Photoevaporation of protoplanetary disks

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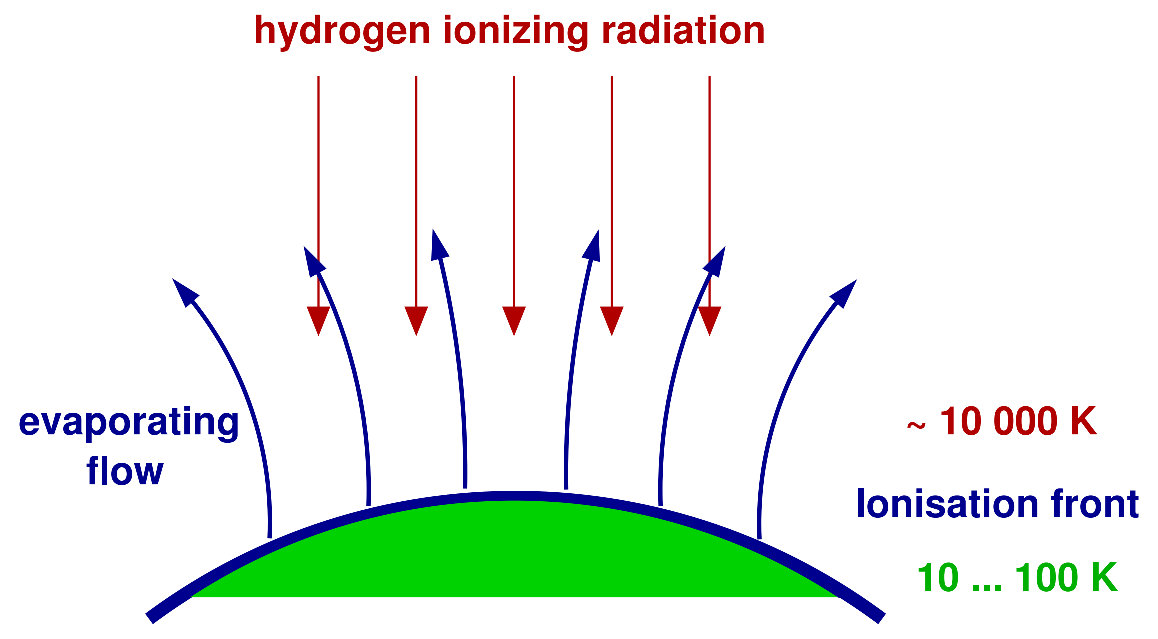
Outline

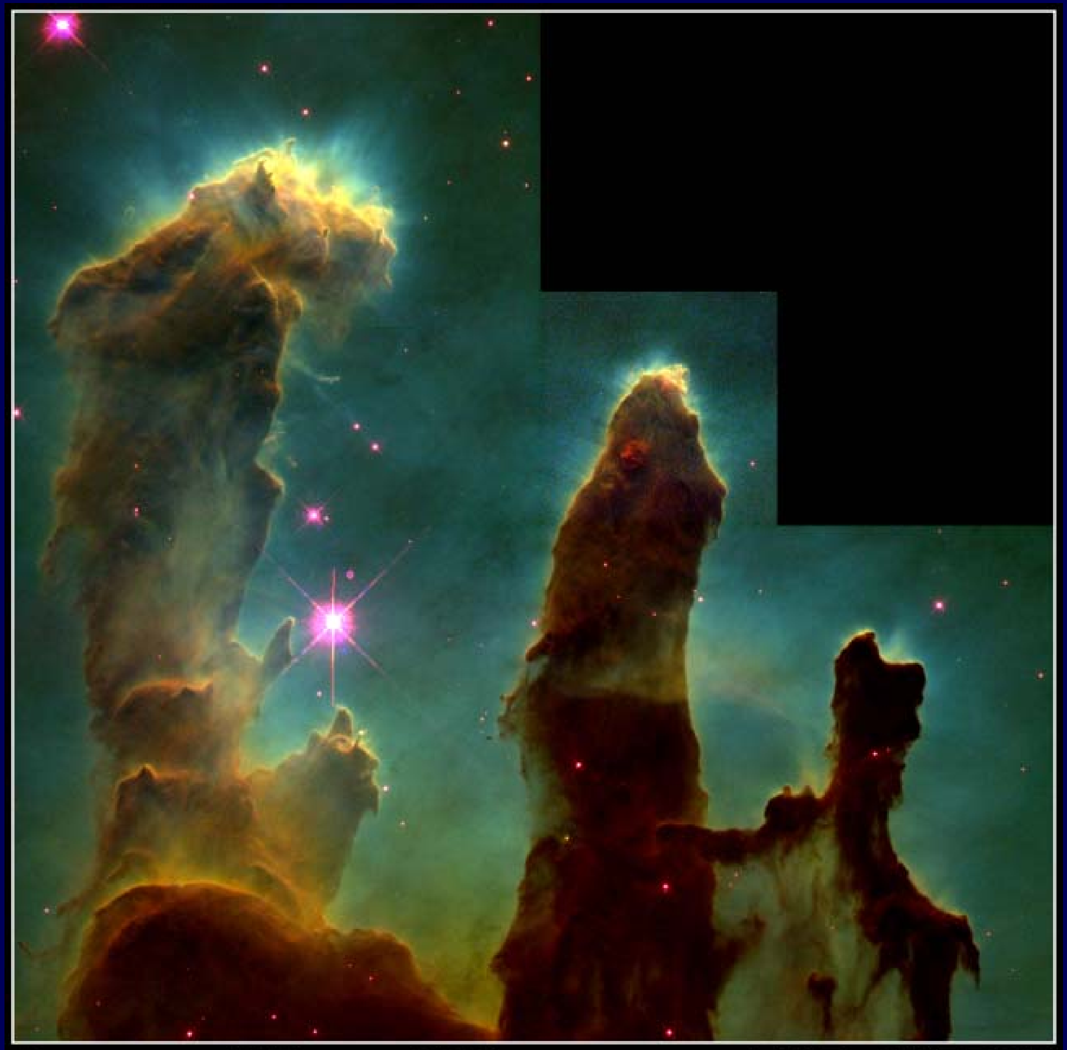
- Photoevaporation of clouds and disks
- Observational properties of the proplyds in M42
- Proplyd candidates in other star forming regions
- (Semi-)Analytical models for proplyds
  - general structure of proplyds
  - photoevaporation rate
- Two-dimensional numerical simulations
  - physics involved
  - formation of tails and jets
  - time-dependent photoevaporation rate
- Photoevaporation from inside
- Importance of other disk dispersal mechanisms
- Consequences for the formation of the solar system

The photoevaporation process



- UV photons (hν>13.6 eV) reach surface of dense material
- UV photons ionize hydrogen and heat the region behind the advancing ionization front up to $\sim 10^4$ K
- hot material expands $\longrightarrow$ evaporating flow

Photoevaporation of molecular clouds



Gaseous Pillars · M16 HST · WFPC2

PRC95-44a · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA

Eagle Nebula M16

- dense molecular clouds at border of HII region

- structure of the evaporating flow:

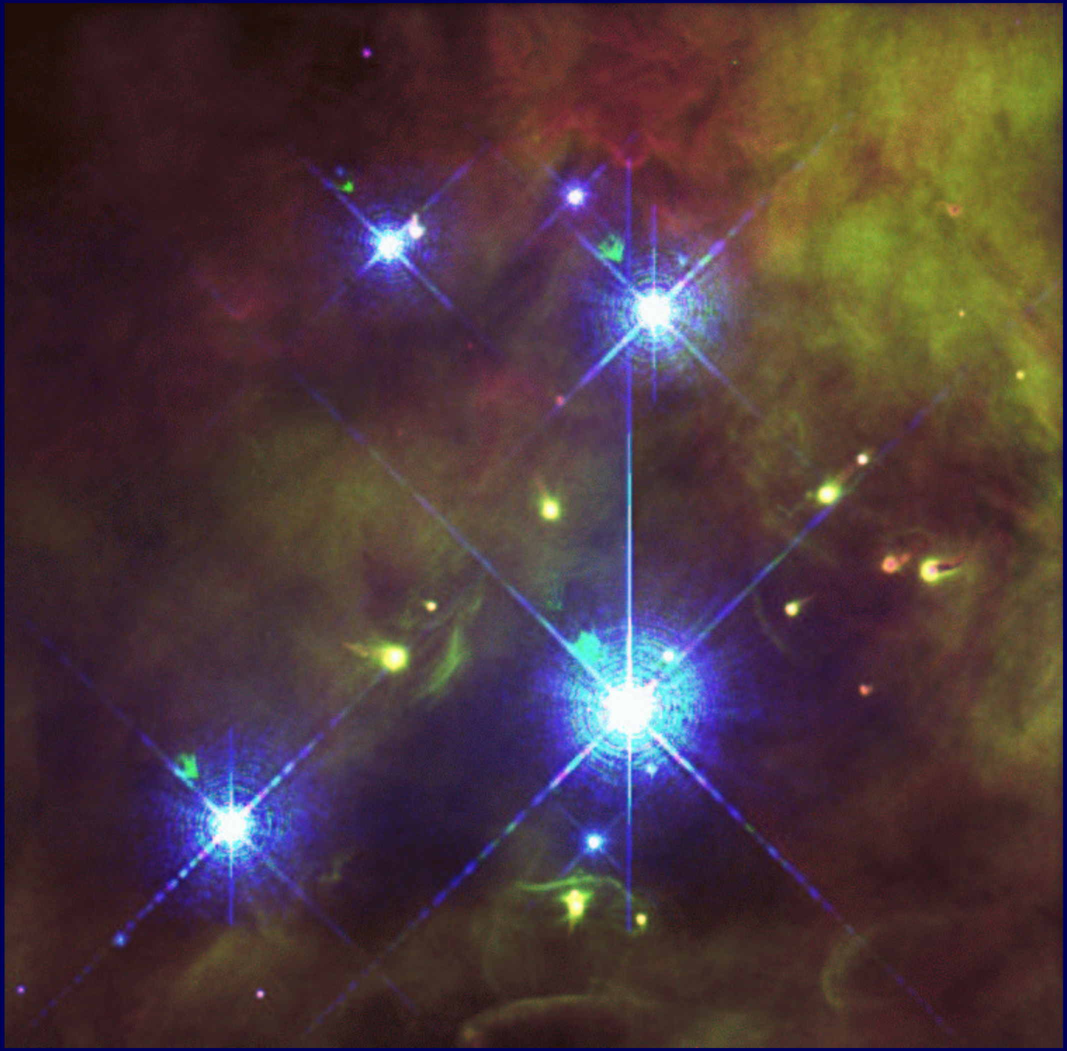
  $$n \propto d^{-2}$$

  n: density of the flow
  d: distance from ionization front

- strong free-free emission and emission in forbidden lines close to the ionization front

- ionization front traces cloud surface

Photoevaporation of protoplanetary disks



Bally et al. (1998)

Orion Nebula M42

- UV photons
  from Trapezium Cluster

- Emission lines:
  Hα $\longrightarrow$ green
  [NII] $\longrightarrow$ red
  [OI] $\longrightarrow$ blue

- Photoevaporating disks appear as head-tail objects (proplyds)

- tails are pointing away from main ionizing star θ^1 Orionis C

The acronym

PROPLYDS = PROtoPLanatarY DiskS

Protoplanetary disks made visible by being in or in front of an H II region.

(O'Dell, Wen & Hu 1993)

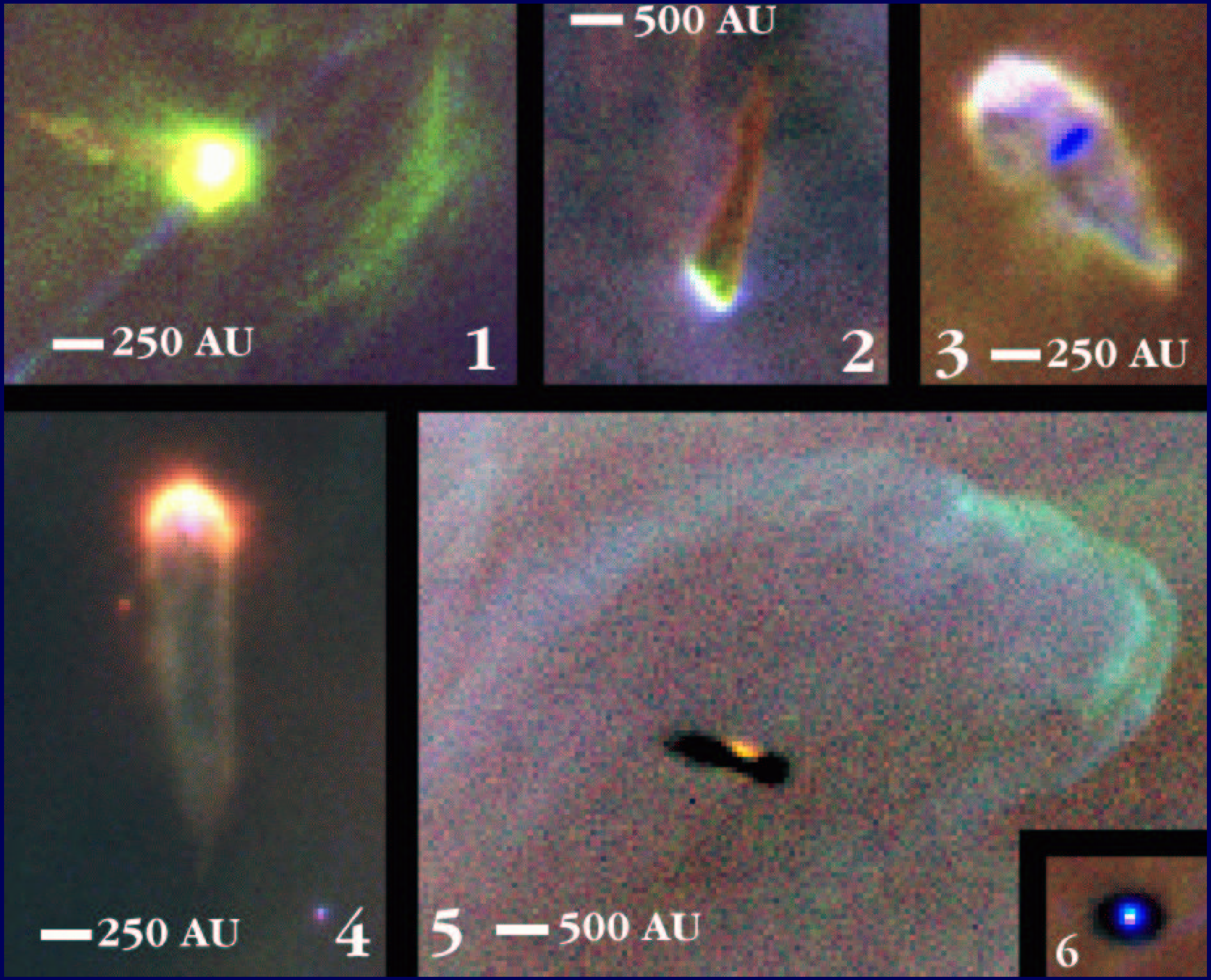
Two types of proplyds:

"protoplanetary disks being in an HII region" ⟶ proplyds (star-disk system + head-tail envelope)
"protoplanetary disks being in front of an HII region" ⟶ dark proplyds, silhouette disks

Other propositions:

PIGS = Partially Ionized GlobuleS (Dopita et al. 1974, Garay 1987)
EIDERS = Externally Ionized Disks in the Environs of Radiation Sources (Felli et al. 1993)

Proplyds in the Orion Nebula

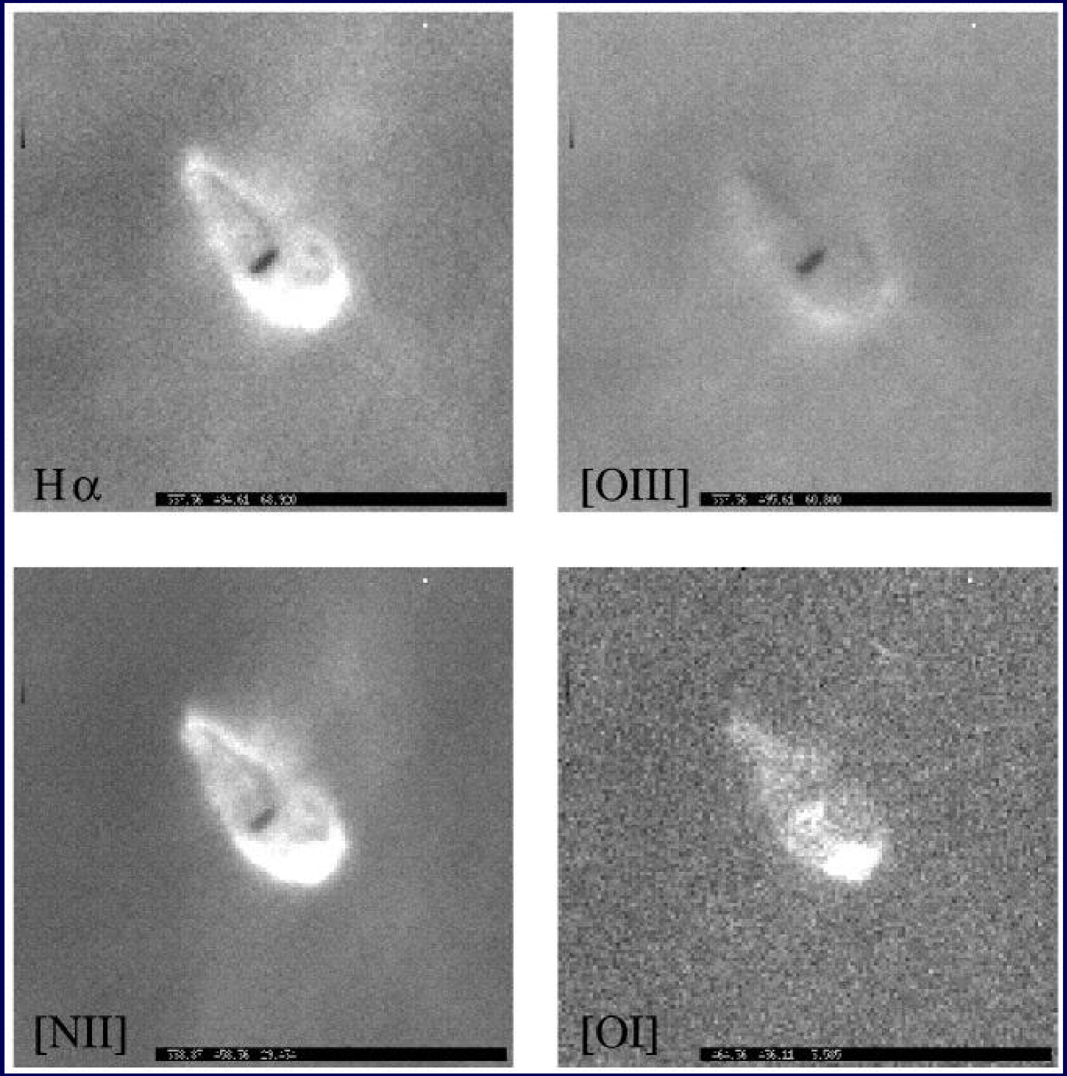


Bally et al. (1998)

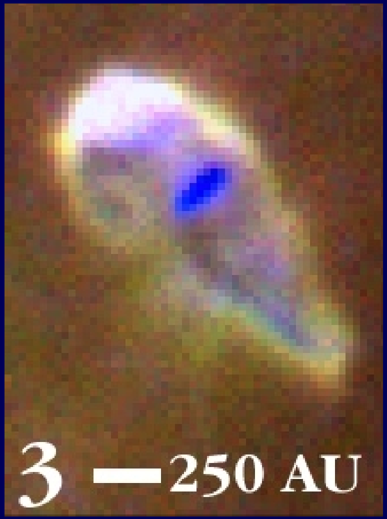
Properties of the Orion proplyds

- first detection of 6 nebulosities (Laques & Vital 1979)
  ⟶ LV objects
- radio continuum (VLA) (Garay et al. 1987, Churchwell et al. 1987, Felli et al. 1993)
  ⟶ compact radio sources with $n_e \sim 10^6$ cm^{-3}
- IR images (McCaughren & Stauffer 1994)
  ⟶ IR sources within the proplyds
- optical images (HST: O'Dell et al. (1993), O'Dell & Wong (1996); adaptive optic: McCullough et al. (1995))
  ⟶ head-tail structure, orientation towards UV source
- Chen et al. (1998) (HST)
  ⟶ disk-like H_2 emission
  ⟶ stand-off of ionization front
- Bally et al. (1998, 2000) (HST)
  ⟶ dark silhouettes within the proplyds (30%)
  ⟶ tail length 100 - 1700 AU, limb brightened
  ⟶ micro-jets, [0III] arcs
- Spectroscopic observations (Maebuern et al. 2002, de la Fuente et al. 2003)
  ⟶ velocity in the ionized flow: $\sim$ 20 km/s
  ⟶ velocity of the micro-jets: $\sim$ 100 km/s

Proplyd HST 10



Johnstone et al. (1998)

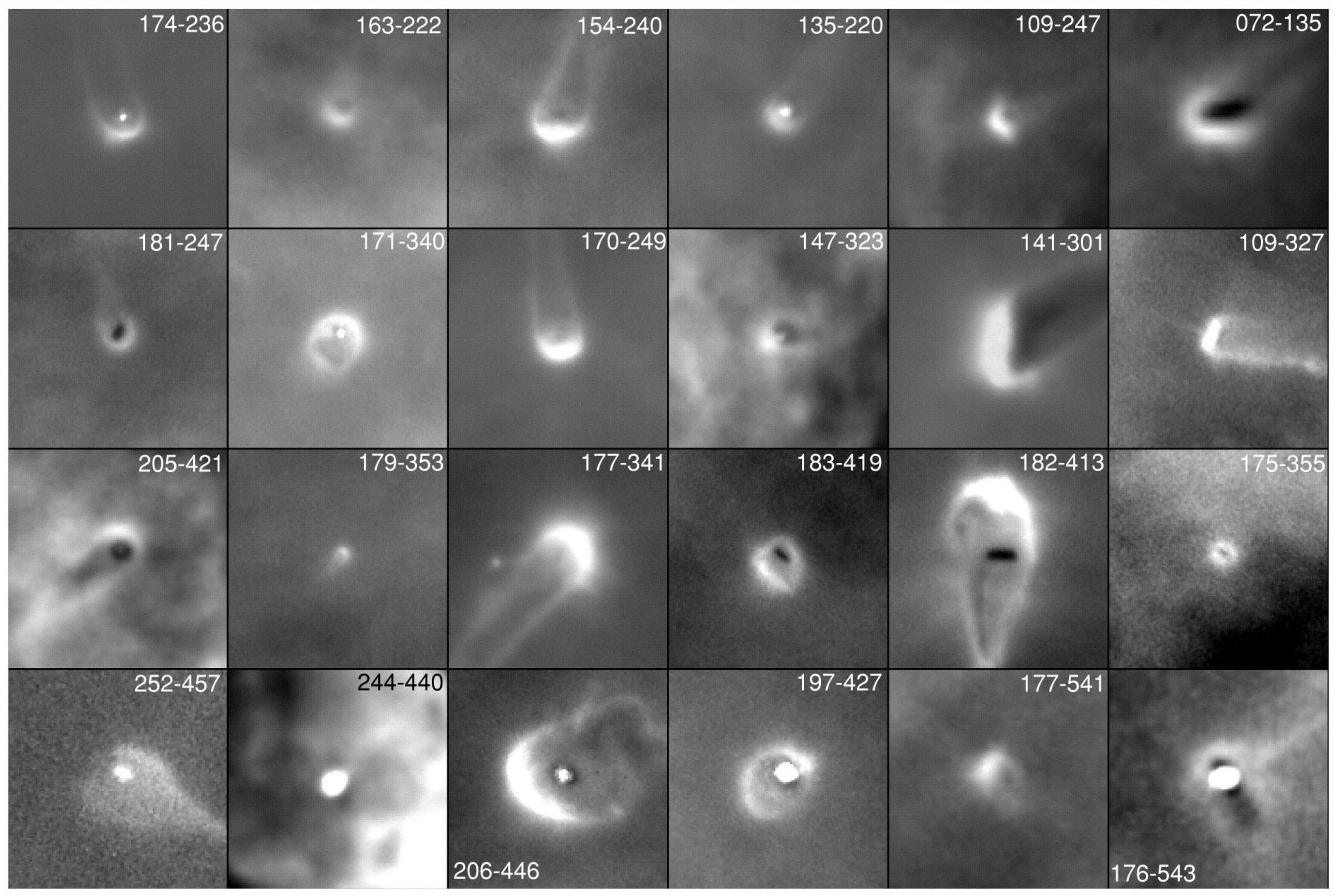


Hα, [OIII], [NII]:
⟶ ionized envelope in emission
⟶ disk in absorption

[OI], molecular hydrogen:
⟶ disk in emission

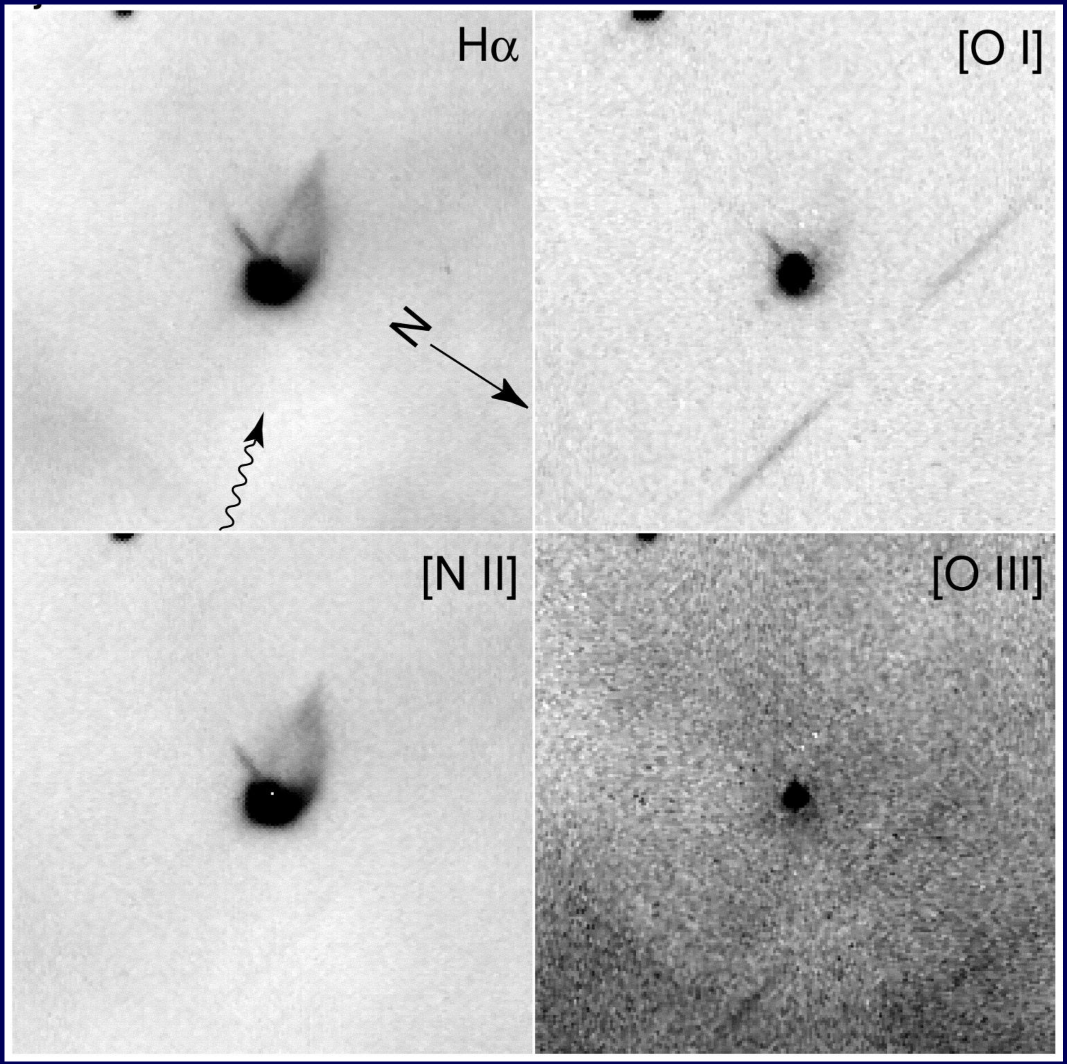
⟶ stand-off of ionization front

Orion proplyds in Hα



Bally et al. (2000)

Micro-jet in proplyd 282-458 (HH527)

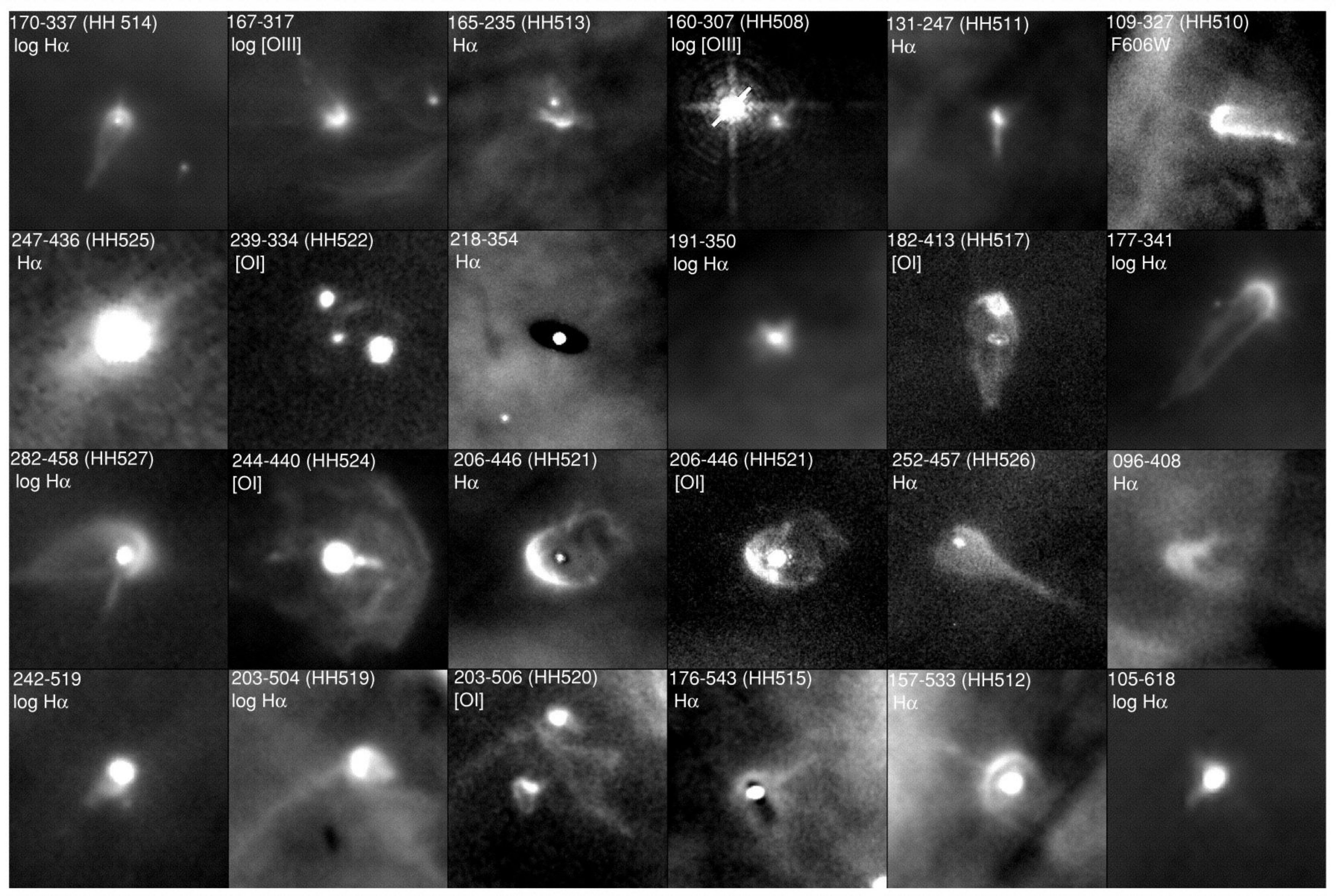


Bally et al. (2000)

→ one-sided micro-jet

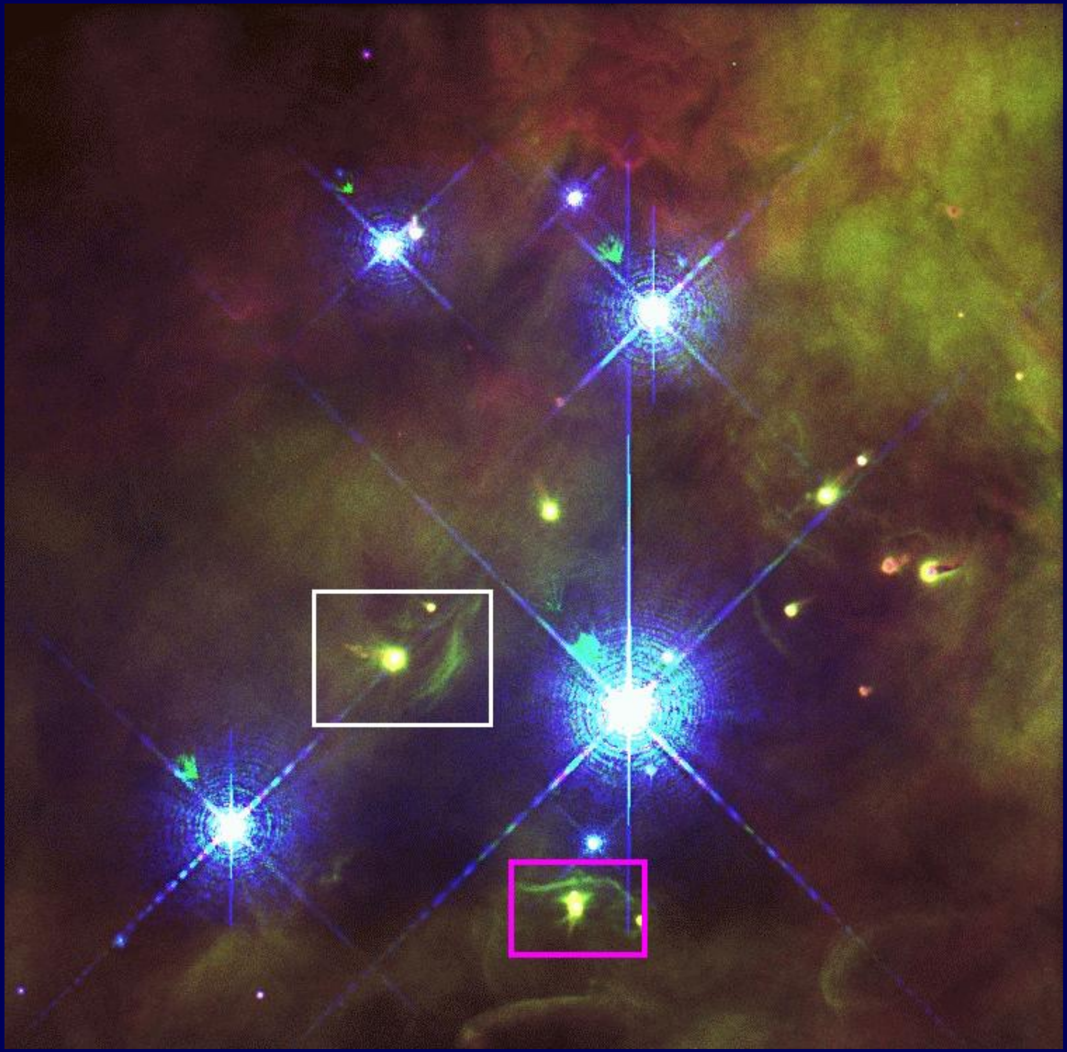
→ rotation axis ≠
direction of UV source

More micro-jets in Orion proplyds

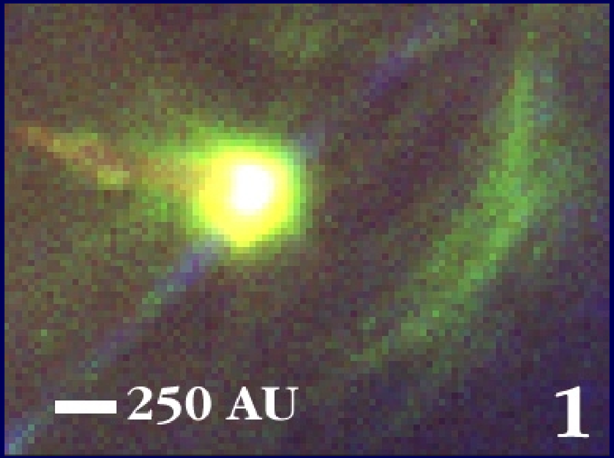


Bally et al. (2000)

[OIII] arcs – Wind interaction



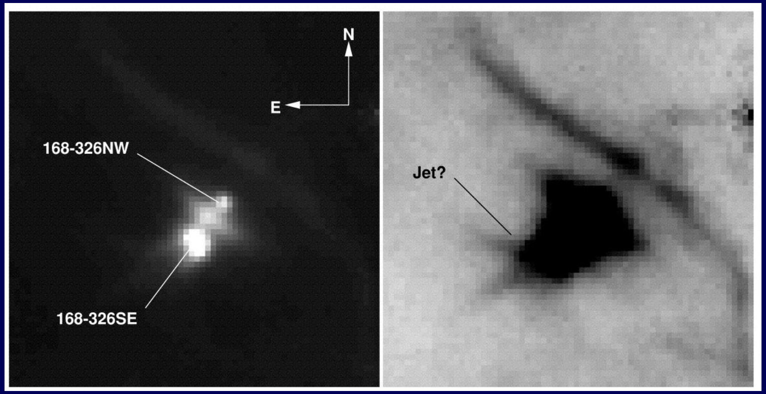
Bally et al. (1998)



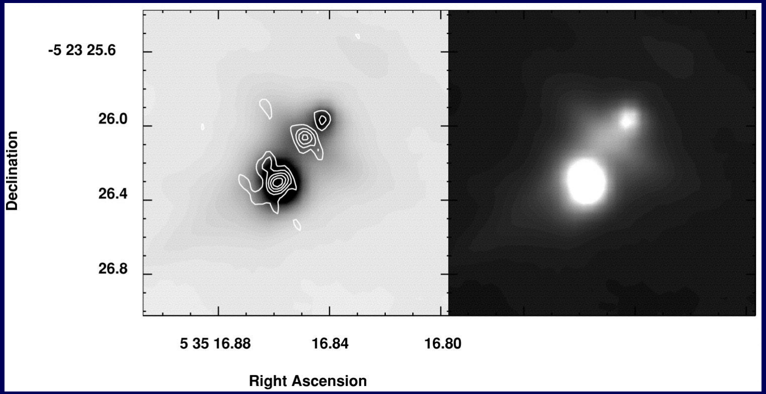
- Interaction of stellar wind with evaporating flow from proplyd head
- Position of shock front is defined by pressure equilibrium between both flows

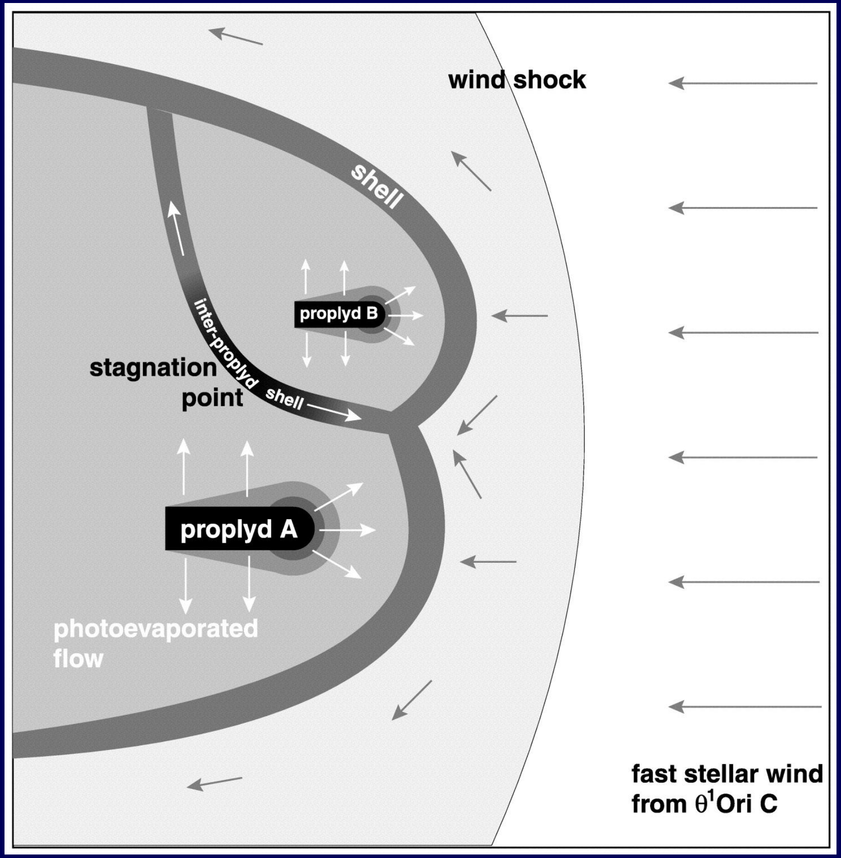
Binary proplyd LV1 – Interaction between winds from proplyds

[OIII] λ 5007 image (high and low resolution)



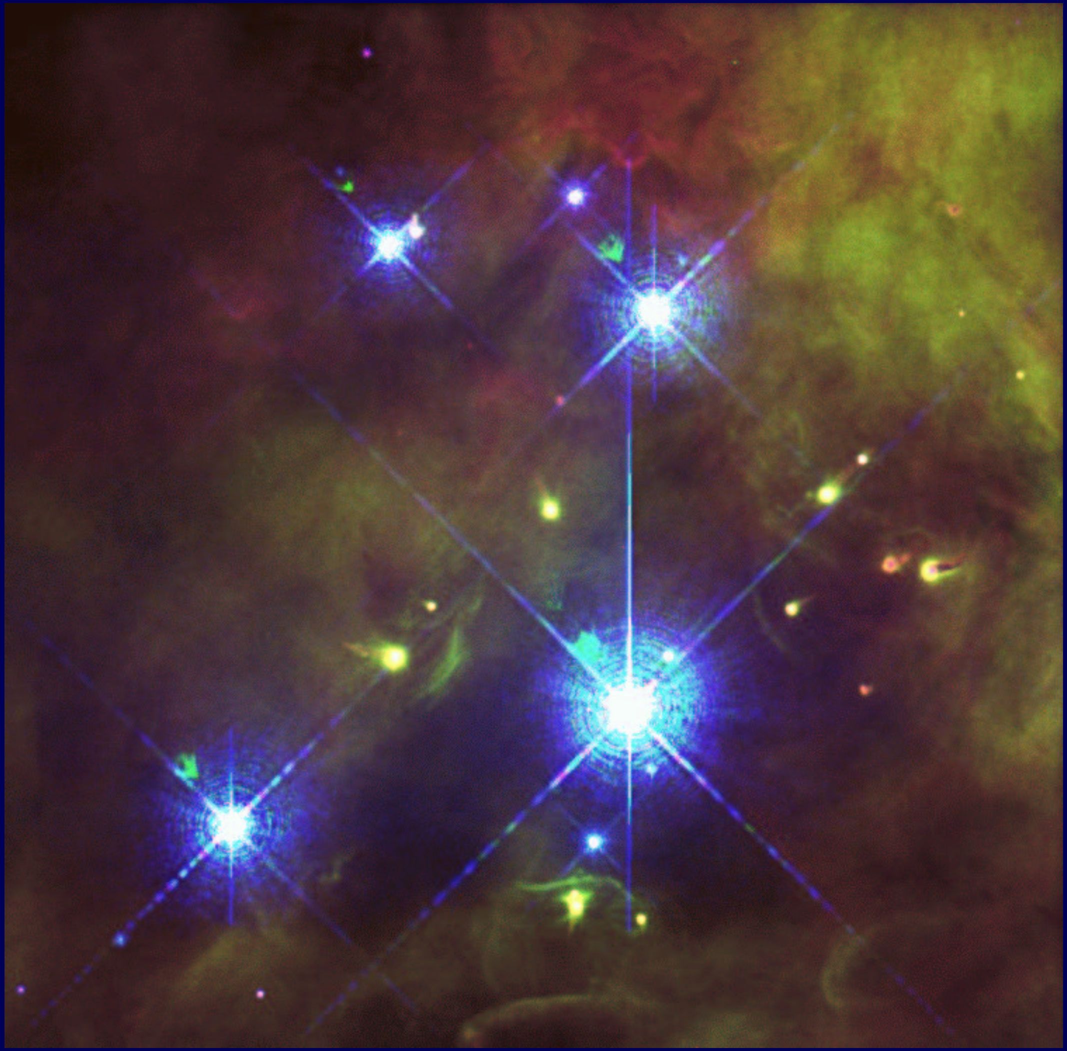
HST Hα image and MERLIN 5 GHz contours





Graham et al. (2002)

Proplyds in the Orion Nebula



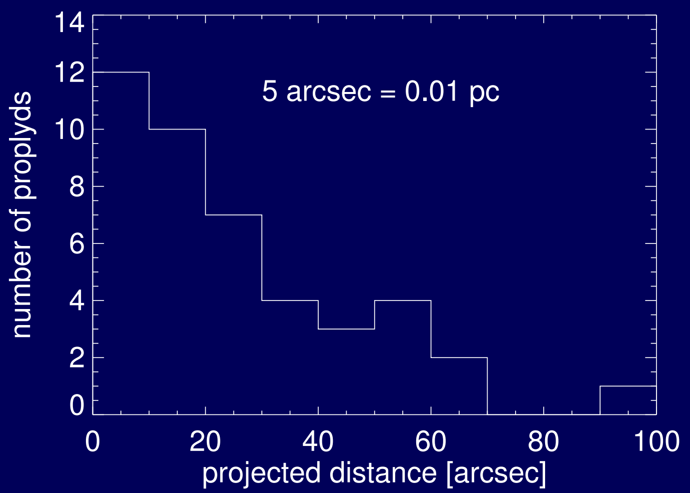
Bally et al. (1998)

Orion Nebula M42

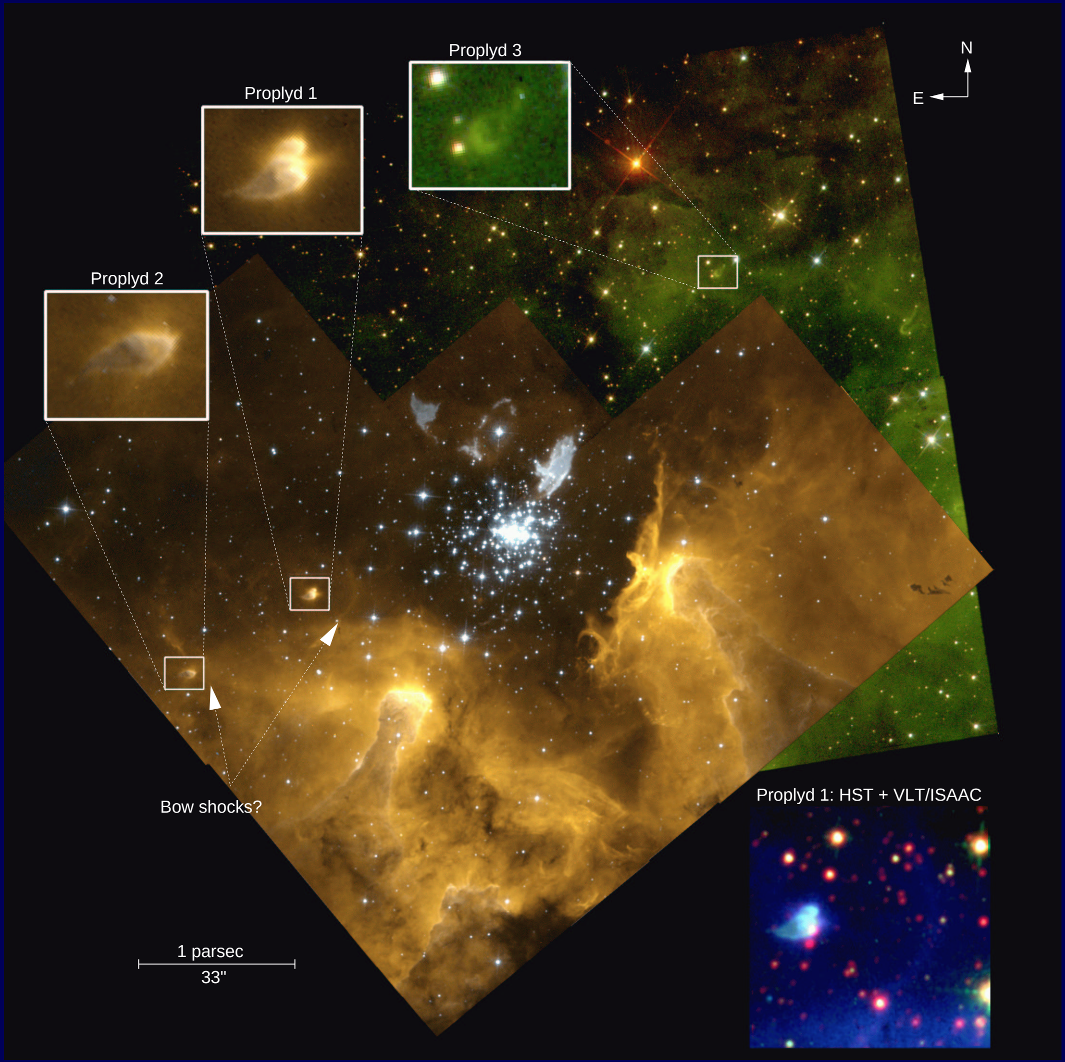
Main ionizing source:
O6 star θ^1 Orionis C

Luminosity: $L_{bol} \sim 10^5\ L_\odot$

UV photon rate: $S_{UV} = 1.5\text{x}10^{49}\ s^{-1}$



Proplyd candidates in NGC 3603



Brandner et al. (2000)

Giant HII Region NGC 3603

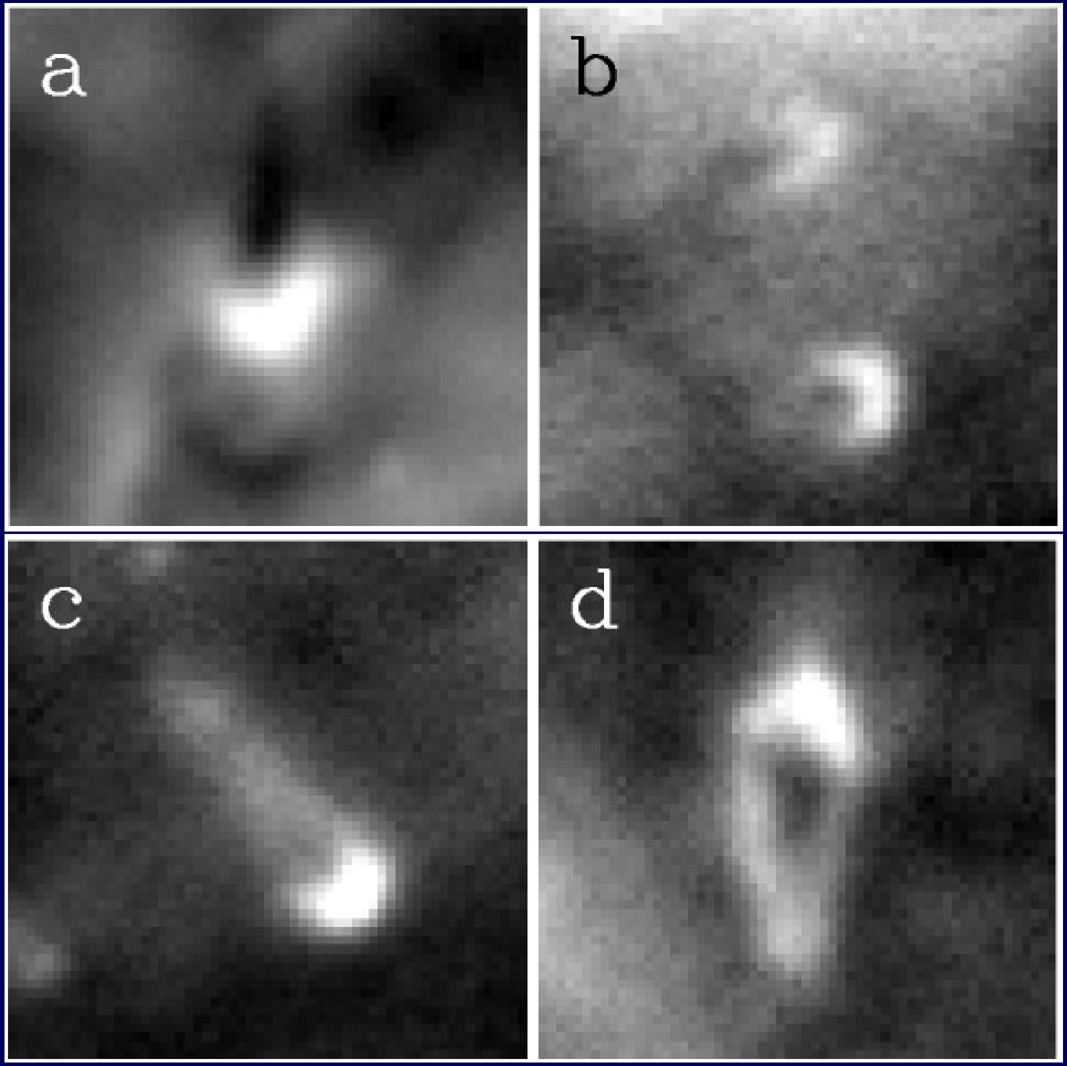
Ionizing source:
compact massive cluster ($>$4000 $M_\odot$)
with $\sim$70 O-type stars and 3 WR stars

Luminosity: $L_{bol} > 10^7\ L_\odot$

UV photon rate: $S_{UV} = 10^{51}\ s^{-1}$

Proplyd \#	distance from cluster pc
1	1.3
2	2.2
3	2.0

Proplyd candidates in the Carina Nebula



Smith et al. (2003)

Carina Nebula NGC 3372

Ionizing source:
several clusters of young massive stars
$\sim$60 O-type stars + η Car (LBV)

Luminosity: $L_{bol} \sim 10^7\ L_\odot$

UV photon rate: $S_{UV} \sim 10^{51}\ s^{-1}$

Distance from UV source: $\sim$ 0.1 pc

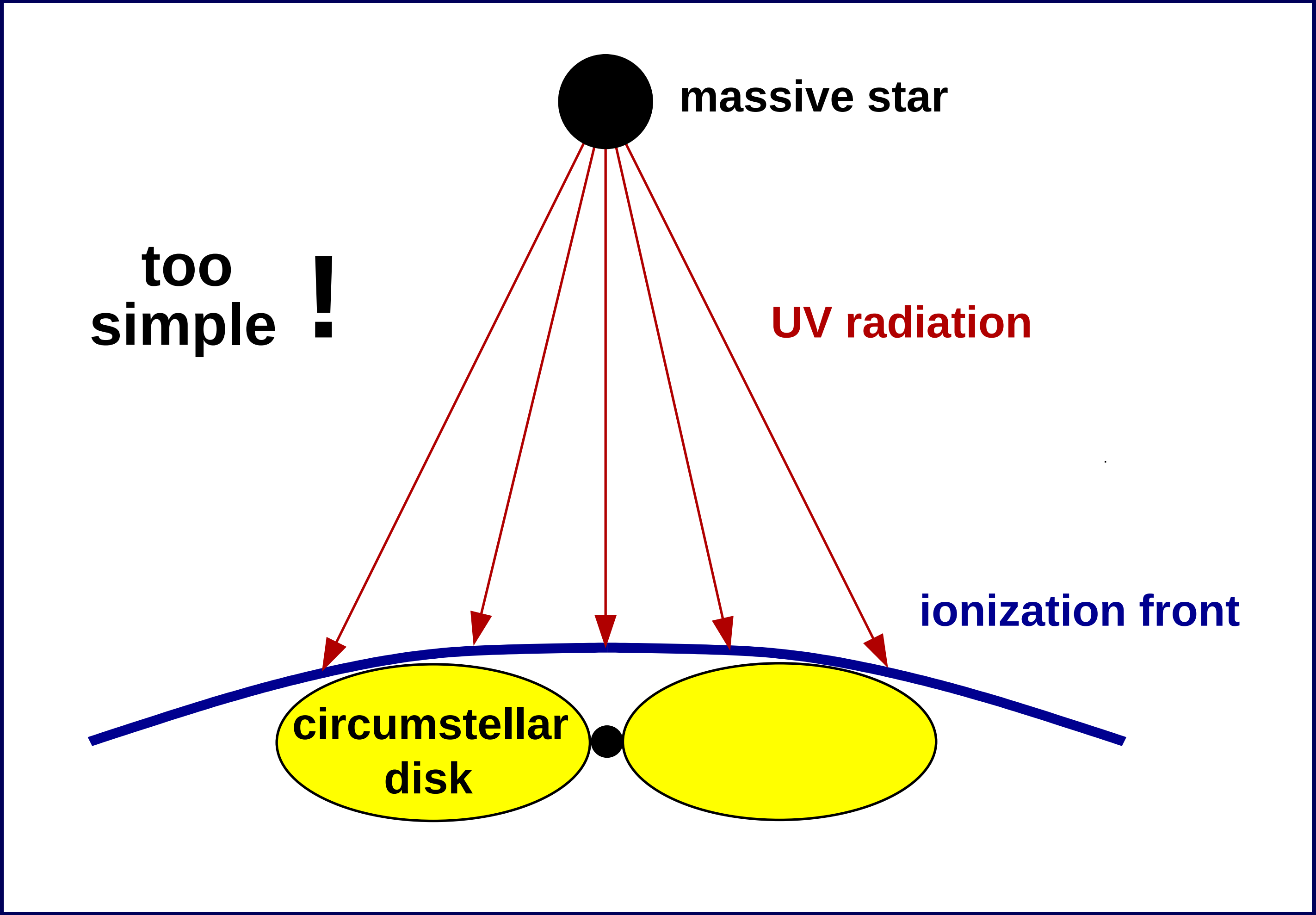
Comparison of proplyds in different environments

star formation region			proplyds		
name	distance kpc	UV photon rate s^{-1}	distance pc	tail size AU	mass loss rate $M_\odot$ yr^{-1}
Orion M42	0.43	10^{49}	0.01–0.15	$\sim$ 500	$\sim 10^{-7}$
Carina Nebula	2.3	10^{51}	$\sim$ 0.1	$<$ 10 000	$\sim 10^{-5}$
NGC 3603	6	10^{51}	1.3–2.2	$\sim$ 20 000	$\sim 10^{-5}$

Possible reasons for difference in size:

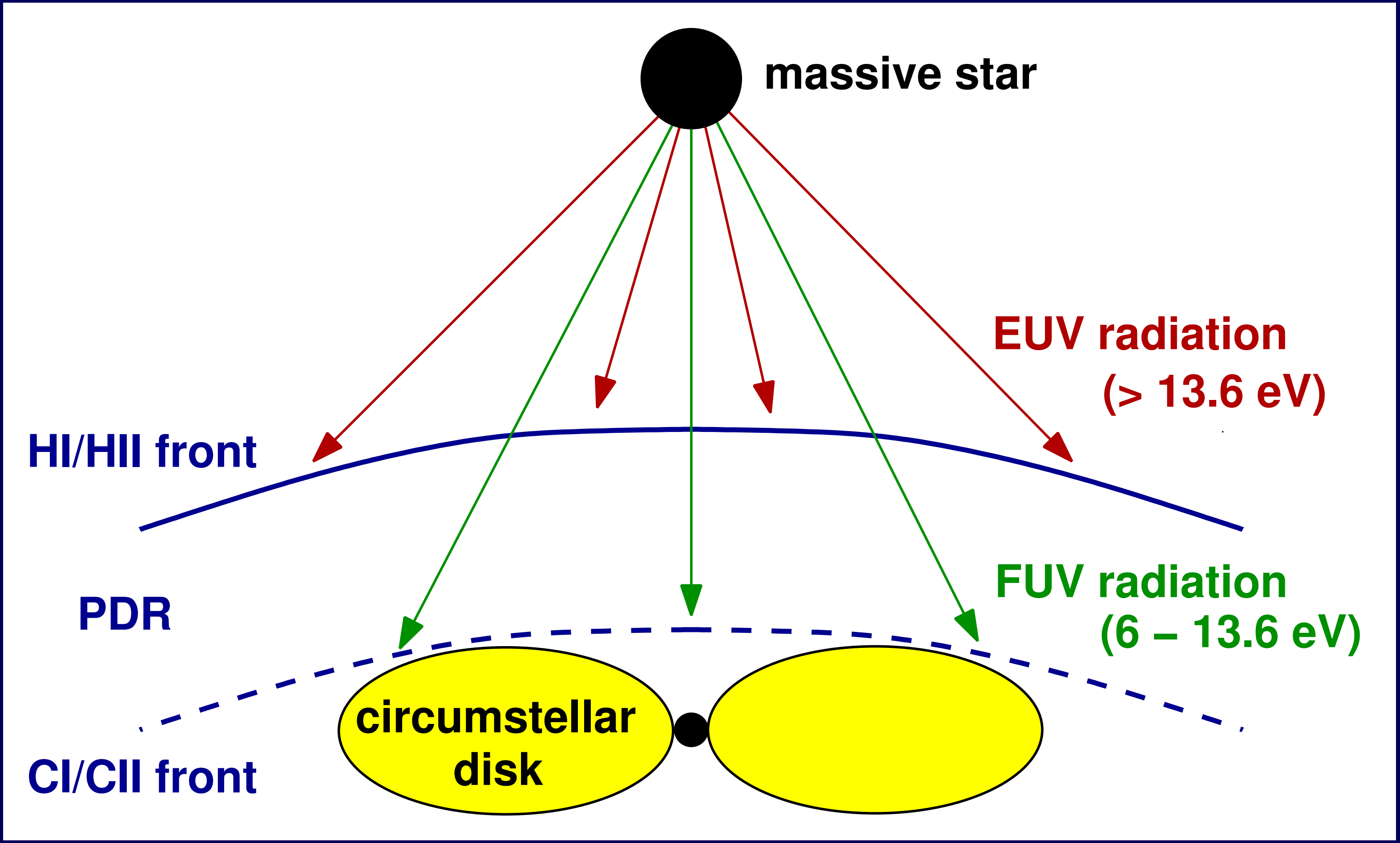
- selection effect
- larger disks, only recently separated from clouds
- FUV/EUV ratio very high

External UV illumination



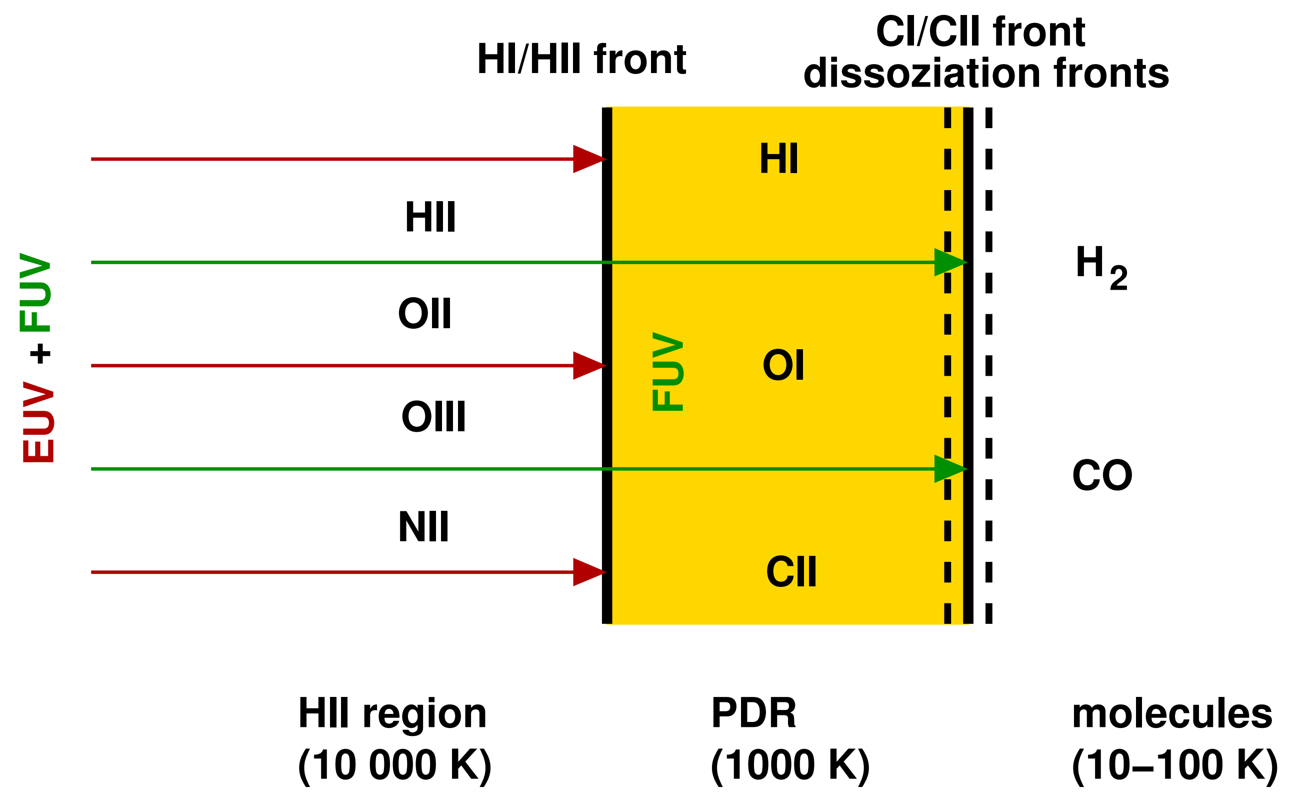
- Hydrogen ionization front directly envelopes the disk
- Lifetime of tails is very short ($\sim 10^4$ yr)

External UV illumination



Simple PDR model

PDR = PhotoDissociation Region or Photon-Dominated Region



PDR heating mechanisms:
photo-electric effect on dust grains, ionization of C, dissociation of molecules

PDR cooling mechanisms:
OI 63 μm, CII 158 μm, H_2 lines

Important radii

Gravitational radius R_g

thermal velocity = escape velocity

$$R_g = \frac{GM}{c_s}$$

$R_g \sim 10$ AU

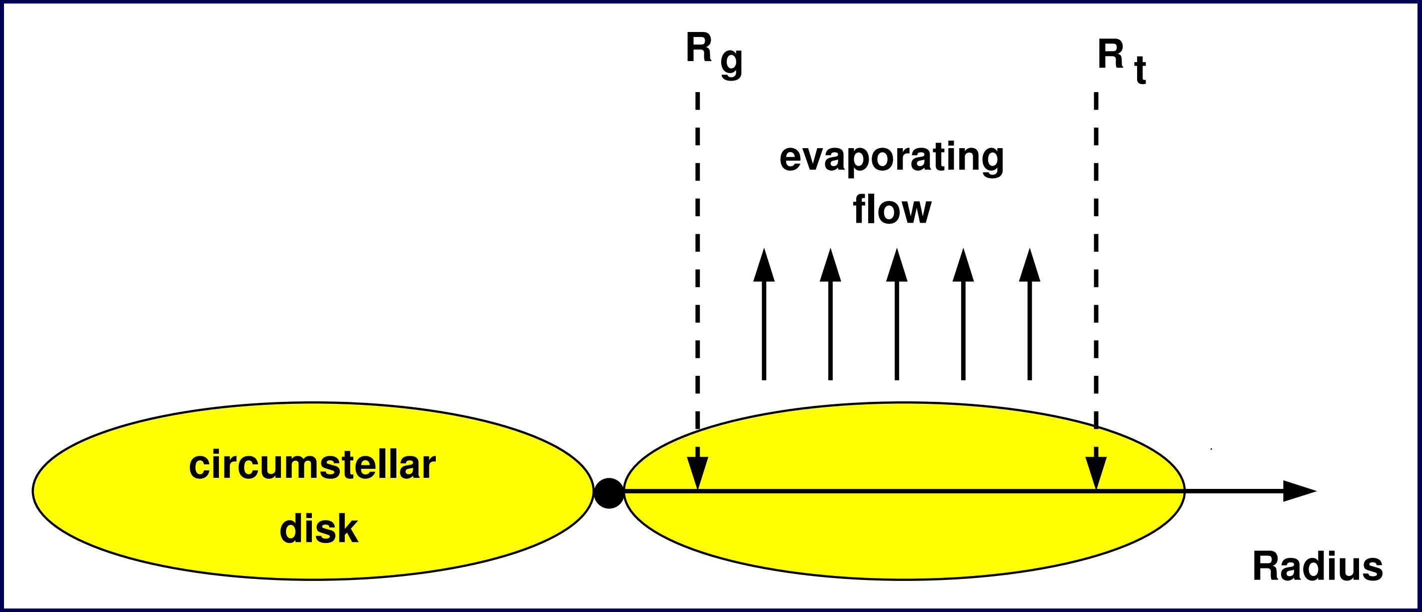
(for $M = 1\ M_\odot$ and $c_s = 3$ km/s)

Truncation radius R_t

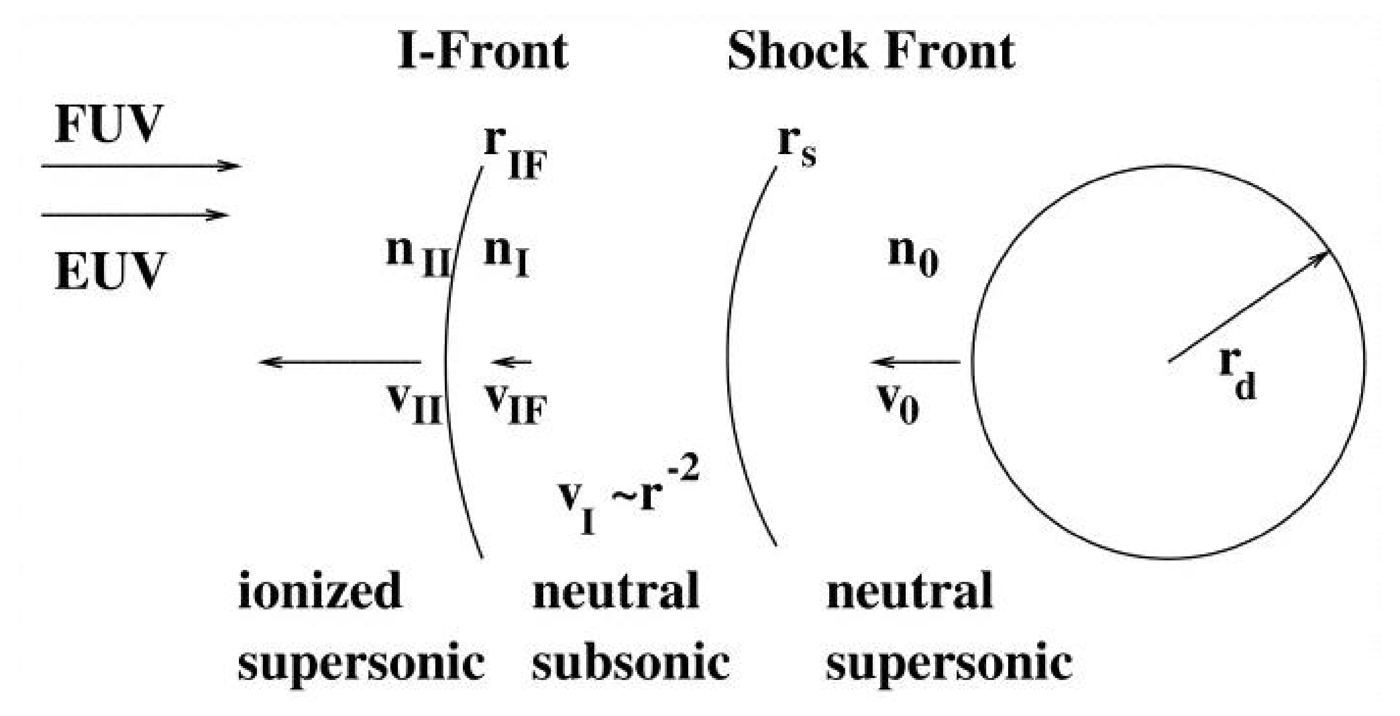
pressure of advancing ionization front = midplane pressure in disk

$R_t \sim 300$ AU

(for $M = 0.5\ M_\odot$, $M_d = 0.1\ M_\odot$, surface density profile $\propto r^{-1.5}$)



FUV dominated flows

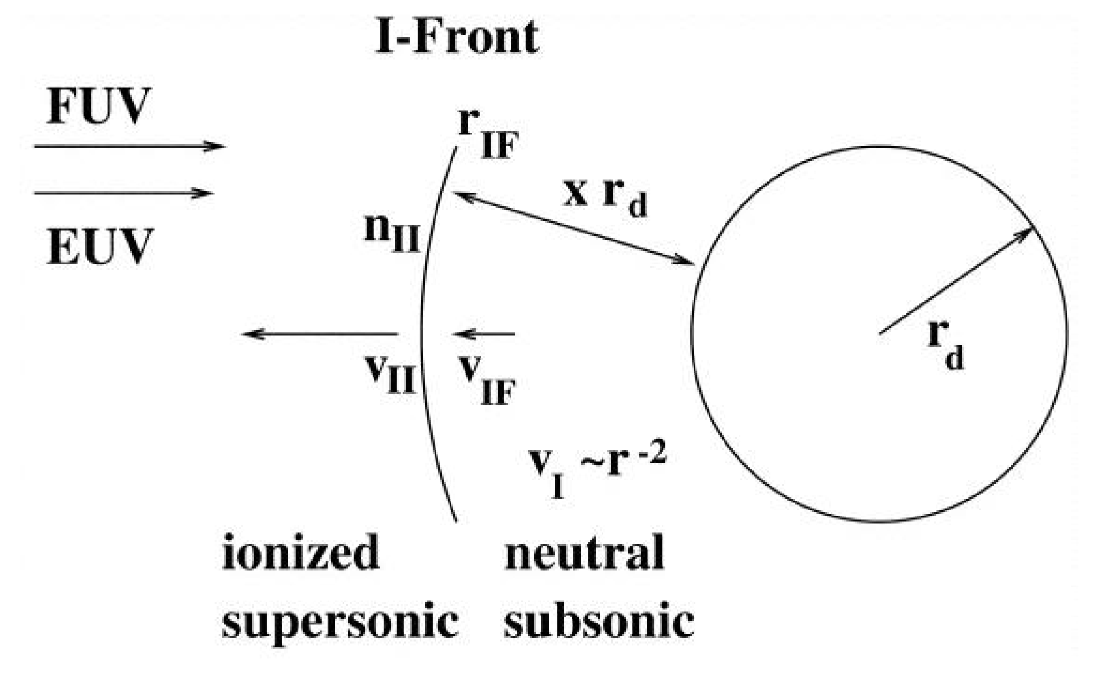


$$\dot{M}_{\rm FUV} = 2 \times 10^{-8}\ {\rm M_\odot\ yr^{-1}} \left(\frac{N_{\rm d}}{5 \times 10^{21}\ {\rm cm^{-2}}}\right) \left(\frac{r_{\rm d}}{10\ {\rm AU}}\right)$$

$N_{\rm d}$: gas column density of the neutral region ($\tau_{\rm FUV} \sim 1$)

(Johnstone et al. 1998, Störzer & Hollenbach 1999)

EUV dominated flows



$$\dot{M}_{\rm EUV} = 7 \times 10^{-9}\ {\rm M_\odot\ yr}^{-1} \left(\frac{\Phi_{\rm EUV}}{10^{49}\ {\rm s}^{-1}}\right)^{0.5} \left(\frac{d}{10^{17}\ {\rm cm}}\right)^{-1} \left(\frac{r_{\rm d}}{10\ {\rm AU}}\right)^{1.5}$$

$\Phi_{\rm EUV}$: EUV photon rate

d: distance to the UV source

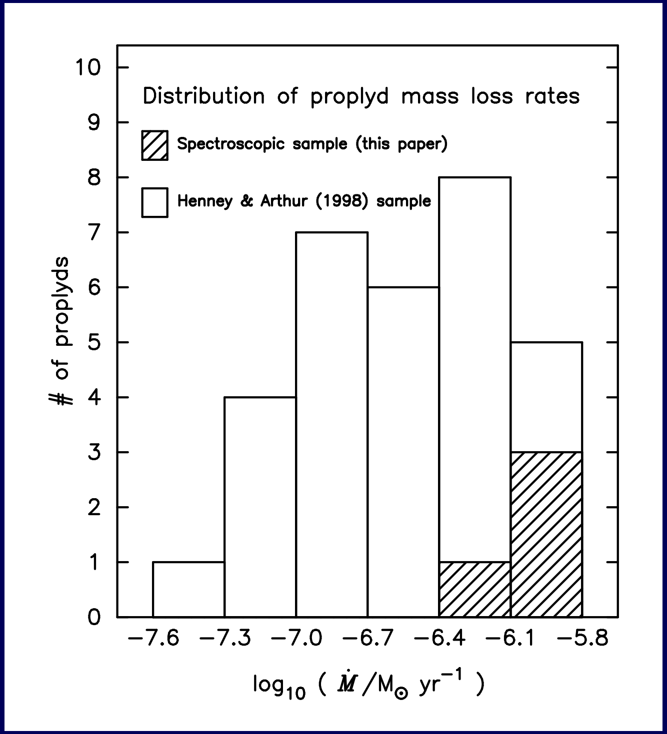
(Johnstone et al. 1998, Störzer & Hollenbach 1999)

Photoevaporation rate and the lifetime of disks

Orion Nebula

$r_\mathrm{d} = 20 – 100$ AU and $d = 0.01 – 0.15$ pc

$\longrightarrow \dot{M}_\mathrm{theory} = 10^{-7} – 10^{-6}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$



Estimated from: $\dot{M}_\mathrm{obs} \sim \pi r^2 m_\mathrm{H} n_\mathrm{e} c$

(Henney & O'Dell 1999)

Lifetime of disks

Photoevaporation time scale: $\tau = M_d/\dot{M}$

But: disk radius is not constant

Assumption: surface density $\Sigma \propto r^{-1.5}$

$M_d(\mathrm{current}) = \dot{M} t_i$

Illumination time $t_i < 10^5$ yr

for $M_d(\mathrm{current}) = 0.01\ \mathrm{M}_\odot$

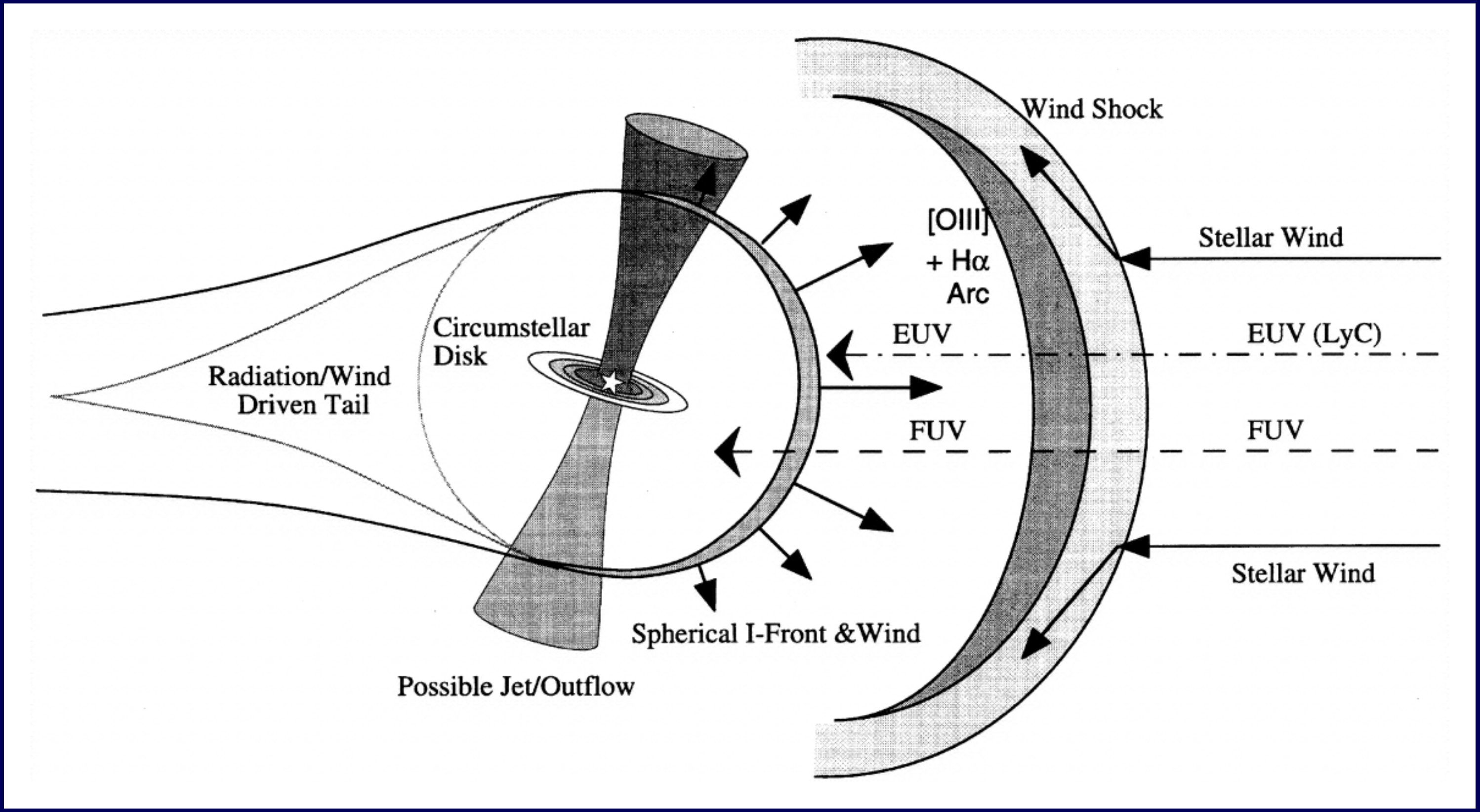
Small in comparison of cluster age $\sim 10^6$ yr

(Johnstone et al. 1998)

Uncertain:

- disk evolution: $\Sigma(r, t)$, $r_\mathrm{d}(t)$
- orbits of low-mass stars in cluster: $d(t)$
- contribution of the dark side of the disk

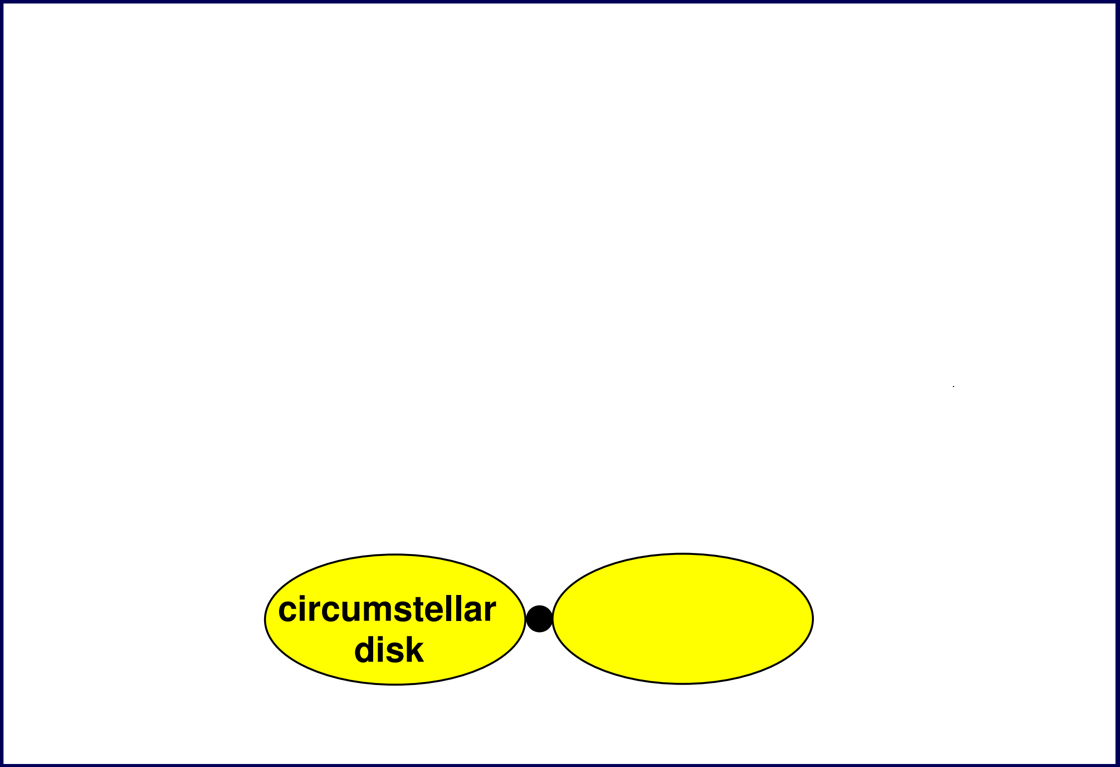
A model for proplyds – The whole picture



- disks at any angle, disks with jets
- formation and evolution of tails
- interaction with external stellar winds
- spectral appearance of photoevaporating disks

→ Numerical simulations

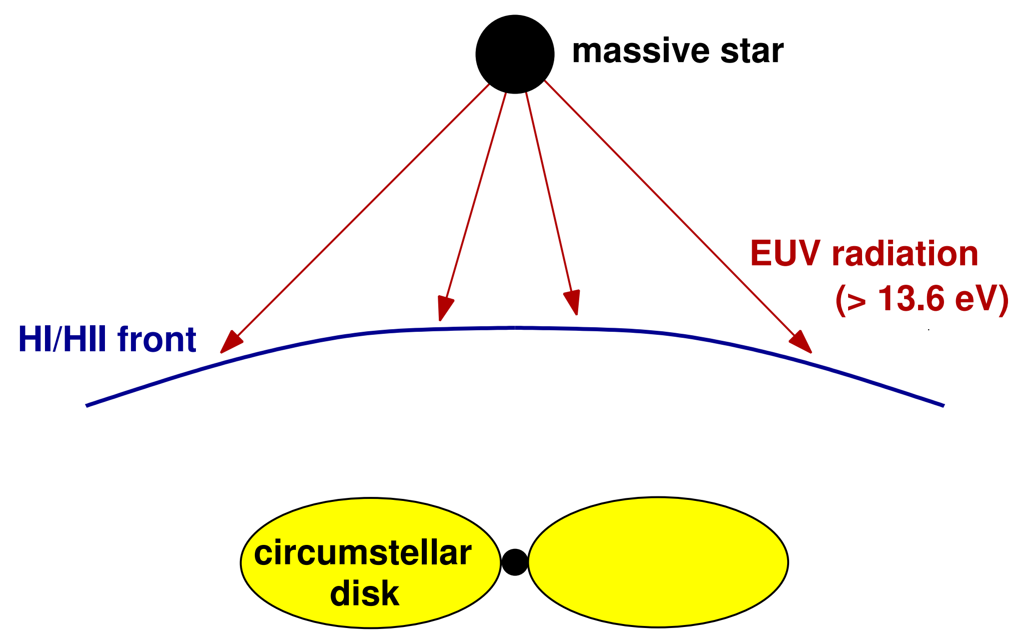
Numerical simulations – Physics



- Hydrodynamics

- hydrodynamics
- self-gravity
- angular momentum transfer
- continuum radiation transfer

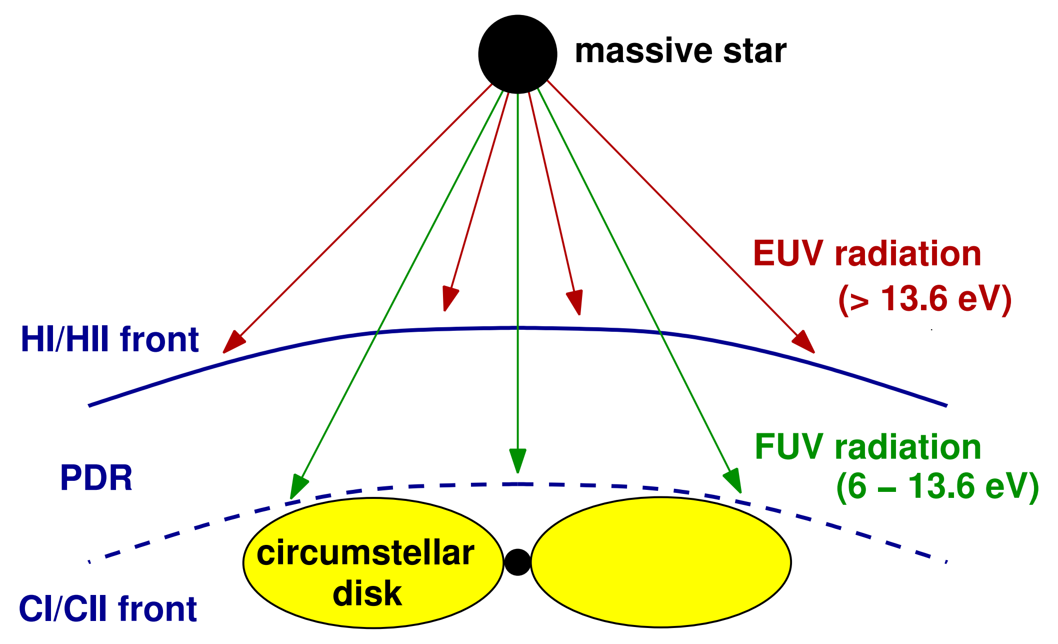
Numerical simulations – Physics



- **Hydrodynamics**
- **EUV radiation**

- transfer of direct EUV photons
- transfer of diffuse EUV photons
- ionization/recombination of hydrogen
- heating/cooling (HII region)

Numerical simulations – Physics



- **Hydrodynamics**
- **EUV radiation**
- **FUV radiation**

- transfer of direct FUV photons
- transfer of diffuse FUV photons
- ionization/recombination of carbon
- heating/cooling (PDR)

Hydrodynamics and continuum radiative transfer

Equation of continuity:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho v_i) = 0$$

Equation of motion:

$$\frac{\partial}{\partial t}(\rho v_i) + \frac{\partial}{\partial x_j}(\rho v_i v_j) = -\frac{\partial p}{\partial x_i} - \rho\frac{\partial \Phi}{\partial x_i} + \rho\frac{\partial T_{ij}}{\partial x_j} + \rho\frac{\kappa F_i}{c}$$

Energy equation:

$$\frac{\partial e}{\partial t} + \frac{\partial}{\partial x_i}(e v_i) = -p\frac{\partial v_i}{\partial x_i} + \rho T_{ij}\frac{\partial v_i}{\partial x_j} - \Lambda_{\mathsf{gas-dust}} + (\Gamma - \Lambda)_{\mathsf{UV}}$$

Equation of state:

$$p = p(\rho, e)$$

Poisson equation:

$$\Delta\Phi = 4\pi G\rho$$

Radiative transfer (dust continuum, grey approximation, isotropic point source):

$$\frac{\partial F_i}{\partial x_i} = \begin{cases} \epsilon & \text{at position of point source} \\ 0 & \text{elsewhere} \end{cases}$$

Direct UV radiation

Transfer equation for integration along lines of sight:

$$\nabla \cdot \mathbf{F}_{\mathsf{star}} = -\chi_{\mathsf{star}}^{\mathsf{ext}} F_{\mathsf{star}}$$

Extinction coefficient for EUV photons:

$$\chi_{\mathsf{star}}^{\mathsf{ext}} = n(1-x)\sigma_{\mathsf{star}} + \kappa_{\mathsf{dust}}^{\mathsf{ext}}$$

Extinction coefficient for FUV photons:

$$\chi_{\mathsf{star}}^{\mathsf{ext}} = n_{\mathsf{C}}(1-x_{\mathsf{C}})\sigma_{\mathsf{C}}^{\mathsf{FUV}} + \kappa_{\mathsf{dust}}^{\mathsf{ext}}$$

Solution for spherical symmetry:

$$F_{\mathsf{star}} = \frac{S_{\mathsf{star}}}{4\pi r^2}\exp(-\tau) \quad \text{mit} \quad \tau = \int \chi_{\mathsf{star}}^{\mathsf{ext}} ds$$

Diffuse UV radiation

Flux-limited diffusion (FLD) approximation (Levermore & Pomraning 1981):

$$\mathbf{F} = -\frac{\lambda c}{\chi^{\text{ext}}} \nabla u$$

Flux-limiter:

$$\lambda = \frac{1}{S}\left(\coth S - \frac{1}{S}\right) \quad \text{and} \quad S = \frac{|\nabla u|}{\chi^{\text{ext}} u}$$

Advantage:

$$\mathbf{F} \longrightarrow \begin{cases} \frac{c\nabla u}{3\chi^{\text{ext}}} & \text{for} \quad S \longrightarrow \infty \quad \text{(optically thick)} \\ cu \cdot \frac{\nabla u}{|\nabla u|} & \text{for} \quad S \longrightarrow 0 \quad \text{(optically thin)} \end{cases}$$

Diffuse UV radiation

$$\frac{\partial u}{\partial t} - \nabla \cdot \left(\frac{\lambda c}{\chi^{\mathsf{ext}}} \nabla u \right) = \epsilon - \chi^{\mathsf{abs}} c u$$

EUV: Recombination of hydrogen into the ground state:

$$\epsilon_{\mathsf{rec}} = \alpha(T_{\mathsf{gas}}) n^2 x^2$$

$$\chi^{\mathsf{ext}}_{\mathsf{rec}} = n(1-x)\sigma_{\mathsf{rec}} + \kappa^{\mathsf{ext}}_{\mathsf{rec}}$$

$$\chi^{\mathsf{abs}}_{\mathsf{rec}} = n(1-x)\sigma_{\mathsf{rec}} + \kappa^{\mathsf{abs}}_{\mathsf{rec}}$$

EUV: Scattering on dust grains:

$$\epsilon_{\mathsf{dust}} = \kappa^{\mathsf{scat}}_{\mathsf{dust}} c u^{\mathsf{EUV}}_{\mathsf{star}} \;,$$

$$\chi^{\mathsf{ext}}_{\mathsf{dust}} = n(1-x)\sigma_{\mathsf{star}} + \kappa^{\mathsf{ext}}_{\mathsf{dust}}$$

$$\chi^{\mathsf{abs}}_{\mathsf{dust}} = n(1-x)\sigma_{\mathsf{star}} + \kappa^{\mathsf{abs}}_{\mathsf{dust}}$$

FUV: Scattering on dust grains:

$$\epsilon_{\mathsf{dust}} = \kappa^{\mathsf{scat}}_{\mathsf{dust}} c u^{\mathsf{FUV}}_{\mathsf{star}}$$

$$\chi^{\mathsf{ext}}_{\mathsf{dust}} = n_{\mathsf{C}}(1-x_{\mathsf{C}})\sigma^{\mathsf{FUV}}_{\mathsf{C}} + \kappa^{\mathsf{ext}}_{\mathsf{dust}}$$

$$\chi^{\mathsf{abs}}_{\mathsf{dust}} = n_{\mathsf{C}}(1-x_{\mathsf{C}})\sigma^{\mathsf{FUV}}_{\mathsf{C}} + \kappa^{\mathsf{abs}}_{\mathsf{dust}}$$

Ionization/Recombination

Rate equation for the degree of ionization of hydrogen x:

photoionization (only EUV photons)

$$\frac{\partial \rho x}{\partial t} + \nabla \cdot (\rho x \mathbf{v}) = \rho(1-x)[\sigma_{\mathrm{star}} u^{\mathrm{EUV}}_{\mathrm{star}} + \sigma_{\mathrm{rec}} u^{\mathrm{EUV}}_{\mathrm{rec}} + \sigma_{\mathrm{star}} u^{\mathrm{EUV}}_{\mathrm{dust}}]c$$

$$+\rho C(T) n x(1-x) - \rho \alpha_{\mathrm{A}}(T) n x^2$$

collisional ionization recombination

Rate equation for the degree of ionization of carbon x_{C}:

photoionization (EUV and FUV photons)

$$\frac{\partial x_{\mathrm{C}}}{\partial t} = (1 - x_{\mathrm{C}}) \left[\sigma^{\mathrm{FUV}}_{\mathrm{C}} (u^{\mathrm{FUV}}_{\mathrm{star}} + u^{\mathrm{FUV}}_{\mathrm{dust}}) + \sigma^{\mathrm{EUV}}_{\mathrm{C}} (u^{\mathrm{EUV}}_{\mathrm{star}} + u^{\mathrm{EUV}}_{\mathrm{rec}} + u^{\mathrm{EUV}}_{\mathrm{dust}}) \right] c$$

$$-\alpha_{\mathrm{C}} x_{\mathrm{C}} n_{\mathrm{e}}$$

recombination

Heating/Cooling

region	main heating mechanism	main cooling mechanism
HII region	photoionization $\Gamma = n(1-x)\sigma c u[\langle h\nu\rangle_\sigma - 13.6\,\text{eV}]$	radiative cooling [OIII],[OII],[NII] $\Lambda_{\nu_{ij}} = n_i A_{ij} h\nu_{ij}$
PDR	photo-electric effect on dust grains $\Gamma = 10^{-24}\eta\, G_0\, n\ \text{erg s}^{-1}$ $\eta(T, G_0, n_e)$: efficiency	radiative cooling [OI],[CII] $\Lambda = n_i A_{ij} h\nu_{ij} \beta_{\text{esc}}(\tau_{ij})$ β_{esc}: escape probability

Numerical methods

RHD-Program EXTERN

RHD-Package

- explicit 2D hydrodynamics (method of nested grids)
- angular momentum transfer
- self-gravity
- wind generator for stellar wind
- continuum radiation transfer

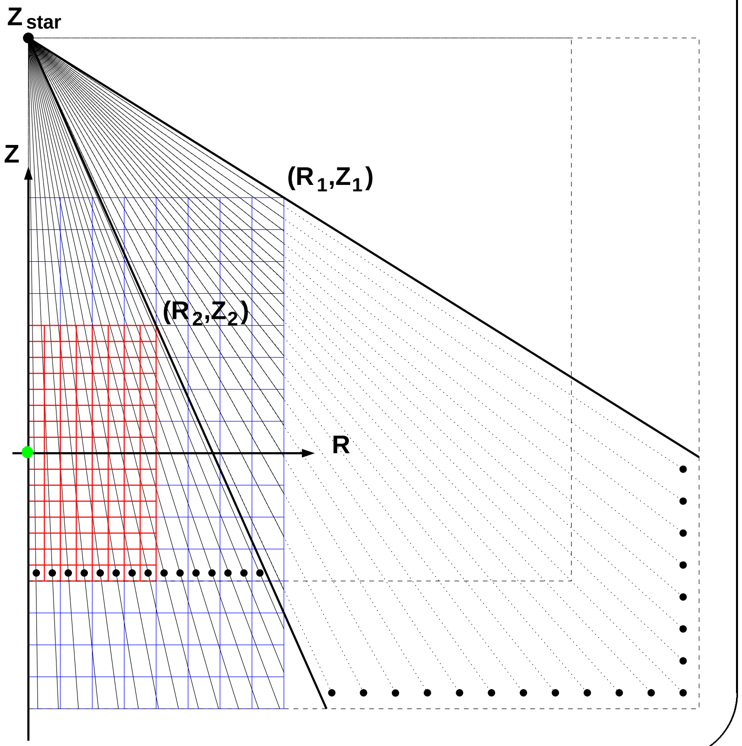
EUV-Package

- transfer of direct EUV photons along lines of sight
- transfer of diffuse EUV photons (recombination of H)
- transfer of diffuse EUV photons (dust scattering)
- ionization/recombination of H
- heating/cooling (T ~10000 K)

FUV-Package

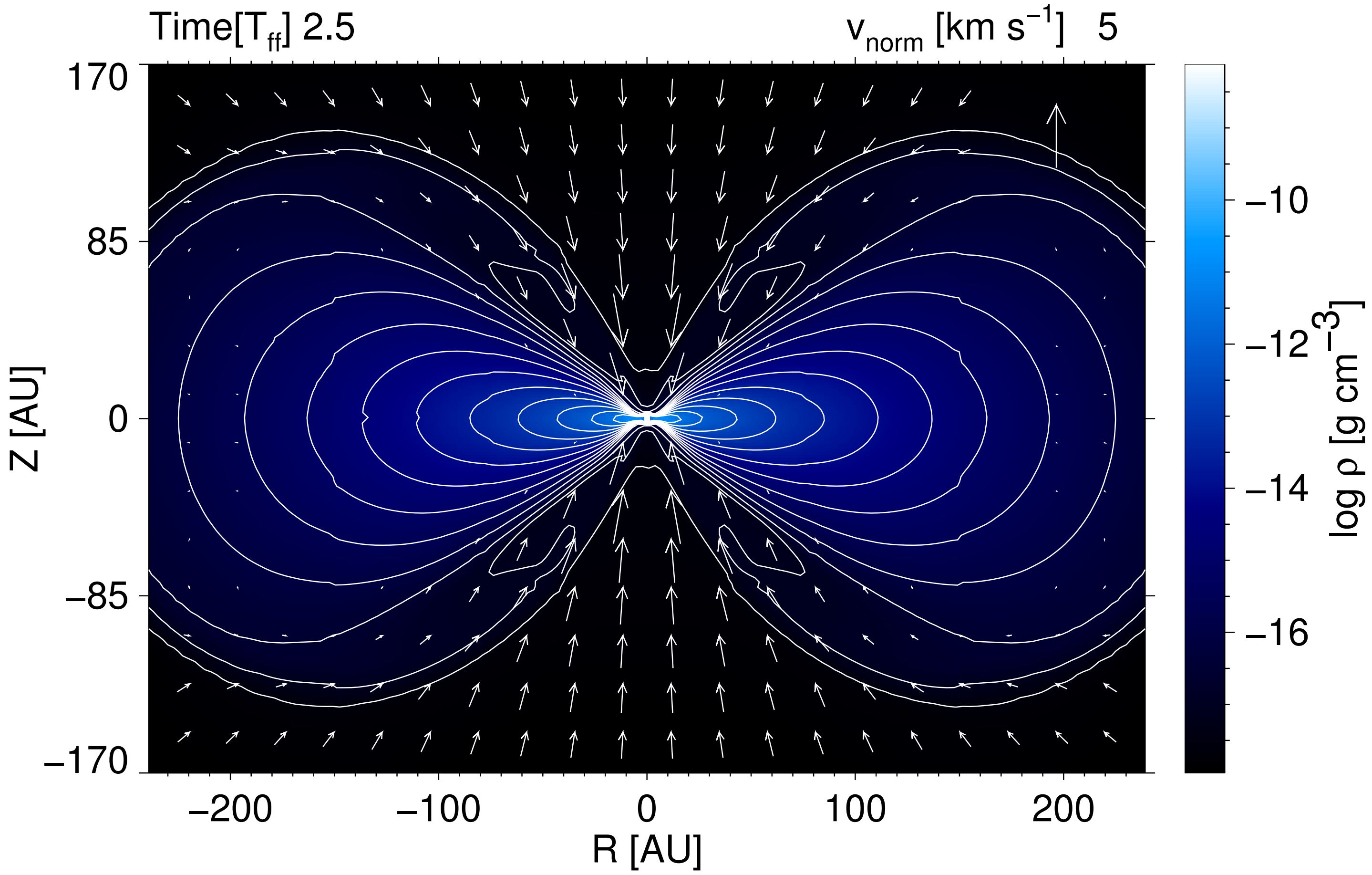
- transfer of direct FUV photons along lines of sight
- transfer of diffuse FUV photons (dust scattering)
- ionization/recombination of C
- heating/cooling (T ~1000 K)

Grid architecture and lines of sight arrangement

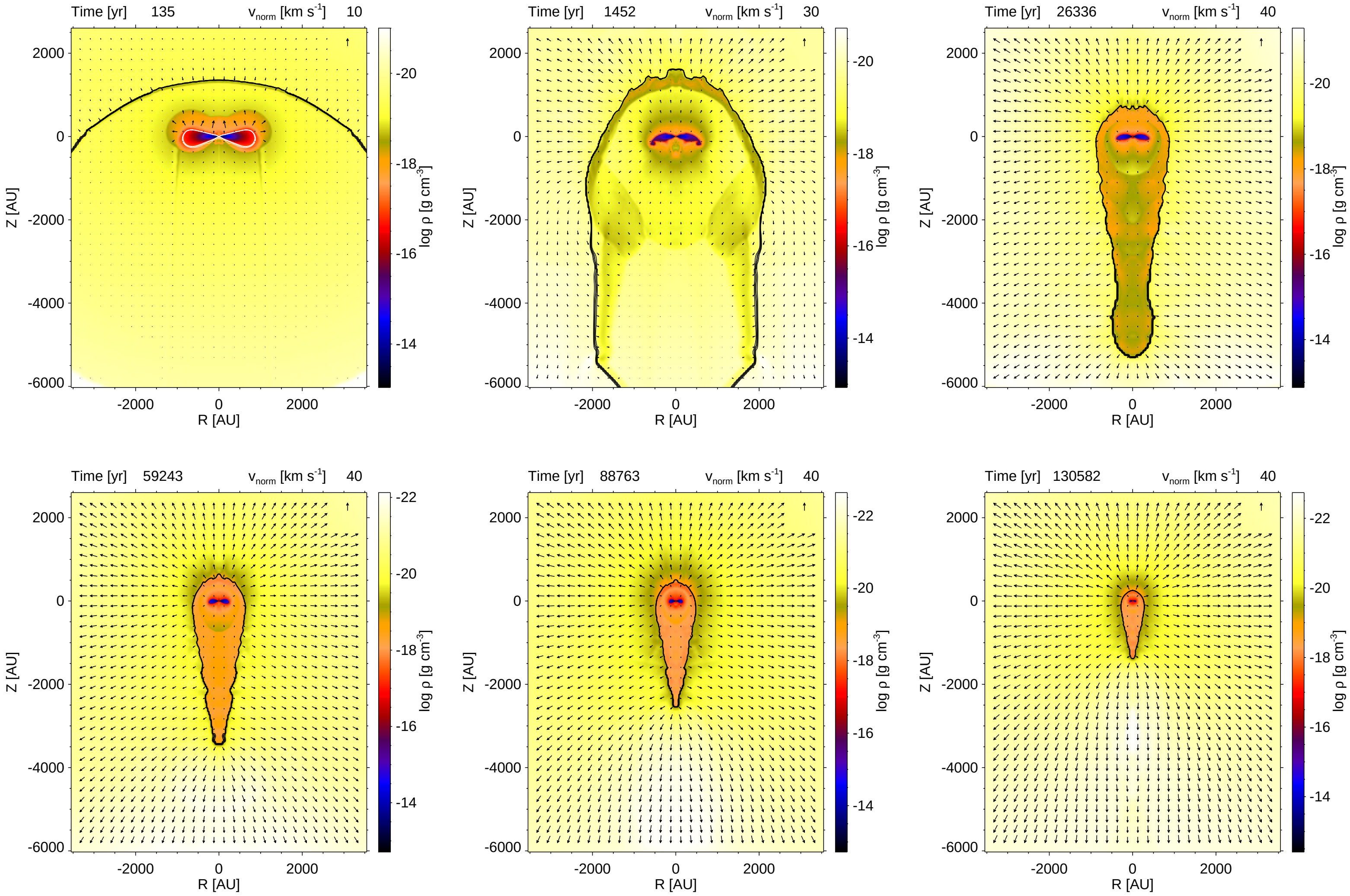


Initial star-disk models

Results from collapse simulations (e.g. Yorke & Bodenheimer 1999):



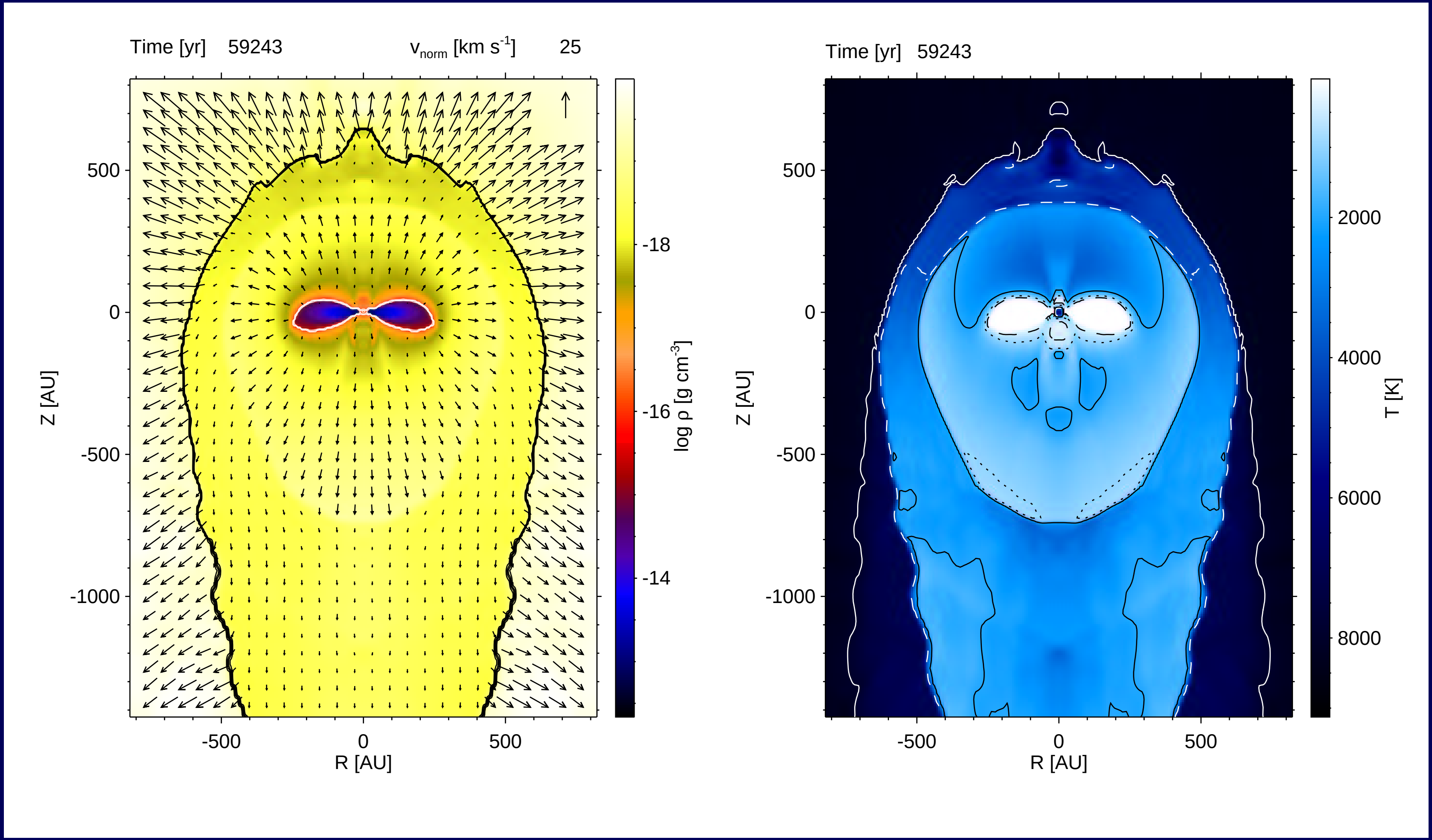
External UV illumination – Evolution



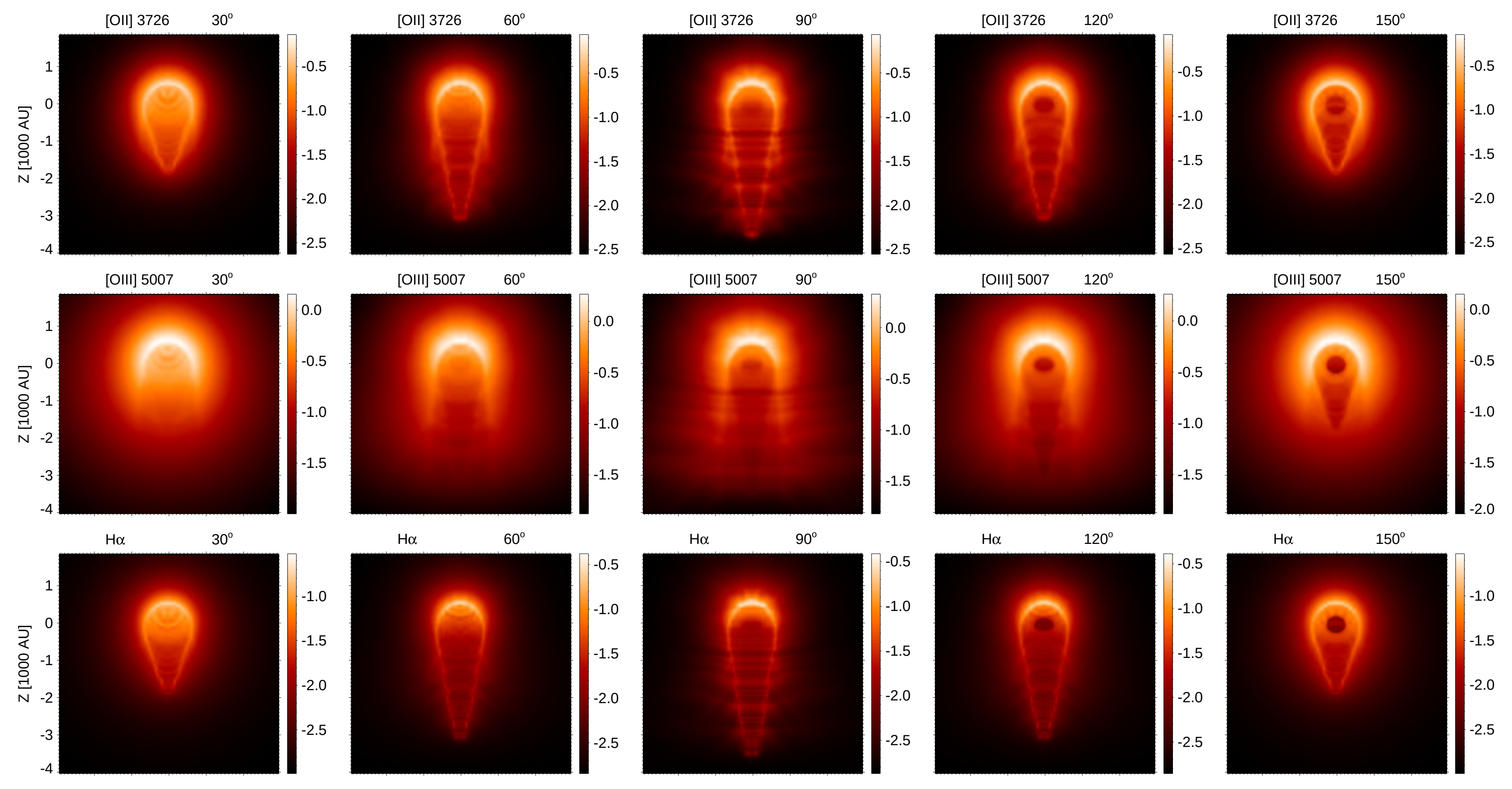
External UV illumination – Head of object

Density

Temperature

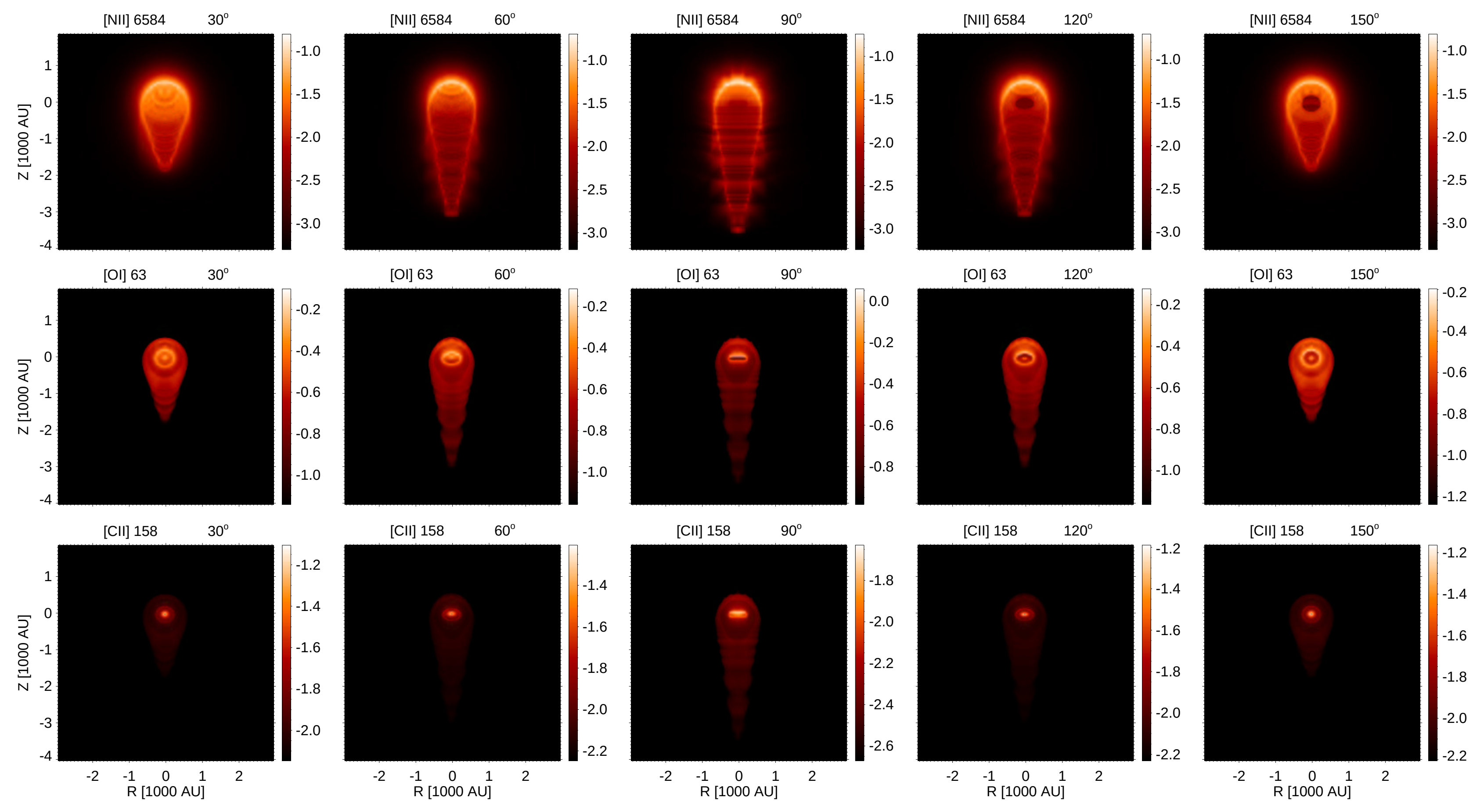


Comparison with observations – Emission lines



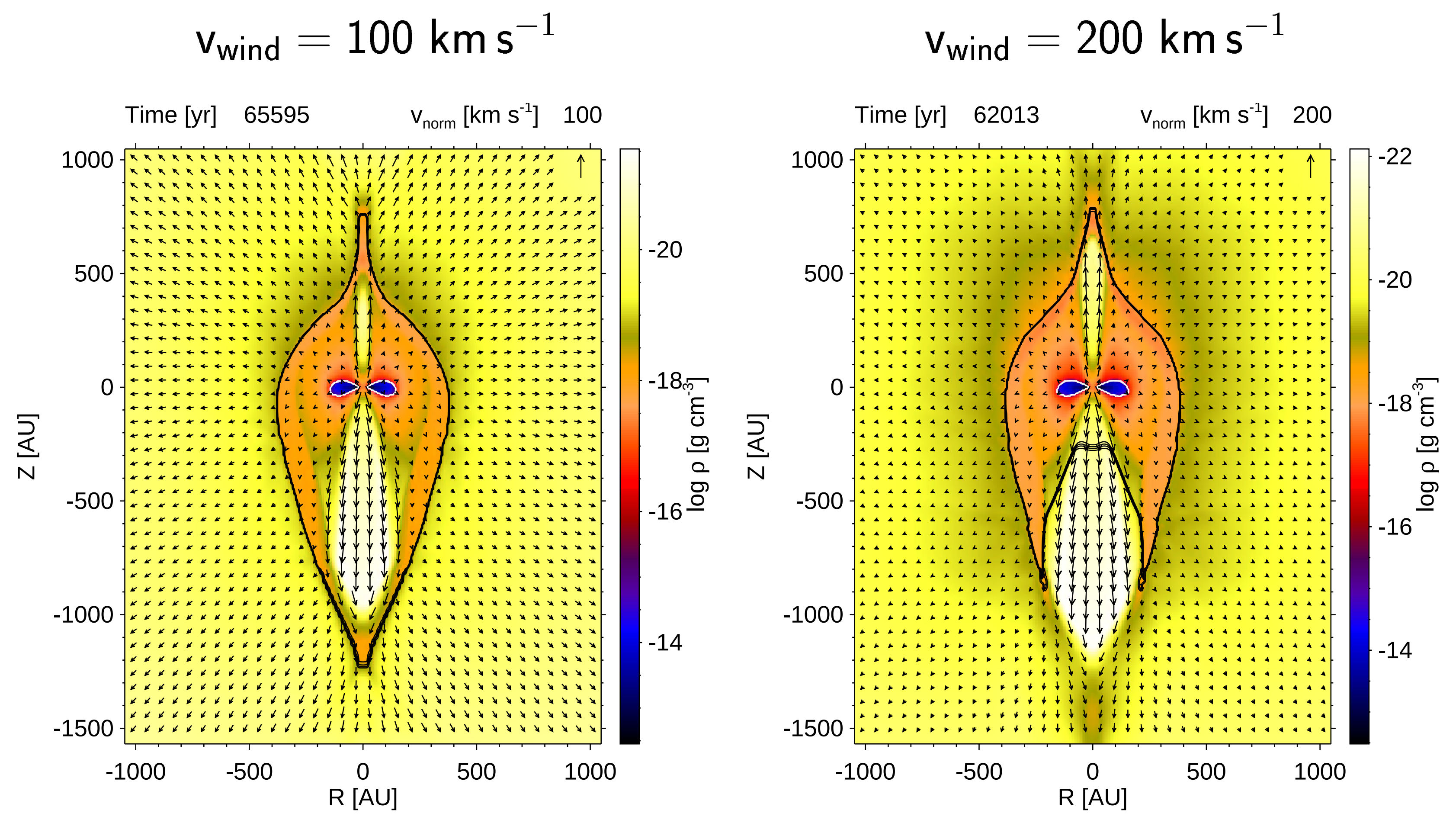
Richling & Yorke (2000)

Comparison with observations – Emission lines

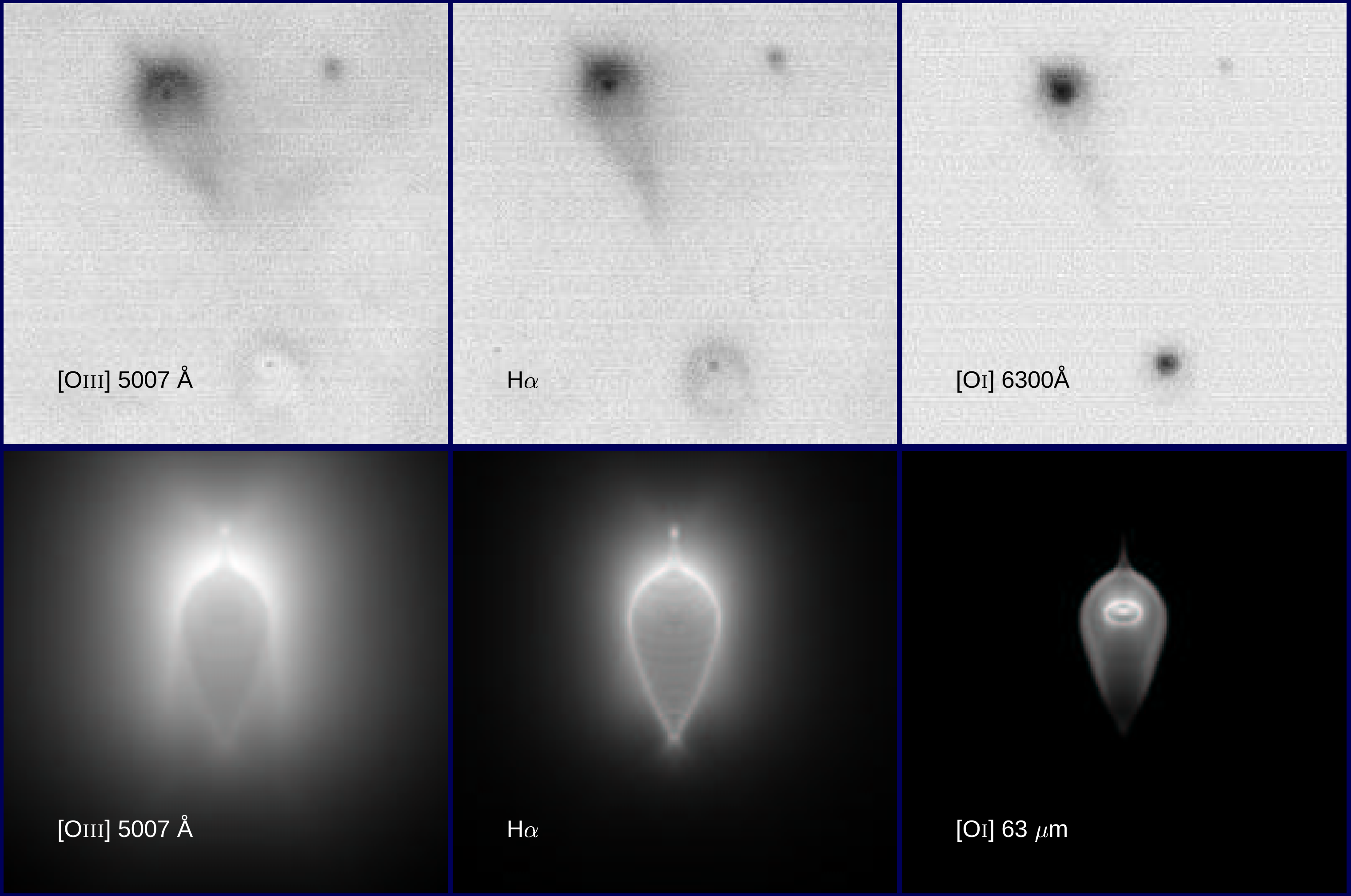


Richling & Yorke (2000)

Influence of stellar winds



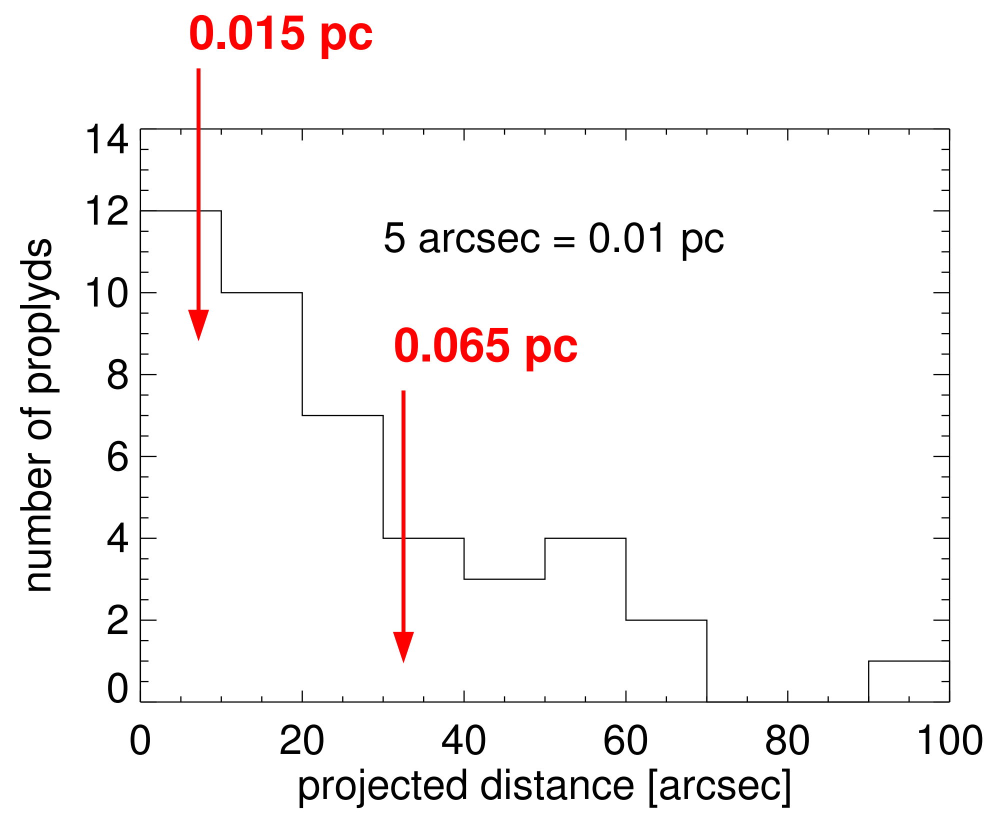
Influence of stellar winds – Micro-jets



Distance from ionizing source

Orion Nebula

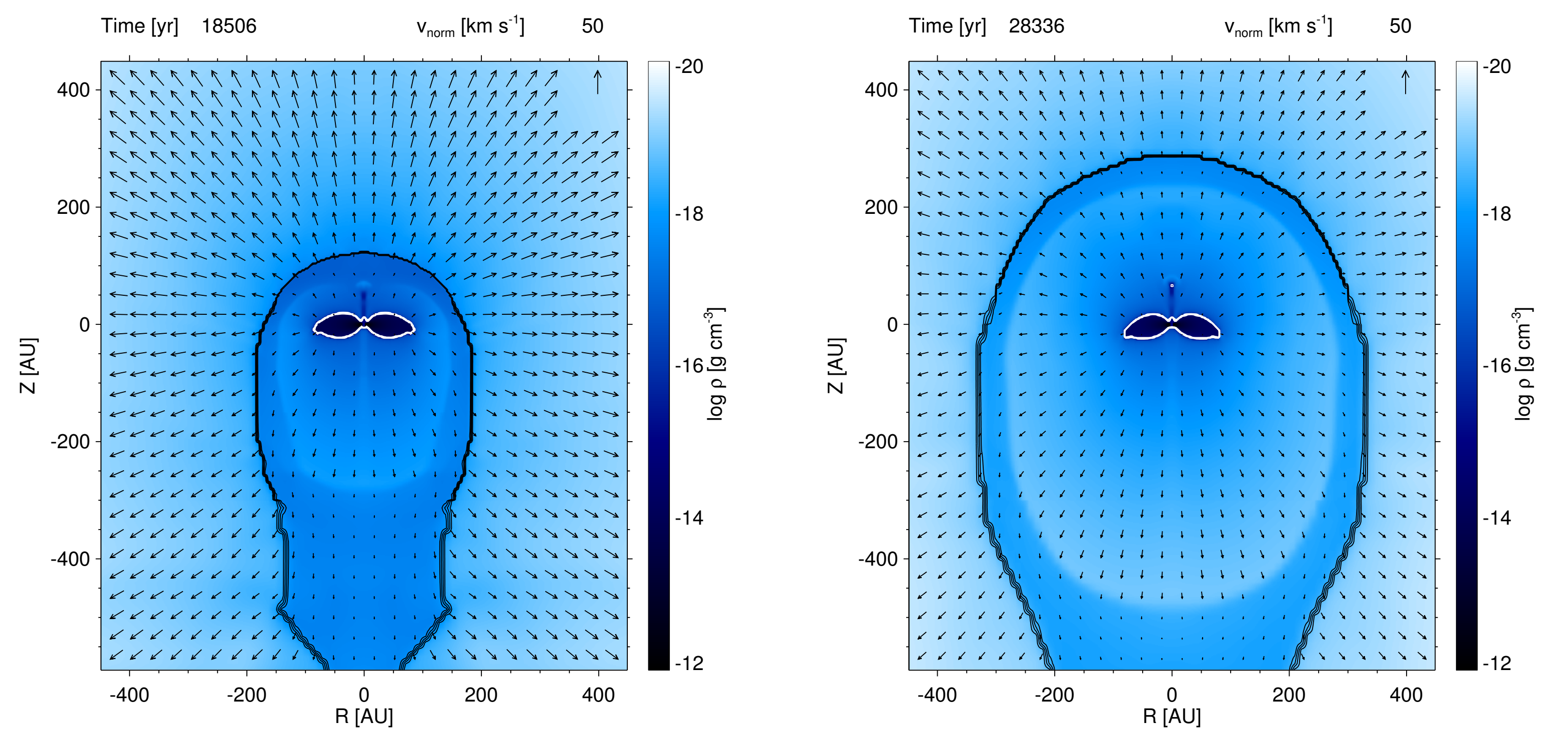
UV photon rate: $\Phi_{\rm UV} = 1.5{\rm x}10^{49}\ {\rm s}^{-1}$



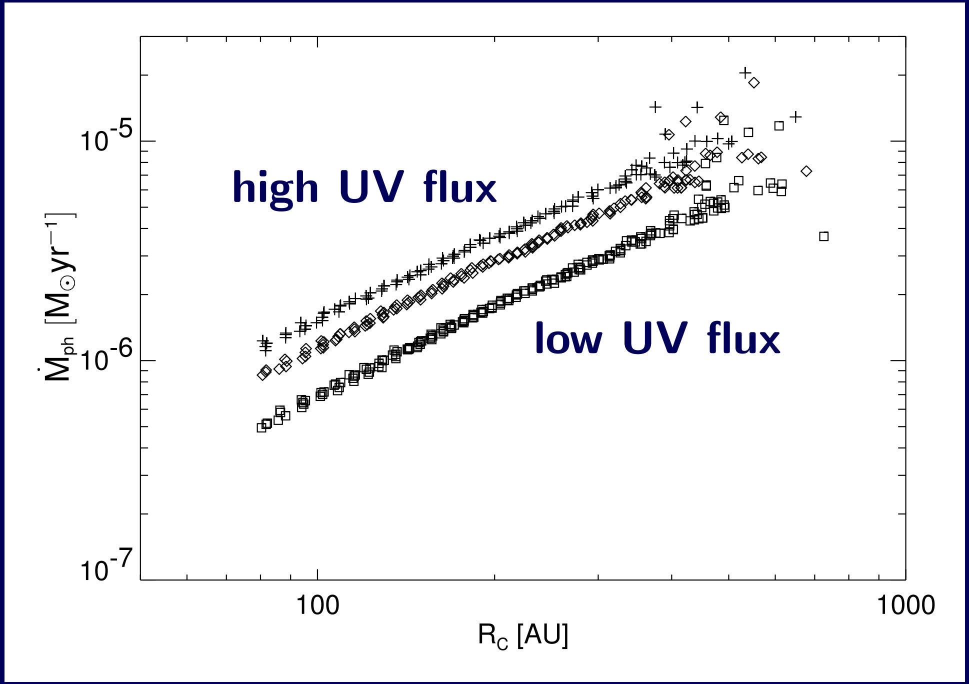
Distance from ionizing source

EUV-dominated flow

FUV-dominated flow



Photoevaporation rate



EUV dominated: $\dot{M} \propto r^{1.5}$

$\longrightarrow$ Simulations: $\dot{M} \propto r^{1.25}$

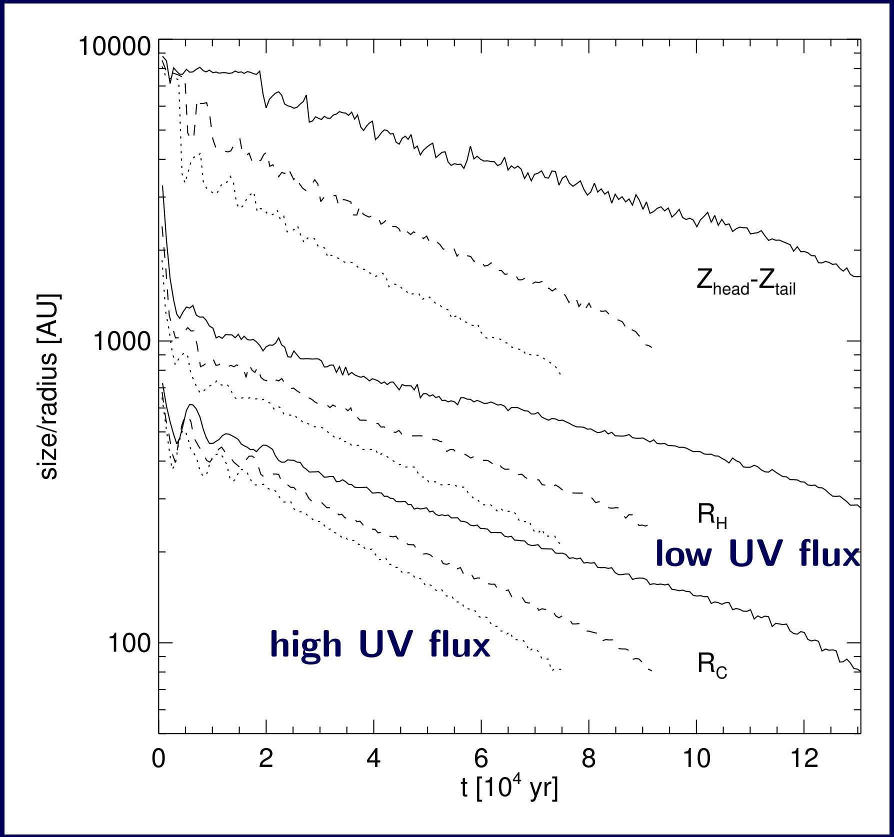
FUV dominated: $\dot{M} \propto r^{1.0}$

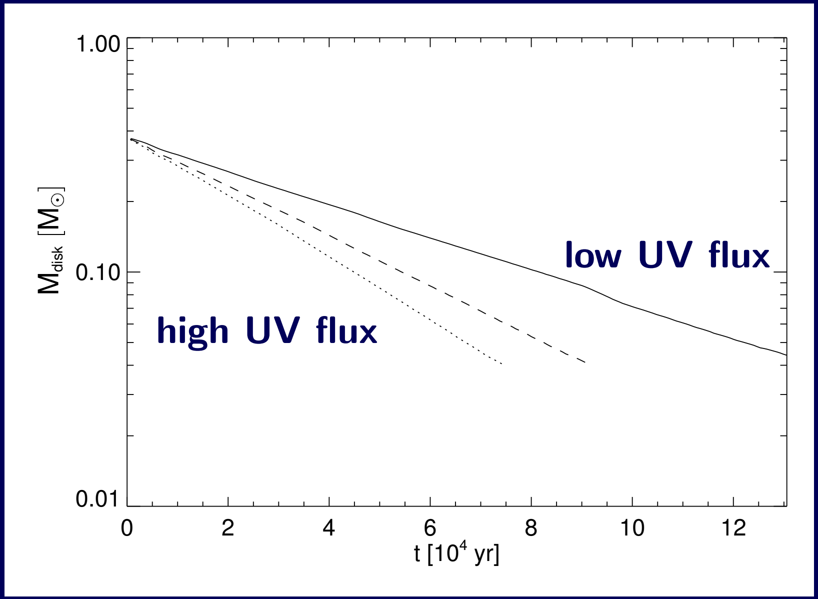
$$\dot{M} = 1.6 \times 10^{-6}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1} \left(\frac{d}{10^{17}\ \mathrm{cm}}\right)^{-0.75} \left(\frac{r_\mathrm{d}}{100\ \mathrm{AU}}\right)^{1.25}$$

for log $\Phi_{\mathrm{EUV}} = 48.89$ and log $\Phi_{\mathrm{FUV}} = 49.25$

$\longrightarrow$ $\dot{M} = 10^{-7}$ – 10^{-6} $\mathrm{M}_\odot\ \mathrm{yr}^{-1}$ for Orion proplyds

Time-dependent photoevaporation





- ⟶ Radius decreases with time
- ⟶ Photoevaporation from “outside in”
- ⟶ Photoevaporation time scale increases

$M(t) = M_0(t) \times \exp(-t/\tau)$

$\tau_{1/10} \sim 10^5$ yr

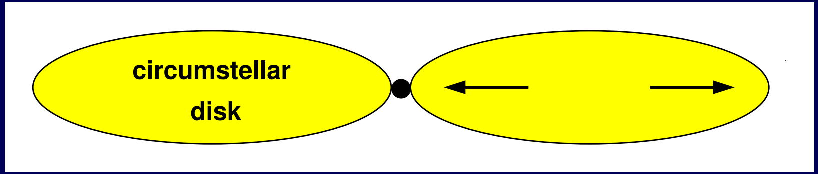
in agreement with semi-analytical calculations

Photoevaporation and viscous accretion

Angular momentum transfer

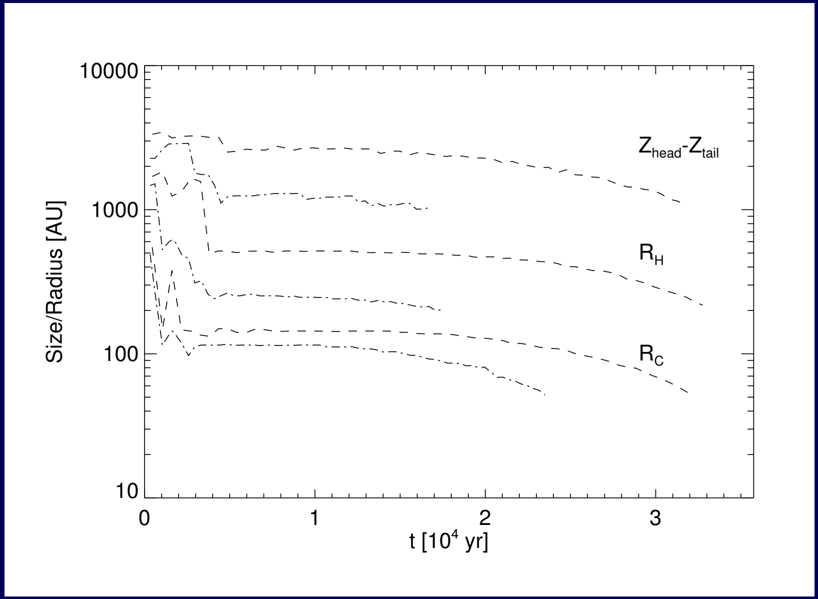
Redistribution of angular momentum:

- Inner material moves closer to the star
- Outer material spreads out



Photoevaporation and accretion

- Disk radius decreases more slowly

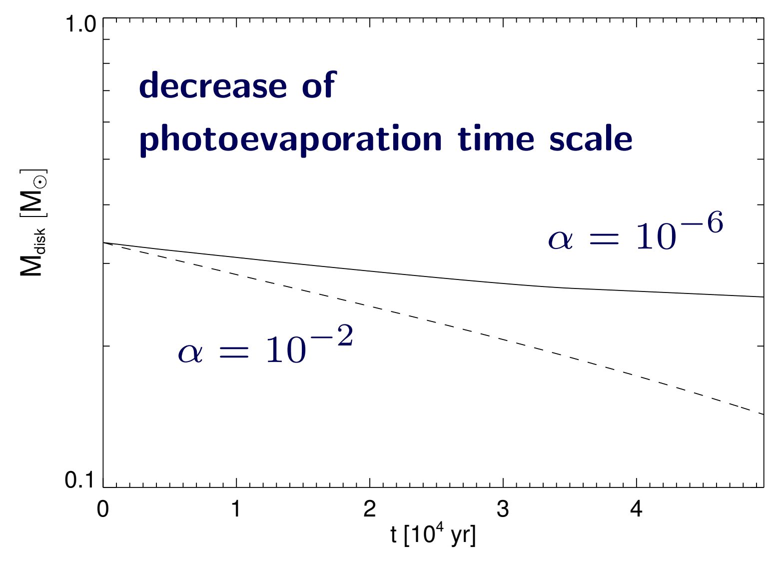


"α–prescription" (Shakura & Sunyaev 1973)

viscosity coefficient: $\nu \propto \alpha H c_s$

(H: scale height, c: sound speed)

$$T_{ij} = \nu \left[\frac{1}{2} \left(\frac{\partial v_j}{\partial x_i} + \frac{\partial v_i}{\partial x_j} \right) - \frac{1}{3} \delta_{ij} \frac{\partial v_i}{\partial x_i} \right]$$



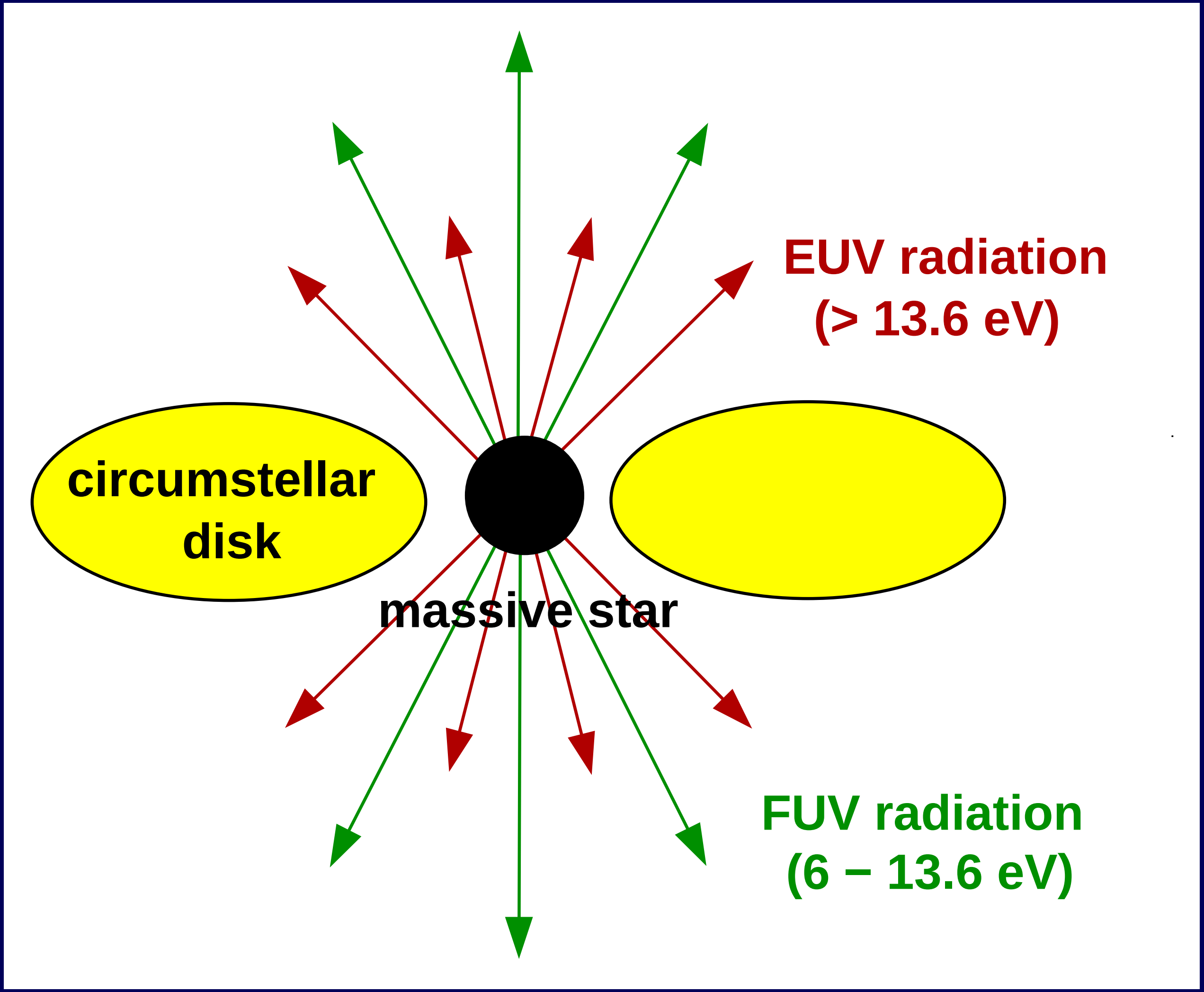
1D study (Matsuyama et al. 2003)

Photoevaporation and accretion destroy entire disk

external FUV radiation: $10^6 - 10^7$ yr

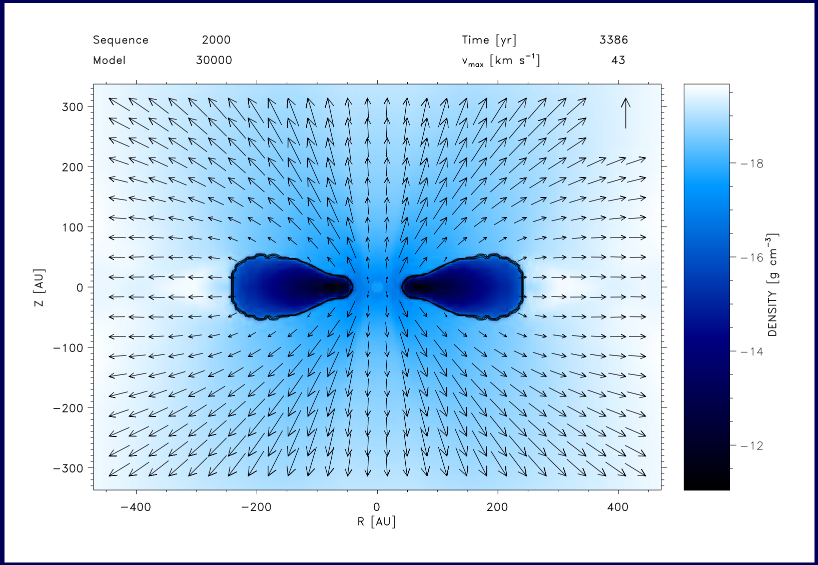
external EUV radiation: $10^5 - 10^6$ yr

Photoevaporation from the central star



Photoevaporation from the central star

EUV radiation:



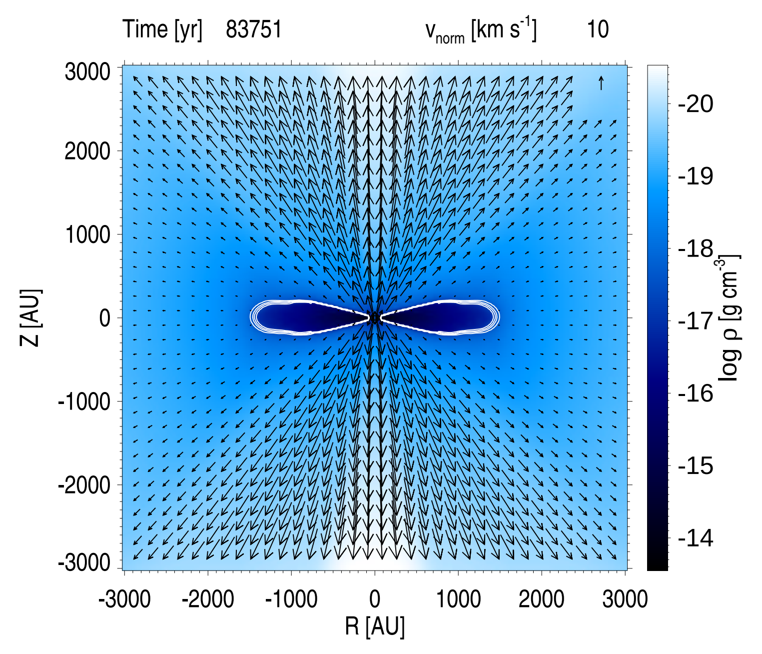
(Richling & Yorke 1997)

Important for massive stars (> 8 M$_\odot$)
$\longrightarrow$ formation of UCHII regions

$$\dot{M} = 4\times10^{-10}\ \mathrm{M_\odot\ yr^{-1}} \left(\frac{\Phi_{\rm EUV}}{10^{41}\ \mathrm{s^{-1}}}\right)^{0.5} \left(\frac{M_\star}{\mathrm{M_\odot}}\right)^{0.5}$$

(Hollenbach et al. 1994)

FUV radiation:



New Simulation:

2.5 M$_\odot$, log $\Phi_{\rm FUV}$=44.68, log $\Phi_{\rm FUV}$=45.17

$\longrightarrow\ \dot{M} = 5.4 \times 10^{-6}$ M$_\odot$ yr^{-1}

Important for low-mass stars?

Other disk dispersal mechanisms

- viscous accretion onto the central source

$$\tau_{\mathsf{acc}} = 10^5\ \mathsf{yr}\ \left(\frac{\alpha}{0.01}\right)^{-1}\left(\frac{r}{10\ \mathsf{AU}}\right)$$

- internal photoevaporation

$$\tau_{\mathsf{ph}} = 10^7\ \mathsf{yr}\ \left(\frac{\Phi_{\mathsf{EUV}}}{10^{41}\ \mathsf{s}^{-1}}\right)^{-1/2}\left(\frac{\Sigma_0}{\Sigma_{\mathsf{min}}}\right)$$

- close stellar encounters (dense clusters)

$$\tau_{\mathsf{se}} = 2\times 10^7\ \mathsf{yr}\ \left(\frac{n_\star}{10^4\ \mathsf{pc}^{-3}}\right)^{-1}\left(\frac{v}{1\ \mathsf{km\ s}^{-1}}\right)^{-1}\left(\frac{r}{100\ \mathsf{AU}}\right)^{-2}$$

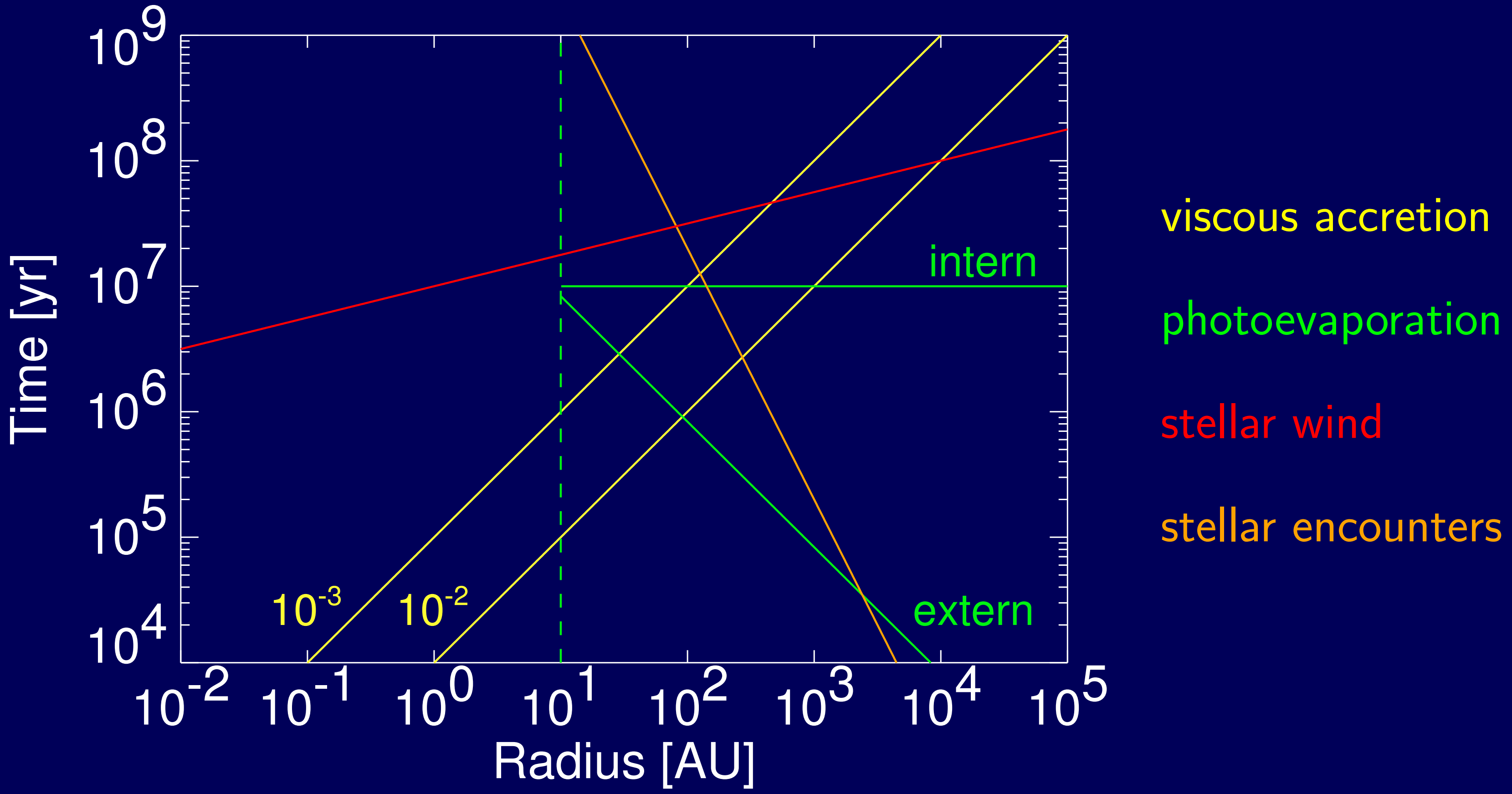
- stellar winds (early evolutionary phases)

$$\tau_{\mathsf{sw}} = 10^7\ \mathsf{yr}\ \left(\frac{r}{1\ \mathsf{AU}}\right)^{1/4}\left(\frac{\epsilon(\sin\theta)^2}{10^{-4}}\right)^{-1}\left(\frac{M_{\mathsf{d}}}{M_{\mathsf{min}}}\right)\left(\frac{v}{100\ \mathsf{km\ s}^{-1}}\right)^{-1}\left(\frac{\dot{M}_{\mathsf{w}}}{10^{-8}\ \mathsf{M}_\odot\ \mathsf{yr}^{-1}}\right)^{-1}$$

(Hollenbach et al. 2000)

Comparison of disk dispersal time scales

Trapezium conditions, $M_{\mathrm{d}} = 0.01\ \mathrm{M}_\odot$, radial orbits



Implications for the formation of the solar system

R $< \sim$ 10 AU: viscous accretion

R $> \sim$10 AU: photoevaporation

$$\mathrm{R_g} = \frac{\mathrm{G}M}{c_s}$$

Jupiter, Saturn
Rock-ice cores: 15 $\mathrm{M_E}$
H/He envelope: $\sim$300, 75 $\mathrm{M_E}$

Uranus, Neptune
Rock-ice cores: 15 $\mathrm{M_E}$
H/He envelope: ~ 2 $\mathrm{M_E}$

Planet formation via core accretion?

Rapid planet formation?

Boss (2003): timescale $\tau = 10^4$ yr
gravitaionally bound clumps evolve in a
marginally graviationally unstable disk