Coronagraphs on the Hubble Space Telescope

John Krist
Jet Propulsion Laboratory, California Institute of Technology

The Hubble Space Telescope (HST) is the most successful high-contrast astronomical imaging instrument that has yet been built (Krist 2004). It has provided numerous images of the scattered light from circumstellar disks and the glow from faint substellar companions. The key to its performance is the stability and high resolution provided by its placement above the atmosphere. Typically, on the ground, high-contrast observations are carried out using coronagraphs that suppress the diffracted light from the central source, some of which remains unsuppressed because of scatter introduced by the uncorrected turbulence of the atmosphere (which exists to some extent, even with adaptive optics, at levels equal to or greater than the scatter created by imperfections in the telescope optics). The residual light is difficult to subtract out because of time-dependent variations in the optics and atmosphere.

On Hubble, though, even without a coronagraph, the diffraction pattern and the scattered light from the optics created by a star can be largely subtracted out because the point spread function (PSF) does not vary greatly over time. In some cases, an image of another star taken months after the science observation can be subtracted out, for instance. Such direct (non-coronagraphic) HST observations have been made of many circumstellar disks and jets near stars.

Coronagraphs do, however, provide additional performance benefits to HST. Simply by occulting the star, scatter from optics after the occulter is reduced, as are detector artifacts such as saturated columns and electronic ghosts. With the addition of a Lyot stop, the diffraction pattern of a bright star can be suppressed to below the level of the scattered light from the optics (which cannot be suppressed optically without some sort of wavefront correction such as a deformable mirror). This reduces the effects of PSF instability caused by time-dependent aberration changes and color mismatches between the target and reference star PSFs, as well as reducing photon noise by diminishing the wings of the PSF.

HST has three coronagraphs that cover the near-UV to near-IR wavelength range, with varying levels of performance. While none of these coronagraphs could be considered to be anything close to optimal, they have provided high-contrast imaging that has not been matched by ground-based telescopes.

NICMOS (Near Infrared Camera and Multi-Object Spectrometer)

NICMOS provides imaging over the near-IR wavelength range (λ=0.95–2.4 μm) with three separate channels providing different resolutions (0.043″, 0.076″, and 0.22″ per pixel). Each channel uses a 256 × 256 element detector. The mid-resolution channel (NIC2) includes a coronagraphic capability (Schneider 2002) with an r=0.3″ (2.2 λ/D at λ=1.6 μm) occulting spot (actually a hole drilled in a field offset mirror) and Lyot stop. The occulting spot is located near the corner of the NIC2 field to minimize its impact on normal imaging (because it is always in place). The Lyot stop is actually the cold stop of the camera, which is intended to block emission from the warm obscurations of the telescope (primary edge, secondary mirror, spiders). Because the cold stop is always in place, throughput in normal imaging mode was optimized at the expense of diffraction suppression performance (i.e., the Lyot stop is not well matched to the rather small occulter). Unfortunately, deformation of the NICMOS dewar due to abnormal thermal expansion of the cryogen on-orbit resulted in a misalignment of the stop, so diffraction from the spiders and much of the primary and secondary mirror edges is not reduced. In addition, small instabilities in the Lyot stop alignment during the deformation period (the first couple of years on-orbit) caused significant time-dependent variations in the residual coronagraphic starlight pattern. Such variations are greatly reduced today (NICMOS now uses an external cooler that was installed in a later servicing mission).

The NICMOS coronagraph reduces the surface brightness of the PSF wings by a factor of 2–3 (a factor of two worse than if the Lyot stop were aligned). Because of scatter by the rough edge of the drilled occulter hole, the effective inner working radius is usually r>0.5″. Despite these limitations, the NICMOS coronagraph has been used to view a number of circumstellar disks for the first time in scattered light (e.g., HD 141569, HD 32297). So far, ground-based coronagraphs operating in the near-IR have not been able to match its performance on such disks.

STIS (Space Telescope Imaging Spectrograph)

STIS is primarily a spectrograph with three separate channels: far-UV and near-UV using MAMA detectors and visible-light using a CCD (0.05″ per pixel). Its coronagraph was a (relatively) low-cost addition to the CCD channel (Grady et al. 2003). Its occulter consists of two crossed wedges (r>0.3″) and is moved into the beam on command (because of pointing and focus uncertainties, the effective inner working angle is *r*>0.7″ in most circumstances). The Lyot stop masks only the diffraction from the outer edge of the primary mirror and is always in place, reducing throughput by about 20%. Diffraction suppression was sacrificed for better throughput in non-coronagraphic observations, with the coronagraph providing a 2–6 times reduction in the PSF wing brightness. Much of this contrast improvement is gained by blocking the star image so that its light does not enter the STIS CCD, which internally scatters light to large angles at λ>0.7 μm (up to 30% at λ=1.0 μm). Besides the incomplete masking of the diffracting edges (secondary and spiders), the greatest limitation of the STIS spectrograph is that it can only be used in an unfiltered mode, covering the entire bandpass of the CCD (λ = 0.2–1.0 μm). This makes it particularly sensitive to color mismatches between target and reference PSFs.

The STIS coronagraph has been used to image a number of circumstellar disks, including Beta Pictoris, HD 141569, and HD 163296. Because of its higher resolution and more stable PSF, STIS has been able to view fainter disks than has been possible with the NICMOS coronagraph. At present, STIS is not functional due to an electronics failure, though it is scheduled to be repaired in the next HST servicing mission. For most coronagraphic imaging, however, STIS has been succeeded by the ACS camera.

ACS (Advanced Camera for Surveys)

ACS, the newest of HST's instruments, consists of a near-UV camera with a MAMA detector and wide-field (200″ × 200″, 0.05″/pix) and high-resolution, narrow-field (25″ × 25″, 0.025″/pix) visible-light CCD cameras. The high-res channel (HRC) includes a coronagraphic mode (Krist 2003) that allows imaging using a variety of filters over λ = 0.2–1.0 μm. The occulters and Lyot stop are located on a flap that flips into the beam on command. This allows the Lyot stop to be appropriately matched to the occulters without sacrificing throughput in the normal imaging mode. The Lyot stop thoroughly masks all of the diffracting edges in the system, reducing throughput by 52%.

The coronagraphic mode was added to the HRC after construction of the camera began, and it was not possible to place the occulters at an intermediate image plane after the spherically aberrated beam from HST was corrected. Thus, the occulters are located at a spherically-aberrated focus, and the beam is corrected afterwards (by a mirror at which the Lyot stop is located). This resulted in the need for large (hard-edged) spots of *r*=0.9″ and 1.8″ (17 and 35 λ/D at λ = 0.6 μm). While significantly impacting the inner working angle, the well-matched occulters and Lyot stop effectively reduce the brightness of the PSF wings by a factor of 6 – 7, to the point that the uncorrectable scattered light from the optics is greater than the residual diffraction pattern. This allows the ACS coronagraph to view the faintest disks yet seen in scattered light (e.g., Fomalhaut, HD 92945, and the outer regions of HD 141569). Despite its strong performance, however, it is not capable of imaging extrasolar planets in reflected light around even the nearest stars (Figure 2).

Performance Advantages and Limitations of the HST Coronagraphs

The HST coronagraphs have a number of advantages over ground-based systems. The primary one is that the stability of the HST allows subtraction of the residual light from the central source at greater levels than can be achieved on the ground. When HST is rolled between observations of the same star and the images from the two orientations are subtracted from each other (thus avoiding color differences between the target and reference PSFs), it is possible to reduce the residual light by up to factors of nearly 500. When another star is used as a reference PSF, improvements of 50× – 100× are often achieved. In comparison, a factor of 10 reduction is considered good on the ground.

HST also provides sharp images over the entire coronagraphic fields, while the corrected fields on ground-based systems are limited by the number of deformable mirror elements. Of course, HST also allows detailed high-contrast imaging at visible wavelengths where ground-based AO does not currently work.

While a powerful high-contrast tool, HST is still just a 2.4 meter telescope, and it can collect only so many photons from faint sources within a reasonable amount of time. In the near-IR, ground-based telescopes are beginning to approach the capabilities of NICMOS for substellar companion searches. The very large telescopes being proposed with extreme AO systems will be able to outperform HST in the near-IR on point sources (e.g., brown dwarf companions), but will still probably not achieve as high a contrast on disks due to optical instabilities in the regions around the star common to both space and ground.

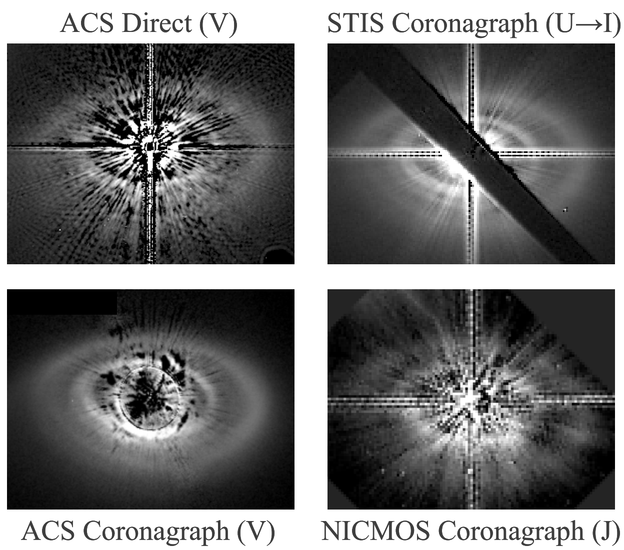

Figure 1: *HST images of the circumstellar disk around the Herbig Ae star HD 141569a. All of the images have been subtracted using images of reference PSF stars. The upper left image shows a non-coronagraphic image taken with ACS, and the others are coronagraphic images. The disk is ~7" across, and the total disk flux is about 0.02% of the total stellar flux. Subtractions by the author.*

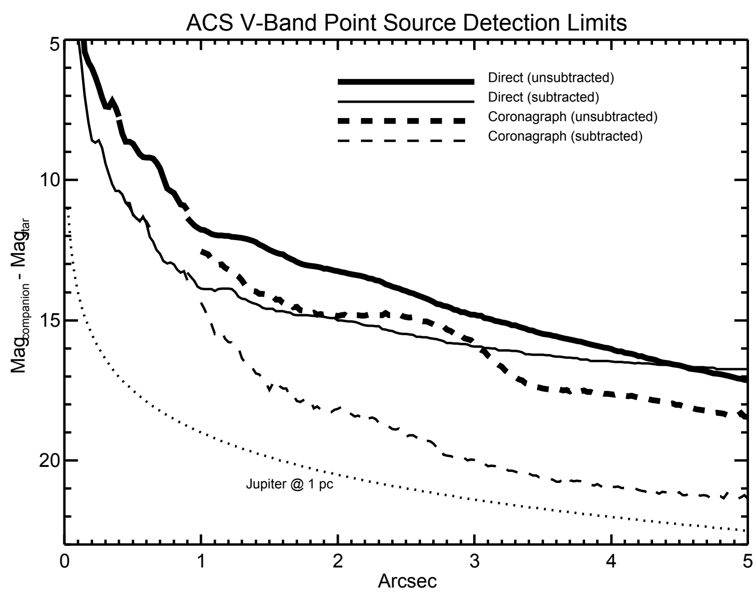

Figure 2: *Robust visual detection limits for a point source near a star in the ACS in V band, with and without the coronagraph and with and without subtraction of the stellar light (roll subtraction). Also plotted is the corresponding brightness of Jupiter as it would appear at various radii from a star located 1 parsec away.*

REFERENCES

Grady, C.A., et al., 2003, P.A.S.P., 115, 1036

Krist, J.E., et al., (2003) in Proceedings of the SPIE, 4860, 20

Krist, J.E., 2004, in Proceedings of the SPIE, 5487, 1284

Schneider, G., 2002, in Proceedings of the 2002 HST Calibration Workshop (available on-line at http://www.stsci.edu/hst/HST_overview/documents/calworkshop/workshop2002)