Astronomical Demonstration of an Optical Vortex Coronagraph

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As of this writing, some 300 extrasolar planets have been deduced from the gravitational wobble or transit-dimming intensity of nearby stars. Little is known, however, of their composition because direct optical detection is exceedingly difficult, owing to the extraordinary glare of the parent star. The problem is compounded for small Earth-like worlds whose possible spectral biomarkers are too weak to discern from background starlight. The challenge for optical scientists is to extinguish the Airy disk image of the star without sacrificing precious planetary photons.

The optical vortex coronagraph (OVC) provides an elegant solution by taking advantage of the unique diffraction properties of an optical vortex lens[1,2] or subwavelength diffraction grating.[3] To approach the large contrast enhancement afforded by the OVC on a telescope, one must: (1) fabricate a high quality vortex lens, (2) design a high Strehl imaging system, and (3) apply adaptive optics techniques to eliminate atmospherically generated wavefront aberrations.

For our experiment, we fabricated a vortex lens using electron beam lithography.[4] The optical system was designed using achromatic doublet lenses. The image of the star was made stationary by using a feedback system composed of a piezoelectrically controlled tip-tilt mirror and a fast (500 Hz) camera. Jitter from both mechanical motion of the telescope and atmospheric turbulence was eliminated. By stopping down the aperture of the refractive telescope below the Fried parameter, we were able to nearly eliminate higher order atmospheric aberrations and achieve Strehl ratios of about 99 percent through a 25 mm diameter aperture.

The telescope was directed at the binary star system, Cor Caroli, shown in the figure, with and without the vortex lens in place. Exposure time was 300 s and dark frame subtraction was used. The bright primary star suffered a peak suppression of 97 percent, whereas the weaker secondary star was unaffected. In comparison, the system achieved a peak suppression of 99.8 percent in the laboratory using a mock star. In that case, we achieved a contrast exceeding 2×10^4 at an angular displacement of $\geq 4\lambda/D$—the region in which astronomers hope to find Earth-like planets.[5] Our numerical studies suggest that improvements in the quality of the vortex lens and better correction for higher order aberrations may allow the OVC to reach contrasts that are suitable for a space telescope mission.

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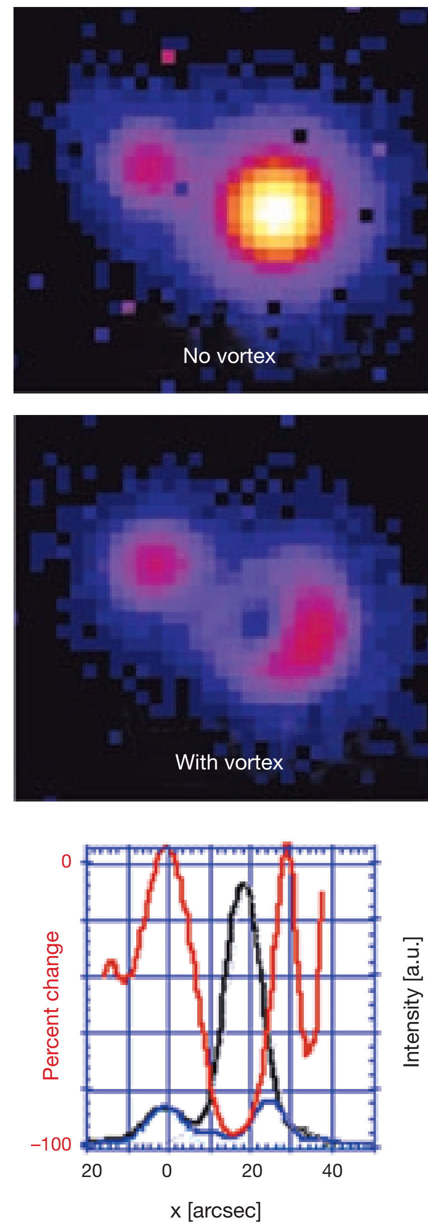

Imaged binary star system Cor Caroli through the optical vortex coronagraph with and without the vortex lens in place. The bright primary star is suppressed, whereas the weaker secondary star is unaffected. The plotted intensity curves (black, blue lines) show a peak suppression of 97 percent (red line).