HST NICMOS Coronagraphic Polarimetry of AFGL 2591, S140 IRS1, and Mon R2 IRS3

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Abstract

Whereas the nearby low-mass young stellar objects (YSOs) are observed to be isolated and without substantial interaction from other stars, most, if not all, massive stars (> 8 Msun) are observed to form in clusters. This combination of massive stars and clusters has led to the suggestions that massive stars form by coalescence after stellar collisions or by enhanced accretion due to the gravitational potential of the cluster. It is also possible that massive stars form by accretion through a disk, similar to the formation of low-mass stars, although the presence of a disk in any star with mass > 25 Msun (O stars) has not been observed and the existence of disks is still controversial. We are studying the massive YSOs in the nearest star-forming regions using 2 micron polarimetry with the 0.2" resolution of the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) on Hubble Space Telescope (HST). These stars, which are still embedded in dense envelopes, have lobes of scattered light along their outflow axes. Because these nearby massive YSOs are bright, their point-spread functions (PSFs) put substantial scattered light, usually polarized, into their immediate vicinity on the array. Because our goal is to determine any effects of interactions with other stars on possible disk structure, these PSFs must be removed; the best way is by coronagraphic imaging. We find that AFGL 2591, S 140 IRS1, and the two components of Mon R2 IRS3 all have very wide opening angles, asymmetric structure near the stars, and indications of episodic outflows.

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Introduction

Although there has been substantial progress in understanding the formation of solar mass stars in recent years, the formation of massive stars is still not understood. It is most likely that the early B stars, at least, are formed by accretion through a disk; however, no evidence yet exists for rotating disks surrounding the more massive O stars ($L > 10^5$ Lsun). What are commonly seen emanating from YSOs deeply embedded in the dense envelopes from which they are accreting gas are wide-angle outflows with shocked gas at the extreme, distant ends. However, to observe the details of the outflow ejection requires impossibly high AU resolution for objects at the >kpc distance of even nearby massive YSOs. Some effects should be seen within a few thousand AU, for which we can use the 0.2" resolution of NICMOS on HST.

Observations

In order to take advantage of the 0.2" resolution of NICMOS, we must remove as much of the HST diffraction pattern and instrumental scattered light as possible. We did this by observing each YSO through the NICMOS Camera 2 coronagraph, using the 2.0 micron polarization filters, and then subtracting the image of a PSF standard star (here Oph N9 and GJ784) to remove any scattered light from the coronagraph hole. Since the hole is in a corner of the array, we also observed each YSO centered in the array with the same filters and four dither positions, thereby enabling us to determine the polarization of the YSO itself in addition to the scattered light close to the YSO. Each object was observed in two orbits at different telescope orientations. The composite images shown here include both the coronagraph images and the dithered images, and the pixels occulted by the coronagraph are either replaced by the bright core of the YSO or by solid black dots. Because the PSF standard is not a perfect fit, even at H-K = 2.86, the subtraction is poor near the edge of the hole such that the radius of unusable data is ~0.4" (but contrast this to the PSF-affected data in Fig. 1 of 5" and more in the diffraction spikes).

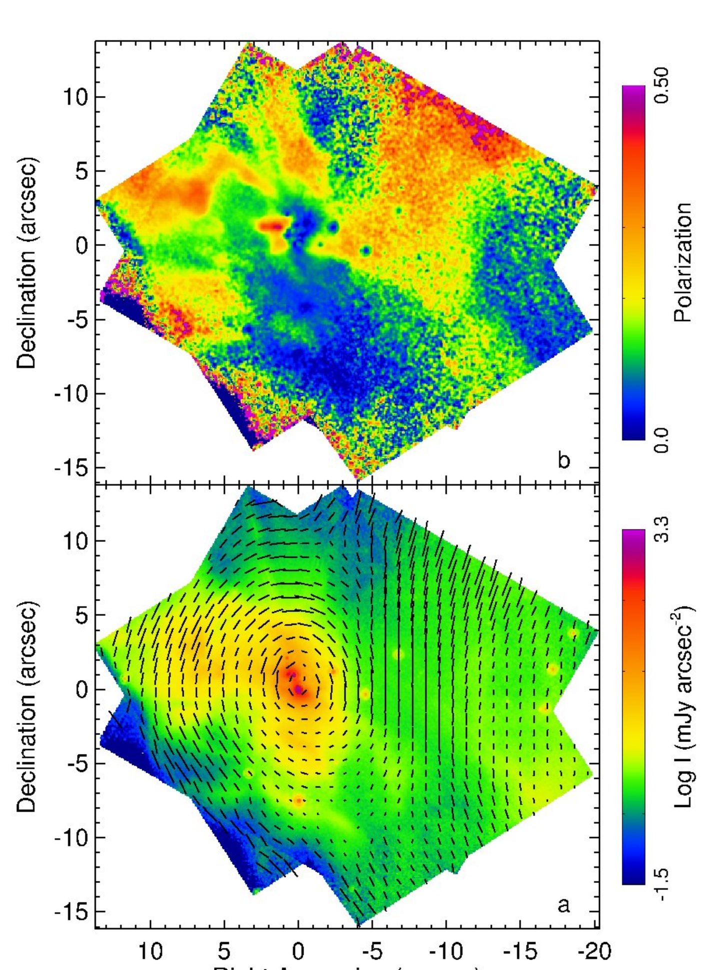

Fig. 5. Intensity and fractional polarization images of Mon R2 IRS3. The data were taken on 8/31/06 and 10/8/06. The western third of the image is the ring surrounding IRS1 and IRS2. At a distance of 830 pc, the separation of the two brightest stars corresponds to a separation of ~720 AU in the plane of the sky. The total luminosity of this compact group is ~1.4 x 10^4 Lsun (Henning et al. 1992). The brighter star, A, was the star occulted by the coronagraph hole. Star B is extremely red and more polarized than star A, which has been modeled as being tipped toward the Earth by ~45° (Alvarez et al. 2004). We suggest that some of the extinction of star B is due to the disk and envelope of star A.

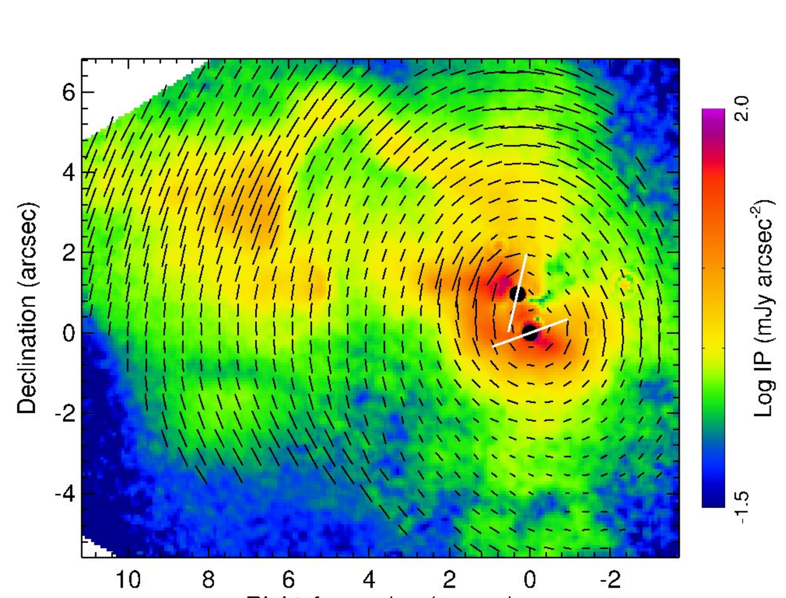

Fig. 7. Plot of the polarized intensity. The white lines through the star locations indicate the polarization position angles of the stars. The position angle of the big lobe to the east is very similar to the polarization position angle of star B minus 90°. We infer that a small disk (<100 AU) might be present around star B; the axis is pointed toward the Earth on the east side. The opening angle for the outflow is very large, almost 180°, and the outflow is either episodic or it is warped and clumped by the molecular cloud in which IRS3 is embedded. The scattered light cone from star A also has an opening angle ~180° and is oriented in a direction perpendicular to the star's polarization position angle.

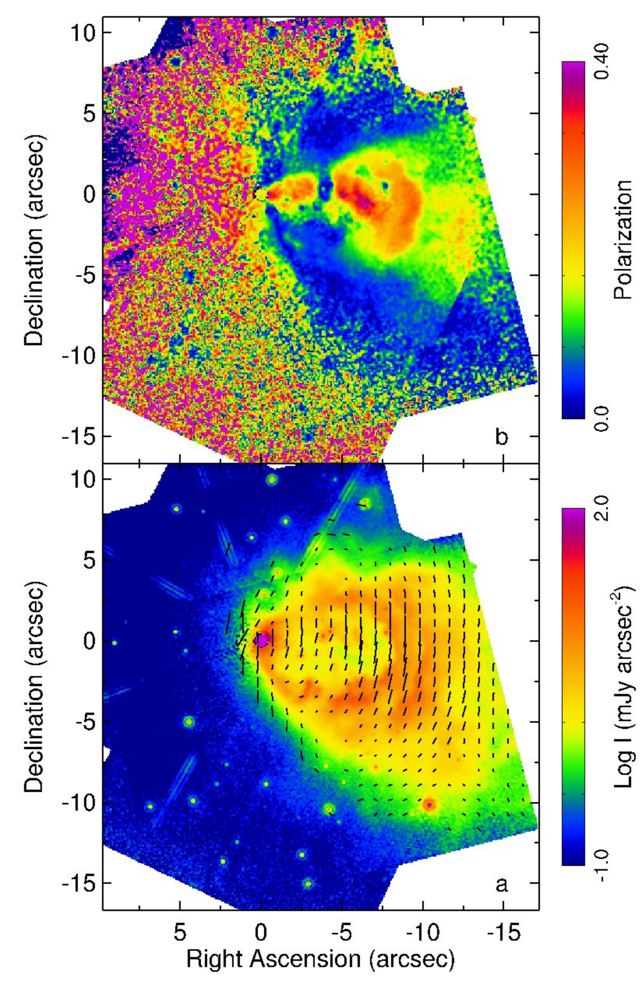

Fig. 1. Intensity and fractional polarization images of AFGL 2591. The data were taken on 5/17/06 and 7/1/06. AFGL 2591 has a luminosity ~2 x 10^4 Lsun for a distance of ~1 kpc (van der Tak et al. 1999). Only the west scattered light cone is visible at NIR wavelengths, although there are H_2 bow shocks ~45" east of the central star (Tamura & Yamashita 1992). The outflow axis can be pictured as approaching the Earth on the west side at an inclination angle of 20° – 40° from the plane of the sky; the east scattered light cone is completely obscured by the dense envelope and/or circumstellar disk. Thanks to the removal of the PSF of the 7.58 mag central star, we see that the east side of the image is very dark (except for the HST diffraction pattern in the part of the combined image that was not observed with the coronagraphic hole).

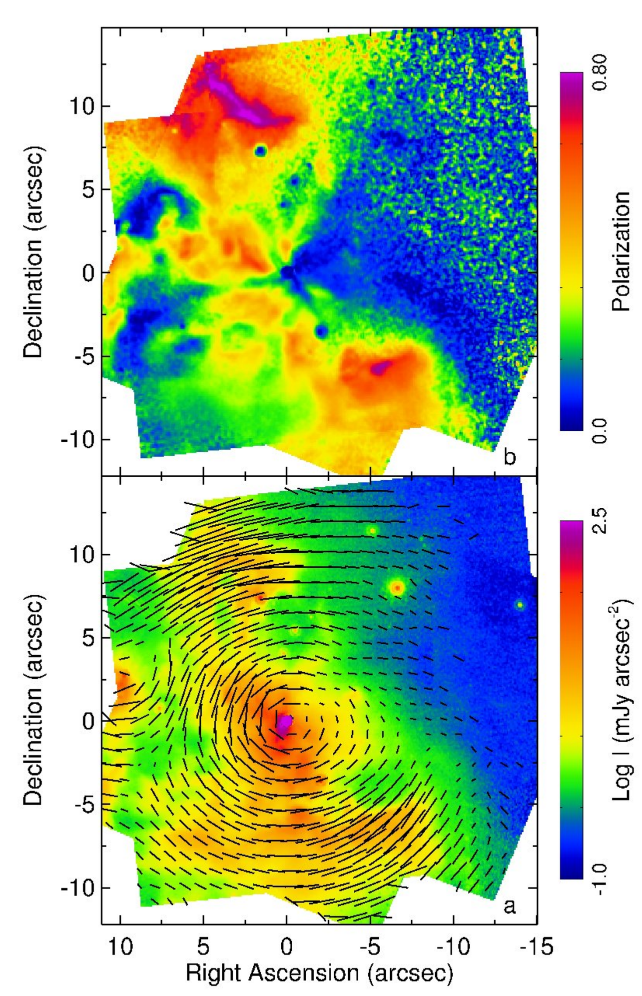

Fig. 3. Intensity and fractional polarization images of S140 IRS1. The data were taken on 3/30/06 and 4/22/06. S140 IRS1 has a luminosity ~2 x 10^4 Lsunfor a distance of ~0.9 kpc (Lester et al. 1986). The source illuminating the east side of the image is IRS3. The clumps in the southern part of the image are also strong emitters of shocked H_2 (Preibisch & Smith 2002).

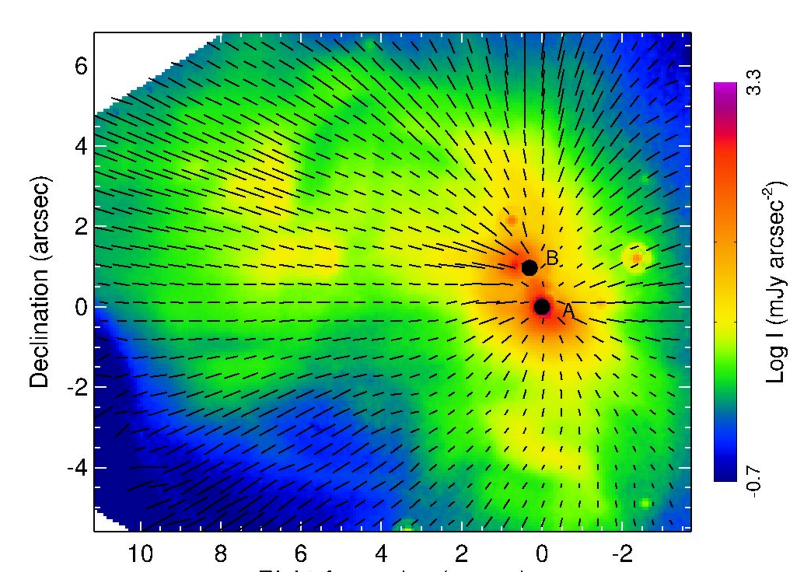

Fig. 6. Plot of intensity image with polarization vectors rotated by 90°. Star B is almost as bright as star A (magnitude 9.46 vs. 9.23 at 2.0 micron), and since it is 12% polarized, its diffraction pattern and instrumental scattered light are also polarized. Consequently, we removed its PSF by subtracting the image of the very red PSF standard star (Oph N9) that we also used for the coronagraph imaging. Now the locations of both stars A and B are blocked out by black dots and their PSFs should not contribute appreciably to the images.
The polarization vectors should point to the illuminating star. We see that although the southern lobe is indeed illuminated by star A (as was previously modeled by Alvarez et al. 2004), the much larger east lobe is illuminated by both stars A and B.

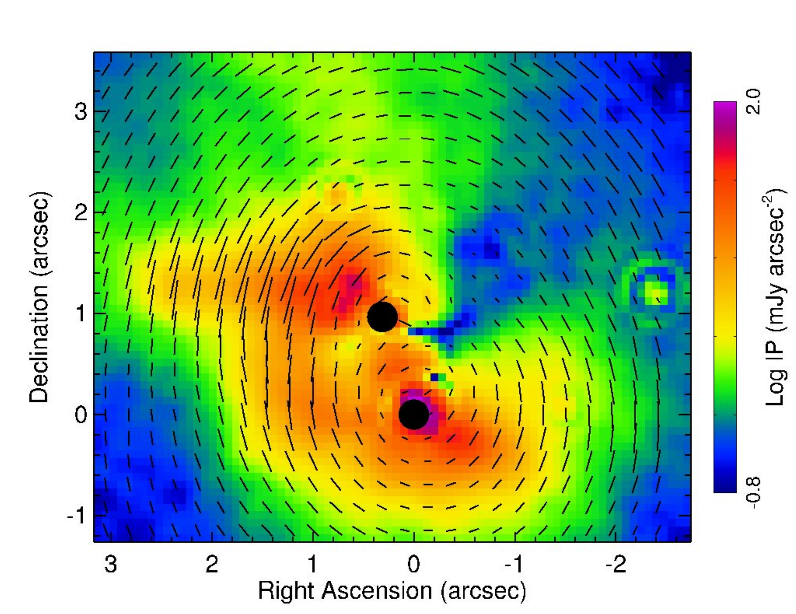

Fig. 8. Polarized intensity image of the central few arcsec. The scattered light lobes of both stars A and B are clearly asymmetric with regard to their axes, as inferred from the polarization position angles of the stars themselves.

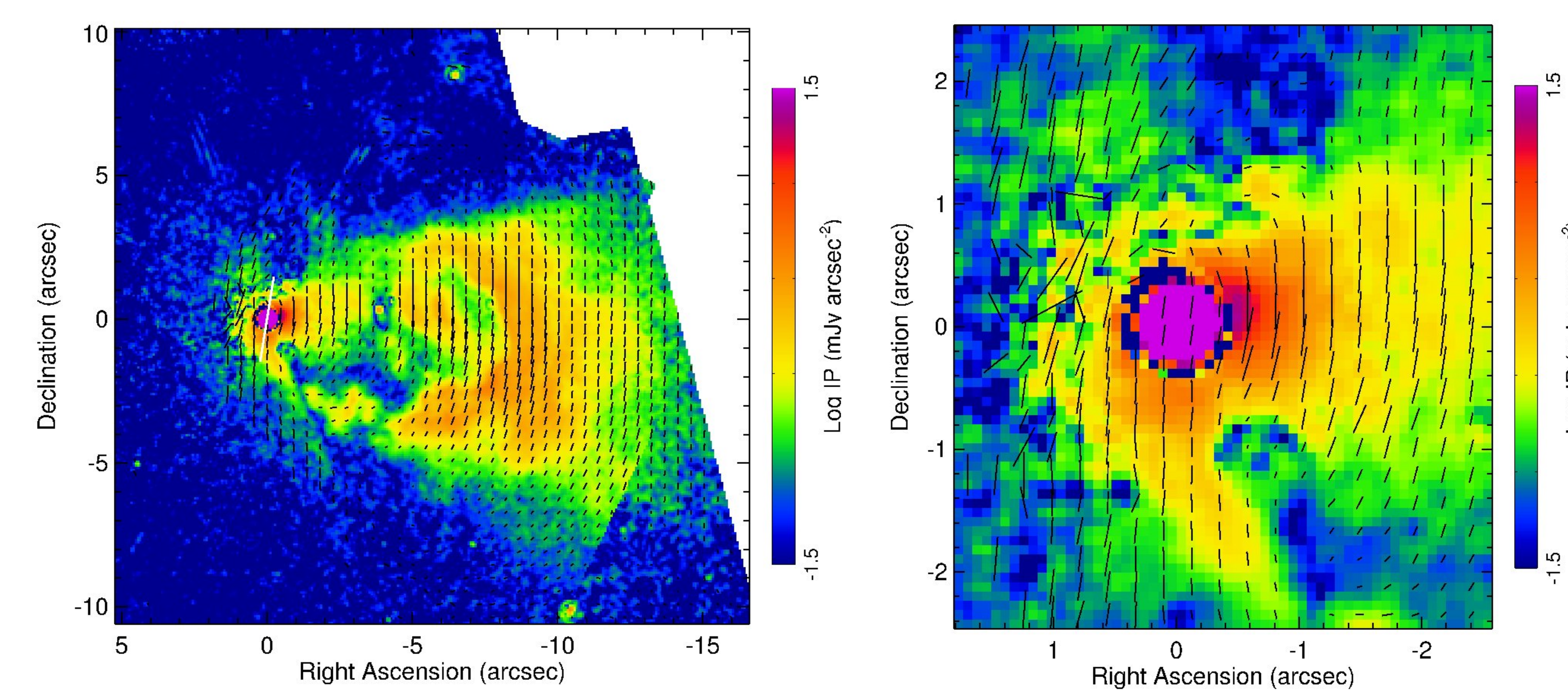

Fig. 2. Plots of polarized intensity. The west scattered light cone can be pictured as having its far side approximately in the plane of the sky and its near side close to the line of sight. Consequently, the light from the far side is quite polarized (scattering angle close to 90°) but the light from the near side is forward scattered and is essentially unpolarized. The sides of the cone are curved such that the light scatters from a series of rims (there are at least two more at 20-30" west of the star). The interior of the cone is almost empty of dust except for the asymmetric jet seen close to the star in the right hand figure. The white line crossing the star in the left hand figure shows the polarization position angle of the star (P=16% at an angle, theta=171°). The star's polarization position angle is almost exactly perpendicular to the outflow axis. Polarization perpendicular to the cone axis is due to multiple scattering in an optically thick envelope or disk close to the star (resolution 200 AU for distance 1 kpc).

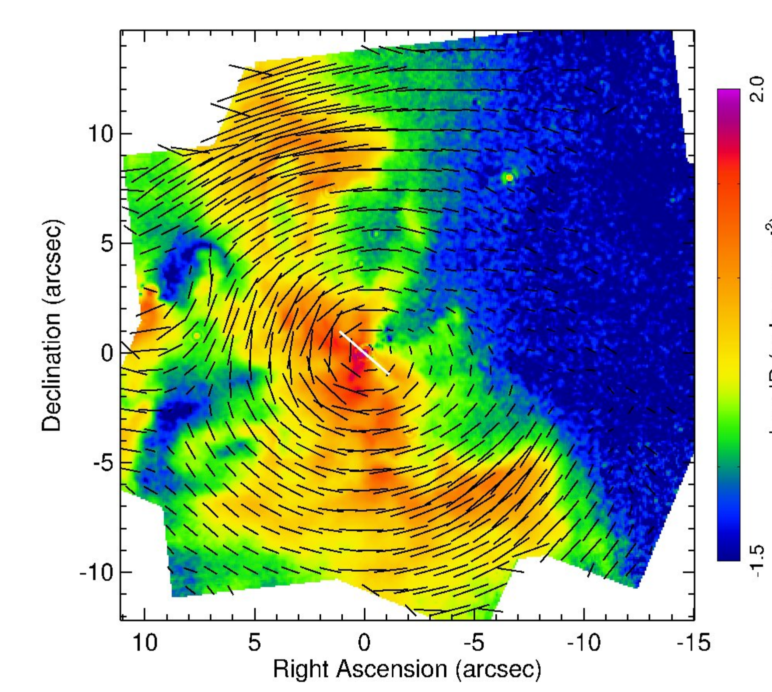

Fig. 4. Polarized intensity. The white line through the star shows the position angle of the polarization of the star (P=3% at theta=49°). If this represents the position angle of a disk (as was suggested by Hoare 2006 from radio interferometry observations), then the opening angle of the scattered light cone is ~180°. An alternative explanation is that the multiple lobes correspond to separate outflows of a close binary with misaligned axes.

Conclusions

- Coronagraphic polarimetry allows us to see details in the central arcsec around very bright stars that would not otherwise be accessible due to extended stellar PSFs.
- Even so, care must be made to measure a PSF standard star of similar color to the desired target to remove the residual scattered light from the coronagraph hole.
- The four massive YSOs discussed here all have very wide scattered light cones with numerous condensations that could indicate episodic outflows.
- Even in the innermost parts of the scattered light cones, that should not be affected by clumps in the surrounding molecular clouds, there are clumps and substantial asymmetries with respect to the overall axes of the scattered light cones/outflows.
- Some small condensations close to the YSO and along the outflow axis may be the massive star equivalent of the low mass YSO "jets".
- The asymmetries in the clumps of dust may be due to each apparent YSO actually consisting of a pair of binary stars embedded in a single large torus or disk but with misaligned outflow axes.
- The polarization position angles of all four stars are almost exactly perpendicular to the position angles of the associated scattered light lobes and probable outflows. The probable explanation is multiple scattering in optically thick envelopes or perhaps a dense, rotating disk.

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