Class 8: Stellar feedback

ASTR 4008 / 8008, Semester 2, 2020

Mark Krumholz

Outline

- Formalism
  - IMF averaging
  - “Energy” versus “momentum” feedback
- Feedback menagerie:
  - Radiation and radiatively-driven winds
  - Protostellar outflows
  - Photoionisation
  - Trapped stellar winds
  - Supernovae

IMF-averaged outputs

A tool to think about feedback budgets

- Write IMF as $\xi(m) = m\ \mathrm{d}n/\mathrm{d}m = \mathrm{d}n\ /\ \mathrm{d}\ \ln m$, normalised so $\int \xi(m)\ \mathrm{d}m = 1$
- Mean stellar mass = $\int m\ \xi(m)\ \mathrm{d}\ \ln m\ /\ \int \xi(m)\ \mathrm{d}\ \ln m = 1\ /\ \int \xi(m)\ \mathrm{d}\ \ln m$
- Suppose that we know the rate q at which stars of a given mass and age produce a quantity Q (e.g., Q = radiated energy, q = luminosity)
- Given mass of stars M of age t, production rate is $q(t) = M \int \xi(m)\ q(m, t)\ \mathrm{d}\ \ln m$
- Define IMF-averaged production rate per unit mass $\langle q/M \rangle = \int \xi(m)\ q(m, t)\ \mathrm{d}\ \ln m$
- Similarly, IMF-averaged yield yield / mass $\langle Q/M \rangle = \iint \xi(m)\ q(m, t)\ \mathrm{d}\ \ln m\ \mathrm{d}t$

Energy-driven vs. momentum-driven feedback

An important distinction

- Consider stars that “turn on” at t = 0 and produce “wind” with momentum and energy output per unit time $\dot{p}_w$ and $\dot{E}_w$
- The is drives an expanding spherical shell around the stars; two cases:
  - Shell conserves momentum, but most energy lost to radiation:

$$p_{\mathrm{sh}} = M_{\mathrm{sh}} v_{\mathrm{sh}} = \dot{p}_w t \quad \Longrightarrow \quad E = \frac{p_{\mathrm{sh}}^2}{2M_{\mathrm{sh}}} = \frac{1}{2} v_{\mathrm{sh}} \dot{p}_w t$$

  - Shell conserves energy, little lost to radiation: $E = \dot{E}_w t$
- Energy is greater in energy-conserving case by $\dfrac{1}{v_{\mathrm{sh}}} \dfrac{2\dot{E}_w}{\dot{p}_w}$
- This may be big: for light (a photon “wind”), this factor is $\approx 2c/v_{\mathrm{sh}}$

Radiation pressure feedback

Basics

- Most unavoidable feedback is radiation pressure: when stars form, they emit light, which pushes on the material around them
- Most energy from young stars is in the UV, and even a dust-poor galaxy will absorb a reasonable fraction of this
- A large fraction of energy comes out in first ~5 Myr, when massive stars are alive and shining
- Once absorbed, energy re-emitted in IR and most escapes due to low dust opacity in IR, so this is a mostly momentum-driven feedback (possible exception when we discuss massive stars)

Radiation pressure

Budgets

- IMF-averaged luminosity and momentum:

$$\left\langle \frac{L}{M} \right\rangle = 1140 \, \frac{L_\odot}{M_\odot} \qquad \left\langle \frac{\dot{p}_{\rm rad}}{M} \right\rangle = \frac{1}{c} \left\langle \frac{L}{M} \right\rangle = 23 \text{ km s}^{-1} \text{ Myr}^{-1}$$

- Meaning: for each gr of mass that goes into stars, those star produce enough light to accelerate another gr of mass to 23 km s^{-1} in 1 Myr

- Integrated output:

$$\left\langle \frac{E_{\rm rad}}{M} \right\rangle = 1.1 \times 10^{51} \text{ erg } M_\odot^{-1} \qquad \epsilon = \frac{1}{c^2} \left\langle \frac{E_{\rm rad}}{M} \right\rangle = 6.2 \times 10^{-4} \qquad \left\langle \frac{p_{\rm rad}}{M} \right\rangle = 190 \text{ km s}^{-1}$$

- Meaning: for each gr of mass going into stars, those stars release ~10^{-3} of their rest mass as light, which can accelerate another gr of mass to 190 km s^{-1}

Protostellar outflows

Basics

- When a star forms, it is fed by an accretion disc; the disc launches ~10% of the incoming mass into a wind
- Typical wind speed is Keplerian speed at stellar surface:

$$v_w \approx \sqrt{\frac{GM_*}{R_*}} = 250 \text{ km s}^{-1} \left(\frac{M_*}{M_\odot}\right)^{1/2} \left(\frac{R_*}{R_\odot}\right)^{-1/2}$$

- Post-shock temperature after wind hits ISM and stops is

Mean mass / free particle; =0.61 in fully-ionised gas

$$T = \frac{\mu m_{\mathrm{H}} v_w^2}{3k_B} \sim 5 \times 10^6 \text{ K}$$

- This is low enough that, at high density found near star, gas can cool fairly rapidly; thus outflows are momentum-driven, not energy-driven

Protostellar outflows

Budgets

- Consider a star of mass *m* that forms over time t_{form}; mean mass flux in outflow is $f\, m\, /\, t_{\mathrm{form}}$, $f \sim 0.1 - 0.2$
- IMF-averaged momentum budget $\left\langle \frac{p_w}{M} \right\rangle = \int \xi(m) \int_0^{t_{\mathrm{form}}} \frac{f m v_K}{t_{\mathrm{form}}}\, dt\, d\ln m$
- Approximate *f* and v_K ~ constant during formation:

$$\left\langle \frac{p_w}{M} \right\rangle = f v_K \int \xi(m) m\, d\ln m = f v_K$$

- Momentum budget ~10s of km s^{-1}, smaller than radiation by factor ~10
- However, outflow momentum comes out over t_{form} ~ 0.1 Myr, compared to ~5 Myr for radiation, so much stronger while outflows are on

Supernovae

- Majority of stars over ~8-9 $M_\odot$ end their lives as core-collapse SNe, exploding w/energies of ~10^{51} erg; 1 SN per 100 $M_\odot$ of stars

- Ejecta velocity higher than winds, so cooling time is long — drives a bubble of hot gas like winds, which eventually cools due to adiabatic losses

- Terminal momentum of bubble must be determined by numerical simulations:
  - For isolated SNe, strong consensus: terminal $p \approx 3 \times 10^5\ M_\odot$ km s^{-1}, so momentum budget $\langle p / M \rangle \approx 3000$ km s^{-1}
  - Significant uncertainty for clustered SNe; yield may be higher, though probably by < a factor of 10

- However, there is a long time delay: no feedback at all until ~5 Myr after stars form

Photoionisation

Basics

- When massive stars form, they produce a large flux of ionising (>13.6 eV) photons: $\langle S / M \rangle \approx 6 \times 10^{46}$ photons s^{-1} $M_\odot^{-1}$

- Cross section of these photons with a neutral H atom is huge ($\sim 10^{-18}$ cm^{-2}), so mean free path is tiny — all photons absorbed, creating a bubble of ionised gas where ionisations and recombinations are in balance

- Typical temperatures in these ionised regions, called HII regions, are $\sim 10^4$ K — set by balance between collisional cooling and heating by ionising photons

- Regions where stars form are typically at ~10 K, so when an HII region first forms, it is overpressured compared to its surroundings by a factor of $\sim 10^3$ — explosive expansion follows

The Strömgren radius

- Size of bubble set by ionisation balance:

Ionising luminosity

Recombination rate coefficient, $\approx 3 \times 10^{-13}$ cm^3 s^{-1}

Gas mass per H

$$S = \frac{4}{3}\pi r_S^3 \alpha_B n_e n_p \implies r_S = \left(\frac{3S\mu^2 m_{\mathrm{H}}^2}{4\pi f_e \alpha_B \rho}\right)^{1/3}$$

Density

Strömgren radius

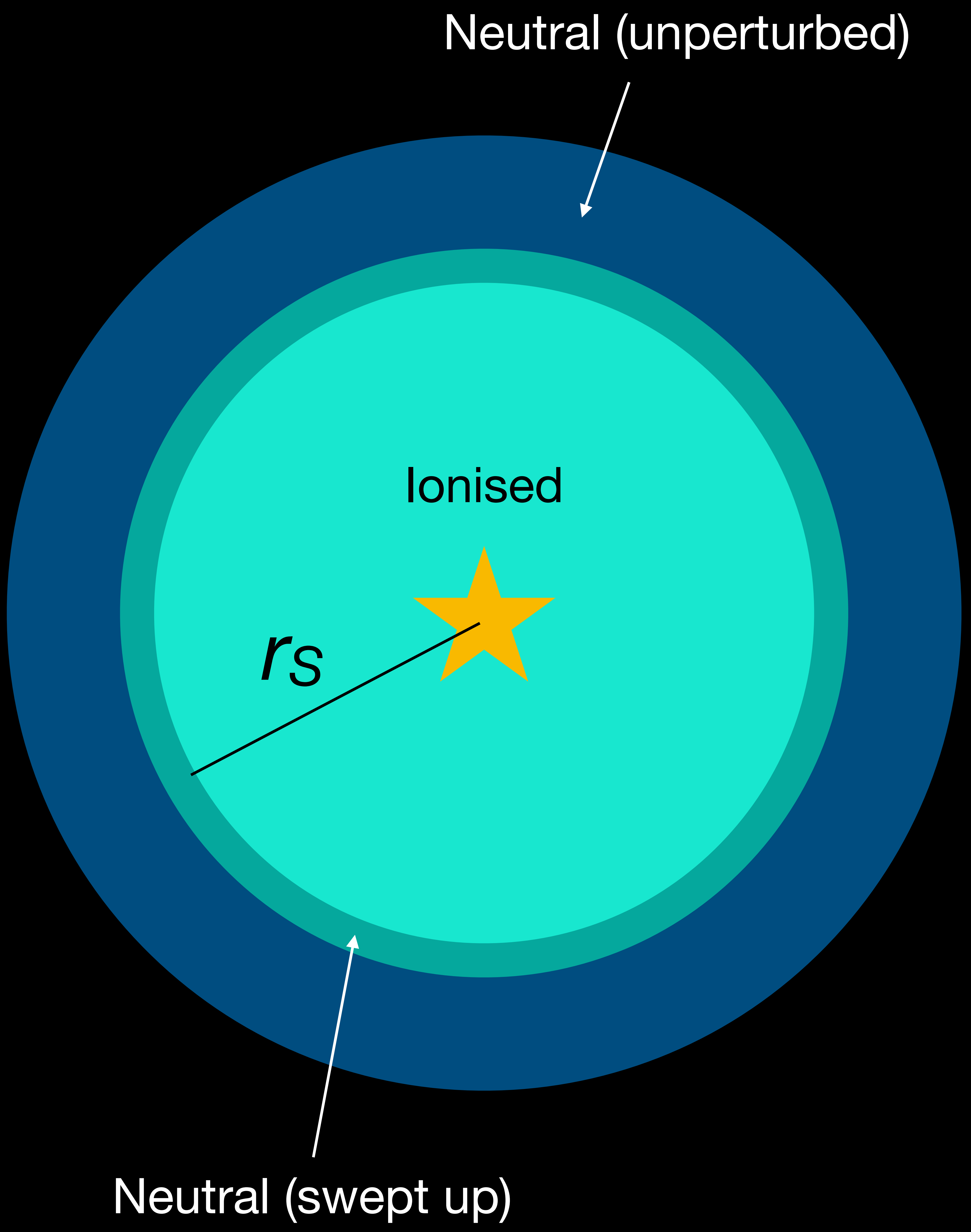
Free electrons / H $\approx$ 1.1

- For a typical O star ($S \sim 10^{49}$ s^{-1}) and density ($n_H \sim 100$ cm^{-3}), $r_S \sim$ few pc

- Sound speed in ionised region is

$$c_i = \sqrt{(1.1 + f_e)\frac{k_B T_i}{\mu m_{\mathrm{H}}}} \approx 10 \text{ km s}^{-1}$$

- As bubble expands, it sweeps up a shell of neutral gas, maintaining ionisation balance



Dynamics of the shell

Physical considerations

- As shell expands, density of ionised interior region must drop in order to maintain ionisation balance: $\rho_i = \sqrt{3S\mu^2 m_{\rm H}^2/4\pi f_e \alpha_B r_i^3}$
- Density $\rho_i \sim r_i^{-3/2}$, ionised mass $\sim r_i^{3/2}$, but swept up mass $\sim r_i^3$, so once $r_i \gg$ initial radius, almost all mass is in the shell: $M_{\rm sh} \approx (4\pi/3)\rho_0 r_i^3$

Initial density

- Motion of shell determined by momentum conservation: $\frac{d}{dt}(M_{\rm sh}\dot{r}_i) = 4\pi r_i^2 \rho_i c_i^2$
- Rewrite problem entirely in terms of shell position:

$$\frac{d}{dt}\left(\frac{1}{3} r_i^3 \dot{r}_i\right) = c_i^2 r_i^2 \left(\frac{r_i}{r_{S,0}}\right)^{-3/2}$$

Strömgren radius evaluated at initial density

HII region expansion

Similarity solution

- ODE $\frac{d}{dt}\left(\frac{1}{3}r_i^3\dot{r}_i\right) = c_i^2 r_i^2 \left(\frac{r_i}{r_{S,0}}\right)^{-3/2}$ can be solved by a similarity solution
- First step: make change of variables, by letting $x = r_i / r_{S,0}$, $\tau = t\, c_i / r_{S,0}$, so ODE becomes $\frac{d}{d\tau}\left(x^3 \frac{dx}{d\tau}\right) = 3x^{1/2}$
- Now look for a solution of the form $x = f\tau^\eta$
- Substituting in this trial form, one can solve for η and f. Solution is

$$x = \left(\frac{49}{12}\tau^2\right)^{2/7} \implies r_i = r_{S,0}\left(\frac{7tc_i}{2\sqrt{3}r_{S,0}}\right)^{4/7}$$

Feedback effects of HII regions

Mass and momentum budgets

- In reality most HII regions are not spherical — ionised gas escapes the cloud through low-density channels. Associated mass flux is

$$\dot{M} \approx 4\pi r_i^2 \rho_i c_i = 4\pi r_{S,0}^2 \rho_0 c_i \left(\frac{7tc_i}{2\sqrt{3} r_{S,0}}\right)^{2/7} = 7.3 \times 10^{-3} t_6^{2/7} S_{49}^{4/7} n_2^{-1/7} \; M_\odot \; \mathrm{yr}^{-1}$$

$S/10^{49}$ photons/s — typical for O star

$t/10^6$ yr

$n/10^2$ cm^{-3}, where n = initial number density

- Over ~4 Myr lifetime of O star, can ejected ~10^4 M$_\odot$ of gas!

- Momentum carried by shell is $p_{\mathrm{sh}} = M_{\mathrm{sh}} \dot{r}_i = 1.1 \times 10^5 \, t_6^{9/7} S_{49}^{4/7} n_2^{-1/7} \; M_\odot \; \mathrm{km \; s^{-1}}$

- We get ~1 shell this size per ~300 M$_\odot$ of stars formed, lasting for ~4 Myr, to total momentum budget of HII regions is $\langle p / M \rangle$ ~ 3000 km s^{-1}, ~10 × larger than for radiation

Hot stellar winds

Basics

- O stars launch winds at ~1000-2000 km s^{-1}, with mass fluxes ~10^{-7} $M_\odot$ yr^{-1}, accelerated by radiation pressure on metal atoms in stellar atmosphere
- Wind carries ~half the radiative momentum, so mechanism luminosity is

$$L_w = \frac{\dot{p}_w^2}{2\dot{M}_w} \approx \frac{L_*^2}{8\dot{M}_w c^2}$$

Stellar luminosity

Wind mass flux

- Due to high speed, post-shock temperature 10 - 100 × larger than for protostellar outflows, so gas does not rapidly cool
- Wind can blow a bubble with a shell at its edge, similar to HII region

Hot stellar winds

Bubble solution

- Assume no losses to radiation, ~half wind energy in shell (other half in interior); then we have

$$\frac{d}{dt}\left(\frac{1}{2}\cdot\frac{4}{3}\pi\rho_0 r_b^3 \dot{r}_b^2\right) \approx \frac{1}{2}L_w$$

(1/2) x bubble mass x velocity²

Wind mechanical luminosity

- Can be solved by similarity solution just like HII region; solution is

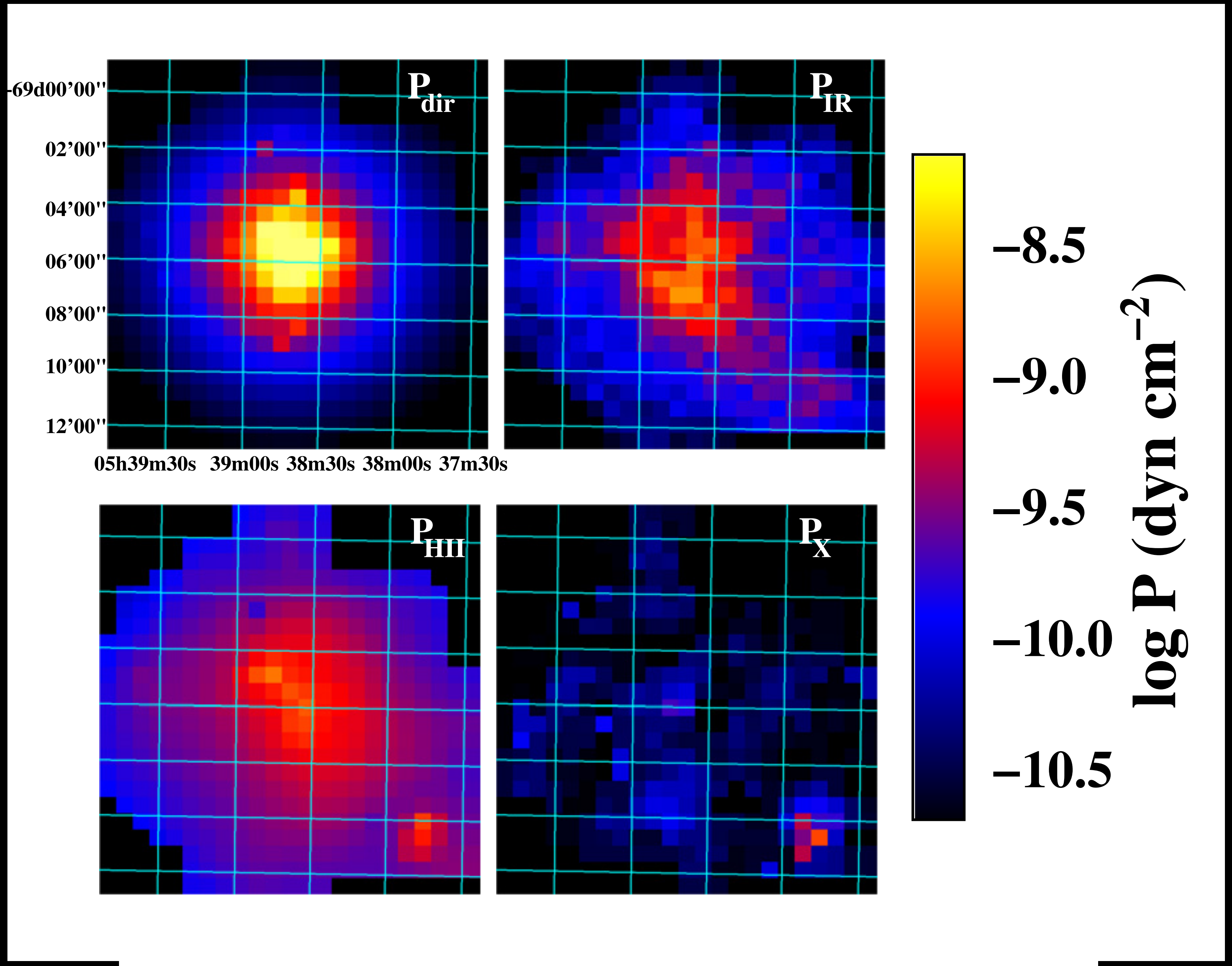
$$r_b = \left(\frac{25 L_w t^3}{12\pi\rho_0}\right)^{1/5} \approx \left(\frac{25 L_*^2 t^3}{96\pi \dot{M}_w c^2 \rho_0}\right)^{1/5}$$

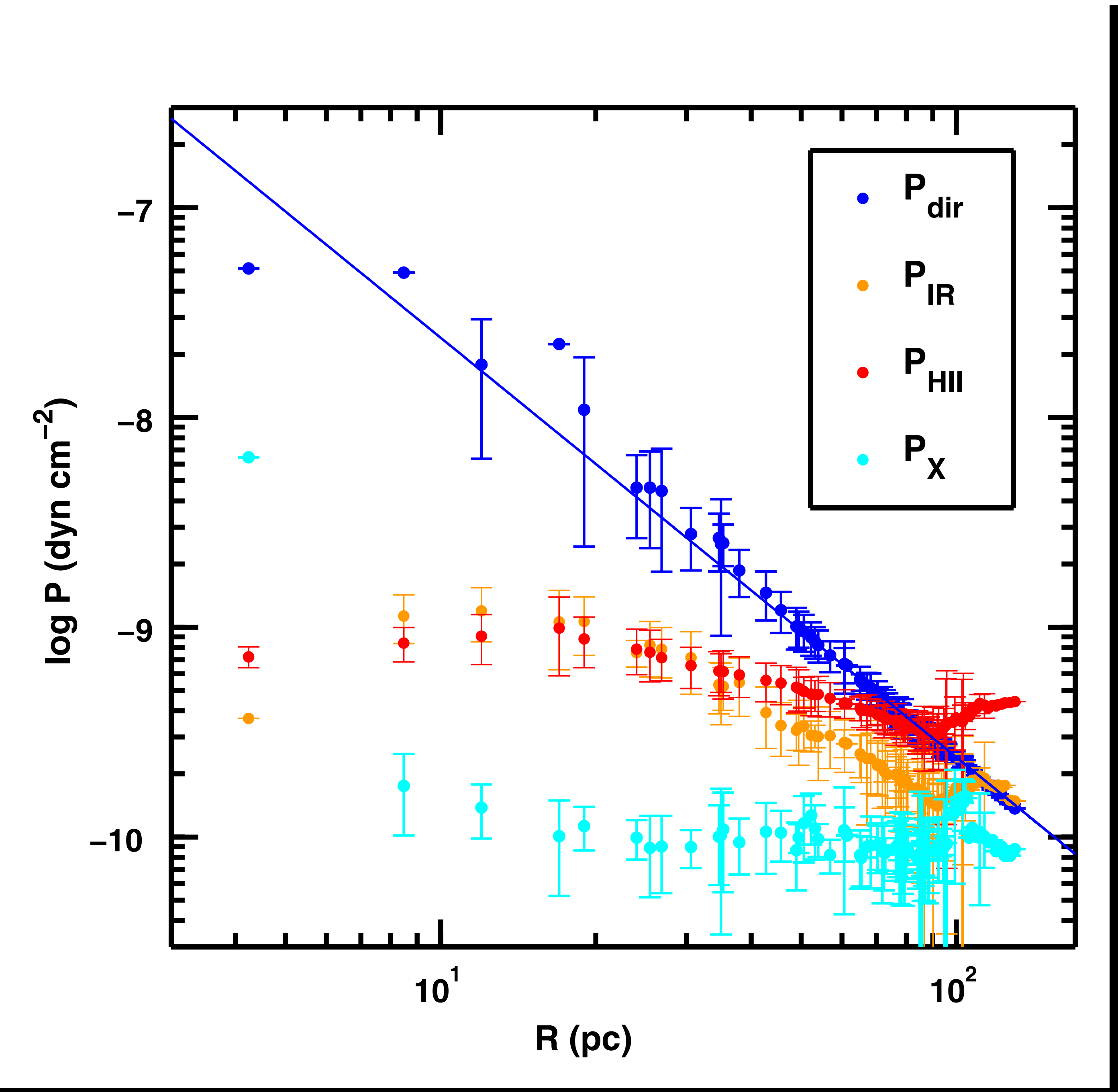
- Wind bubble generally larger than HII region at equal time, so, if wind bubble exists, it dominates the expansion, not the photoionised gas pressure

Hot stellar winds

The trapping factor

- Main uncertainty: is shocked stellar wind gas trapped, or does it leak out of bubble?
- Since wind and radiation have ~equal momentum, can use result from E-driven vs p-driven expansion: if shocked gas it trapped, its pressure should be larger than radiation pressure by $\sim v_w / v_b$
- Define trapping factor $f_{trap} = P_w / P_{rad}$ — measure from X-ray and optical data
- Observations suggest $f_{trap} \sim 1$, so winds leak





Lopez+ 2011