High Dynamic Range Coronagraphy from Ground and Space

Russell B. Makidon
Space Telescope Science Institute
October 20, 2002
Acknowledgements

- This talk would not be possible without the efforts of…
  - Anand Sivaramakrishnan (STScI)
  - Ben Oppenheimer (AMNH)
  - Lewis Roberts (Boeing)
  - James Graham (UC Berkeley)
  - Paul Kalas (UC Berkeley)
  - James Lloyd (UC Berkeley)
  - Marshall Perrin (UC Berkeley)
  - Chris Koresko (Caltech)
  - John Krist (STScI)
  - Phil Hodge (STScI)

- Many thanks to the STScI Director’s Discretionary Fund and the NSF Center for Adaptive Optics
The Talk

- Talk will be broken down into five main areas…
  - Motivation (Why Coronagraphy?)
  - What is a Coronagraph?
    - One-dimensional Lyot Coronagraph (foundations, simple theory)
  - Ground and Space-based Coronagraphy
    - Seeing-limited coronagraphy
    - Diffraction-limited coronagraphy
    - Coronagraphy with HST instrumentation
  - Theoretical and Practical Considerations
  - Future Directions
    - NGST coronagraphs (NIRCam, MIRI)
    - Discovery-class missions (Jovian Planet Finder, Eclipse)
    - Terrestrial Planet Finder
  - Alternatives to Coronagraphy
Motivation

- New technologies have enabled astronomers to image the environments of nearby stars on scales close to that of our solar system.
  - Hubble Space Telescope
  - Adaptive Optics (AO) systems on ground-based telescopes

- New classes of astrophysically interesting targets have been discovered, including brown dwarfs, super-Jupiter mass planets, and circumstellar debris disks.
  - Discoveries have pushed our understanding of star formation in general and of the formation and evolution of planetary systems like our own.
Motivation

- The principal difficulty in imaging faint companions and circumstellar material is the contrast required to do so.
  - work by Nakajima and Oppenheimer on coronagraphic imaging brown dwarfs, super-Jupiters, etc.
  - work by Schneider et al., Krist et al., and Kalas et al. on coronagraphic imaging circumstellar disks

- AO and coronagraphy are two key technologies which will enable the high dynamic range imaging required to effectively study close circumstellar environments in solar neighborhood.
  - AO increases angular resolution and contrast
  - Diffraction-limited coronagraph rejects 95-98% light from on-axis source, increasing dynamic range
Motivation – Why Coronagraphy?

• Lots to learn about IMF, frequency of brown dwarfs, circumstellar disks, possible pre-planetary systems.
  – insight into formation of planetary systems like our own.

• More generally, technique of AO coronagraphy also applicable to studies of AGNs and host galaxies of quasars.

• AO Coronagraphs already being considered for systems at Gemini, Keck, CELT, GSMT.
What is a coronagraph?

- Create image of ‘on-axis’ source + faint object(s) (im)
- Work on image plane (remove some on-axis light)
  - Lyot: block out object with opaque mask (im)
  - Phase mask: apply phase shift to selected areas (im)
  - Interfero-coronagraph: phase shift light and recombine
- Re-image to second ‘Lyot’ pupil plane (im) (im)
- Work on Lyot plane (remove more on-axis light) (im)
- Re-emerge to final image plane (im)
- Reduce data to find faint object/structure
What is a Coronagraph?

- From Webster’s New World Dictionary (Third College Edition)…
  - coronagraph (ke r_ ' ne graf’) *n. [[earlier coronograph < CORON(A) + -o- + -GRAPH]]
    - a telescope designed for observing the corona of the sun by means of devices that obstruct the light from the sun’s disk.

- From the Columbia Electronic Encyclopedia
  - coronagraph: a device invented by the French astronomer B. Lyot (1931) for the purpose of observing the corona of the sun and solar prominences occurring in the chromosphere. Because of the intense light of the sun, the corona and chromosphere can ordinarily be seen only during a total solar eclipse. The coronagraph consists of two refracting telescopes in tandem. A solid disk placed in front of the prime focus of the first telescope plays the part of the moon and eclipses the sun’s image in the telescope so only the outer layers of the sun’s atmosphere are focused by the second telescope.
The Solar Coronagraph

Bernhard Lyot (1897 - 1952)

- Devised instrument to block solar disk in order to study solar corona at times other than during solar eclipse.
  - secured first photograph of solar corona ever taken outside of solar eclipse on 12 July 1931 at Observatoire du Pic-du Midi
  - coronagraph allowed first cinematographic movie of solar prominences
  - allowed extensive spectroscopic studies of faint coronal lines
The Solar Coronagraph

- Lyot’s coronagraph design had two main components
  - occulting disk (image-plane stop) in focal plane of first ‘telescope’
  - occulting ‘Lyot Stop’ in pupil plane of second ‘telescope’
The One-Dimensional Coronagraph


October 22, 02
Russell B. Makidon
Common to think of optical elements in coronagraphic system in terms of resolution elements \(_/D\), where \(_\) is the wavelength of observation and \(D\) is the telescope diameter.

Image plane stop many, many \(_/D\) across…
- solar disk is of order 30’, which is \(~16,000 \_/D\) for \(D = 1\) m with \(_ = 550\) nm.
The Solar Coronagraph

- Large Angle and Spectrometric COronagraph (LASCO)
  - One of 11 instruments included on the joint NASA/ESA Solar and Heliospheric Observatory (SOHO)

- LASCO uses a set of three coronagraphs to image the solar corona from 1.1 to 32 solar radii
  - C2 Coronagraph image
  - White circle defines solar disk
  - Occulting disk at 2 $R_{\text{sun}}$; field stop limits field-of-view to 6 $R_{\text{sun}}$
Stellar coronagraphy remained a relatively obscure technique until observations by B. A. Smith and R. J. Terrile (1984) of _Pictoris…

— “…a rather inconspicuous star in an equally obscure constellation”

Science vol. 226, Dec. 21, 1984, p. 1421-1424

— observations from Las Campanas Observatory, Chile 15-18 April 1984 using the du Pont 2.5 m telescope, a CCD camera, and a coronagraph with a 7 arcsec circular mask.

— I-band observations

— excess infrared emission detected with the Infrared Astronomy Satellite (IRAS) led the IRAS team to conclude _Pictoris “was surrounded by a cloud of cold, solid material, possibly in the form of a circumstellar disk.”
The Stellar Coronagraph

- _Pictoris at 0.5 microns
  - observed 12 Oct 1993 from Mauna Kea with University of Hawai’i 2.2 m telescope
  - Coronagraphic image-plane stop 6.5” diameter (~63 _/D)
  - observing dust reflecting light from central source

- _Pictoris
  SpType = A5V     V = 3.86 mag,
  d = 19.3 pc     T_{eff} = 8200 K
  M = 1.75 M_{sun} Age: 10 - 100 Myr

AO PSFs with increasing numbers of actuators, normalized to unity at image center (azimuthally averaged, unobstructed aperture, no coronagraph)

As the image gets better the Airy rings emerge as the halo ‘tide’ recedes

A Lyot coronagraph planes off these emerging rings…
The Stellar Coronagraph with Adaptive Optics

- _Pictoris at 1.2 microns
  - observed 05 Jan 1996 with ESO 3.6 m telescope at La Silla with the ADONIS Adaptive Optics system
  - Coronagraphic stop of 0.8” diameter in K-band (~3.25 /D)

- Confirmation of inner-disk warping as seen from HST.
  - Warping once thought to be evidence of a planet in inclined orbit around _Pictoris.

The Stellar Coronagraph
The Stellar Coronagraph with Adaptive Optics

- _Pictoris at 1.2 microns
  - observed 05 Jan 1996 with ESO 3.6 m telescope at La Silla with the ADONIS Adaptive Optics system
  - Coronagraphic stop of 0.8” diameter in K-band (~1.76 /D)

- Confirmation of inner-disk warping as seen from HST.
  - Warping once thought to be evidence of a planet in inclined orbit around _Pictoris.

Adaptive Optics Coronagraphy

- **JHU Adaptive Optics Coronagraph (AOC)**
  - Stellar coronagraph with image stabilizer (tip-tilt correction)
  - Used successfully on 2.54 m Du Pont telescope at Las Campanas Observatory to image Pictoris and on Palomar 60”
  - Image plane stop of 1.3” for faint targets
  - Reduced dynamic range demanded of CCD

- **Gliese 229B discovered with AOC on Palomar 60”**
  - Nakajima et al. (1994) – first detection of a cool brown dwarf companion
    - $7.78 \pm 0.01”$ from $M_V = 9.3$ star
    - Gl 229 ($M_J = 5.43$)
    - Gl 229B: $J = 14.32, _J = 8.89$
Adaptive Optics Coronagraphy and HST Imaging: GL229B

Brown Dwarf Gliese 229B

Palomar Observatory
Discovery Image
October 27, 1994

Hubble Space Telescope
Wide Field Planetary Camera 2
November 17, 1995

PRC95-48 - ST ScI OPO - November 29, 1995
T. Nakajima and S. Kulkarni (CalTech), S. Durrance and D. Golimowski (JHU), NASA
Adaptive Optics Coronagraphy

- Nakajima et al. (1994) discovery of GL 229B only positive brown dwarf detection out of 24 target stars.

- Oppenheimer et al. (2001)
  - Coronagraphic survey for companions to stars within 8 parsecs
  - optical imaging through Gunn r and z filters; near-infrared imaging in J and K filters
  - sample of 163 stars, including 2 brown dwarfs (GL 229B and 2MASS-discovered T-dwarf companion to GL 570ABC system (Burgasser et al. 2000)
  - no new detections between 3” and 30” from target stars
The End of Ground-based Stellar Coronagraphy?

- Not quite…

- The discovery of radial-velocity companions to nearby stars has prompted a renaissance in thinking about ground-based coronagraphy.
The End of Ground-based Stellar Coronagraphy?

51 Pegasi

Mass = 0.45 $M_{\text{Jup}}$ /$\sin i$

$P = 4.230$ day,

$K = 55.4$ m s$^{-1}$,

$e = 0.00$

RMS = 4.49 m s$^{-1}$

Orbital Phase
Diffraction-limited Adaptive Optics Coronagraphy

• PalAO: Dekany et al. (1997)
  – 241 actuator AO on monolithic Hale 5m primary
  – Range of image plane stops
  – Dynamic range within AO control radius up

• Oppenheimer et al. (2000)
  – Observational investigation of available dynamic range
  – using JHK camera PHARO (Hayward et al. 2002) on PalAO

• Sivaramakrishnan et al. (2001) theory
  – Interaction of coronagraph w/AO system
  – Optimization of image and Lyot stop combinations
  – Interaction of coronagraph with telescope pupil geometry
Coronagraphy at the AEOS Facility

- Air Force Electro-Optical System (AEOS) 3.6m telescope on Mt Haleakela, Maui, Hawai‘I

- Good Seeing
- 941 actuator AO, $\Delta = 1.5''$
- 0.9 m Strehl > 0.2
- implies 1.6 m Strehl > 0.6
  - and can be improved: ~.9
  - Prototypical ExAO system
- Suited to H-band coronagraphy
Coronagraphy at the AEOS Facility

Final optical design for AEOS Coronagraph

October 22, 02
Russell B. Makidon
Coronagraphy at the AEOS Facility

- Mass v. separation parameter space for currently known faint companions to nearby stars.

- A coronagraphic search with AEOS of 300 nearby stars (within 20 pc) should probe shaded region.

Work by B. R. Oppenheimer

October 22, 02
Russell B. Makidon
Other ground-based coronagraph projects…

- Coronagraphic instrumentation is available on Keck
  - relatively low-order AO system
  - segmented mirrors a bit of a problem…

- Currently, there are plans for coronagraphs on VLT, CELT/GSMT, Gemini telescopes.
  - All coupled with high-order AO systems (~3000 actuators)
  - Coronagraphs for existing 8 m class telescopes planned by 2007 or so.
  - Monolithic primary mirrors would mitigate scattered light problem faced by Keck…

- Larger telescopes can go very deep because of very small Airy disk and large collecting area, despite high background. AO advantage is a steep function of D once Strehl ratios become respectable.
When Does a Coronagraph Help on an AO System?

- Actuator spacing ‘a’ on primary diameter D: N = D/a
  - spatial Nyquist frequency 1/2a = N/2D from actuator spacing
  - AO control radius is $\_\text{Ao} = \_/2a = N_/2D$
  - image quality improved only out to $\_\text{Ao}$
  - Coronagraphic stop radius = s_/2D

- AO benefit realized only if  s < N/2
  - Keck, Palomar: N~16, so 8_/D or smaller stops help

- For s < 3 or 4 Lyot coronagraphs don’t help much…
  - Lyot throughput goes down too much
Beating Atmospheric Speckle Noise

- Dual-channel polarization (Potter, Kuhn year)
  - broad band, polarized (e.g. reflected light) objects
- Speckle sweeping (Bloemhof et al. 2001)
  - speckles pinned to bright Airy rings: no speckles in dark rings
  - speckle amplitude modulated by square root of Airy pattern (pinning)
- Speckle symmetries (Sivaramakrishnan et al. 2002)
  - first-order pinned speckles antisymmetric about image center
  - unpinned 2nd order speckle halo limits dark ring dynamic range
  - pinned 2nd order term (reduces to Marechal approximation at center)
- Dual star PSF subtraction (Lloyd et al. 2002)
  - Observe binaries closer than isoplanatic patch
- Multiband simultaneous observing (Marois et al. 2000)
  - In-band, out-of-band imaging for self-luminous objects w/spectral features (e.g. methane)
Stellar Coronagraphy from Space

• Currently, there are three stellar coronagraphs on a space-based platform…
  – ACS
  – NICMOS
  – STIS
Stellar Coronagraphy from Space: HST’s Advanced Camera

- Advanced Camera for Surveys (ACS) provides a selectable coronagraphic mode in the High Resolution Channel (HRC)
  - HRC FOV of 26” x 29” with plate scale 0.027 arcsec/pixel
  - Aberrated Beam Coronagraph functions on spherically-aberrated wavefront from HST primary
  - Two occulting spots: 1.8” and 3.0” diameter, blocking 88% and 95% of aberrated PSF respectively
    - hard-edged (non-apodized) masks deposited on anti-reflection coated substrate
    - occulting spots located in plane of the circle of least confusion
  - In addition, 0.8” wide finger always in place in direct imaging or coronagraphic modes
    - designed to block the central portion of 3.0” spot, but slightly mis-aligned due to launch and gravity release
Stellar Coronagraphy from Space: HST’s Advanced Camera
Stellar Coronagraphy from Space: HST’s Advanced Camera

- Pre-launch image of ACS coronagraphic spots
- Noticeable evolution of spot positions since gravity release and installation of ACS
Stellar Coronagraphy from Space: HST’s Advanced Camera

• Complete system (image-plane stop, Lyot stop)
• Multi-band (_ = 0.20 to 1.00 _m)
• Highest contrast coronagraphic imager beyond 1.2” from central source.

• Problem:
  – Because the PSF is broadened by spherical aberration and defocus at the occulting spot, significant vignetting occurs for sources up to 0.5” outside the spot.
  – Large spots required for coronagraphy in aberrated beam
  – Need to use techniques like “roll deconvolution” to deconvolve residual PSF from imaging.
Stellar Coronagraphy from Space: HST’s NICMOS

- Coronagraphic hole with 0.3” radius available in NICMOS Camera 2
  - physical hole bored through Camera 2 FDA mirror, which when combined with a cold mask at the pupil (Lyot stop) provides coronagraphic imaging capability
  - edge of coronagraphic hole acts as new diffracting aperture, with roughness from machining creating complex image
  - asymmetries in OTA and coronagraphic optics produce residual “speckles” in coronagraphic image
    - residual speckles limits useful coronagraphic radius of detector to 0.4”
    - rolling telescope and PSF deconvolution still required
  - Per-pixel background light rejection of 2 x 10-4 with coronagraphic imaging; rejection approaches 10-6 with coronagraphic imaging and PSF subtraction (from differentially rolled images)
Stellar Coronagraphy from Space: HST’s NICMOS

NICMOS coronagraphic images of HR 4796A

October 22, 02
Russell B. Makidon
Stellar Coronagraphy from Space: HST’s NICMOS

NICMOS coronagraphic images of HD 141569 and HR 4796A

Dust Disks around Stars
PRC99-03 • STScI OPO • January 8, 1999
B. Smith (University of Hawaii), G. Schneider (University of Arizona),
E. Becklin and A. Weinberger (UCLA) and NASA
Space Coronagraphy: HST’s STIS

• STIS has a single coronagraphic mask for imaging with CCD consisting of an occulting bar and two intersecting wedges
  – wedges vary in width from 0.6” to 3.0” across their length (50”)
  – occulting bar measures 10” x 3”

• STIS coronagraphic aperture cannot be combined with a filter, so when used with the STIS CCD the effective bandpass of coronagraph is from \(~2000\) to \(10,300\).
Stellar Coronagraphy from Space: HST’s STIS

- STIS mask has 2x throughput of ACS+F606W
- Smaller occulting stops, but incomplete Lyot stop only reduces diffraction wings by a factor of 2 to 3.
HST Coronagraphic Images of HD 141569

NICMOS (1.1\textmu m)  STIS  ACS (F606W)
Stellar Coronagraphy from Space

• Many advantages to stellar coronagraphy from space-based platforms
  – Highly corrected, smooth optics, stable PSFs (not on segmented mirrors!)
  – High Strehls in optical
  – Smaller D for same resolution as ground-based IR

• Enables reflected light imaging searches for older Jovian and terrestrial planets

• Caveat
  – More expensive, longer lead times
  – Difficult to adapt to changing situations quickly
Stellar Coronagraphy from Space

• Multiple space-based coronagraphs proposed for the next decade

• NGST’s Near-Infrared Camera (NIRCam, PI: M. Rieke) and Mid-Infrared Imager (MIRI, PI: G. Rieke) are currently planned to have coronagraphic capabilities.

• MIDEX-class and Discovery-class coronagraphic missions
  – Jovian Planet Finder (PI: Mark Clampin)
  – Eclipse (PI: John Trauger)

• Visible-light coronagraphic designs being considered for Terrestrial Planet Finder (TPF)
  – requires mirror 3 to 4 times larger than HST with at least 10 times more precision
What is Best for Coronagraphy?

- Small \( _/D \): small \( _/ \) (space-based) or large \( D \) (ground-based)
- Unobstructed aperture
  - control waffle modes at \( _/2D \) (ground), good WFR
  - apply fast (ground) or slow (space) speckle theory
  - remove secondary diffraction: off-axis, small FOV (~10")
- High Strehl, low scatter
  - good AO or active/static correction
  - few, smooth optics
  - possibly apodization (space only?) if fabrication well-controlled
- PSF stability, speckle reduction
  - fast or slow speckle theory applicable
  - moderate to narrow band filters available
  - dual or multiple channel
- Multiple coronagraph instruments
  - Lyot. phase-mask, interfero-coronagraphs
Alternatives to Coronagraphy: Shaped apertures

• Kuhn et al. (2001)
  – choice of secondary diameter to reduce secondary Airy pattern at selected
dark rings in primary Airy pattern (ground)

• Nissenson, P. and Papaliolios, C. (2001)
  – square aperture, image intensity concentrated along axes, falls as $(xy)^2$ in
image plane, fast on diagonals

  – ‘double-gaussian’ flying-saucer shape, patent applied for. No verticals in
pupil edge mean no scatter in horizontal direction in image plane. Lyot
 coronagraph used to augment on-axis image suppression (space)
Alternatives to Coronagraphy: Apodized apertures

• Fourier fact: the transform of a function that possesses an \( n^{th} \) derivative falls off as \( (1/k)^{n+1} \)
  
  Test:
  
  \[
P(x) \text{ transforms to } \frac{\sin(px)}{px}
  \]
  
  \[
P(x)\ast P(x) \text{ transforms to } \frac{\sin^2(px)}{(px)^2}
  \]

  ‘Smoothest function in the universe’ is a Gaussian (\( C^\infty \))
  
  – If aperture is shaded with a Gaussian, one gets ‘fastest fall-off’ of image (Ftaclas et al. year)
  
  – Caveat: No dark rings to exploit in core

• Nisenson et al. apodize square aperture to increase broad-band dynamic range gain at very high Strehl ratios
Alternatives to Coronagraphy: Apodized Image Plane Stops

- Gaussian or other shaded occulting stop in image plane (e.g. Krist et al.) reduces sensitivity to guiding error

  - use a mask in image plane w/profile of \[\sin^2\left(\frac{q}{D}\right)\] bars in y direction, modulated in x direction. This stop is infinite in extent in the image plane, and its transform is band-limited* in the Lyot plane. Therefore all on-axis light from the perfect wavefront is confined to selected areas in the Lyot plane, thereby providing almost infinite on-axis suppression of light. Other periodic image plane shadings are explored as well.

* A function \(f(k)\) is band-limited if there is some positive number \(\bar{k}\) such that \(f(k) = 0\) for all \(|k| > \bar{k}\)
Alternatives to Coronagraphy: Phase Mask Coronagraph

  - reverse the sign on half the image plane field with a phase shift
  - perfect image through circular aperture: phase shift over the central ~46% of the central peak.
  - tailor radius for different aperture geometries
  - needs wavelength-dependent plate scale for broad-band imaging
Alternatives to Coronagraphy: Four-Quadrant Phase Mask Coronagraph

- Rouan et al. (2001), Riaud et al. (2001), Bocaletti et al. (2002)
  - reverse the sign on half the field by dividing it into quadrants (on square geometry pupils), and using a phase shift on alternate quadrants
  - best on unobstructed apertures: very high monochromatic suppression
  - requires good image motion control (guiding)
  - clean phase mask fab difficult
  - broad-band mask fab in progress

- Lloyd et al. (2002)
  - 100% suppression for perfect wavefront in circular aperture on the optical axis
  - sensitive to integral of gradient of phase over aperture
  - numerical simulations have trouble converging using simple approach of uniform pupil sampling and FFTs: semianalytical methods required?
  - specialized pupil geometry to accommodate secondary obscuration while maintaining high dynamic range
High-Dynamic Range Coronagraphy

- Only the beginning…