Planetary Formation Near Bright Stars: Fast or Rare?

Henry Throop
John Bally
Larry Esposito
University of Colorado, Boulder
Mark McCaughrean
Astrophys. Institut Potsdam

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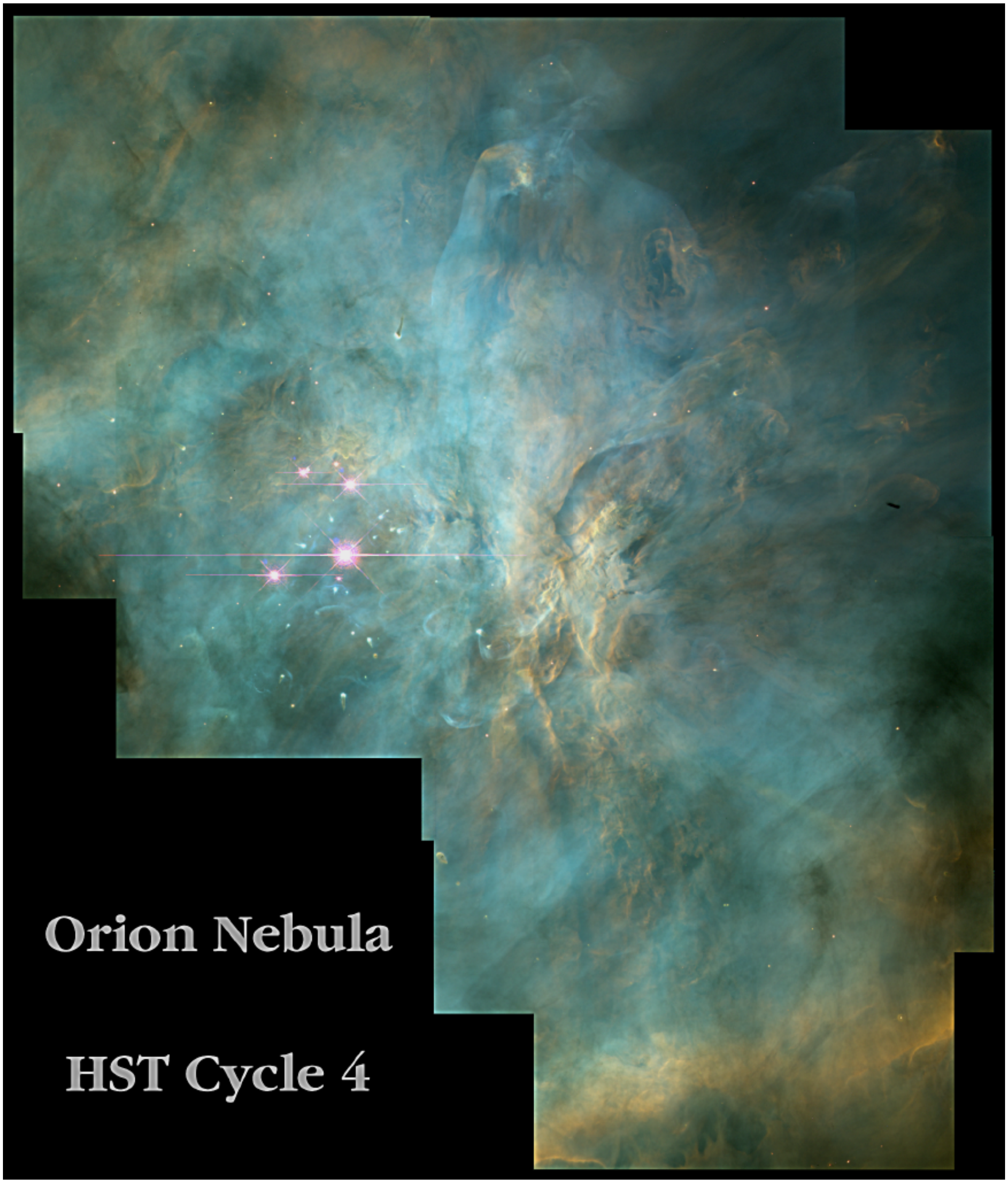
- Where Do Most Stars Form?
- Observations of Young Disks; Evidence for Grain Growth
  * HST
  * OVRO
- Evolutionary Modeling of Young Disks
  * Physical Processes in Externally-Illuminated Environments
- Conclusions

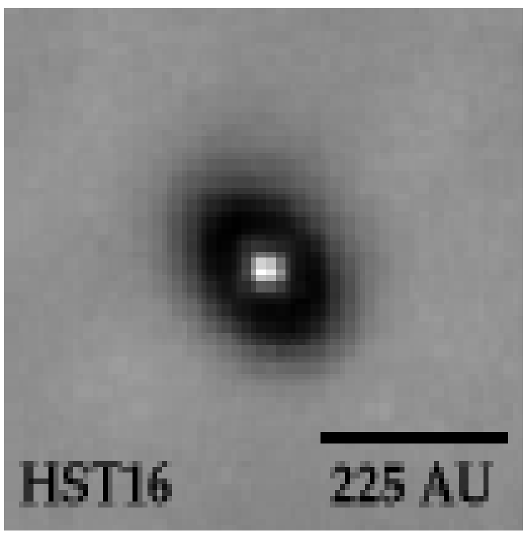
Where Do Most Stars Form?

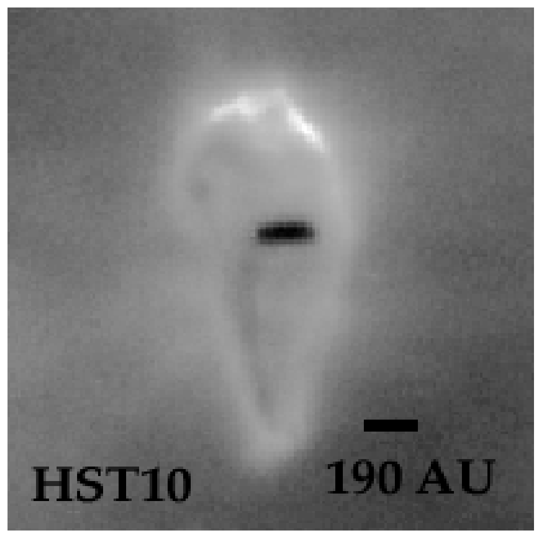
- Dense, Bright Clusters – Orion Nebula
  - 20,000 stars in last 10^7 yr
  - Luminosity $10^5 L_\odot$ from massive O & B stars at core
- Cool Dark Clouds – Taurus
  - Few 10^2 stars formed in last 10^7 yr
  - Regions are common, well-studied, but small
- Majority of stars in our galaxy form in dense, bright clusters like Orion, not small, isolated regions like Taurus.
- To look at disk and planetary formation, need to consider environment!

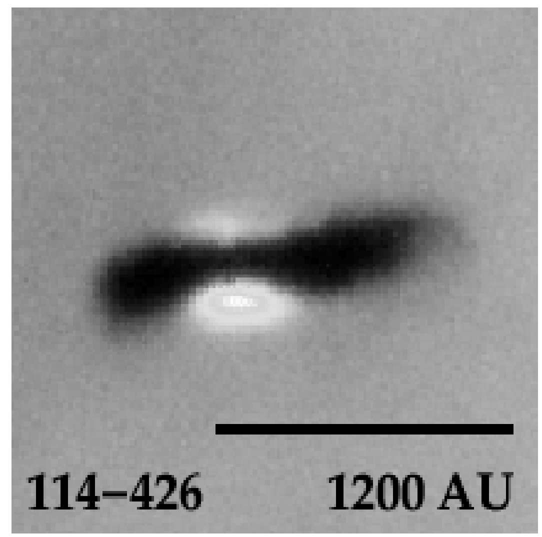

Orion Nebula
HST Cycle 4

HST Observations of Orion Disks

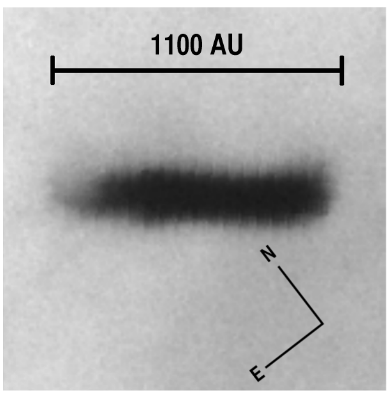
- ~ 50 dark disks seen in **silhouette**; $\lambda = 0.2 - 1.9\ \mu$m
- Apparent disk size is *independent of wavelength!*
  - * Disks dominated by large particles

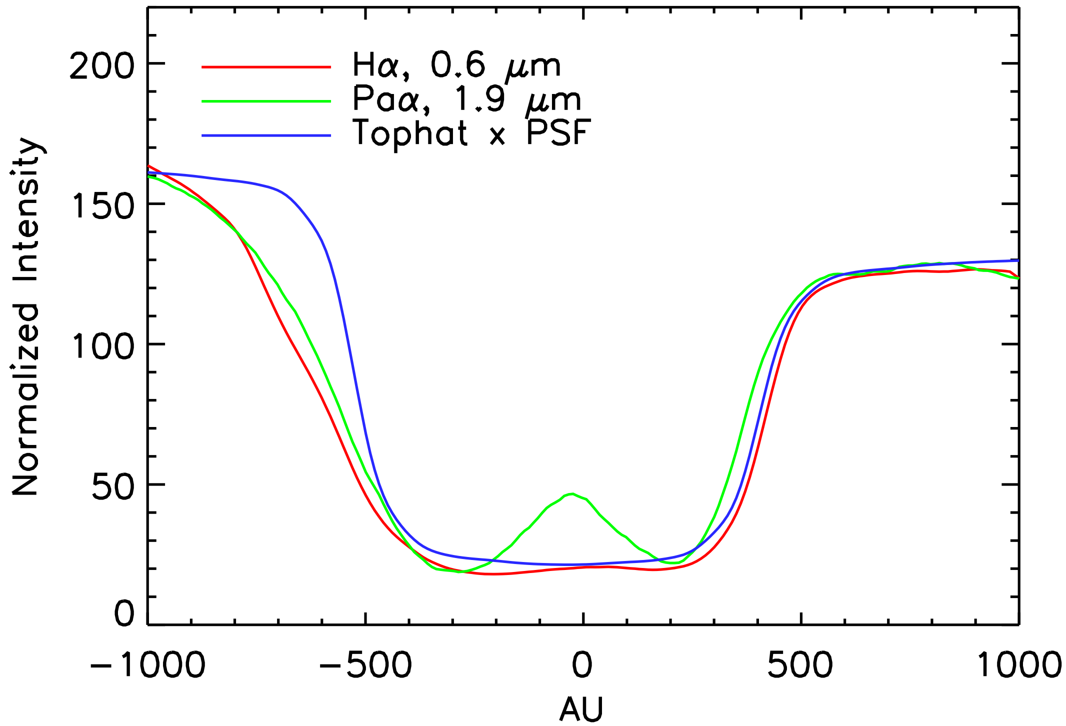






114-426 Disk





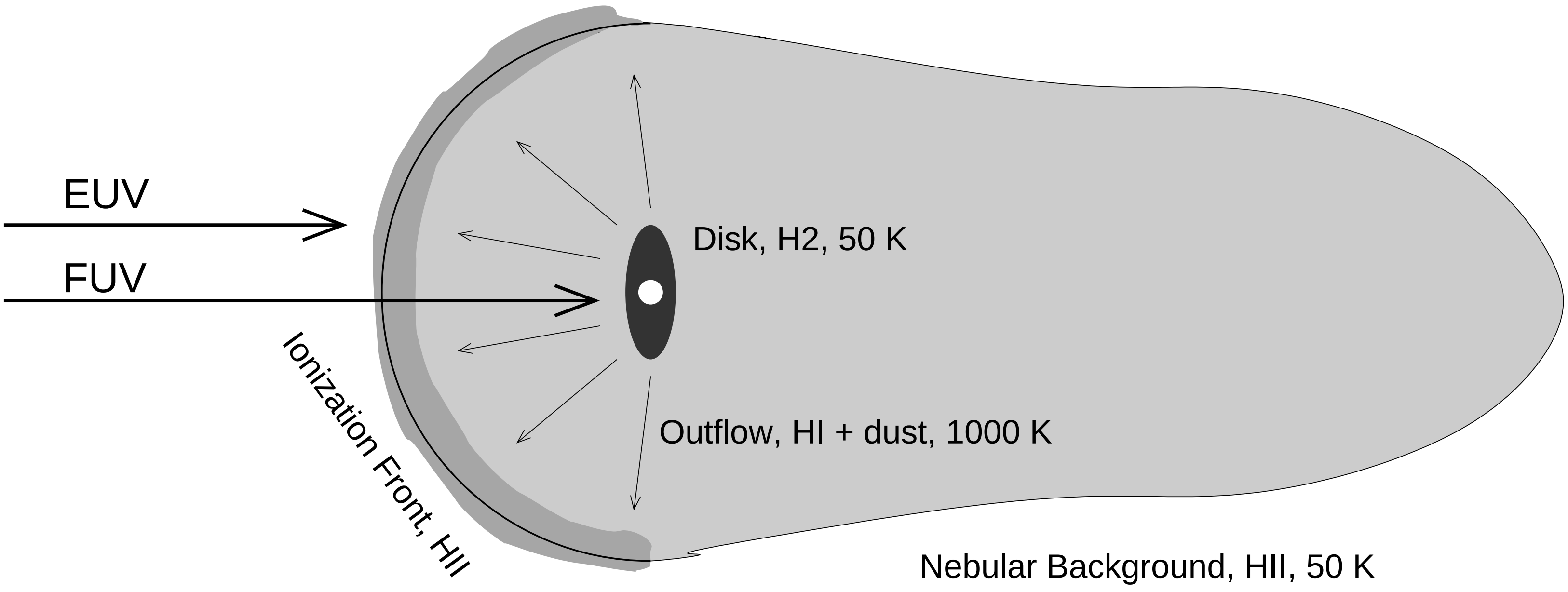
WFPC2 Hα

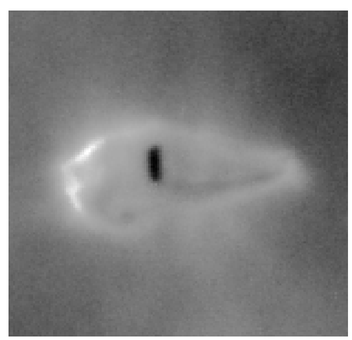
- Translucent NE ansa nearly identical at 0.65 μm, 1.87 μm!
  - **Large** particles: $r \gtrsim 5\mu$m.

Grain Properties From OVRO Observations

- Observations of Bally *et al.* 1998 of six Orion disks
- No 1.3 mm continuum *or* line emission detected
- Optically thick 50K disk **would be visible**
- Non-detections imply **disk is optically thin**
  - * low τ requires low mass opacity k_ν *i.e.*, large particles
  - * $r \gtrsim$ few cm
- Non-detection is **difficult to explain without large particles.**
  - * Alternate explanation: Disk masses very low ($M < 0.02 M_\odot$)
    - – Requires k_ν inconsistent with modeling results

Photoevaporation of Orion Disks





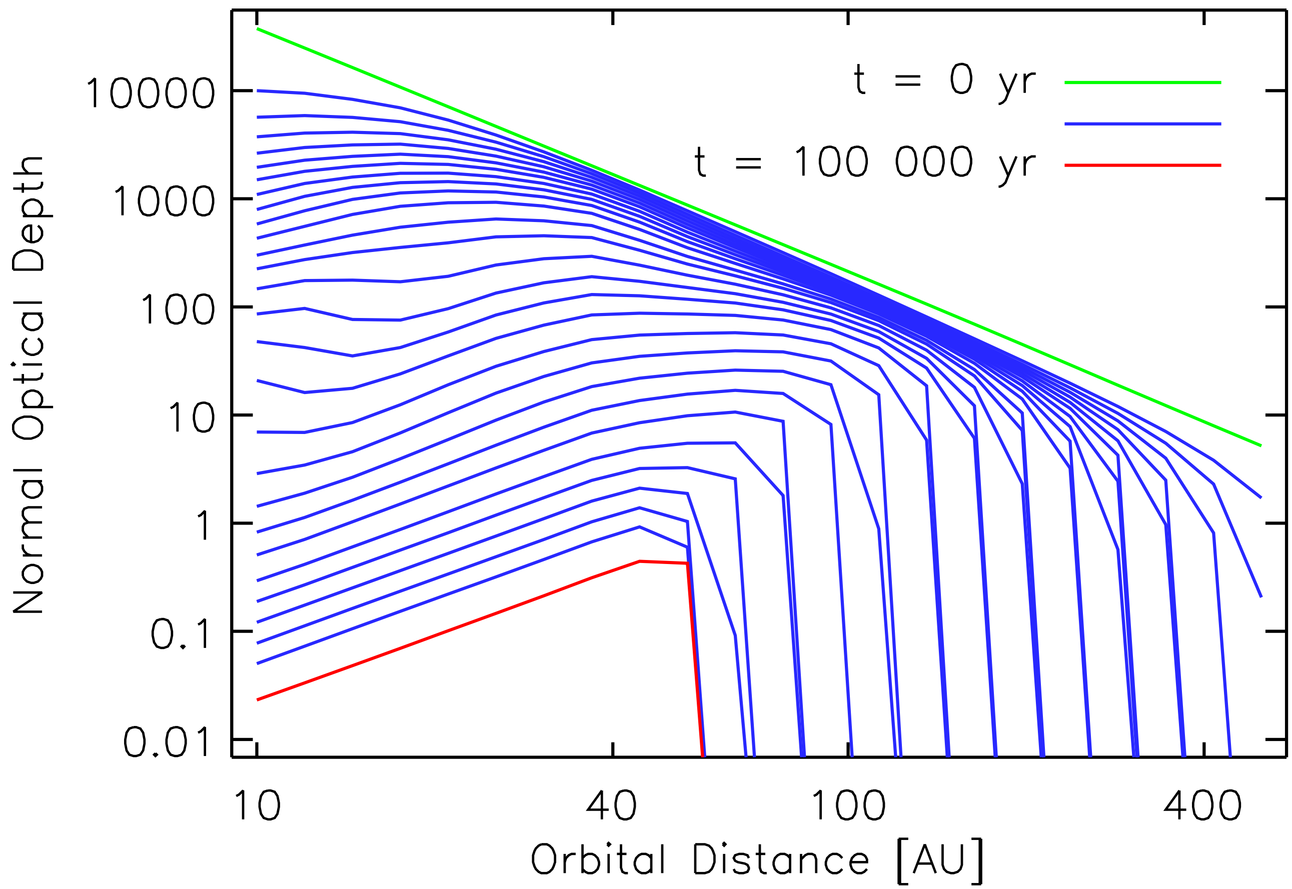
(Johnstone et al. 1998; Störzer & Hollenbach 1999, Henney & O'Dell 1999)

Evolutionary Modeling of Orion Disks

Numerical Model (PAPADUM)

- Tracks state vector $n(r, R, t)$ of ice, silicate, H_2
- Integrate from initial conditions until gas disk is lost or convection stops
- Physical processes in externally-illuminated environments
  - * Grain growth
    - – Turbulent collision velocities $\sim$ cm s^{-1}, Mizuno 1988
  - * Photoevaporation of gas and entrainment of small grains
    - – $\dot{M} \simeq 10^{-6} M_\odot$ yr^{-1}; $r_{\rm entrain} \sim v_0^2\, n_0\, R^2$
  - * Photosputtering
    - – $(dr/dt)_{\rm ice} \sim \mu$m yr^{-1}

Optical Depth Profiles, Orion Disk Models



$$\Sigma \sim R^{-3},\ t_{\rm UV} = 0 \text{ yr}$$

Evolutionary Modeling of Orion Disks

Results:

- Grain growth is rapid: meter-sized particles in 10^5 yr at 10 AU
- Disk is removed outward of ~ 100 AU
- Disk outer edge is sharp, populated with large particles
- Gas, all small particles lost in $\sim 10^5$ yr
- **Formation of planets in bright, dense Orion-like regions:**
  - **Terrestrial planets unaffected**
  - **Jovian planets difficult**
  - **Large EKB difficult**

Conclusions

- **Three lines of evidence** suggest **large particles** in the Orion disks:
  - * Lack of color in disks implies particles > μm
  - * Non-detection at mm implies low optical depth, particles > mm
  - * Numerical modeling shows grains grow quickly throughout disks
- We are witnessing very earliest stages of planetary formation
- Difficult to form Jupiters before disks are destroyed
- **Planetary formation near bright stars is *hazardous***
- **Planets must be formed *rapidly* or *rarely*.**