ALMA Observations of Irradiated Protoplanetary Disks

John Bally\textsuperscript{1}  
Henry Throop\textsuperscript{2}  
\textsuperscript{1,2} Center for Astrophysics and Space Astronomy
\textsuperscript{1} Department of Astrophysical and Planetary Sciences  
University of Colorado, Boulder  
\textsuperscript{2} Southwest Research Institute (SWRI), Boulder
YSOs near massive stars: UV photo-ablation of disks irradiated jets
Outline

• Most stars and planets form in clusters / OB associations: (Lada & Lada 03)
  - UV: External (OB stars) + Self-irradiation
    => Disk photo-ablation => mass loss: EUV, FUV
    Review Orion’s proplyds
    => Metal depletion in wind / enrichment of disk
    => UV-triggered planetesimal formation
    = Jets => active accretion => disks
  - Carina
  - The Bolocam 1.1 mm survey of the Galactic plane

• What will ALMA Contribute?: [5 to 50 mas resolution!]
  - Surveys of HII regions & clusters (Orion, Carina, …)
  - Best done as community-led Legacy surveys
    => Clusters of sources: disk radii, masses, I-front radii
    => Resolve ionized flows, disks features, protoplanets
      f-f, recombination lines, entrained hot dust
    => Neutral flow composition, velocity, structure
      CI, CO, dust, photo-chemistry products
    => Disk B (Zeeman & dust), composition, structure, gaps
      the organic forest
## ALMA & irradiated disks

10 μJy sensitivity & 10 mas resolution

<table>
<thead>
<tr>
<th>Band</th>
<th>3 mm</th>
<th>1.3 mm</th>
<th>850 μm</th>
<th>450 μm</th>
<th>350 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>6</td>
<td>7</td>
<td>9</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resolution (B = 14 km)</th>
<th>0.04&quot;</th>
<th>0.019&quot;</th>
<th>0.013&quot;</th>
<th>0.007&quot;</th>
<th>0.005&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>AU</td>
<td>AU</td>
<td>AU</td>
<td>AU</td>
<td>AU</td>
<td>AU</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>Sco-Cen (150 pc)</th>
<th>Orion (430 pc)</th>
<th>Carina (2,200)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6 3 2 1 0.7</td>
<td>17 8 6 3 2</td>
<td>90 42 29 15 11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>Sco-Cen (150 pc)</th>
<th>Orion (430 pc)</th>
<th>Carina (2,200)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6 3 2 1 0.7</td>
<td>17 8 6 3 2</td>
<td>90 42 29 15 11</td>
</tr>
</tbody>
</table>
The Orion/Eridanus Bubble ($\text{H}_\alpha$): $d=180$ to $500 \text{ pc}$; $l > 300 \text{ pc}$

Orion OB1 Association: $\sim 40 > 8 \text{ M stars}$: $\sim 20 \text{ SN in 10 Myr}$

- $\lambda$ Ori ($< 3 \text{ Myr}$)
- 1a (8 - 12 Myr; $d \sim 350 \text{ pc}$)
- 1b (3 - 6 Myr; $d \sim 420 \text{ pc}$)
- 1c (2 - 6 Myr; $d \sim 420 \text{ pc}$)
- Orion Nebula = 1d ($< 2 \text{ Myr}$; $d \sim 460 \text{ pc}$)

Barnard's Loop

Eridanus Loop
OMC 1
Outflow ($\text{H}_2$

$\tau = 500\text{-yr}$)

Trapezium

($L = 10^5 L_\odot$

$\tau < 10^5 \text{-yr}$)

Hundreds of Proplyds

BNKL

($L = 10^5 L_\odot$

$\tau << 10^5 \text{-yr}$)

OMC1-S

($L = 10^4 L_\odot$

$\tau < 10^5 \text{-yr}$)
0.5 – 2.2 µm

$10^4$ AU
Proplyd photo-ablation flows: \( \frac{dM}{dt} \sim 10^{-7} M_\odot \text{ yr}^{-1} \)

HST4 (LV 6), LV 1

Keck NIRSPEC + AO (Shuping et al. 2006)
Disk Photo-ablation

Ionizing EUV: \( \lambda < 912 \text{ A} \) (\( E > 13.6 \text{ eV} \)):

\[
\begin{align*}
H & \rightarrow H^+ \\
T & \sim 10,000 \text{ K} \quad c_\text{II} \sim 10 \text{ km/s}
\end{align*}
\]

Soft FUV: \( 912 \text{ A} < \lambda < \sim 2,000 \text{ A} \) (\( \sim 6 \text{ eV} < E < 13.6 \text{ eV} \))

heating by dust photo-electrons, \( 2H = \rightarrow H_2 \)

\[
\begin{align*}
T & \sim 100 \text{ to } 5,000 \text{ K} \quad c_\text{I} \sim 1 - 5 \text{ km/s}
\end{align*}
\]

Escape at \( r > fGM / c^2 \sim 5 \text{ AU} \) for \( c_\text{II} \) (for Solar mass)

\( \sim 40 \text{ AU} \) for \( c_\text{I} \)

Self-irradiation vs. External irradiation:

\[
\frac{L_\text{self}(UV)}{4 \pi d_*^2} = \frac{L_\text{external}(UV)}{4 \pi d_{OB}^2}
\]

External irradiation: \( L_\text{external}(UV) \sim 10^{49} \) photons / sec

Self - irradiation: \( L_\text{self}(UV) \sim 10^{40} - 10^{43} \) photons / sec
Anatomy of a proplyd

- Gas bubble
- Protoplanetary disk
- Jet
- Wind shock
- Stellar wind
- Tail
6 – 13.6 eV UV photons
6 – 13.6 eV UV photons
6 – 13.6 eV UV photons
6 – 13.6 eV UV photons
> 13.6 eV photons
6 – 13.6 eV UV photons
6 – 13.6 eV UV photons

> 13.6 eV photons

6 – 13.6 eV UV photons
6 – 13.6 eV UV photons

> 13.6 eV photons

Stellar wind

13.6 eV photons

6 – 13.6 eV UV photons
6 – 13.6 eV UV photons

> 13.6 eV photons

Stellar wind

> 13.6 eV photons

6 – 13.6 eV UV photons
Stellar wind
> 13.6 eV photons
6 – 13.6 eV UV photons
Stellar wind

> 13.6 eV photons

6 – 13.6 eV UV photons
6 – 13.6 eV UV photons
> 13.6 eV photons
Stellar wind
> 13.6 eV photons
6 – 13.6 eV UV photons
Stellar wind

> 13.6 eV photons

6 – 13.6 eV UV photons
\[ t \sim f \ M_{\text{disk}} \ N_{21}^{-1} \ r_{\text{disk}}^{-1} \ C_{I}^{-1} \ \text{(years)} \]
\[ \sim 10^5 - 10^6 \ \text{years} \]

\[ r_{\text{GI}} = \frac{GM}{c_{I}^2} \sim 40 \ \text{AU} \]
\[ c_{I} \sim 3 \ \text{km/s} \]

*Stellar wind*

\[ > 13.6 \ \text{eV photons} \]
\[ 6 - 13.6 \ \text{eV UV photons} \]
Stellar wind

> 13.6 eV photons

6 – 13.6 eV UV photons
Stellar wind

> 13.6 eV photons

6 – 13.6 eV UV photons
Stellar wind

> 13.6 eV photons

6 – 13.6 eV UV photons
6 – 13.6 eV UV photons

> 13.6 eV photons

Stellar wind

> 13.6 eV photons

6 – 13.6 eV UV photons
Stellar wind

$> 13.6 \text{ eV} \quad \text{photons}$

$6 - 13.6 \text{ eV} \quad \text{UV photons}$
Stellar wind

> 13.6 eV photons

6 – 13.6 eV UV photons

\[ t \sim 9 \times 10^6 \quad Q_{49}^{-1/2} \quad c_{\Pi 10}^{-1} \quad d_{1pc}^{-1} \quad M_\odot \quad r_{10AU}^{-3/2} \quad \text{years} \]

\[ < 2 - 5 \times 10^6 \text{ years} \]

\[ r_{\text{GII}} = \frac{GM}{c_{\Pi}^2} \sim 5 \text{ AU} \]

\[ c_{\Pi} \sim 10 \text{ km/s} \]
Orion Trapezium
HST+SMA (Williams et al. 2005)

$M_{\text{disk}} \sim 0.003$ to $0.02 \, M_\odot$
HH 514 micro-jet in Orion: $\text{H}\alpha$, [HII] (HST/STIS)

Nebular $\text{H}\alpha$

Jet

Counter Jet

HST 2
Orion Nebula: > 50 disks seen in silhouette
Irradiated proto-planetary disks:
2.12 μm H$_2$  
0.6563 μm Hα  

$\Rightarrow$ Soft UV photo-heating of disk surface

(Kassis et al. 2007, in preparation)
Evidence for Sedimentation:

Proplyd winds are dust depleted

• Near-UV penetration:
  - UV penetration depth, $N(H) \sim 2$ to $4 \times 10^{21}$ (cm$^{-2}$)
    $\Rightarrow$ gas /dust $> 3 \times$ ISM
  - $R_V \sim 5 \Rightarrow$ grains are larger than ISM
    $\Rightarrow$ grey

• Chandra X-ray attenuation at 0.3 – 1 KeV
  - Ionization front (flux & radius)
    $\Rightarrow$ $n_e = n(H)$, $dM/dt \sim f n(H) c_H$
  - Wind model $\Rightarrow N(H)$
  - Chandra $\Rightarrow N($metals$)$
  - $N(H) / N($metals$) > 3 – 5 \times$ ISM
The Beehive proplyd; HH 240 irradiated jet

Bally et al. 2005
d181-825  “Beehive” proplyd  
Chandra COUP

Jet  
Star

\[ kT \sim 0.57 \text{ keV} \quad \& \quad 3.55 \text{ keV} \]

\[ N_H \sim 8 \times 10^{20} \text{ cm}^{-2} \quad (\text{soft}) \]

\[ N_H \sim 6 \times 10^{22} \text{ cm}^{-2} \quad (\text{hard}) \]

**d181-825 “Beehive” proplyd**

**X-ray absorption:**

$$N_H \sim 8 \times 10^{20} \text{ cm}^{-2}$$  
But, foreground $A_V \sim 1 \text{ mag}$!

**H-alpha:**

$$n_e(r_I) = 2.6 \times 10^4 \text{ cm}^{-3}$$  
$$\frac{dM}{dt} = 2.8 \times 10^{-7} \text{ M}_o \text{ yr}^{-1}$$

**Neutral Column:**

(from 50 AU, $V = 3 \text{ km/s}$)

$$N_H(R_I) = 2.2 \times 10^{21} V_3^{-1} r_{50}^{-1}$$

$\Rightarrow$ **Photo-ablation flow**

**metal depleted!**

Evidence for growing grains: Orion 114-426 (Throop et al. 2001)
Growing grains: Si 10 µm feature (Shuping et al. 2006)
**UV-Induced Planetesimal formation:**

- **Problem:** How do grains grow from $d < 100$ cm (gravity un-important) to $d \sim 1 - 100$ km (gravity dominated)

  - Grains not “sticky”
  - Collisions tend to fragment & bounce
  - Head-wind $\Rightarrow$ radial drift of solids $\Rightarrow$ fast growth

- **Grain growth + sedimentation + UV-photoablation** $\Rightarrow$ Mass-loss from disk is metal depleted
  $\Rightarrow$ Retained disk becomes metal-enriched

  Gravitational instability $\Rightarrow$ planetesimals

UV => Fast Growth of Planetesimals:

Grain growth => Solids settle to mid-plane
UV => Remove dust depleted gas
=> High metallicity in mid-plane
Gravity => Instability
=> 1 - 100 km planetesimals

- Fast Formation of 1 to 100 km planetesimals

Throop & Bally et al. 05
What will ALMA see?

- Magnetospheric gaps?
- Spiral structure?
- Composition gradients?
- Heavy organics?
- Ice lines?
- Accreting protoplanets?
- Planetary gaps?
- Magnetic fields?
What will ALMA see?

- Growing grains & Proto-planetary gravel?
- Photo-dissociation products? (e.g. CI & molecular ions)
- Shock in neutrals & in Plasma?
- Jets & disk winds?
- f-f, recombination lines?
**Possible ALMA Projects:**

**Solicit Legacy programs:**

- Large, comprehensive surveys
- Data to go public immediately

**Surveys of Orion, Carina, M8, M16, M17, W40, π Sco…**

- Disk radii, radial velocity, velocity dispersion, etc.
- Continuum & line fluxes as functions of location, environment, age

**Radial gradients:** dust, gas, τ, composition

**Surface density:** \( \Sigma(r) \sim r^{-\alpha} \) What is \( \alpha \)?

**Composition:**

- The organic forest => chemical evolution
- Ices => gas transitions (H\(_2\)O, NH\(_3\), CH\(_3\)OH, …)

**Velocity fields => dynamical YSO masses**

**Structure:** Gaps, spirals, accretion-heated protoplanets

-Externally ionized protoplanets & disk features (late-phase proplyds)

**Photo-ablation flows:** structure, velocity => mass loss

**Magnetic fields:** polarized dust, Zeeman in CN, SO, …
η Carinae Nebula:
Trumpler 14 region

Pillars with jets

Tr 14 cluster
(< 3 Myr)
Trumpler 14

Dark globule: faces η Car

Jet?
Twin jets from YSOs in Pillars near Tr 14
The Bolocam 1.1 mm survey (as of Sept 2006)

- ~ 90 square degrees of the Galactic Plane
- 5,000 dense cloud cores (> 20 mJy / beam)
- Best tracer of massive star-forming cores

Single 45 min scan of 3 x 1 deg field in Plane (100 mJy / beam)
Conclusions

• Most Stars from in dense clusters, near massive stars
  Most planetary systems likely form in OB associations

• ALMA Resolution to 0.005” (band 10 @ B = 14 km)
  Ionized photo-ablation flows, wind, & jets
  \( f-f, \) recombination lines, dust
  \( V_{\text{radial}}, n, \) grain emissivity, mass-loss rates

Neutral flow (proplyd body)
  Dust, CI, CO, HCO+
  \( V_{\text{radial}}, \) shocks, flow geometry

Disks & Planets: Velocity field, Structure, Composition
  Dust, molecular lines, Zeeman in CN
  Velocity field and Structure: radii, spirals, gaps)
  Grain properties, polarization, ices, ions vs. neutrals
  Giant protoplanets?

• Emphasize Legacy Surveys rather than GO programs
The End