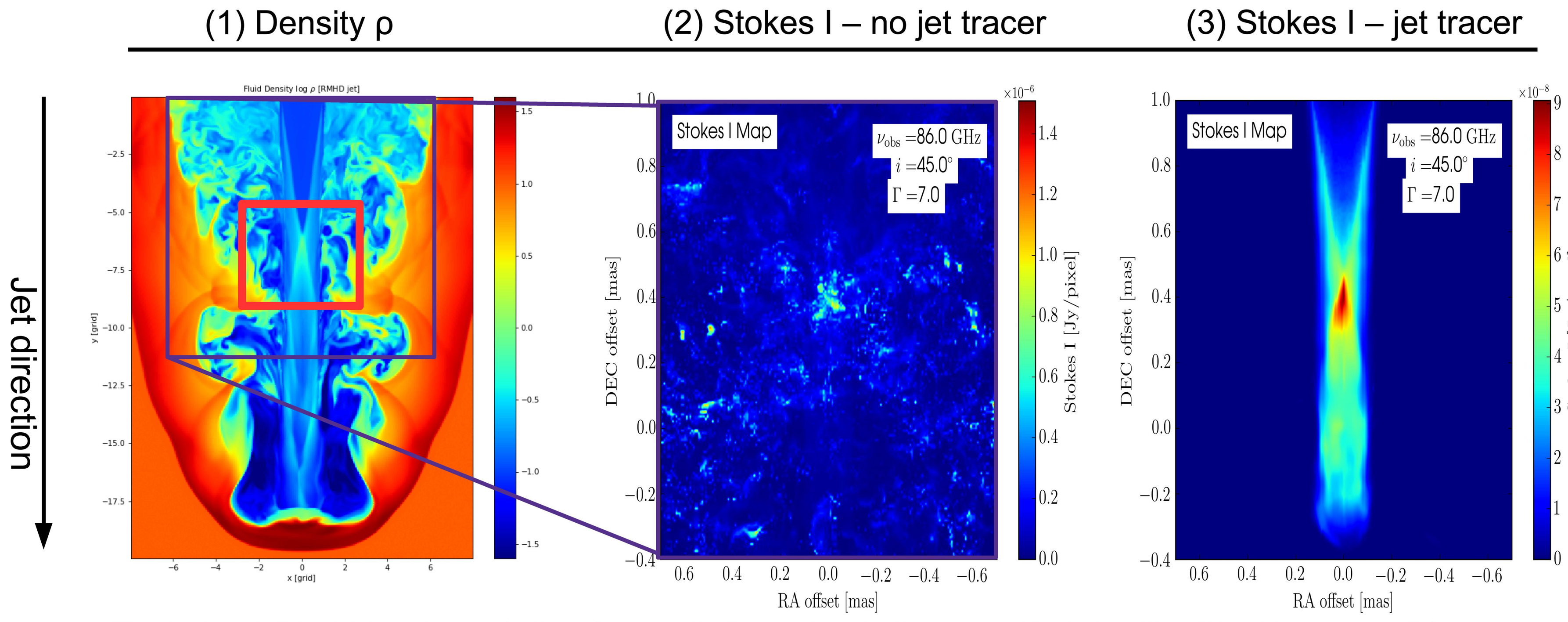

Fig. 1: From left to right - a demonstration of our synthetic imaging pipeline: panel (1) starts with a 2D cut through our 3D RMHD jet colored by thermal density, the next panels are zoomed into an unobscured region of the jet's stranding shock (demarcated with a purple box) and show: (2) the ray-traced synchrotron emission without the use of a jet tracer and (3) the ray-traced synchrotron emission with the use of a jet tracer to exclude the ambient medium.

Resolved Polarized Images

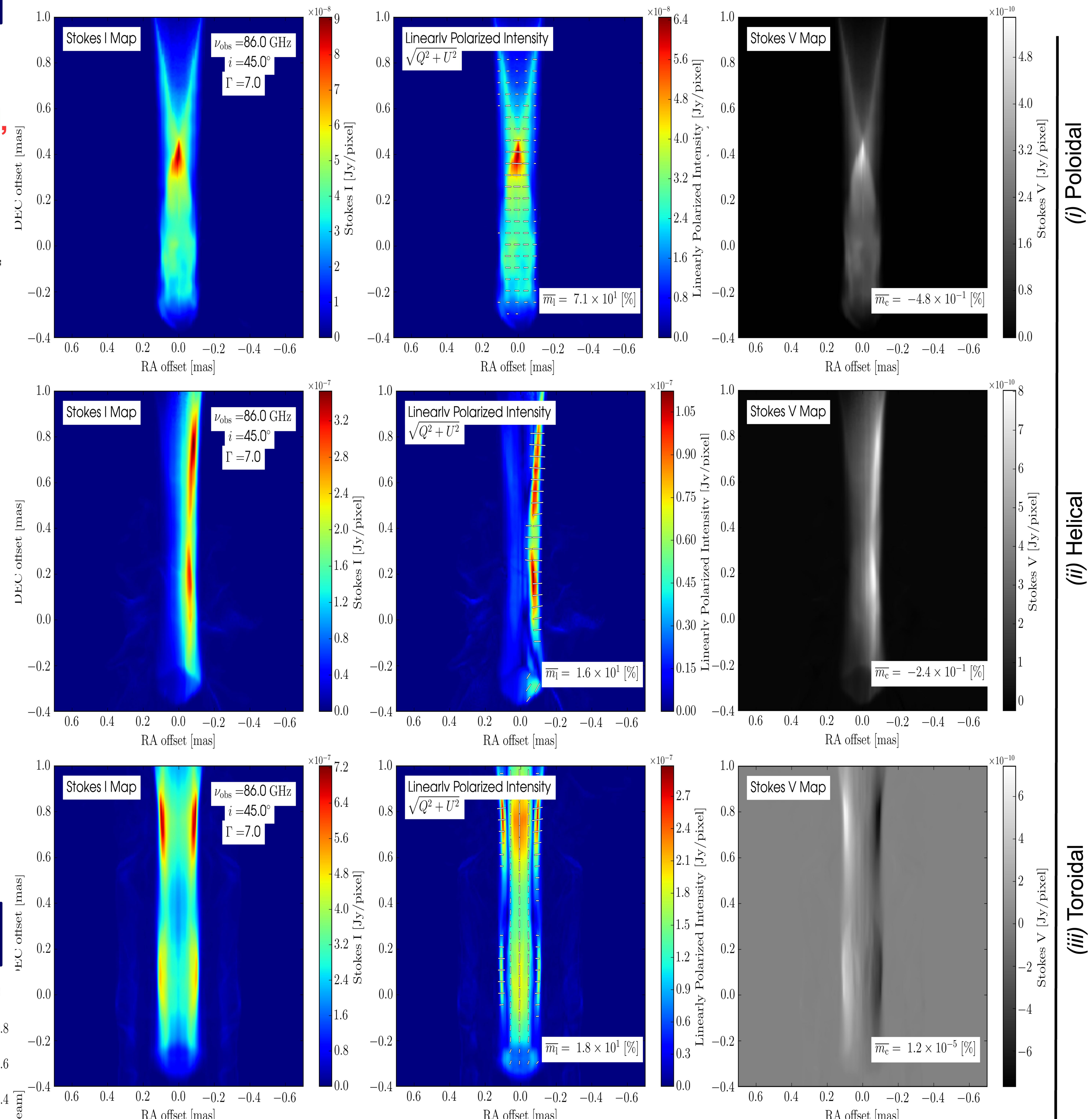

Fig. 2: Resolved ray-traced images of our jet propagating from top to bottom in total intensity (left), linearly polarized intensity (middle), and circular polarization (right column). Calculated integrated values of fractional linear and circular polarization are listed to the lower left in the middle and right column.

Total Intensity *Linearly Polarized Intensity* *Circular Polarization*

Conclusions

- Resolved/convolved circular polarization imaging at 45°/5° can be used to distinguish between a purely poloidal or purely toroidal magnetic field morphology within the relativistic jet. The toroidal magnetic field morphology results in both positive and negative Stokes V parameters.
- When the jet is resolved, toroidal magnetic fields result in jet edge-brightening whereas the poloidal magnetic field cases seem to highlight the jet's spine/recollimation shock.
- The integrated levels of fractional linear and circular polarization decrease from the poloidal magnetic field within the jet to the toroidal magnetic field description.

References

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