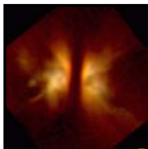
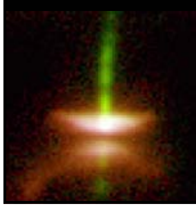
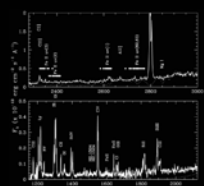


Star Formation Legacy of the Hubble Space Telescope

Deborah L. Padgett

Spitzer Science Center

California Institute of Technology


Outline of Talk

- HST Capabilities and Status
- Major Contributions to Star Formation
  - Structure and population of massive star formation regions
  - Outflows and Accretion
  - Circumstellar Material
- The Future of HST
- Note – due to limited time, no extragalactic star formation; emphasis on low mass sources

Hubble Space Telescope Current Capabilities

- 2.4 meter telescope in low Earth orbit
- < 0.1" resolution at shortest wavelengths
- 1150 Å – 2.2 microns imaging (degraded UV imaging with old WFPC2 CCDs + small ACS MAMA array)
- Low res. spectroscopy in near-IR (NICMOS grisms) & UV (ACS SBC); none in optical due to STIS failure
- High dynamic range - Very stable PSF; can subtract modeled or empirical PSF to gain large factor in wings of PSF; ACS/NICMOS coronagraphs gain an additional factor of a few
- 2 gyro mode coming very soon; minimal impact for most science

HST Studies of HII Regions

- ISM
  - Shock fronts and ionized structures
  - Illumination of molecular cloud structure
- Population studies
  - Binary studies
  - Surveys for substellar companions and lower IMF
- Just a sampling of the many important studies follows…

M16 – Erosion of Molecular Cloud by O Stars

- Hester et al. (1996)
- Supports idea that massive stars limit lifetimes of planet-forming environments

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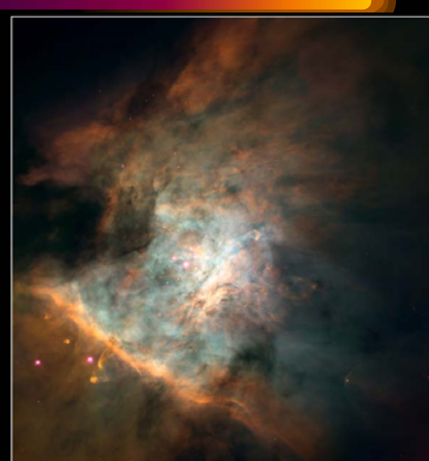
Orion Nebula

- Many studies: O'Dell et al. 1993 (etc.), Bally et al. 2000, etc
- Discovery of "Proplyds" = ionized rims at interface between circumstellar material and ionized ISM
- Enables 3D modelling of ionization fronts and cloud structure

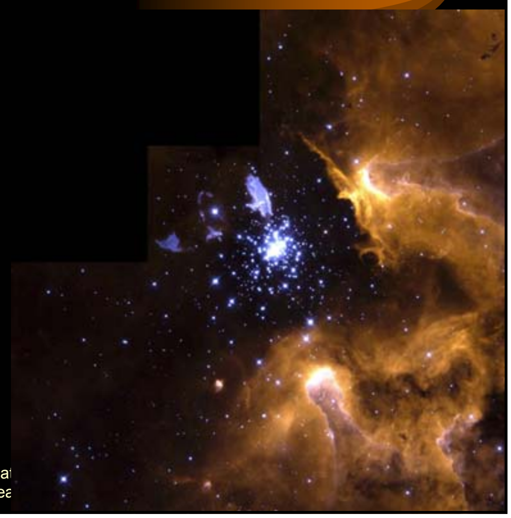


Orion Nebula Mosaic HST · WFPC2
PRC95-45a · ST ScI OPO · November 20, 1995
C. R. O'Dell and S. K. Wong (Rice University), NASA

July 13, 2005 Star Formation in t Three Great Obse

NGC 3603

- Brandner et al. (2000)
- "Proplyd"-like structures in extreme region near cluster of Wolf-Rayet stars

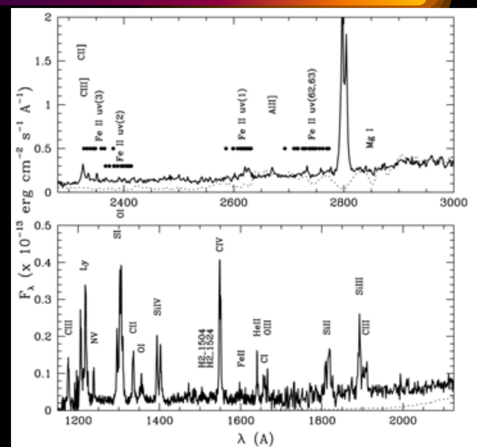


Population Studies

- Mass Accretion Rates – Orion (Robberto et al. 2004)
- Binary fraction – generally lower than Taurus numbers
  - Prosser et al. (1994) – Orion Trapezium
  - Padgett et al. (1997) – NGC 2024, 2068, optical
  - Liu et al. (2004) – NICMOS N2024
  - Spatially resolved SEDs – Smith et al. (2005), White & Ghez (2001)
- Substellar companions and low end of the IMF
  - Weak-line T Tauri stars (WTTS) – Brandner et al. (2000), Massorotti et al. (2005)
  - Brown dwarfs (BD) – Brandner et al. (2005), Luhman et al. (2000, 2005), etc.

Spatially Resolved and UV Spectroscopy of Young Stellar Objects

- Rotating jets - Coffey et al. (2004), Woitas et al. (2005), Bacciotti et al. (2002)
- Mass accretion rates from UV spectra – Calvet et al. (2004), etc.
- Resolved disk/envelope spectroscopy – Roberge et al. (2004), TW Hya; Grady et al. (2005), Hartigan et al. (2004), etc.
- Binary spectra – Hartigan et al. (2003), White et al. (1999)



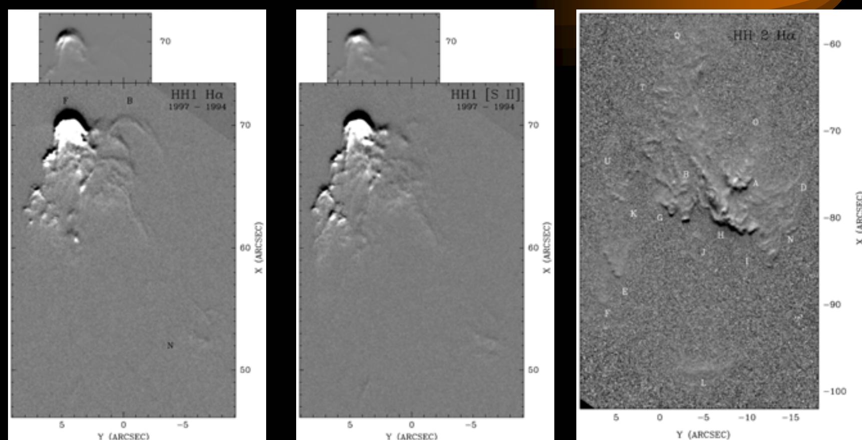
Calvet et al. (2004)

Herbig-Haro Object Imaging

- Proper Motion Studies – Bally et al. (2002), HH 1 – 2; Noriega-Crespo et al. (2002), HH 7 – 11; etc.
- Microjets - Bally et al. (2000, 2005); mostly Orion proplyds
- Externally illuminated jets – Andrews et al. (2004), Orion; Yusef-Zadeh et al. (2005), Trifid nebula
- Time evolution of new HH objects – Krist et al. (1998, 2005)

HH Proper Motions

(Bally et al. 2002



Krist et al. 2005

Evolution of XZ Tau Outflow

Animation of PSF-subtracted R band images :

1995: Filled bubble, bright knot inside

1998: Onset of limb-brightening; knot elongates and fades

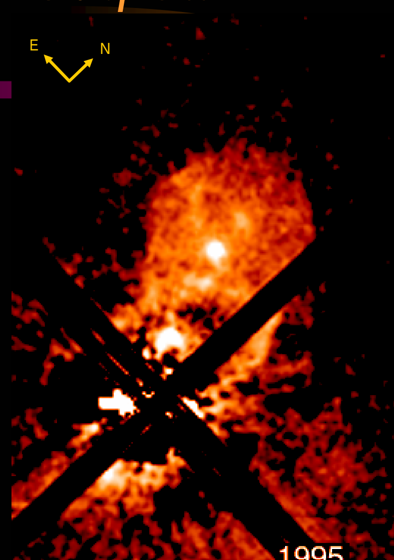
1999: Second bubble clearly apparent in the wake of the first

2000: Outer bubble begins to decelerate; cusp forms on its upper left edge

2001: Several internal knots appear just inside the outer bubble. 1.7 mag flare in XZ Tau N

2002: Cusp sharpens; XZ Tau N drops back to normal brightness

2004: Knot brightens near apex of outer bubble; bow-like knot detected in counterflow



Importance of High Resolution to Disk Studies

- Currently known disks are relatively distant
  - Handful at d < 20 pc (Fomalhaut, AU Mic, beta Pic)
  - other nearby stars TW Hya association (65 pc)
  - nearest star formation regions (100 - 150 pc)
- Disks are small; size of solar system (~50 AU) ~ 0.3 arcsec at the distance of Taurus star forming cloud
- Disk structures are very small (expected gaps might a few AU in extent)

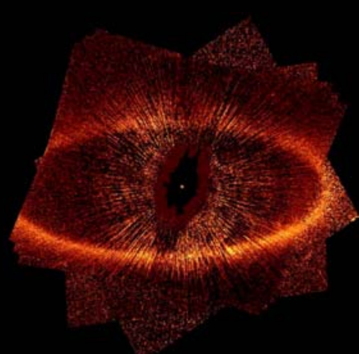
What is Learned from HST Disk Imaging?

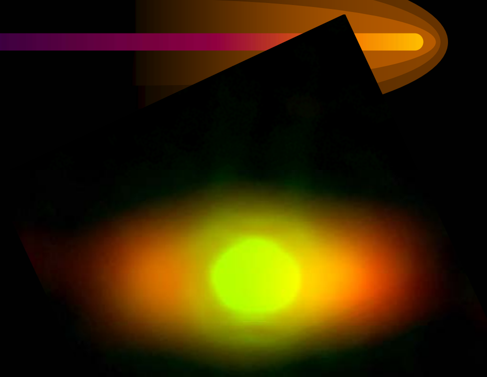
- Confirms basic disk morphology of dust distribution
  - position angle
  - major and minor axes (outer radius of disk)
- Measurable disk parameters
  - dust lane thickness (if close to edge-on)
  - Radial disk structure (gaps, rings)
  - Azimuthal disk structure (asymmetries)
- Derivable disk parameters
  - Inclination
  - Radial surface brightness (radial surface density for optically thin)
  - Vertical disk structure if edge-on (scale height, flaring)
  - Disk mass
  - Dust properties (*caveat emptor*) – $\kappa(\lambda)$, phase function
- Some of the derivable properties are degenerate

Varieties of Disk Images

- Optically thin debris disks of MS stars
- YSO Disks/envelopes with visible central star(s)
  - Mostly around Ae and T Tauri stars identified by IRAS
  - Relatively few imaged thus far; diffficult to detect with current techniques
- Externally illuminated YSO disks or “Proplyds”
- Edge-on YSO Disks (+ envelopes)
  - Optically thick disk becomes natural coronagraph
  - Found serendipitously for the most part; mostly too faint for IRAS

Fomalhaut

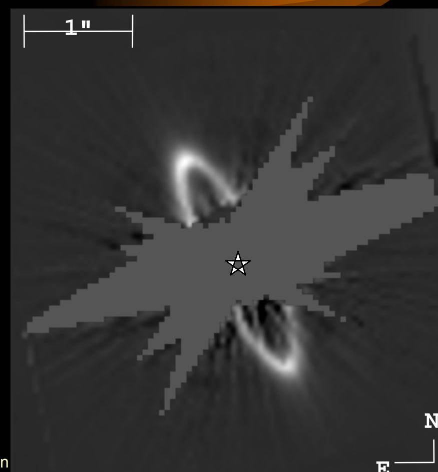




- HST/ACS
- Elliptical ring – shepherding?
- *Spitzer*/MIPS

HR 4796A HST Imaging

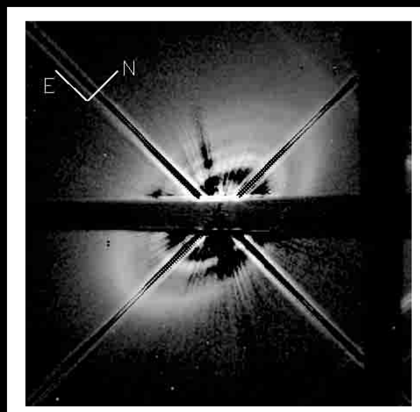
- Ae star in binary; 67 pc in TW Hya association
- Discovered by MIR imaging (Koerner et al. 1998; Jayawardhana et al. 1998)
- NICMOS imaging: Schneider et al. 1999
  - Ring that peaks at 70 AU; less than 17 AU in width; abrupt edges
  - Ring is redder than star; amount of scattered light accounts for IR excess seen by IRAS
- STIS imaging: asymmetric ansae (Schneider et al., in prep.)



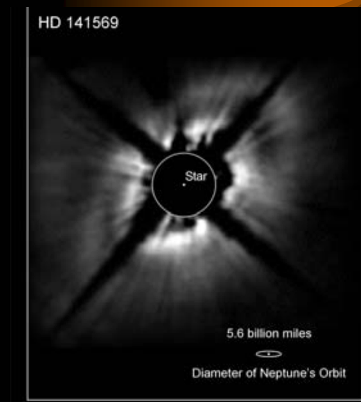
HD 141569 – AeBe Disk Structure

- 10^6-10^7 yr old Ae star at 99 pc; triple system with young M companions
- NICMOS observations: Weinberger et al. 1999, 2000; Augereau et al. 1999
  - 400 AU radius disk
  - "gap" at 250 AU
  - Radial structure due to unseen planet (1.3 M_{Jup}) or effects of companions
- STIS coronagraphy: Mouillet et al. 2001
  - Rings at 200 and 325 AU; arc at 250 AU
  - No material seen 125 – 175 AU
  - Argues asymmetries due to non-axisymmetric density distribution not grain forward scattering

Images of HD 141569



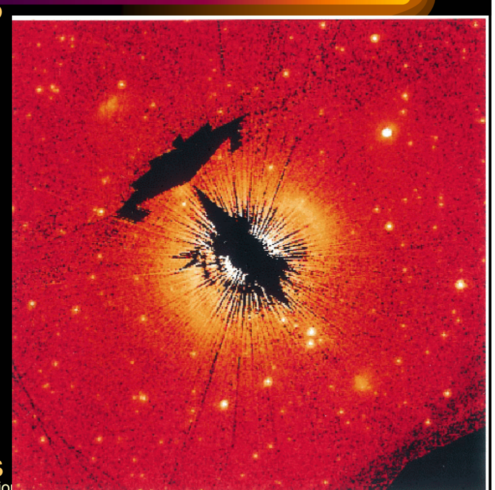
STIS (Mouillet et al. 2001)

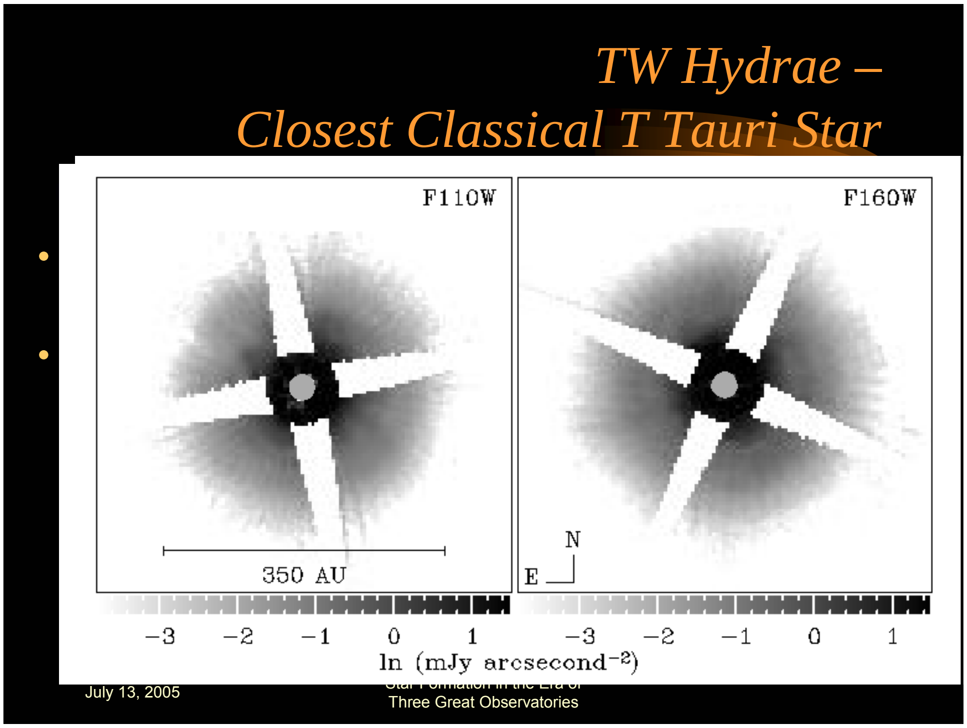


NICMOS (Weinberger et al. 1999)

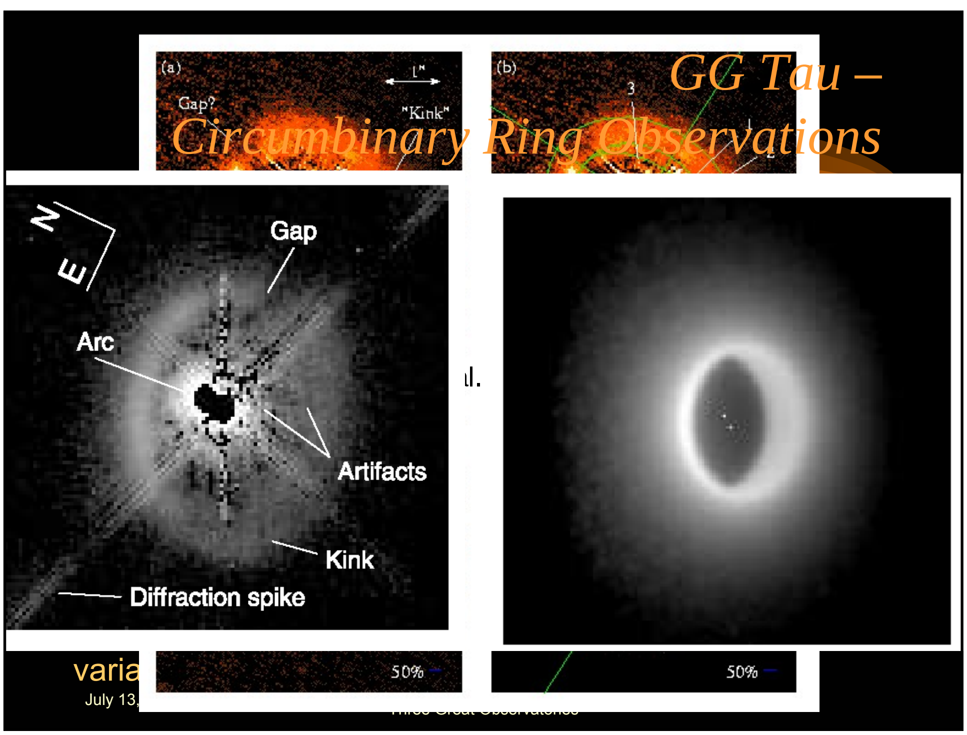
HD 163296

- Isolated Ae star at 122 pc; ~ 5 Myr; Mannings & Sargent 1997 CO disk
- Grady et al. 2000; STIS observations
  - 450 AU radius disk inclined by 60 degrees
  - Zone of reduced scattering 325 AU
  - Brightness flat from 120 – 180 AU; drops as $r^{-3.5}$ beyond 370 AU
  - Possible HH objects perpendicular to disk major axis
- Krist et al. - ACS observations of HD 163296





TW Hydrae –
Closest Classical T Tauri Star
F110W
F160W
350 AU
N
E
−3 −2 −1 0 1
−3 −2 −1 0 1
ln (mJy arcsecond^{-2})
July 13, 2005
Three Great Observatories



GG Tau –
Circumbinary Ring Observations
(a)
(b)
1"
Gap?
"Kink"
N
E
Gap
Arc
Artifacts
Kink
Diffraction spike
50%
50%

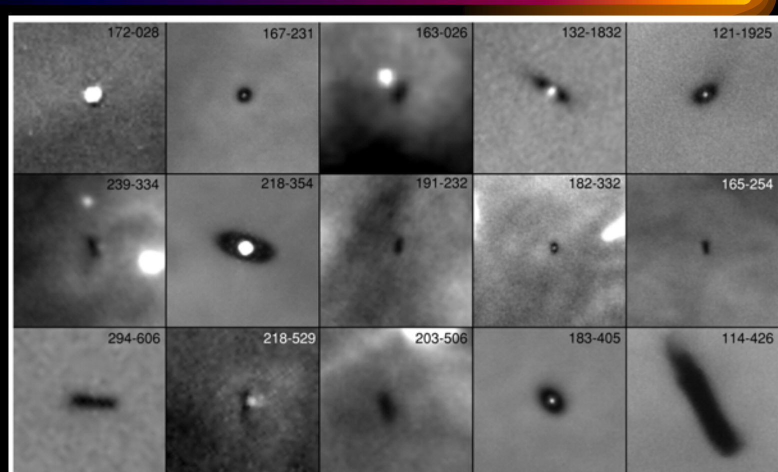
GM Aurigae – Brightest CTTS Disk?

- GM Aur is a mm bright TTS in Tau-Aur
- Stapelfeldt et al. 1997: 600 AU “disk nebula” detected by WFPC2
- Schneider et al. 2003: NICMOS coronagraphic imaging
  - 300 AU radius disk at inclination of 50º - 55º
  - Dark midplane revealed in silhouette; scale height 8 AU @ 100 AU
  - Self-consistent scattered-light and SED modeling
- Disk scatters 2% - 4% of starlight

NICMOS image
Schneider et al. 2003

Orion Proplyds and Silhouette Disks

(Bally et al. 2000)



114-426:

Proplyd?

bright emission line
light nebulae

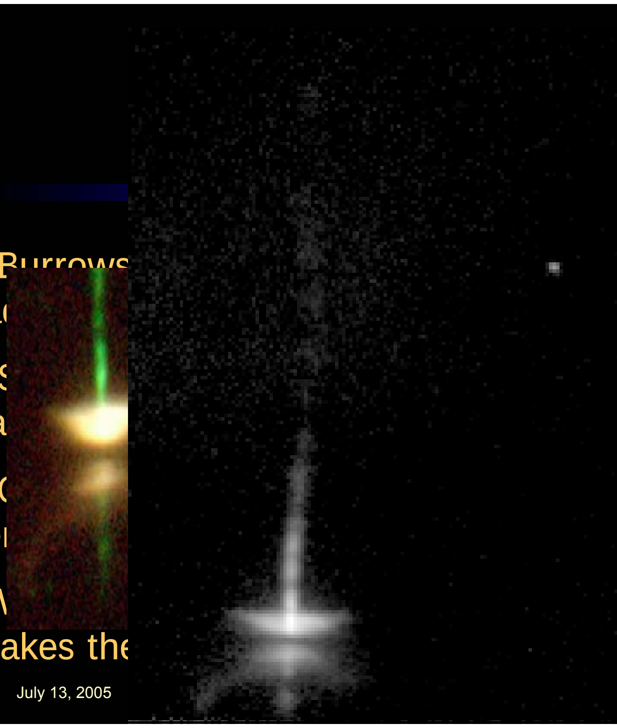
; silhouette radius

s not change in size
arger than ISM size;

houette radius
ger than 2 – 3 µm

HH 30

ervations



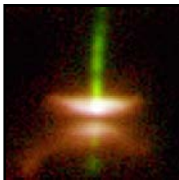
• Burrows ... f 225 AU
ra ... et

• S ... s showing
va ... ae

• (... maging; star
re

• \ ... 0? What
makes the

July 13, 2005



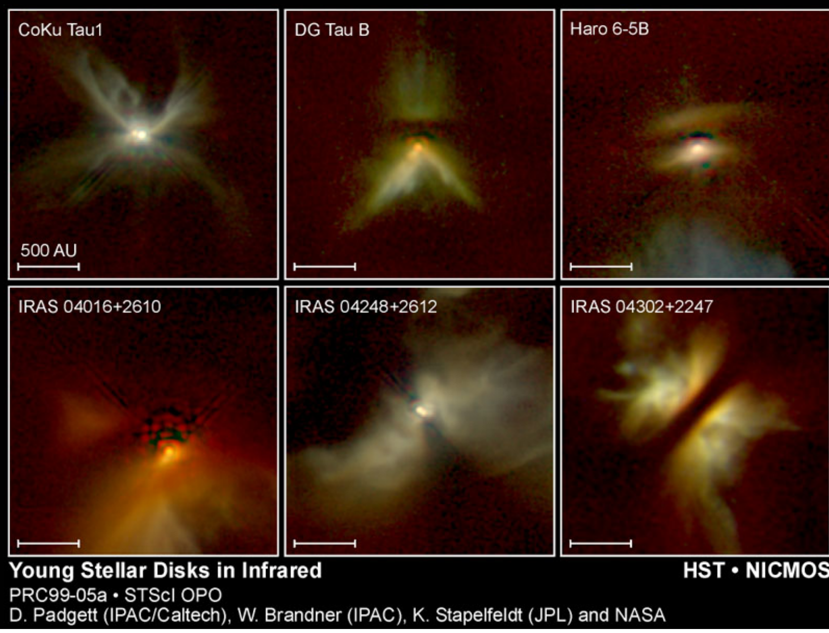
HH 30 Modeling

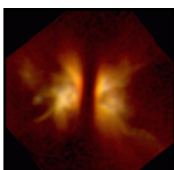
- Burrows et al. 1996: scattered-light modeling; parameterized disk with vertical structure; dust lane thickness varies as product of opacity and disk mass
- Wood et al. 1998, 2002: radiative transfer modeling of disk + envelope; SED modeling constrains inner disk radius and flaring
- Cotera et al. 2001: multiwavelength modeling indicates opacity law must be shallower than ISM; thus grains bigger than ISM
- Watson & Stapelfeldt, submitted: range of allowable density models leads to range in derived opacity ratios; factor of 3 uncertainty but larger than ISM grain conclusion holds
- Asymmetry as variable circumstellar extinction (Stapelfeldt et al. 1999) and accretion hot spot (Wood & Whitney 1999)

HV Tauri C

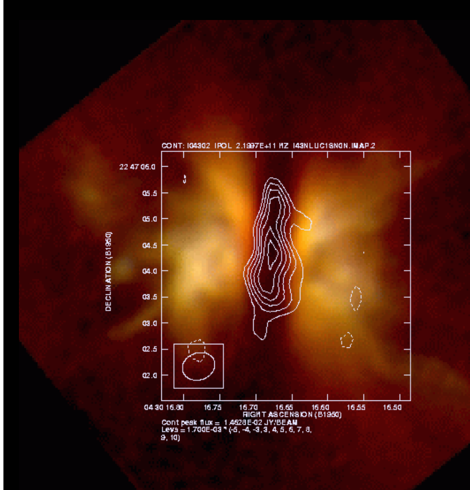
- Nearly edge-on disk discovered in triple system by CFHT AO (Monin & Bouvier 2000)
- Primary is <0.1 arcsec binary
- Stapelfeldt et al. 2003: WFPC2 imaging; 50 AU disk with scale height of 6.5 AU at 50 AU; scattered light modeled with disk + thin envelope

The NICMOS "Spectacular Six"





IRAS 04302+2247- "The Butterfly Star in Taurus"



- 900 AU diameter edge-on system first imaged by UKIRT (Lucas & Roche 1997) and modeled as envelope
- Padgett et al. 1999: HST/NICMOS imaging revealed edge-on disk in absorption against the envelope
- OVRO millimeter interferometry shows resolved disk continuum and rotating CO disk (Padgett et al. 2001)
- Multiwavelength modelling (NIR – mm) shows envelope grains smaller than disk grains (Wolf et al. 2004)

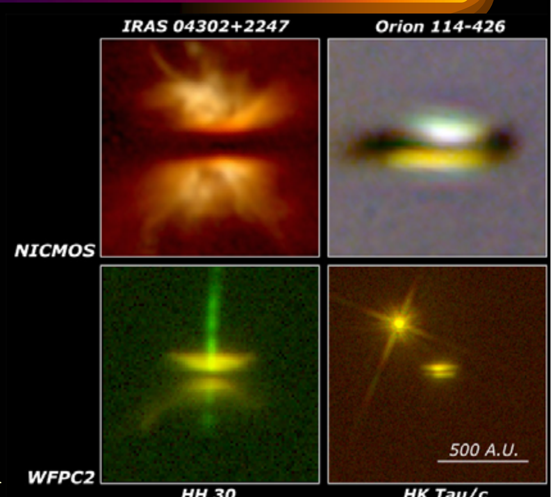
ion in the Era of
t Observatories

Summary of T Tauri Star Survey Results

- Survey of 153 Classical T Tauri stars and 26 Class I YSOs with WFPC2 by Stapelfeldt et al. (2005)
- 16/26 (61%) of optically visible Class I sources show strong nebulosity
  - 10 are nebulous PSFs
  - 6 are fully nebulous (embedded or edge-on)
  - 1 is interacting galaxy pair
- 30% of 153 optically selected classical T Tauri stars are nebulous; < 10% have disklike nebulae
- Other studies – Reipurth et al. (2000), HH exciting stars

Summary of HST Disk Observations

- HST validated the flared disk model of T Tauri star disks with the single image of HH 30
- The diversity of disks is impressive; all these are shown at the same scale
- Morphology and internal structure of disks and rings gives clues about unseen companions
- *Spitzer* is identifying many new nearby targets for high resolution imaging



The Future of HST

- HST needs servicing to last more than 1 – 2 more years; failing gyros, STIS failure, new instruments ready
- The SM4 servicing mission was cancelled by O'Keefe due to safety concerns over Shuttle visit; money spent on robotic servicing options
- Review by National Academy of Science determined that Shuttle servicing only viable option for visiting HST in time; no significant increase in risk for Shuttle
- O'Keefe encouraged complete cancellation of servicing mission, then resigned Dec. '04; no funding in '06 budget
- New administrator Griffin encouraging about Shuttle servicing, possibly at the price of delaying future astronomy missions; would need to be 2006 or early 2007
- HST servicing depends on safe and successful Shuttle flight this week and in September – **Go *Discovery*!**

Cosmic Origins Spectrograph

- High throughput UV/Optical spectrograph
- Restores ultra high spatial resolution spectroscopy capability in UV
- R = 20,000 for λ = 1150 – 3200 Å
- Science goals for star formation
  - Line of sight abundances toward embedded sources
  - UV line and continuum observations of very faint young stellar objects

Wide Field Camera 3

- UV/Optical/NIR imaging (2000 Å – 1.7 μm)
- Restores HST's degraded near-UV imaging
- 62 filters (including many missing from ACS and NICMOS complement); [S II] separate lines
- FOV 2.7 x 2.7 arcmin optical; 2.2 x 2.2 arcmin NIR
- Improves surface brightness detection 4 – 12x over WFPC2 in narrow bands
- Science goals for star formation:
  - High resolution emission line mapping of H II regions
  - Study of the physical structure of photoionized regions, shock waves, and collimated flows.

July 13, 2005 Star Formation in the Era of Three Great Observatories

A Few (Galactic) Star Formation Projects in HST Cycles 13 and 14

- NICMOS YSO and Debris disk coronagraphic survey (Schneider)
- YSO polarimetry in optical & near-IR (Cotera)
- ACS imaging of Orion Nebula (Robberto)
- 0.6-2.2 μm imaging of edge-on disks (Padgett)
- ACS/NICMOS imaging of new Spitzer disks (Stapelfeldt, Hines)

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Speculation on Future Large HST Star Formation Projects

- Imaging of new YSO candidates identified by Spitzer (as with previous IRAS sources); morphology critical for exogal identification
- Chandra follow-on: are faint new sources young stars or AGN?
- Taurus Spitzer/XMM/CFHT surveys as an example
- What incompletely covered star-forming regions could be mapped by HST in a reasonable time?