I 24

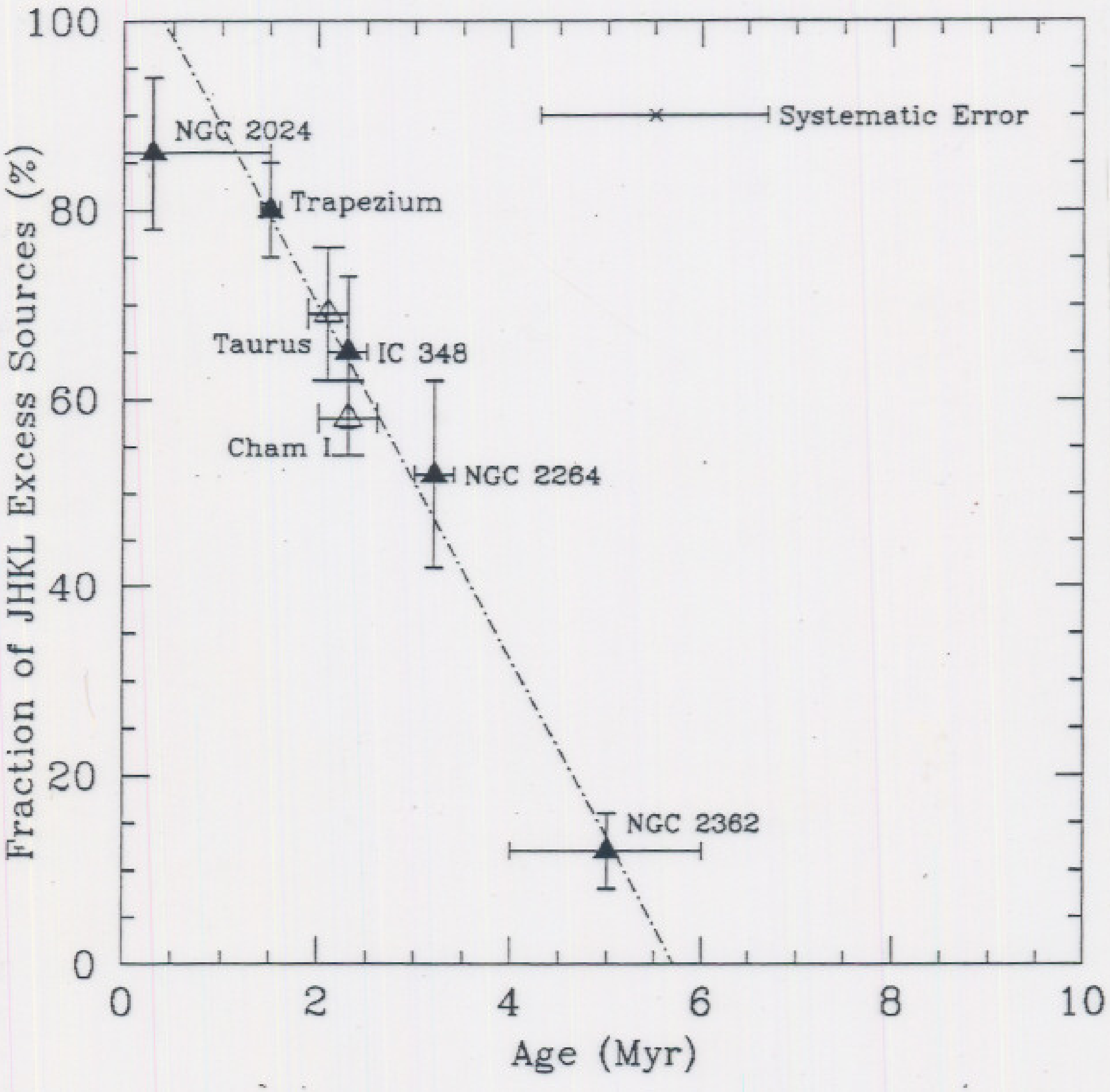
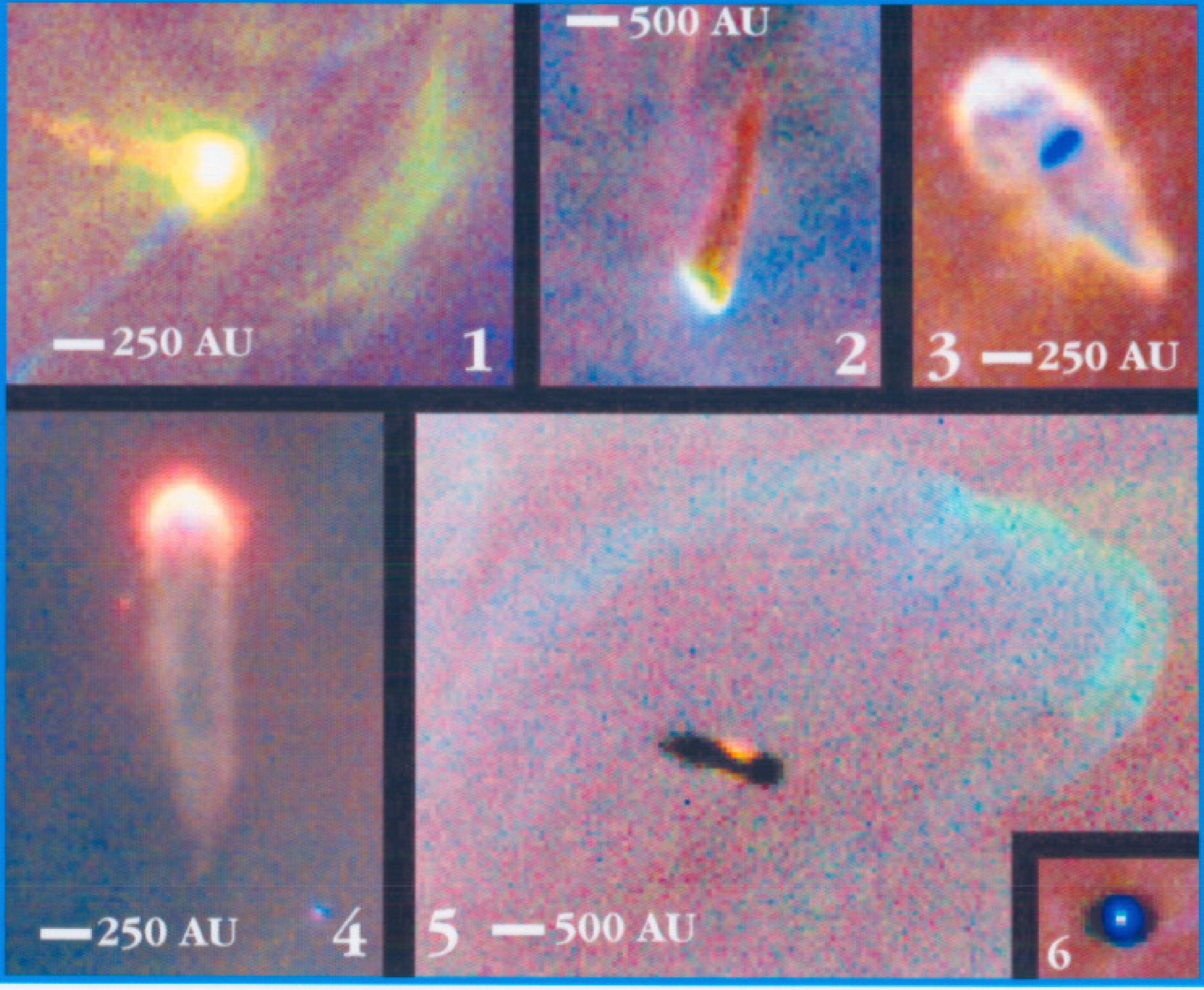


FIG. 1.—*JHKL* excess/disk fraction as a function of mean cluster age. Vertical error bars represent the statistical $\sqrt{N}$ errors in our derived excess/disk fractions. For all star-forming regions except NGC 2024 and NGC 2362, the horizontal error bars represent the error in the mean of the individual source ages derived from a single set of PMS tracks. The age error for NGC 2362 was adopted from the literature. Our estimate of the overall systematic uncertainty introduced in using different PMS tracks is plotted in the upper right corner and is adopted for NGC 2024. The decline in the disk fraction as a

Photoevaporation by External Star Observed!



disc dispersal mechanisms

gas

(= most of mass)

see Balbus + Königl talks:
- viscosity
- magnetospheric clearing

prob. not dominant:
- star-disc interactions
- Xray heating

no global secular theory:
- planet formation

* EUV heating

* FUV heating

dust

(= most of opacity).

- if well coupled to gas, see ↵
- can coagulate (ie $K \downarrow$).
- can migrate differentially.

see Dullemond et al 2006 (PPV).

Preliminary:

- main heating source for discs is radiation of central $*$.

  .... dominated by optical

  .... flux at disc surface exceeds F_{bol} from neighbors even in cluster environments

Xray EUV FUV

- high ν photons are absorbed at high z, low n. They dominate the heating locally.

  ..... dominant source maybe from local massive stars.

  .... they can heat to high T st.

$$c_s > V_{esc}$$

→ DRIVE FLOWS.

... they can excite/pump interesting diagnostic lines.

Irradiation by EUV photons

see e.g. Osterbrock "Astrophysics of gaseous nebulae"

- EUV ⇒ $h\nu > 13.6\,\mathrm{eV} = h\nu_0$ (i.e. $\lambda < 912\,\text{Å}$)

⇒ can ionise hydrogen from ground state.

photoionisation

one ionising photon → one ionisation, cross section per H = a_ν
$[a_{\nu_0} = 6 \times 10^{-18}\ \mathrm{cm}^2]$

↓

thermalisation of e^-, ion population at ~ 10^4 K

timescale for achieving Maxwell Boltzmann distribution ≪ recombination timescale

↓

recombination

recombination rate p.u.v. $\equiv \alpha\, n_e\, n_{\mathrm{ion}}$

$\Rightarrow t_{\mathrm{recombine}} \sim \frac{10^5}{n}$ years.

α_1 → to ground state of H

α_B → to excited state of H → radiative transitions to ground state

↑ regenerates ionising photons

↑ doesn't.

simplifying factors:

- short lifetime of excited states of H against radiative decay ⇒ can assume all H in ground state

- $a_{\nu_0} = 6\times10^{-18}\ \text{cm}^2$ ⇒ all ionising photons absorbed within neutral column of ~ $10^{17}\ \text{cm}^2$

small cf typical ionised column

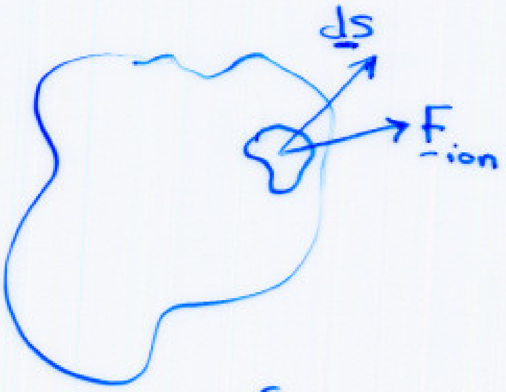
⇒ transition ionised → neutral is <u>sharp</u>

⇒ in ionised region $n_e = n_{ion} \sim n$

so recombination rate p.u.v ~ αn^2

- in absence of dust can equate net consumption of ionising photons in any volume with CASE B recombinations therein

to excited state



i.e $\int_S \underline{F}_{ion}\cdot d\underline{S} = \int_V \alpha_B n^2\, dV$

- in general, computing $\underline{F}_{ion}$ is hard

… not just attenuated flux from source but also DIFFUSE field from recombinations to ground state

(use Monte Carlo radiative transfer methods)

- can sometimes neglect diffuse field

e.g.

i) spherical symmetry : $n = n(r)$

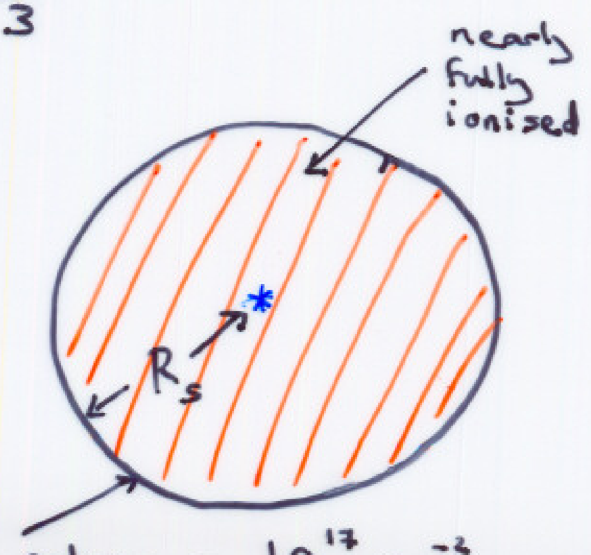
take volume of integration = ionised volume (radius R_s)

$$\Rightarrow \Phi_{ion} = \alpha_B \int_0^{R_s} 4\pi r^2 n^2(r)\, dr$$

ionising photons s^{-1} from source

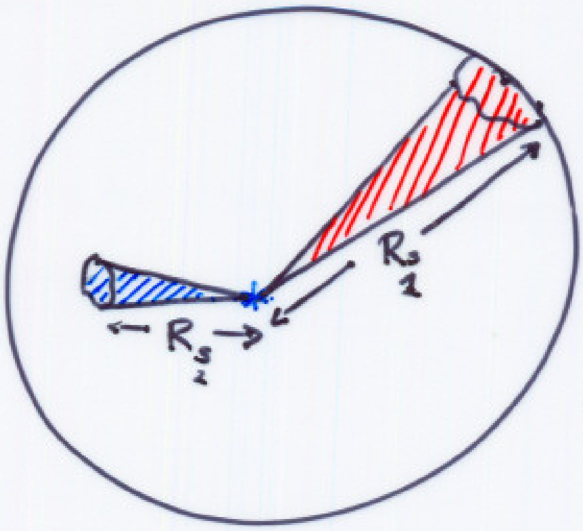
"Strömgren sphere" : if uniform density n_0

$$R_s = \left(\frac{3\,\Phi_{ion}}{4\pi n_0^2 \alpha_B} \right)^{\frac{1}{3}}$$



narrow transition, column ~ 10^{17} cm^{-2}.

ii).



azimuthal variations:

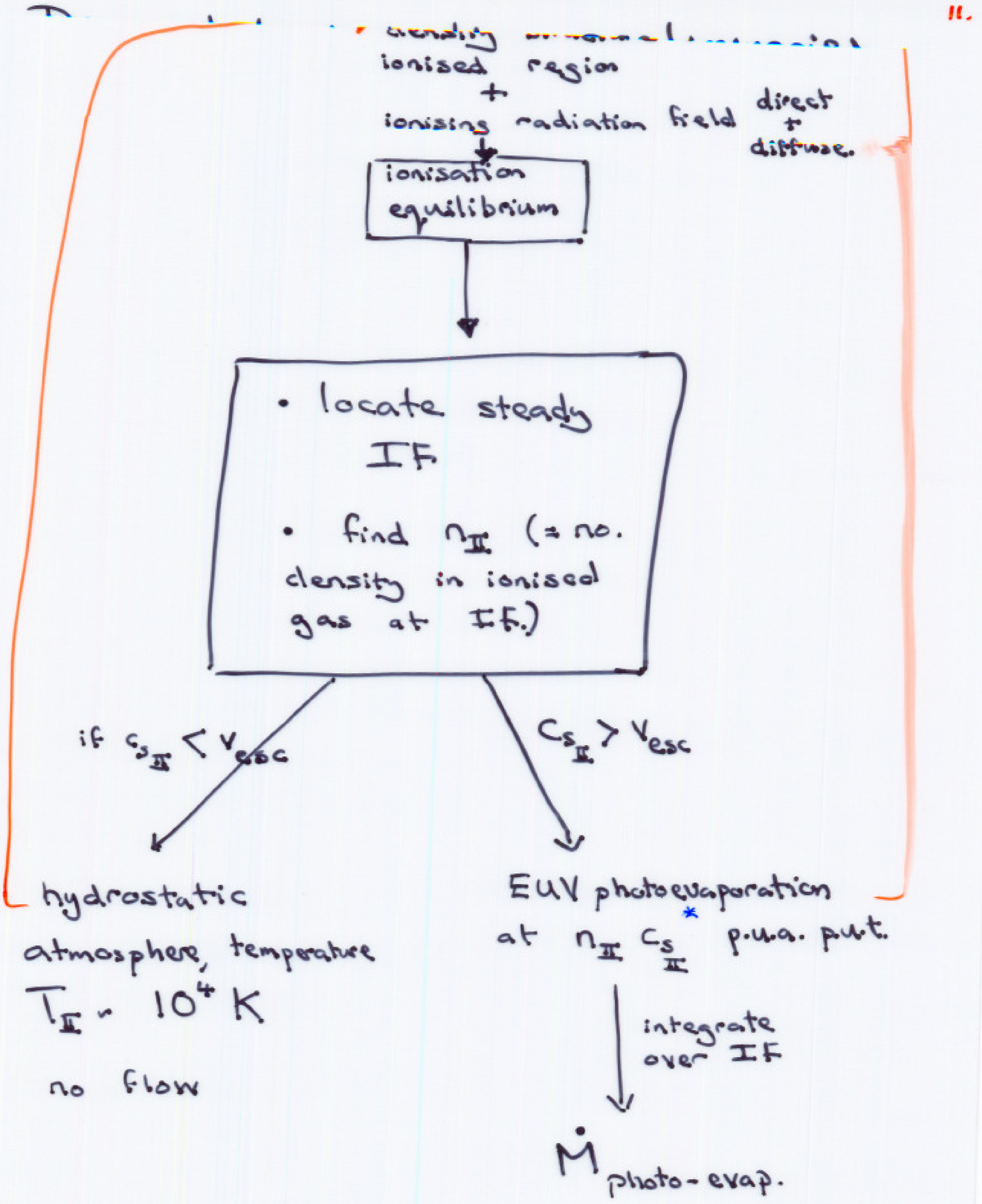
for cone of small solid angle, compute R_s neglecting diffuse flux (*) through sides of cone

$\Rightarrow R_s(\theta, \phi)$ ... "Strömgren volume"

(*) $\Rightarrow$ ionising photons from recombinations to ground state are absorbed locally

$\equiv$ "on the spot" approximation

.... if o.t.s. not valid need full radiative transfer ....



[illegible]
ionised region
+
ionising radiation field direct + diffuse.

ionisation equilibrium

- locate steady IF.
- find n_{II} (= no. density in ionised gas at IF.)

if $c_{s_{II}} < v_{esc}$

$c_{s_{II}} > v_{esc}$

hydrostatic atmosphere, temperature $T_{II} \sim 10^4$ K
no flow

EUV photoevaporation at $n_{II} \, c_{s_{II}}^{*}$ p.u.a. p.u.t.

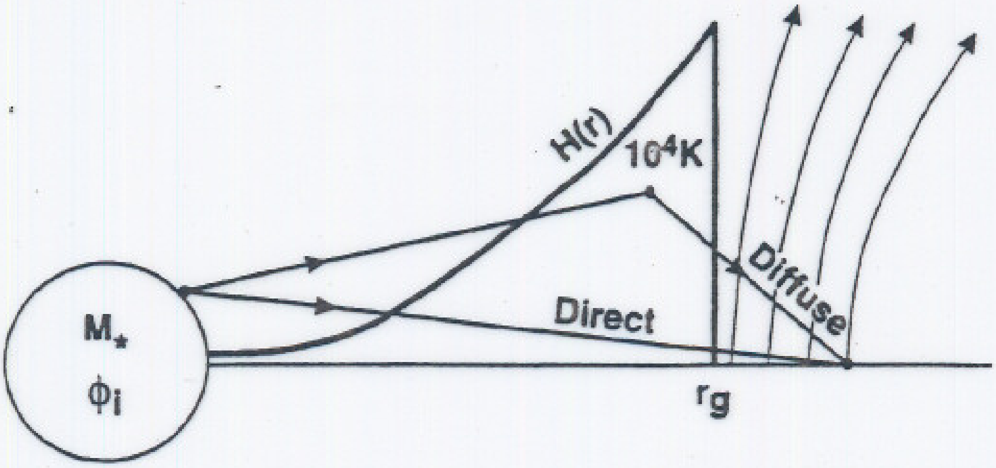
integrate over IF

$\dot{M}_{\text{photo-evap.}}$

[* see Parker wind, later...].

Examples of radiation fields in photoevaporation problems.

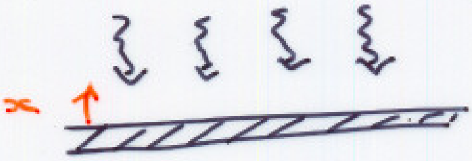
i).



EUV from *, continuous disc (Johnstone, Hollenbach Shu & Lizano 1994).

outer disc irradiated by diffuse field from recombinations in disc atmosphere.

ii).



EUV external source.

(Störzer & Hollenbach 1998)

iii)

EUV central source, disc with inner hole

(Alexander, Clarke and Pringle 2006).

direct field i.e.

$$\frac{e^{-\tau_d}\,\Phi_{ion}}{4\pi d^2} = \alpha_B \int n_{ion}^2\,dx$$

↓ ionising flux attenuated by dust

↓ recombination integral

Examples of density fields in photoevaporation problems

- irradiation of inner disc ($c_{s_{II}} \ll v_{esc}$)

(Hollenbach et al 1994).

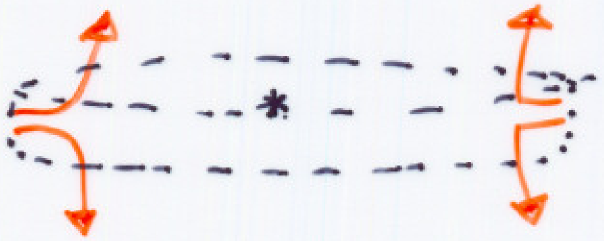
hydrostatic equilibrium of isothermal atmosphere above IF : $n_{ion}(z) = n_{II}\, e^{-\frac{z^2}{2H_{ion}^2}}$

where $H_{ion} \sim \frac{c_{s_{II}}}{\Omega}$

$$\boxed{\text{recomb. integral} \sim n_{II}^2 H_{ion}}$$

below front have P equilibrium, i.e. $n_{II} T_{II} = n_I T_I$

- irradiation of inner hole [r_{hole} s.t. $c_{s_{II}} \gg v_{esc}$]

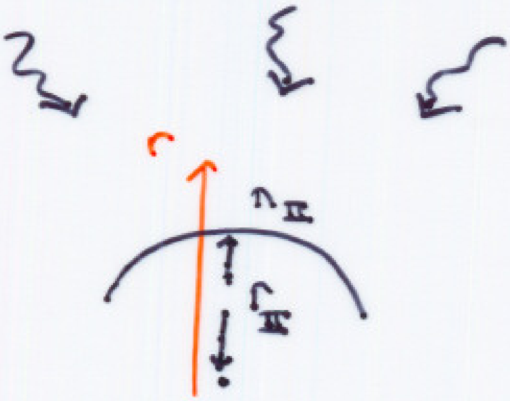


(Alexander et al 2006).

ionised flow "gets out of way" ⇒ recombination dominated by disc edge, thickness $\sim H_{neutral}$

$$\boxed{\text{recomb. integral} \sim n_{II}^2 H_{neutral}}$$

- external irradiation ($c_{s_{II}} \gg v_{esc}$).



- heated gas expands from IF in wind at $v_{II} \sim c_{s_{II}}$ *

- remains ~ isothermal & v ~ constant *

$$\Rightarrow \text{(continuity)} \quad n_{ion}(r) = n_{II}\left(\frac{r}{r_{II}}\right)^{-2}$$

recombination integral ~ $n_{II}^2 \, r_{II}$

- if IF close to disc surface $r_{II} \sim r_d$

so know $n_{II} \Rightarrow \dot{M}$

(irrespective of what's underneath)

"EUV dominated flow"

(Bertoldi & McKee 1990
Johnstone, Hollenbach 1998)
and Bally

* properties of Parker wind: see later

— but if IF isn't coincident with disc surface, don't know r_{II} a priori.

(only know $n_{II}^2 r_{II}$)

locate r_{II} by matching onto flow in neutral region ("PDR")

Γ_{mass} $$n_{II} v_{II} = n_I v_I$$

momentum ~~contin~~ $$n_{II}\left(v_{II}^2 + c_{s_{II}}^2\right) = n_I\left(v_I^2 + c_{s_I}^2\right)$$

e IF $\perp$

since $v_{II} \sim c_{s_{II}}$ $\Rightarrow$ $v_I \sim \left(\frac{c_{sI}}{2_s c_{II}}\right) c_{s_I}$

i.e. SUBSONIC FLOW INTO IF FROM PDR.

now r_{II}, hence n_{II} depends on PDR structure

$\Rightarrow \dot{M}$ determined by $\boxed{\text{FUV}}$ flux, which controls PDR

"FUV dominated flow" Johnstone et al 1998
Störzer & Hollenbach 1999

SUMMARY

ionisation eqn $\Rightarrow \boxed{\text{ionising flux} = \alpha \int n^2 \, dz}$

- for static ionised atmosphere

$$\int n^2 dz \propto n_{II}^2 \underset{\substack{\nearrow \\ \text{scale height} \\ \text{in ionised gas}}}{H} \propto n_{II}^2 r^{3/2}$$

- for wind off inner rim of disc hole

$$\int n^2 dr \propto n_{II}^2 \underset{\substack{\nearrow \\ \text{scale height in cold gas} \\ \simeq \text{ radial scale length at inner edge}}}{H_{neutral}}$$

- for spherical Parker wind

$$\int n^2 dr \propto n_{II}^2 \underset{\substack{\nearrow \\ \text{radius of IF}}}{r_{II}}$$

- direct field dominates
  - .... external radiation source
  - .... case of inner hole
  - ... innermost disc for central source (if $H < r_*$).

diffuse field dominates: outer (flow) regions for central source.

DON'T FORGET: in flow:

flow velocity into IF on neutral side ~ $\frac{c_I}{2c_{II}} \underset{\text{subsonic}\nwarrow}{c_I}$

Final point on EUV dominated flows:

can justify use of recombination integral <u>iff</u> most ionising photons are used to balance recombinations in ionised region, not to ionise fresh neutrals arriving through IF.

$$\frac{\text{\# photons ionising fresh neutrals p.u.a. p.u.t.}}{\text{\# ionising photons from source p.u.a. p.u.t.}}$$

$$\sim \frac{n_{II}\, c_{s_{II}}}{\Phi_{ion}/4\pi d^2}$$

<u>if</u> ratio is small, can write $\alpha\, n_{II}^2\, \lambda_{scale} \sim \dfrac{\Phi_{ion}}{4\pi d^2}$

scale length in ionised flow

$$\hookrightarrow \text{ratio} \sim \frac{c_{s_{II}}}{\sqrt{\dfrac{\Phi_{ion}}{4\pi d^2}\,\alpha\,\lambda_{scale}}}$$

e.g. in ONC, $d \sim 0.3$ pc, $\Phi_{ion} \sim 6\times10^{49}\ s^{-1}$, $\lambda_{scale} \sim 10^{15}$ cm

$\Rightarrow$ ratio ≤ 0.1 so okay.

Irradiation by FUV photons

see Hollenbach and Tielens Rev. Mod. Phys. 1999

- FUV ⇒ $6\,\mathrm{eV} < h\nu_0 < 13.6\,\mathrm{eV}$
  - photodissociates
    $H_2 \rightarrow H$
    $CO \rightarrow C + O$
    $O_2 \rightarrow O$ etc.
  - doesn't ionise
    $H \rightarrow H^+$

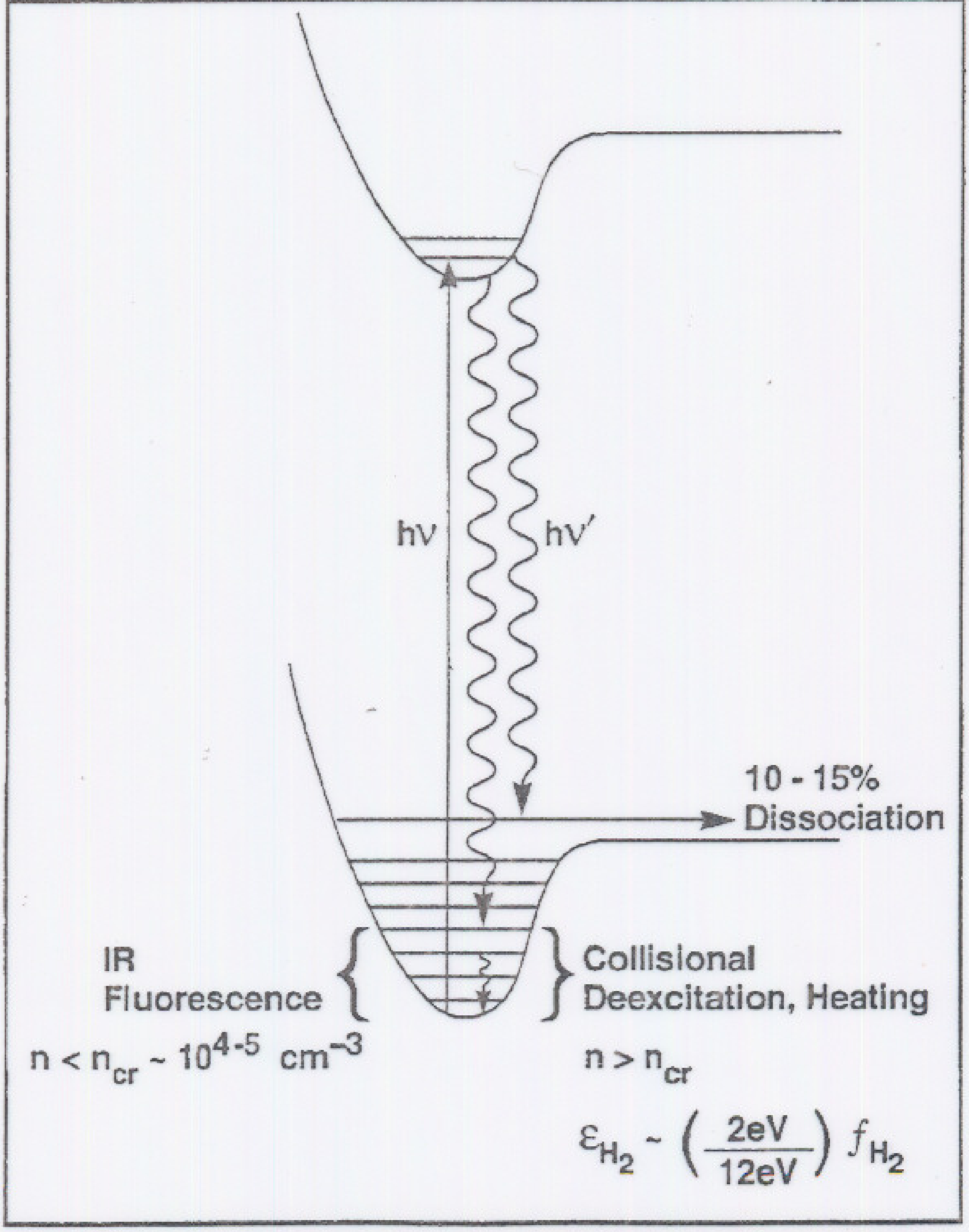
- photodissociation mechanism:

uv photon "pumps" H_2 to (bound) excited electronic state

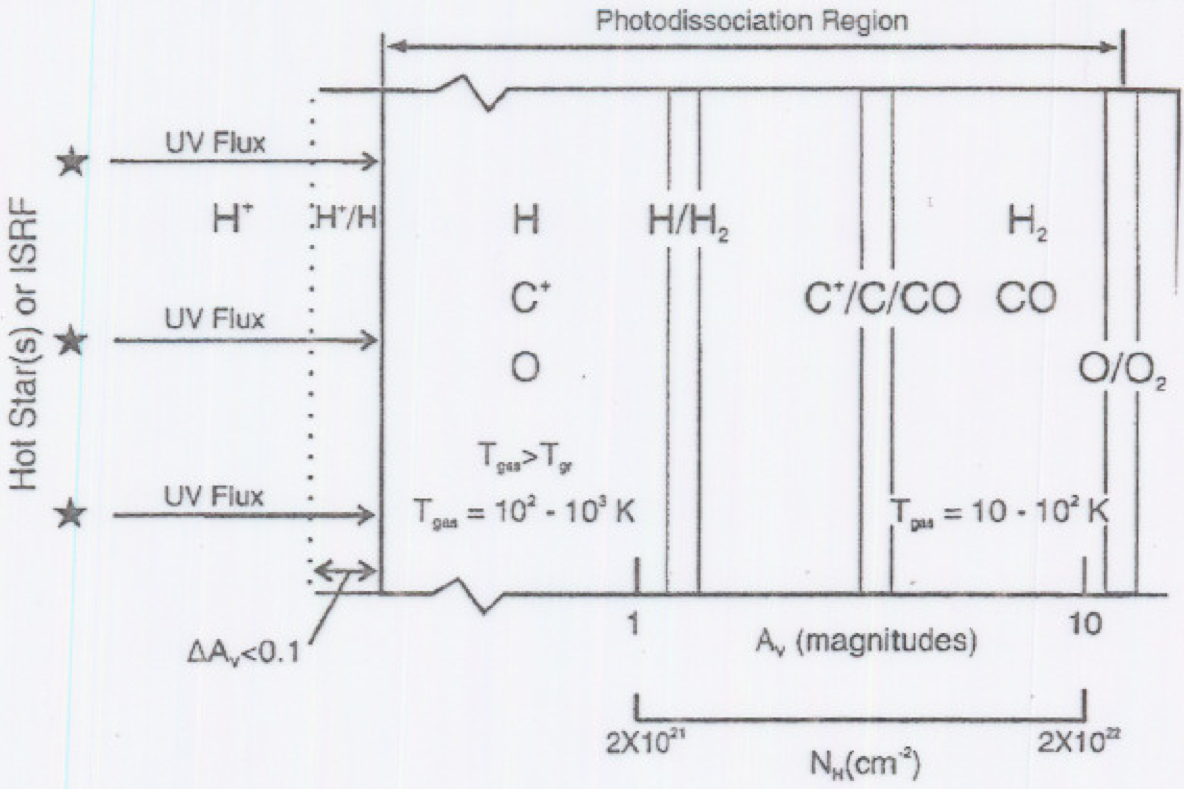
H_2 fluoresces back to electronic ground state

- 10-15%
  - vibrational continuum of electronic ground state
    = photodissociation
- 85-90%
  - vibrationally excited electronic ground state
    - collisionally de-excite $n \gtrsim 10^4\ \mathrm{cm}^{-3}$
      - heating
    - radiatively de-excite $n \lesssim 10^4\ \mathrm{cm}^{-3}$
      - NIR & FIR rovibrational fluorescence lines

UV Pumping of H_2



$$\varepsilon_{H_2} \sim \left(\frac{2\mathrm{eV}}{12\mathrm{eV}}\right) f_{H_2}$$



- Photodissociation regions contain
  ionised species (where IP < 13.6 eV) e.g. C^+
  $+$
  atomic species at depths where H is all H_2 e.g. O.

- PDR chemistry different from normal ISM: importance of reactions mediated by vibrationally excited H_2.

- FUV parameterised by Habing field G_0

= flux 6 – 13.6 eV normalised to interstellar value

= 1.6×10^{-3} erg cm^{-2} s^{-1}

Location of H/H_2 interface

formation rate p.u.v. on grains = photodissociation rate p.u.v.

$$\gamma_{H_2}\; n\; n_H = I_{diss}(0)\; n_{H_2}\; f_{shield}(N_{H_2})\; e^{-\tau_{d_{1000\text{Å}}}}$$

incorporates thermal speed and sticking and migrating probabilities: weak function of T $\sim 1\text{–}3\times10^{-17}\ cm^3\ s^{-1}$ (Jura 1975).

$\propto n_{gr}$

unshielded rate per H_2 $= 4\times10^{-11}\, G_0$

attenuation of fuv photons by self-shielding

$f_{shield} \propto N^{-0.75}$ (Draine + Bertoldi 1996)

attenuatio of fuv photons by dust

- if no dust, define $N_{\substack{self\\shield}}$ s.t. $\frac{n_{H_2}}{n} = \frac{1}{4}$

$$\Rightarrow N_{\substack{self\\shield}} \propto \left(\frac{G_0}{n}\right)^{+4/3}$$

but dust attenuation important at $N \gtrsim 5\times10^{20}\ cm^{-2}$.

$\exists\ \left.\frac{G_0}{n}\right|_{crit} \sim 4\times10^{-2}$ s.t.: $\frac{G_0}{n} > \left.\frac{G_0}{n}\right|_{crit}$ | $\frac{G_0}{n} < \left.\frac{G_0}{n}\right|_{crit.}$

H_2/HI interface: set by dust | self-shielding

Focus on thermodynamics (→ hydrodynamics).

gas heating:

- H_2 pumping

  $\downarrow$ 85%

  excited vib. level

  at $n \gtrsim 10^4\,\text{cm}^{-3} \rightarrow 2\,\text{eV}$ heat

- photoelectric heating

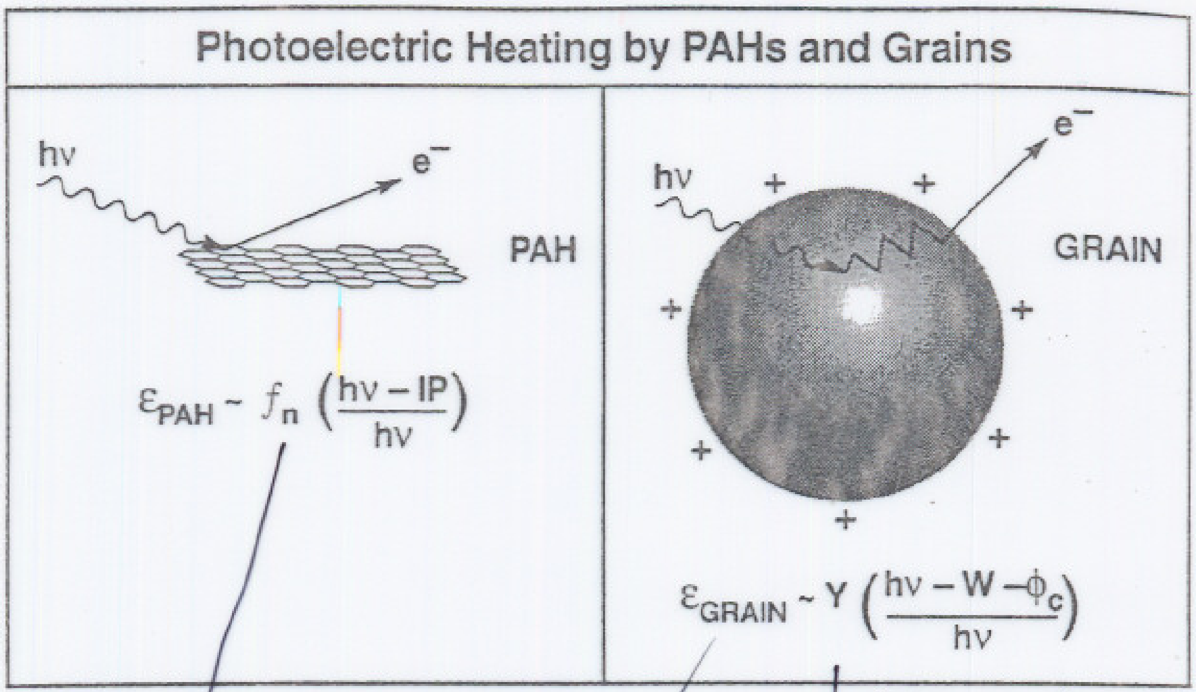
  by (small) grains

  and Polyaromatic Hydrocarbons (PAHs)
  (= planar structures with ~ 50 C
  and aromatic CH bonds).

- gas grain collisions

  at depths where FUV attenuated
  (A_V > a few), the above mechanisms
  fail – gas heated by grains

the relative importance of the above is strongly dependent on assumed dust abundance and grain size distribution.



fraction of photons with $h\nu$ enough to ionise (charged?) PAH.

fraction of absorbed photon energy → e^- k.e.

prob. e^- escapes.

fraction of photon energy carried off as k.e. of photoelectron

Bakes & Tielens (1994):
- about half photoelectric heating from PAHs
- about half from grains $\lesssim 100$ Å
- negligible for grains $\gtrsim 100$ Å

gas cooling

FIR fine structure lines

surface layers → e.g. [CII] 158 μm

[OI] 63 μm

→ gas grain collisions

(if $T_{dust} \ll T_{gas}$)

dominates at depth → rotational lines of CO, H_2, OH

vibrational

dust heating: absorption of fuv continuum

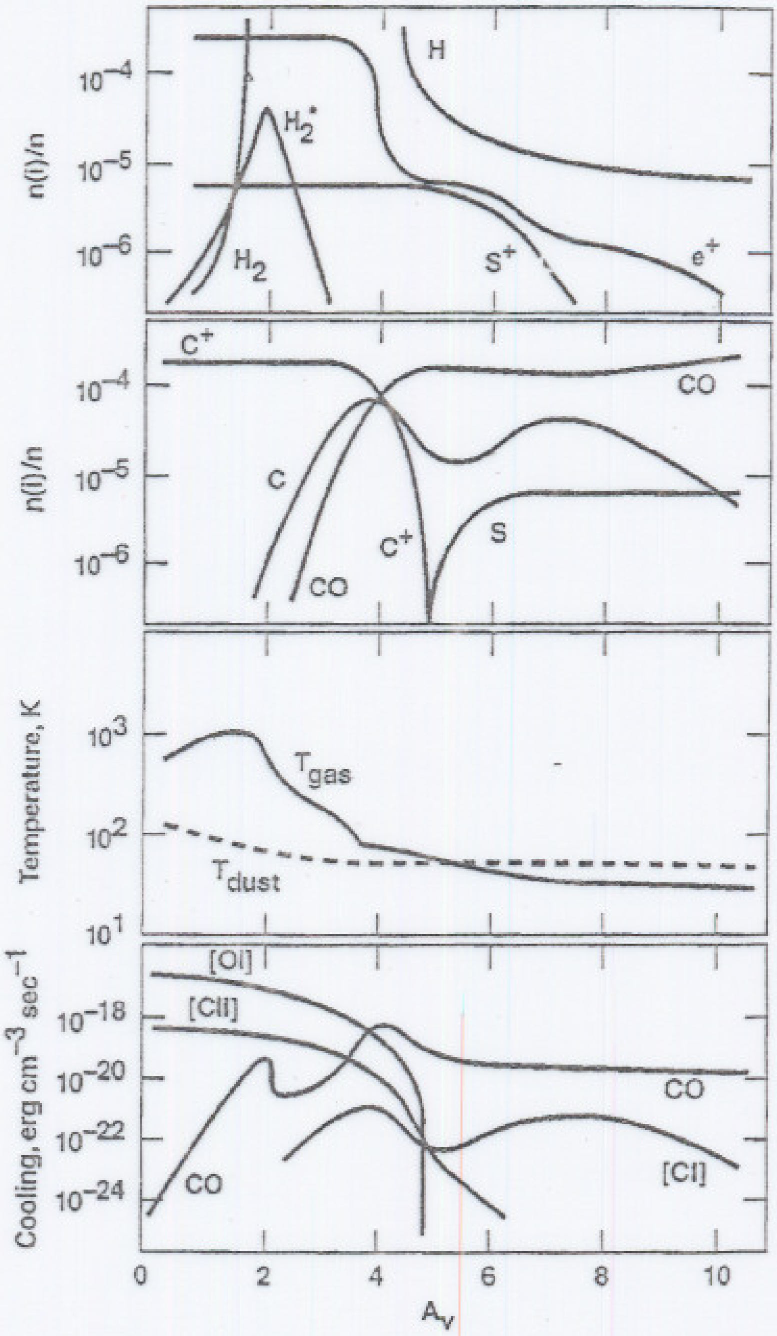
dust cooling: re-emission as IR continuum

PAH band emission

11.3 μm band observed in
Herbig AeBe van Boekel 2004.
T Tauri ??

see poster by Geers et al.

25.



from Tielens & Hollenbach 1999.

PDR models

.... assume thermal and chemical balance

..... semi-infinite, constant density plane slab

..... many species, many reactions!

46 2.22 Kaufman et al 1999.

some good news:

- usually ~ isothermal with increasing A_V until $A_V \sim 1$. Cools to $\lesssim 100$ K by $A_V \sim 4$. ☺

  $N = 2 \times 10^{21}\ \mathrm{cm}^{-2}$

- this column of warm gas is little changed when include advection ($v \sim$ few km s^{-1}). Störzer + Hollenbach 1998 ☺

the bad news

- value of T plateau is complicated (non-monotonic) function of n at fixed G_0 ☹
- for some n and G_0 there isn't a T plateau ☹
- results very sensitive to dust properties as function of depth ☹

27.

Adams, Hollenbach, Laughlin and Gorti 2004,

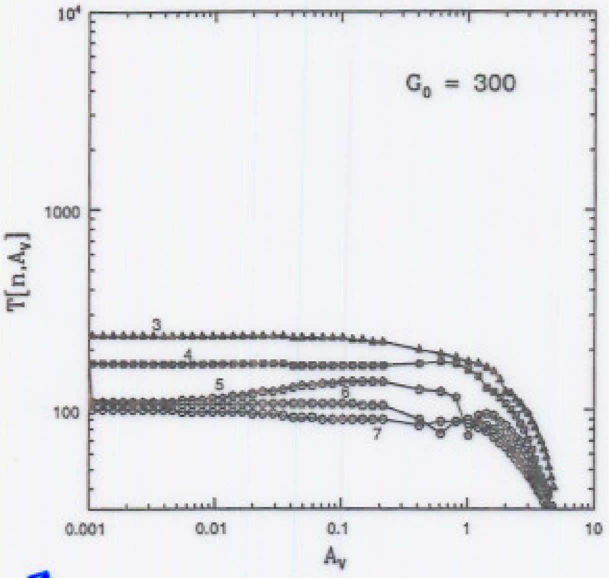


Fig. 2*a*

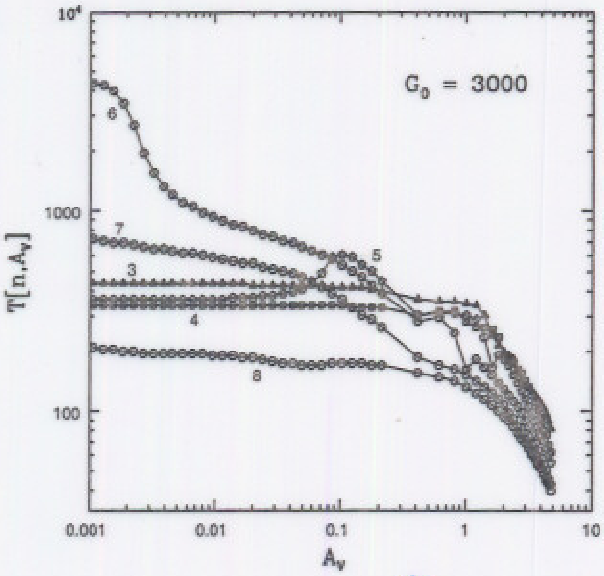


Fig. 2*b*

monotonically declining with n

maximum T at intermediate n.

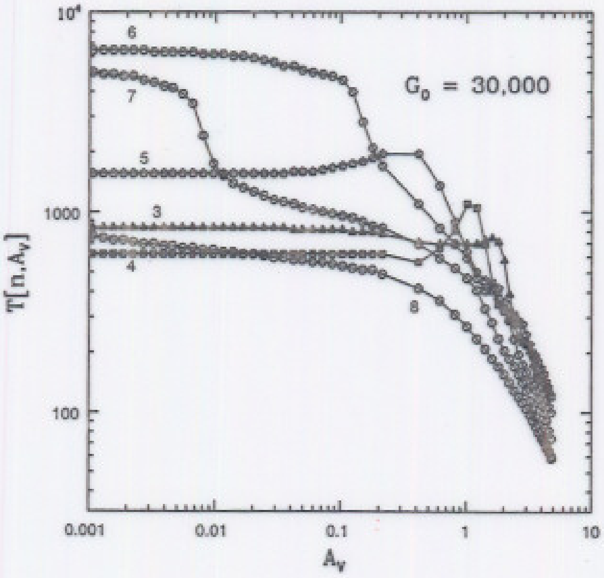


Fig. 2*c*

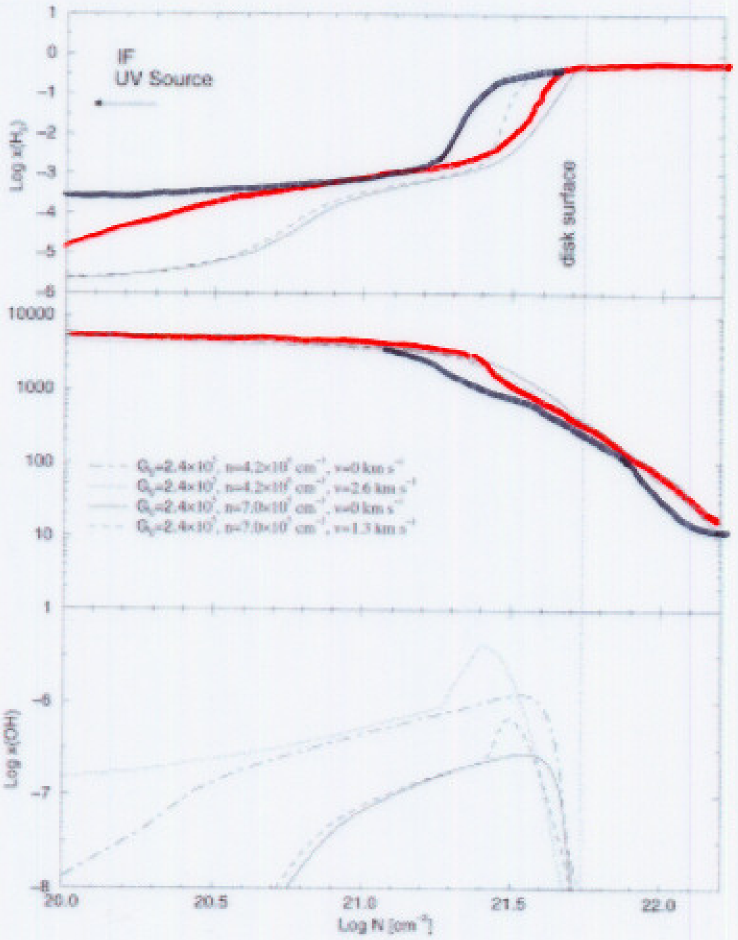
Advection....

(Störzer and Hollenbach 1998)

.... some effect on $[H_2]$

.... minimal effect on T structure

H_2 abundance



🟥 = static

— = v = 2.6 km s^{-1}.

log N

Some environmental (non-) effects:

- Xrays

diffuse soft Xray emission observed by Chandra in clusters with v. massive stars:

M17 2×10^{-7} erg s^{-1} cm^{-2}

Rosette 4×10^{-8} erg s^{-1} cm^{-2}

Townsley et al 200

... too small to produce interesting disc heati

Alexander, Clarke and Pringle 20

- Star-disc interactions

important for a few stars (~100) in core of ONC

Scally and Clarke 2001

Olczak et al 2005

②

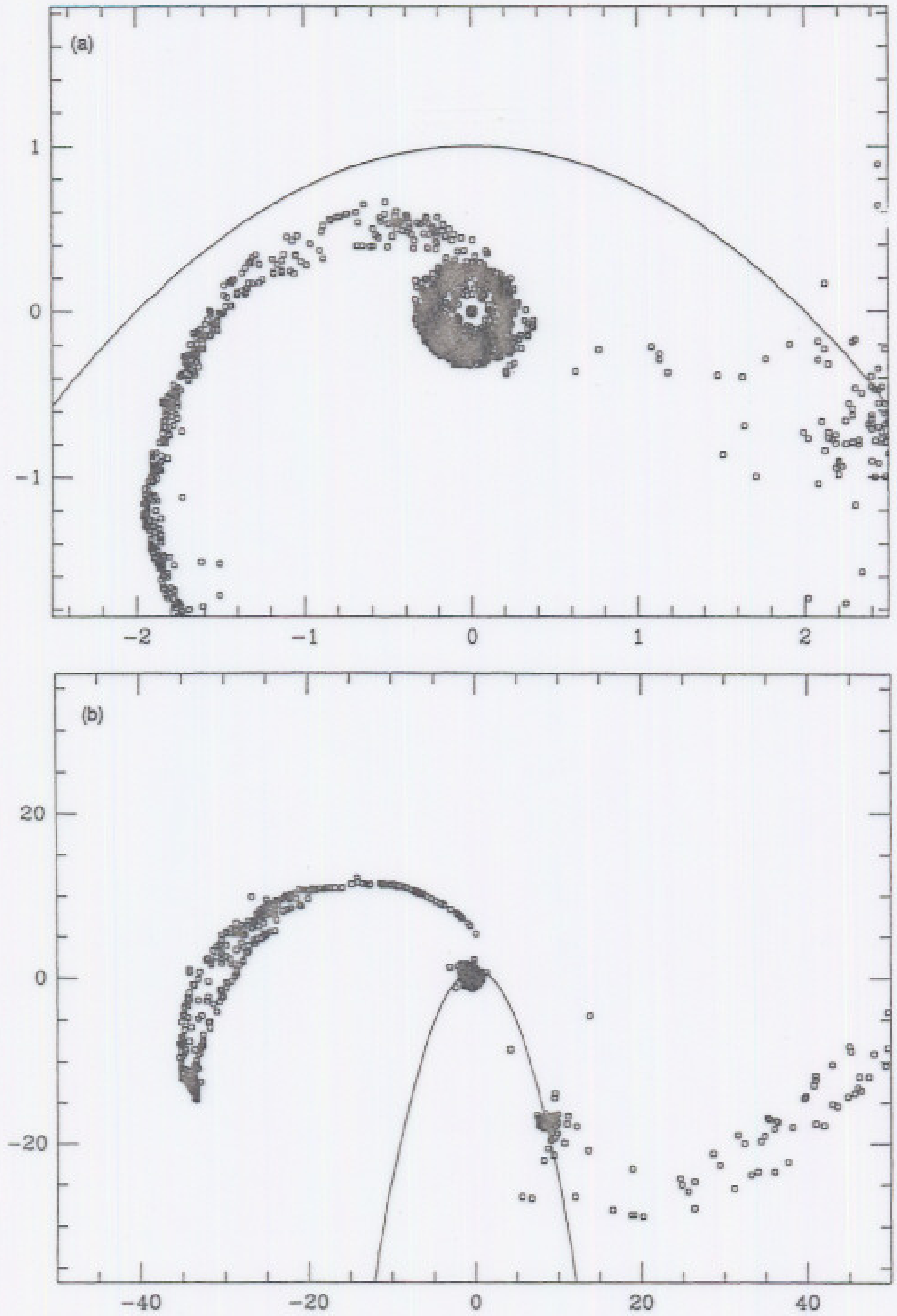
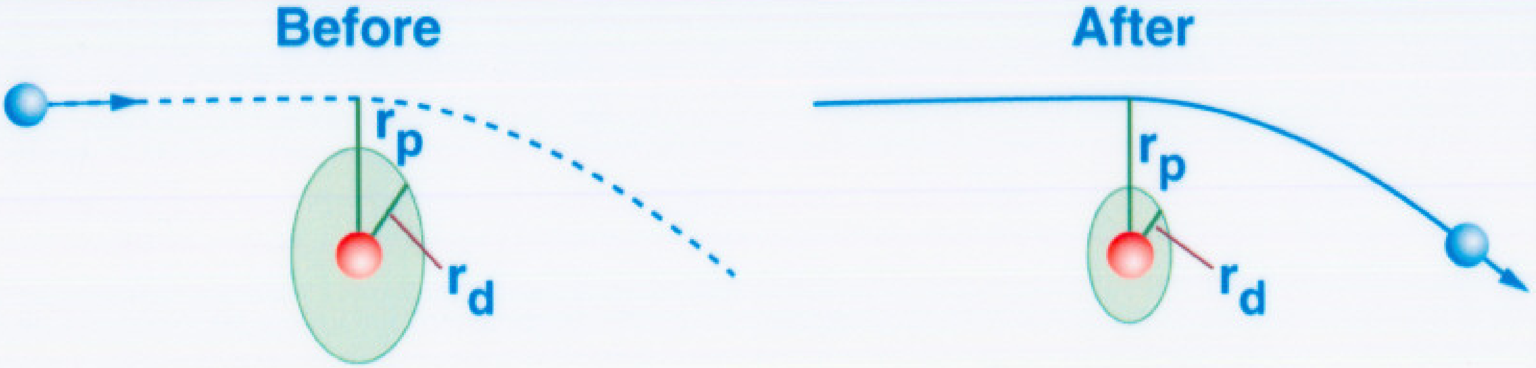


Figure 2. Particle distributions for model B, which is identical to model A except that dissipation is present within a radius of 1.4$r_{\rm peri}$ of the star with the disc. (a) At time $t=4$, corresponding to Fig. 1(b), dissipation has led to the perturbed disc forming a ring around the original star and to the tidal tail becoming more coherent. (b) At time $t=60$, corresponding to Fig. 1(d).

viscosity: the ring spreads radially in both directions but with the majority of the mass being transported *inwards*. Thus, although the disc would eventually grow back to its initial size (and beyond), this would be with a substantially reduced surface density in its outer regions. This depletion results from a combination of factors: mass loss during the encounter, angular momentum loss by the material retained by the original and, finally, the central concentration effected by subsequent viscous evolution. Since the density profile produced by the latter effect is determined by the functional

III. Mechanisms for Dispersal: Truncating by Stellar Encounters in Clusters

Clarke & Pringle (1993), Heller (1995), Hall et al (1996), Larwood (1996), Scally & Clarke (2001), Adams et al (2006), Cabrit et al (2006), Pfalzner et al (2006), Kobayashi et al (2006)



$r_d \simeq 1/3\ r_p$

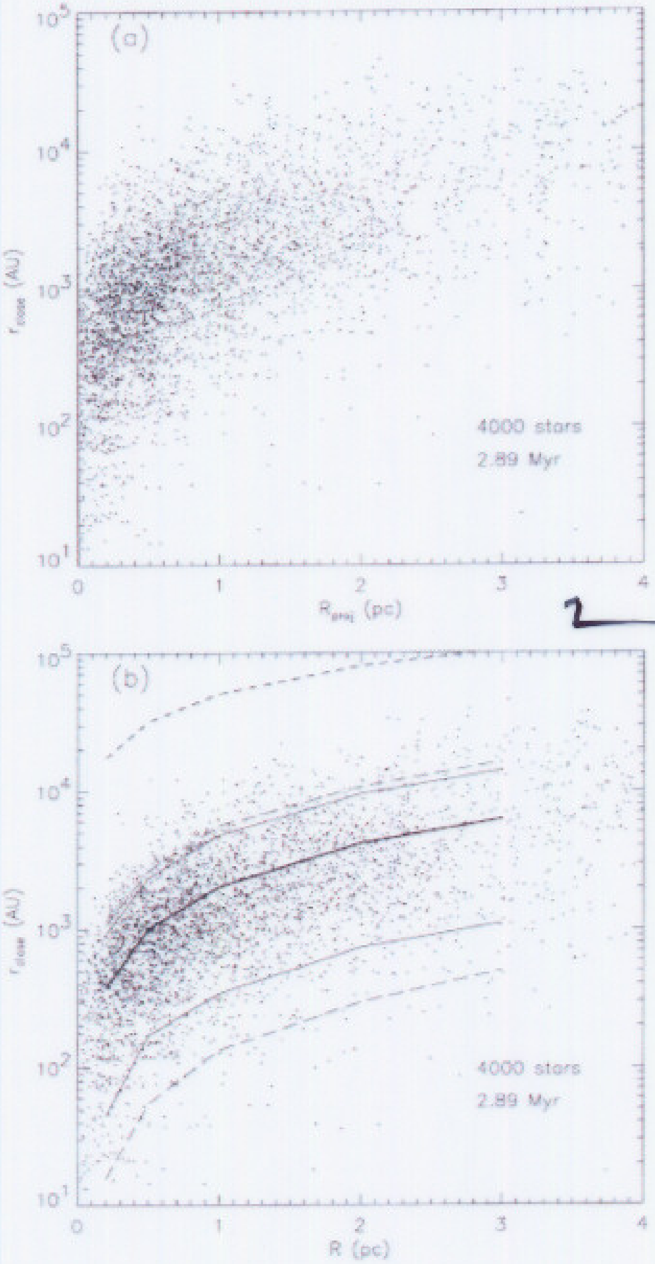
$$t_{SE} \simeq \frac{1}{n_* v \sigma} = \frac{1}{n_* v \pi (3r_d)^2}$$

$$t_{SE} \simeq 2 \times 10^7 \left(\frac{n_*}{10^4\ \mathrm{pc}^{-3}}\right)^{-1} \left(\frac{v}{1\ \mathrm{kms}^{-1}}\right)^{-1} \left(\frac{r_d}{100\mathrm{AU}}\right)^{-2} \mathrm{yrs}$$

Scally and Clarke 2001.

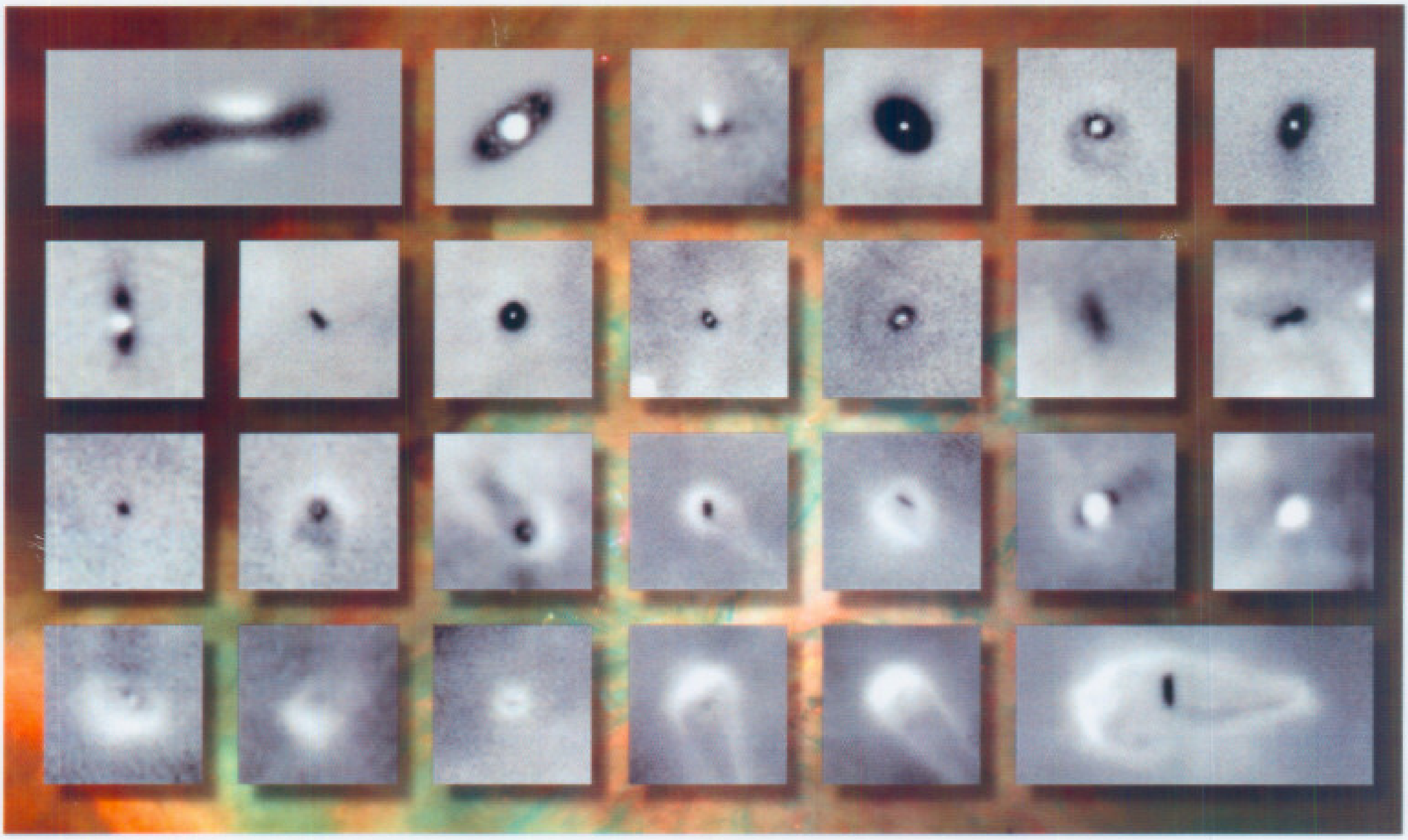
r_{close}

100 A.U. →



← projected distance

lines: predicted centiles of distribution if stars spend their whole time at current radius



Proplyds in the Orion Nebula Cluster

- first identified as Hα knots (Laques & Vidal 1978)

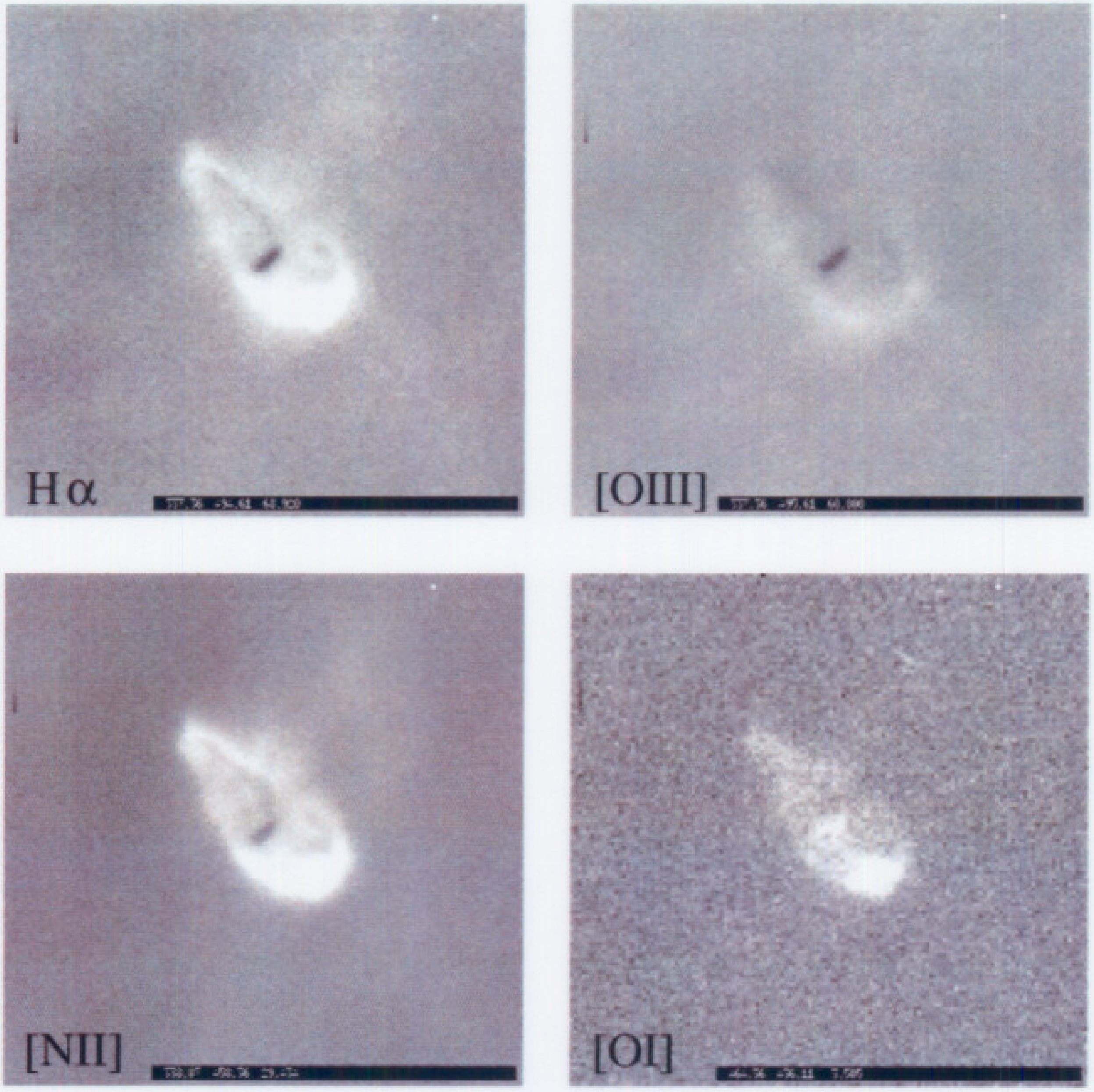
- then as thermal radio sources (Churchwell et al 1987): $T \sim 10^4$ K, $n_e \sim 10^6 \text{ cm}^{-3}$, size $l \sim$ few 100 A.U..

- if ionised gas not confined $\Rightarrow \dot{M} \sim 4\pi n_e \underset{\mathrm{II}}{c_s} l^2 m_H$ $\sim 10^{-7} M_\odot \text{ yr}^{-1}$. $\Rightarrow$ requires $0.1 M_\odot$ over 1 Myr. reservoir can't be spherical because see star optically. Churchwell et al postulated a disc reservoir.

- HST imaging in emission line filters revealed detailed structures and (sometimes) embedded silhouette discs. O'Dell et al 1993 coined term PRO to PLanetarY DiskS.

- Chen et al 1998 detected embedded discs in 2.1μm S(1) line of H_2 $\Rightarrow$ FUV penetrates to disc surface.

HST images of HST 182-413
from Johnstone et al 1998.

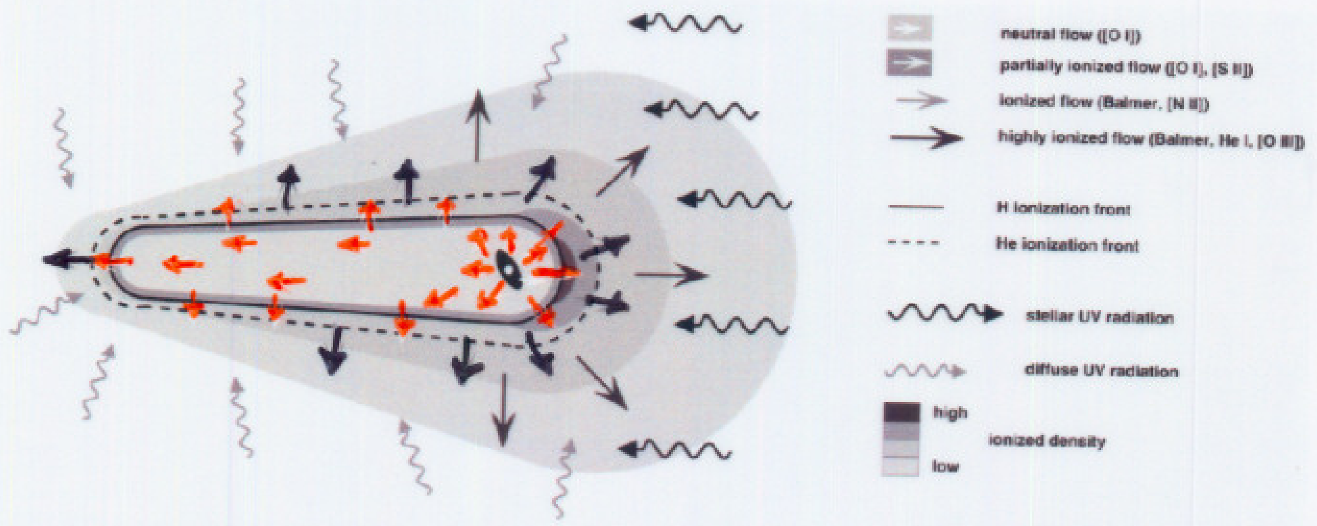


Standard proplyd model

Johnstone, Hollenbach and Bally 1998

→ = ionised flow

→ = neutral flow



Components of the photoevaporating flow in a proplyd

- FUV drives flow from disc which prevents ionising photons penetrating to disc surface

  ⇒ offset ionisation front

- Obvious origin of EUV/FUV photons: OB stars in ONC, especially θ^1C Ori (= O6 star in central Trapezium).

Parker wind tutorial:

- steady, spherically symmetric, [isothermal] flow.
  point mass gravity.

- write momentum equation:

$$u^2 \frac{d \ln u}{dr} = - c_s^2 \frac{d \ln \rho}{dr} - \frac{GM}{r^2}$$

- continuity $2 \ln r + \ln \rho + \ln u = \text{constant}$

$$\Rightarrow \boxed{\left(u^2 - c_s^2\right) \frac{d \ln u}{dr} = \frac{2 c_s^2}{r} \left[1 - \frac{GM}{2 c_s^2 r} \right]}$$

$\Rightarrow$ at radius $r_s \equiv \frac{GM}{2 c_s^2}$ either $u = c_s$ ↙ sonic transition

or u has maximum or minimum.

I and II ... ranges of r for which no solution ✗

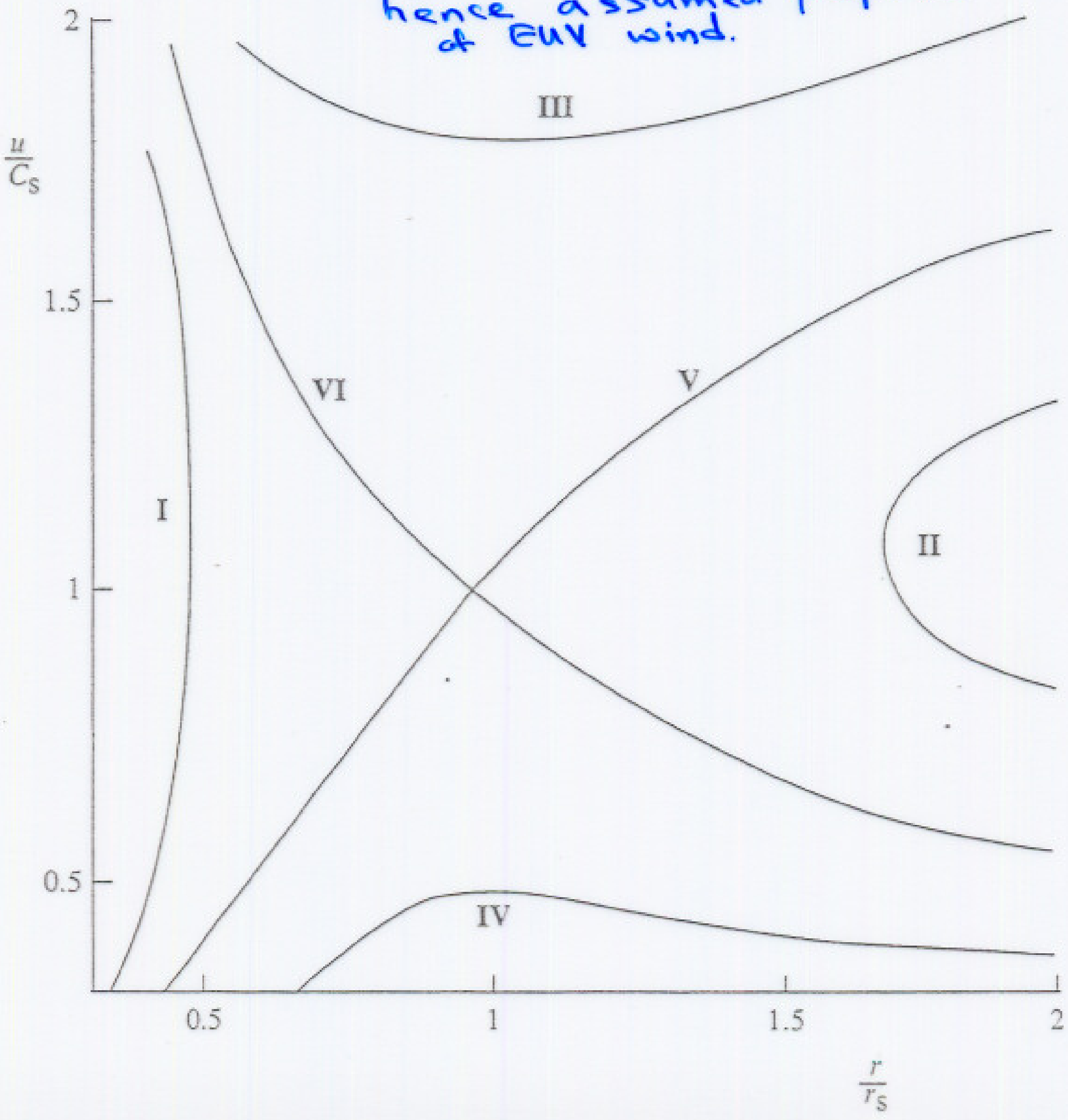
III and VI .... have no mechanism to initiate highly supersonic flow ✗

IV ..... subsonic everywhere; at large r $v \propto r^{-2} \Rightarrow$ $n \sim$ constant $\Rightarrow$ mass/column/recombination integral unbounded as $r \to \infty$

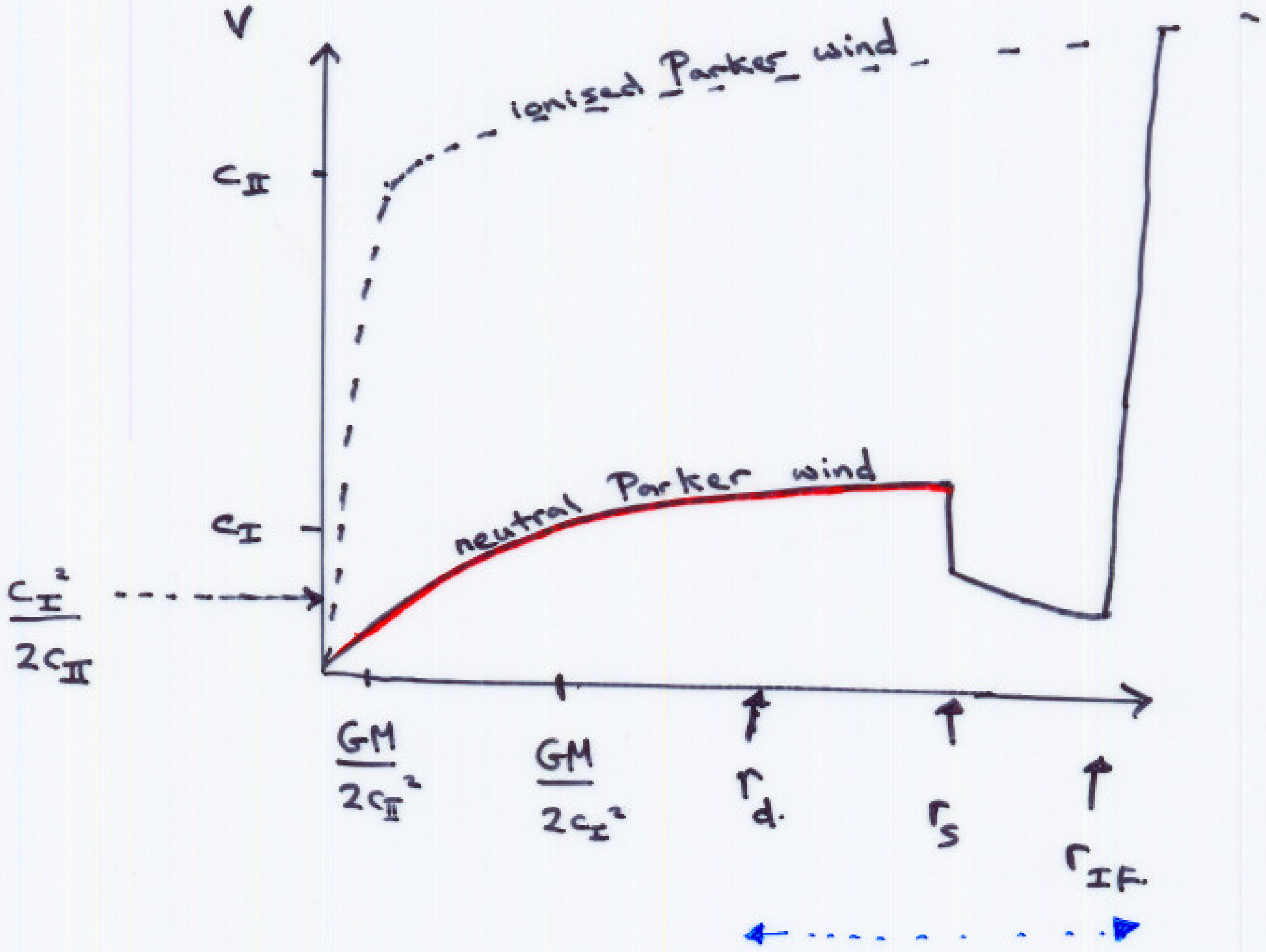
not for $r \to \infty$

V ...... = "Parker wind". Sonic transition at r_s. $r \to \infty$: v increases slowly $\Rightarrow n \propto r^{-2}$ ✓

hence assumed properties of EUV wind.



Consider flow, sound speed c_I from disc surface, r_d, s.t. $r_d \gg \frac{GM}{2c_I^2}$



— = Parker wind solution for neutral gas

- - - = " " " " ionised gas.

neutral flow MUST undergo shock in order to join IF subsonically.

constraint: $\leftarrow A_v \rightarrow \sim 1.$

Elements of theory

(Johnstone et al 1998).

- neutral column mainly provided $r_d \rightarrow r_s$

where $v \sim$ constant $\Rightarrow n \propto r^{-2}$ so

$$\int_{r_d}^{r_s} n\,dr \sim n_d r_d = N$$

← fixed in simplest models.

↑ warm column corresponding to $A_V \sim 1$ [$\sim 10^{21}\,\mathrm{cm}^{-2}$].

- since $v \sim c_I$, $\dot{M} \sim 4\pi r_d^2 n_d c_I \propto r_d$

$$\boxed{\dot{M} \sim 10^{-7} \left(\frac{r_d}{10^{15}\,\mathrm{cm}}\right) M_\odot\, y^{-1}}$$

← independent of dist. to source of FUV !

- how far in does ionising radiation penetrate in flow?

i.e what's r_{IF}?

continuity $\Rightarrow$ $n_{II} = \left(\frac{r_D}{r_{IF}}\right)^2 \left(\frac{c_{sI}}{c_{sII}}\right)$ (i).

for $r > r_{IF}$, $n \propto r^{-2} \Rightarrow \int n^2 dr \sim n_{II}^2 r_{IF}$

ionisation balance $\Rightarrow$ $n_{II}^2 r_{IF} \propto \frac{\Phi_{ion}}{d^2}$ (ii).

dist. to source.

eliminate n_{II} i) + ii) $\Rightarrow$ $r_{IF} \propto \Phi_{ion}^{-1/3} d^{2/3} r_d^{2/3}$

$$\boxed{r_{IF} \sim 300\, \Phi_{ion\,49}^{-1/3} \left(\frac{d}{10^{18}\,\mathrm{cm}}\right)^{\frac{2}{3}} \left(\frac{r_d}{10^{15}\,\mathrm{cm}}\right)^{2/3} \mathrm{A.U.}}$$

Where should proplyds be found?

- as $d \downarrow$, $r_{IF} \downarrow$ until shock reaches disc

$r_s \rightarrow r_d$

$\boxed{r_s ?}$

if pre-shock neutral flow has $v \sim M c_{s_I}$

post-shock " " " $v \sim \frac{c_{s_I}}{M^2}$

shock $\rightarrow$ IF $v \propto r^{-2}$

and flow enters IF at $\frac{c_{s_I}^2}{2 c_{II}}$

$$\Rightarrow r_s = \left(\frac{M c_{s_I}}{2 c_{s_{II}}} \right)^{1/2} r_{IF} \Rightarrow r_s \propto r_{IF}.$$

$$\Rightarrow r_s \sim r_d \Rightarrow \Phi_{ion}^{-1/3} d^{2/3} r_d^{2/3} \propto r_d$$

$$\text{i.e. } d_{crit} \propto r_d^{\frac{1}{2}} \Phi_{ion}^{1/2}$$

min. distance to source for proplyd (= offset IF) to be found

$$\boxed{d_{crit} \sim 0.01 \text{ pc} \left(\frac{r_d}{10^{13} \text{cm}} \right)^{\frac{1}{2}} \left(\frac{\Phi_{ion}}{10^{49}} \right)^{\frac{1}{2}}}$$

- as $d \uparrow$, $G_0 \downarrow$. In reality, neutral column of warm gas $N \downarrow$ (contrary to assumption so far).

Störzer + Hollenbach 1999 investigated, using PDR model to find how $N \downarrow$ . . .

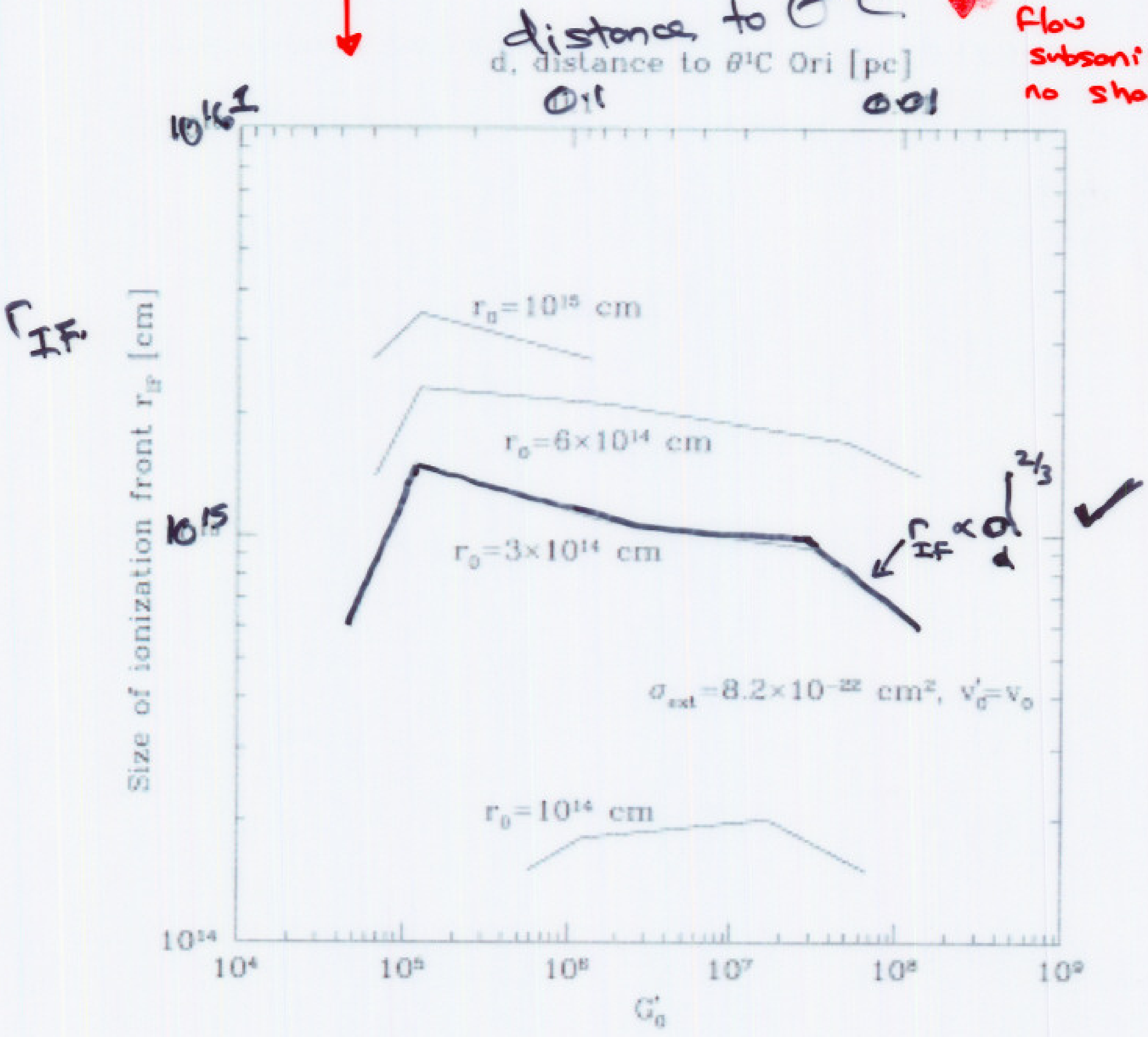
because FUV weak

EUV dominated region.

← FUV dominated: →
r_{IF} offset from
disc ⇒ PROPLYDS.

because EUV strong

EUV dominated region
[IF at disc;
neutral flow
subsonic;
no shock]

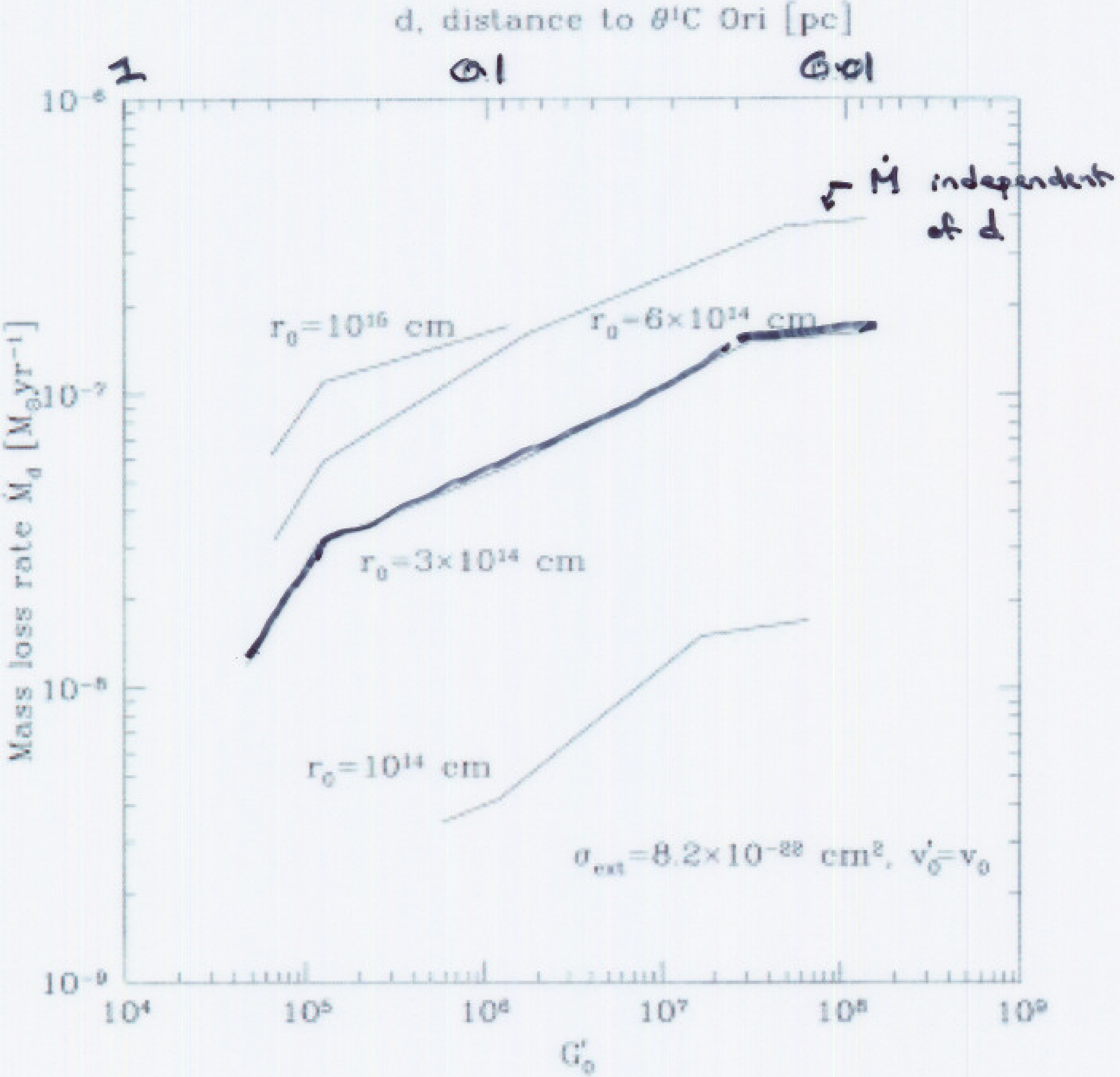


$r_{IF} \propto d^{2/3}$ ✓

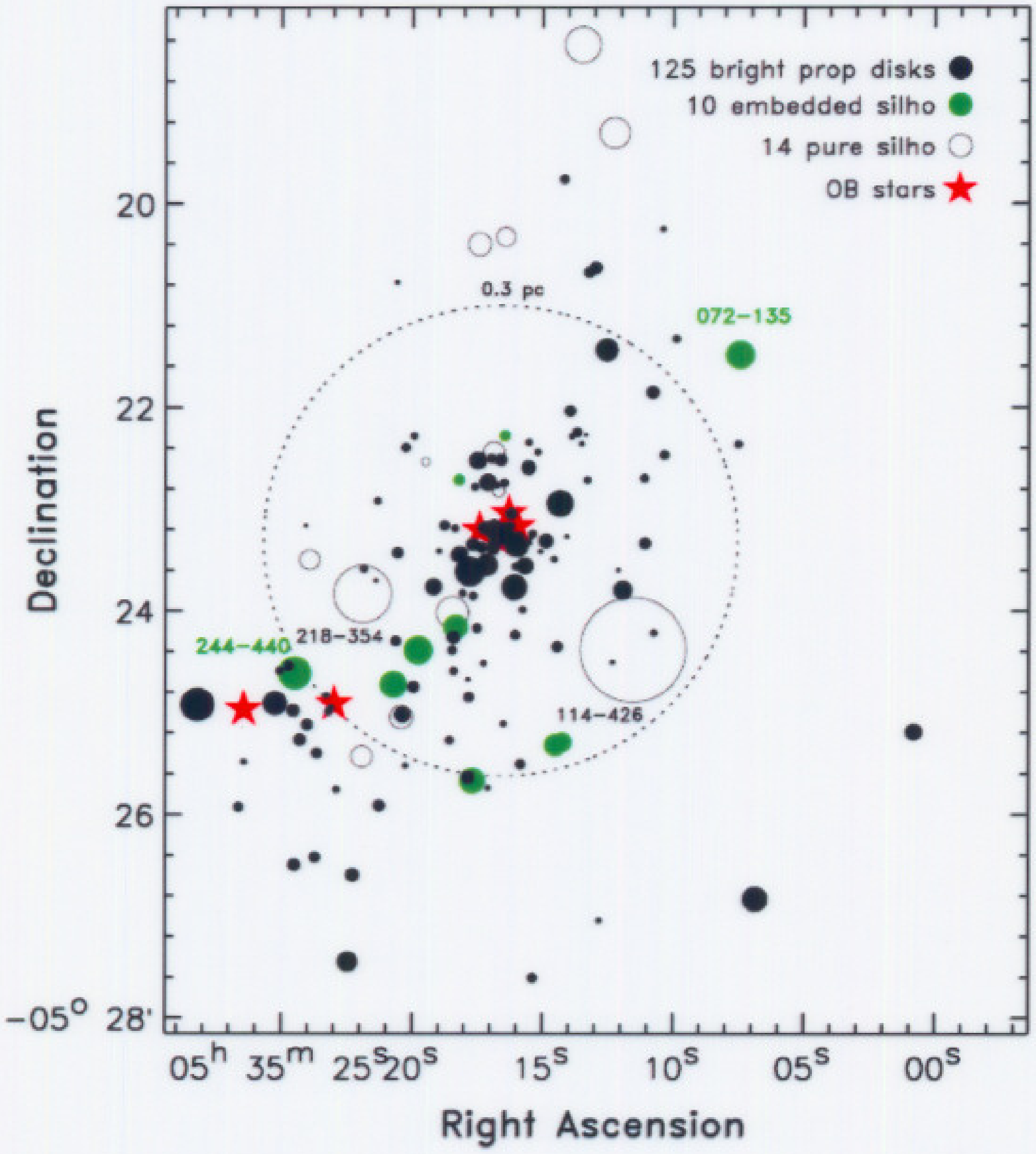
from Störzer + Hollenbach 1999.

$\dot{M}$ ↓ somewhat with d according to reduction in warm column as G_0 ↓

↓



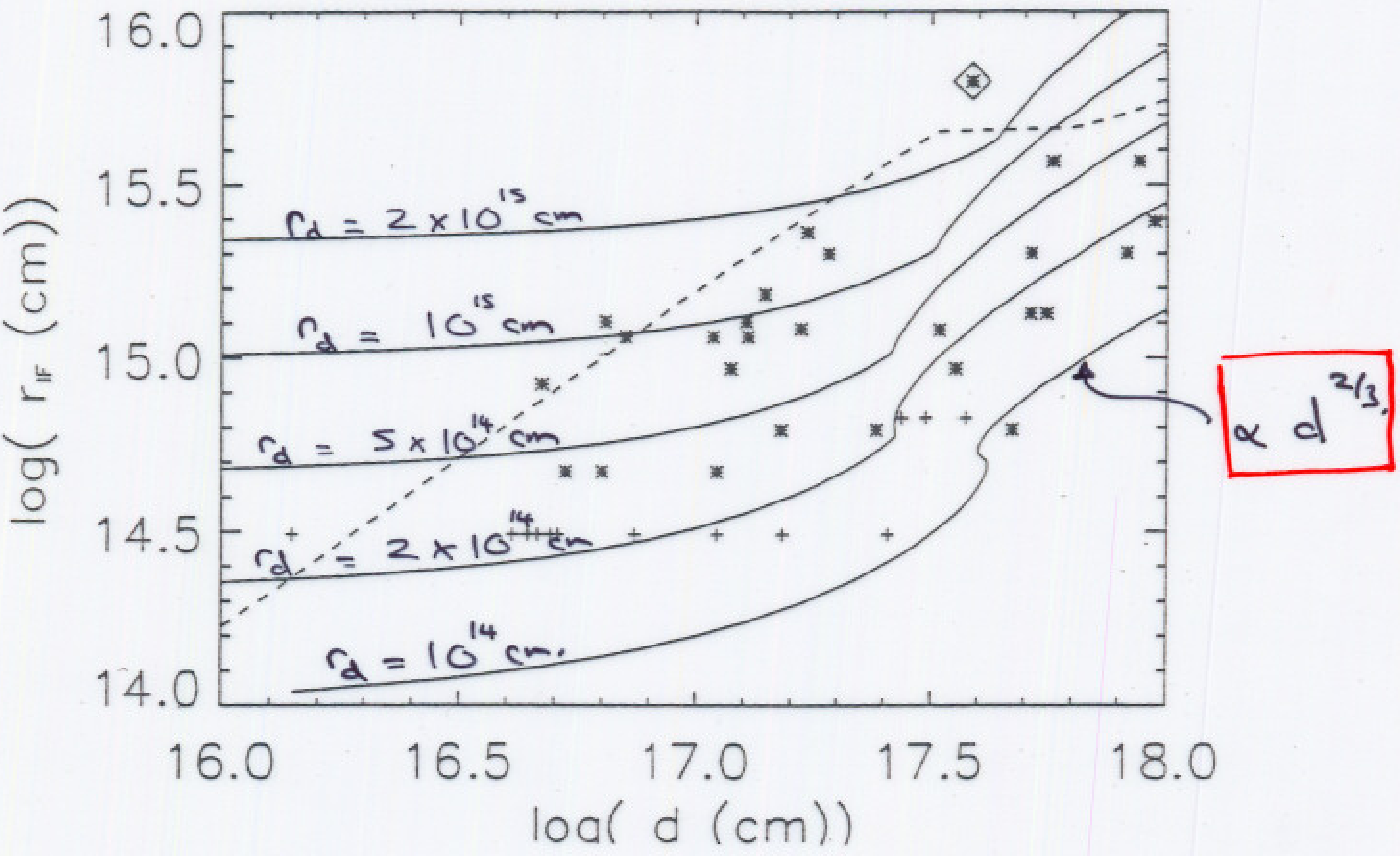
from Störzer and Hollenbach 1999.



from Vicente and Alves

2005.

from Johnstone et al 1998



← EUV region →

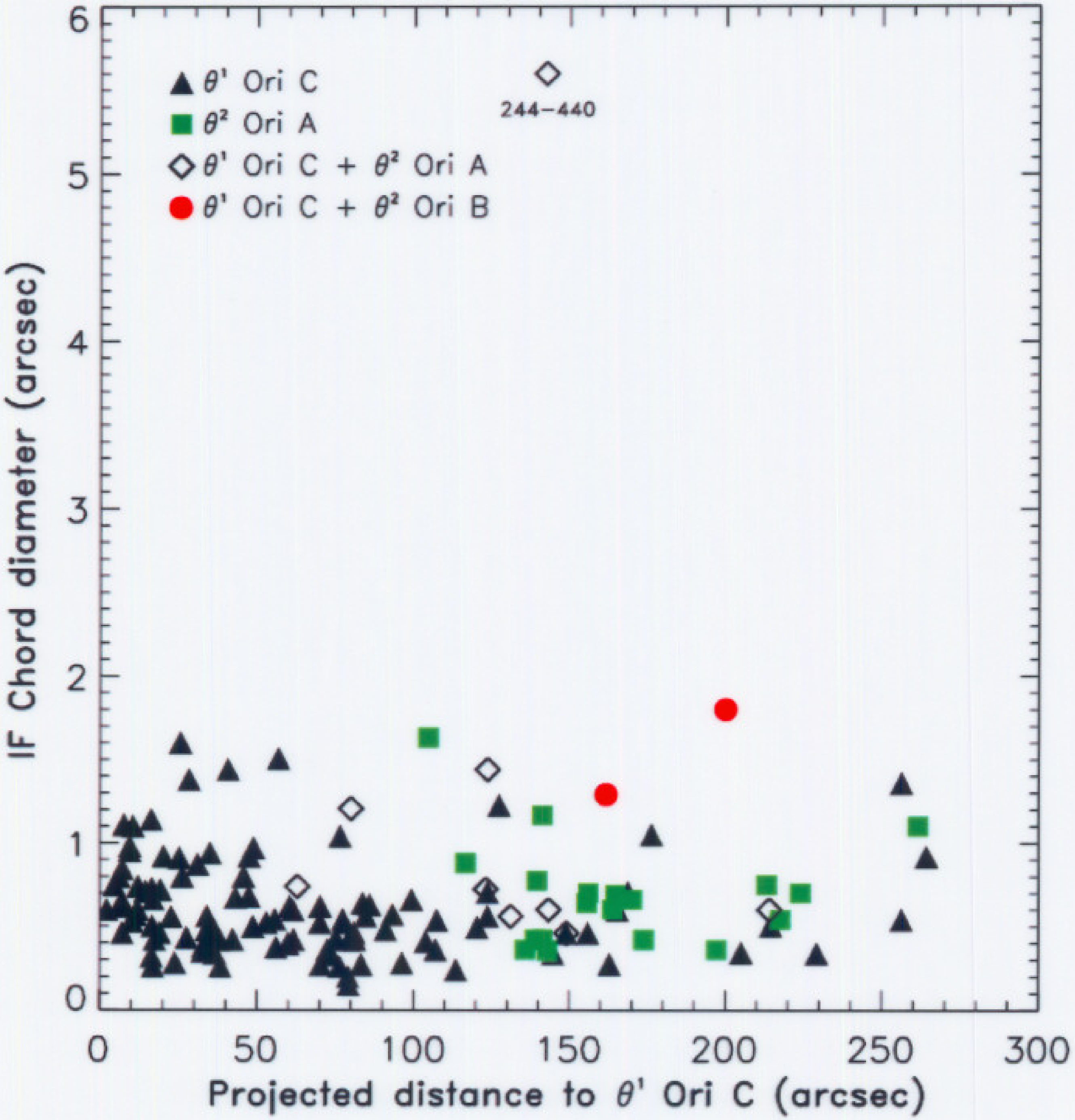
IF at disc

← FUV region: offset $\propto d^{2/3}\, r_d^{2/3}$

.... looks okay

but in more recent analysis (Vicente & Alves 2005) increase of r_{IF} with d less obvious...

..... masked by range of r_d + projection effects?



Cometary structure explained if rear lobe is irradiated by diffuse nebula emission. see Johnstone et al 1998

Symmetry axis should point towards θ^1C .... doesn't always.

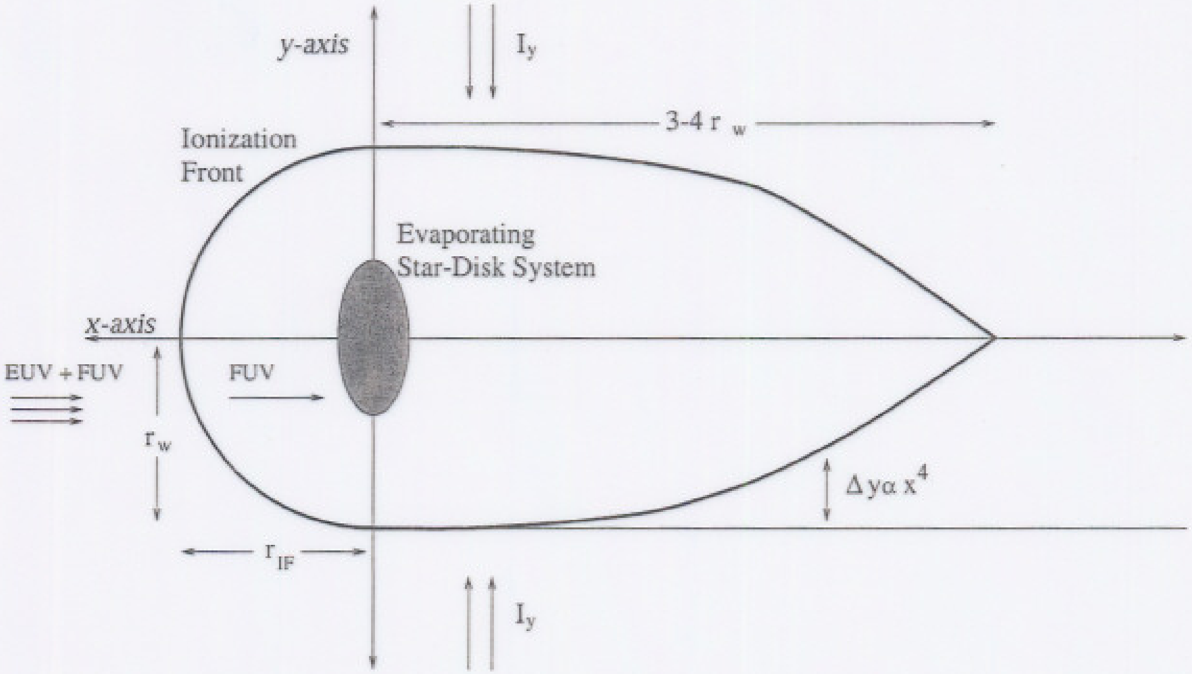


FIG. 7.—Schematic diagram for the formation of a hemispherical ionization front and an ionized tail behind each evaporating source. Diffuse FUV photons heat the disk surface, producing a neutral flow, while diffuse EUV photons penetrate deeper with increasing distance along the shadow axis behind the source.