One momento from Amherst ...

Anna Stapelfeldt, 16 yrs old as of this week!
Young stars among the Strom alumni ...
Best wishes from Russ

Pasadena, 4/2/08
Disks in Hubble Vision: From Zero to Hero

Karl Stapelfeldt (JPL)
Deborah Padgett (SSC), John Krist (JPL),
Francois Menard (Grenoble),
Wolfgang Brandner (Heidelberg)

Apr. 04 2008  Stromfest 2008
“The Formation and Evolution of Solar Nebulae Surrounding Pre-main Sequence Stars”

Steve and an all-star cast, circa 1990

This proposal requests time to bring the power of HST to bear on the problems of solar nebula formation and evolution. During Cycle 1, we plan to use the Planetary Camera to image the circumstellar environment of 3 nearby pre-main sequence stars in order to search for evidence of disks via light scattered earthward by dust embedded in circumstellar disks and investigate the morphology of energetic winds driven by these stars. Our longer term goals (Cycle 2 and beyond) are to image a much larger sample of pre-main sequence stars in order to: determine the frequency with which disks form around single and multiple stars; characterize the morphology of circumstellar disks for a sample of pre-main sequence stars spanning the time soon after stellar birth, to the epoch when disks become optically thin, perhaps following planet building episodes; understand the degree of interaction between winds and circumstellar disks, estimate more accurate mass loss rates for PMS stars, and to assess thereby the effect of PMS star winds on the evolution of disks and the planet-forming environment.
The repaired HST became the major engine for disk scattered light imaging.
The Cycle 1 Targets as viewed by WFPC2

DR Tau  CW Tau  DF Tau

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Famous YSOs with WFPC2

HL Tau | T Tau | GG Tau

HK Tau B | TW Hya | HV Tau C

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and with NICMOS

CoKu Tau1

DG Tau B

Haro 6-5B

IRAS 04016+2610

IRAS 04248+2612

IRAS 04302+2247

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Model results for HK Tau/c

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
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<tbody>
<tr>
<td>Alpha</td>
<td>-0.82</td>
<td>-2.31</td>
<td>-1.41</td>
<td>-2.78</td>
<td>-1.16</td>
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<tr>
<td>Beta</td>
<td>1.12</td>
<td>1.34</td>
<td>1.10</td>
<td>1.32</td>
<td>[1.0]</td>
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<tr>
<td>$H_0$ (AU)</td>
<td>4.02</td>
<td>3.74</td>
<td>3.88</td>
<td>3.81</td>
<td>3.77</td>
</tr>
<tr>
<td>Inclination (deg)</td>
<td>5.7</td>
<td>6.2</td>
<td>5.4</td>
<td>6.0</td>
<td>4.8</td>
</tr>
<tr>
<td>Mass ($M_\odot$)</td>
<td>$6.1 \times 10^{-5}$</td>
<td>$8.8 \times 10^{-5}$</td>
<td>$5.9 \times 10^{-5}$</td>
<td>$1.2 \times 10^{-4}$</td>
<td>$5.6 \times 10^{-5}$</td>
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<tr>
<td>Extinction (mag)</td>
<td>12.4</td>
<td>17.9</td>
<td>[50]</td>
<td>[50]</td>
<td>[50]</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>10.2</td>
<td>10.2</td>
<td>10.6</td>
<td>10.5</td>
<td>11.2</td>
</tr>
</tbody>
</table>

Note.—Brackets indicate quantities held fixed during the fitting process.
Broader WFPC2 imaging survey

• Major objective: Characterize the circumstellar nebulosity of nearby YSOs
• Most sources imaged in R and I band
  – Herbig-Haro jets appear in R, but not I
• Dataset predates ACS: No coronagraph
• Deliberately saturate the target stars:
  – Target same exposure depth on each target
  – No useful information from r < 0.2"
• Focus on circumstellar region r < 5": Accurate PSF subtraction is essential
Selecting the target sample

(Only 10 reported on before this study)

• **Location in nearby clouds** $d < 200$ pc
  – Taurus, Chamaeleon, Lupus, Oph, CrA

• **Stars with nebulosity in prior imaging**

• **Disks resolved with mm interferometry**

• **Stars with millimeter continuum emission**

• **Stars with IRAS excess**

• **Stars with strong Hα emission**
  (accretion)

• **Stars with strong optical polarization**

• **Edge-on disk candidates**
Edge-on Disks 1.

V375 Lac
central 5"

V376 Cas
central 10"

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Edge-on Disks II.

IRAS 04264+2642
5” FOV

IRAS 04158+2805
10” FOV

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Disks against direct starlight I.

Bright star artifacts can make these disks difficult to analyze.

GM Aur
5” FOV

UY Aur binary
15” FOV

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Disks against direct starlight II.

GO Tau
420 AU diameter

DoAr 25
310 AU diameter

Sz 82
750 AU diameter

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ISM Interactions

DoAr 21
10" FOV

CoKu Tau/4
15" FOV

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Circumsecondary Envelopes?

VV CrA
5” FOV

S CrA
5” FOV

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Jets in R band

DL Tau
10” FOV

DP Tau
5” FOV

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Jets in the plane of the sky

CoKu Tau/1
10" FOV

Sz 102
10" FOV

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Cloudlets?

Sz 22
10” FOV

RNO 91
10” FOV

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Miscellaneous other objects …

Haro 6-10
IRAS 04264+2433
Apr. 04 2008

Haro 6-13
Reipurth 4

Haro 6-33
V1057 Cyg

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Nebulosity detected in 70 of the 184 targets (37%)

- 34 % of binary systems
- 50 % of edge-on candidates
- 36 % of strong Hα emitters
- 40 % of mm continuum sources
- 36 % of strongly polarized sources
- 86 % of HH jet sources
- 83 % of known nebulously sources
- 4 % of Weak-line T Tauri stars
**Large Undetected Disks**

17 of 30 mm-resolved disks have no scattered light in our survey

Outer radii from millimeterwave CO maps

<table>
<thead>
<tr>
<th>Star</th>
<th>Radius</th>
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<tbody>
<tr>
<td>DN Tau</td>
<td>3.5”</td>
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<tr>
<td>MWC 480</td>
<td>3.9”</td>
</tr>
<tr>
<td>UZ Tau E</td>
<td>2.1”</td>
</tr>
<tr>
<td>DL Tau</td>
<td>3.7”</td>
</tr>
<tr>
<td>DG Tau</td>
<td>2.8”</td>
</tr>
<tr>
<td>V1121 Oph</td>
<td>2.1”</td>
</tr>
<tr>
<td>CI Tau</td>
<td>1.5”</td>
</tr>
<tr>
<td>FT Tau</td>
<td>1.5”</td>
</tr>
<tr>
<td>CW Tau</td>
<td>1.6”</td>
</tr>
<tr>
<td>DR Tau</td>
<td>1.8”</td>
</tr>
<tr>
<td>BP Tau</td>
<td>0.8”</td>
</tr>
<tr>
<td>DM Tau</td>
<td>5.7”</td>
</tr>
<tr>
<td>AA Tau</td>
<td>2.2”</td>
</tr>
<tr>
<td>LkCa 15</td>
<td>4.6”</td>
</tr>
</tbody>
</table>

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**Stromfest 2008**
Twin disks: only one detected

Mystery!

<table>
<thead>
<tr>
<th>LkCa</th>
<th>GM</th>
</tr>
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<tbody>
<tr>
<td>15</td>
<td>Aur</td>
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<table>
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<tr>
<th>Inclin</th>
<th>52°</th>
<th>56°</th>
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</table>

<table>
<thead>
<tr>
<th>Router (AU)</th>
<th>650</th>
<th>525</th>
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<table>
<thead>
<tr>
<th>1.3 mm (mJy)</th>
<th>167</th>
<th>253</th>
</tr>
</thead>
</table>

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Observed WFPC2 detection limits

Grey band: noise floor measured from PSF subtractions
Green circle: limiting contrast of Δmag = 7 at 100 AU separation

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Modeling detectability vs. Inclination

Disk Detectability at 100 AU = 0.7 arcsec

Delta SB, mag per square arcsec

Disk Inclination, degrees from pole-on

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Modeling detectability vs. disk scale height

Disk detectability at 100 AU = 0.7 arcsec

Delta SB, mag per square arcsec

Scale height at 100 AU radius

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Modeling detectability vs. strength of disk flaring

Disk Detectability at 100 AU = 0.7 arcsec

Delta SB, mag per square arcsec

Scale height radial power law index $\beta$
Scattered light detectability vs. IR SED

Filled circles: detected disks. Open circles: undetected disks

No correlation with strength of far-IR excess
Apparent correlation with weakness of mid-IR excess!
Flatter or more tenuous inner disk ... or absence of a puffed-up inner rim (?) ... enhances 100 AU detectability

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Spitzer data from c2d and Taurus Legacy surveys
Edge-on disks in nearby clouds

- Expected to be faint without being highly reddened
- Outflows in the plane of sky
- 8/15 candidates are not edge-on disks
- Brown dwarf contamination?
- 2 peculiar cases: SpTypes earlier than M3. How to explain?
Edge-on Disk Deficit

- $H/R \approx 0.1$ for 100 AU radius disk $\Rightarrow$ 10% of all YSO disks should be edge-on.
- Only $7^{+5}_{-5}$ out of $184^{+8}_{-8}$ YSOs imaged by HST are consistent with being edge-on: 6%
- Selection bias against low luminosity edge-on disks in IRAS-derived YSO catalogs
- New YSO catalogs from Spitzer surveys have the potential to greatly increase the number of known edge-on disks
New edge-on candidates in Taurus
New edge-on candidates from c2d

- Comprehensive catalog search is being done

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Dust Properties

• Modeling of scattered light images constrains
  – Dust phase function
  – Dust opacity vs. wavelength in edge-on disks

• Shows that grains at disk surface can be larger than in ISM, but still μm sized
Dust lane chromaticity in HH 30

Watson & Stapelfeldt 2004

- Combined optical & near-IR images in $\chi^2$ minimization; found 120 variations in $\rho(r,z)$ law that fit the multiwavelength data set equally well.
- Even among these, the dust opacity ratio $\kappa_B/\kappa_K$ has a most likely value of 2 (vs. a nominal 8-10 in the ISM)
Edge-on Disk Strangeness: Variable nebulosity in HH 30 disk

18 epochs 1994-2005
Watson & Stapelfeldt 2007

If asymmetry is periodic, few days < P < 300 days

• Periodic disk illumination from accretion hotspots on a rotating star?
  (Wood and Whitney 1998)
• Moving inner disk inhomogeneities that shadow the outer disk?
• Stochastic flaring events?

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Next round of HST Edge-on Disk Images (Padgett et al. 2008)

NICMOS JHK or ACS VI images 10” square

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The Future of YSO Disk Imaging

• Combined modeling of existing multiwavelength images & spectral energy distributions
• Complete HST imaging reconnaissance of the YSO population of nearby clouds (to lower luminosity YSOs & smaller IR excesses)
• ALMA, ALMA, ALMA (a disk imaging machine)
• JWST/NIRCam for the 3-5 μm scattered light
• ELTs for imaging into the 0.05” horizon (0.1-30 AU region currently inaccessible @ 140 pc)
• Future proposed optical space telescopes designed for higher contrast imaging (e.g., TPF or its precursors), to detect the flatter/settled/shadowed disks