Review Slide 10 from Chapter 01 and Slides 8&9 from Chapters 02/03/04.

Problems with the two-phase 'FGH' model:

i) cosmic ray ionization rate 10x too high
the cosmic ray rate is measured from
$D+H^+ \rightarrow D^+ + H$
$D^+ + H_2 \rightarrow HD + H^+$

photo-electric heating is needed to bridge the gap
McKee: Γ from photo-electric effect on small grains

ii) pervasive supernova (SN) cavities sweep up phase 'F' (intercloud) within 10^7 years

iii) observations imply a coronal gas
a) OVI absorption 1032/1037Å — Copernicus satellite 1972-1981
$\Rightarrow$ 3-7·10^5 K — York & Jenkins 1977-78 suggest shock heating with v>100 km/s
1. O star stellar winds — Castor, McCray, & Weaver 1975
2. SN shells/cavities

b) soft x-ray background $\Rightarrow$ hot plasma
E_x~200 eV must be local (τ=1 at 200 eV within 100 pc)

c) hotter gas at 10^6 K $\Leftarrow$ SiIV

iv) high-velocity optical and UV absorption lines
$\Rightarrow$ v~20-50 km/s
CaII H and K; 21 cm; CII, CIII, HII
therefore not in dynamic equilibrium

⇒ ISM not in equilibrium, but in steady state

1) SNR (supernovae remnants) pervasive
2) hot SN gas conductively heats clouds
3) clouds evaporate

Incorporating effects of SN remnants on the ISM: Cox & Smith74; McKee & Ostriker77
Hot SN cavities become an interconnected tunnel system, like swiss cheese

Fraction of galactic volume within SN cavities?

Let S = # of SNe per unit volume per unit time
V_{SNR} = volume of SNR
τ_{SNR} = time the cavity lasts

cavities overlap if ________________________

S = # of SNe in galaxy per year / volume of galactic disk
= [1/ yr] / [π (kpc)^2 pc] = $1.1 \cdot 10^{-12}$ SNe/pc^3/yr

SNR experiences momentum-conserving phase: Isn't momentum always conserved?

$v_{initial} = 200$ km/s, $R_{initial} = 20$ pc, $v_{final} \sim 5$ km/s

$R_{final} = \qquad = \qquad = 68$ pc

therefore $V_{SNR} = 4\pi/3(68\text{pc})^3 = 1.3 \cdot 10^6$ pc^3

τ_{SNR}: adopt the shorter of $\tau_{recombination}$ or $\tau_{compression\ by\ external\ medium}$

$\tau_{rec} \sim 10^{7\text{-}8}$ yr for $n_e \sim 10^{-2}$–10^{-3} cm^{-3}

$\tau_{comp} = R_{final}/c_s \sim 68$ pc/10 km/s $= 6.7 \cdot 10^6$ yr

Therefore $SV_{SNR}\tau_{SNR} = 1.1 \cdot 10^{-12}\ 1.3 \cdot 10^6\ 6.7 \cdot 10^6 = 9.5 > 1$ ⇒ SNR overlap

Therefore Warm Ionized Medium of FGH (1969) will be swept up by SNR, but ...

- i) SNR are clustered, therefore effect dampened
- ii) SNe occur in denser than average ISM, therefore SNR must be smaller
- iii) GMCs (H_2) entirely left out
- iv) SN and O* rates variable with:
  radius in galaxy, in spiral arms
  time: starburst galaxy ⇐ triggered dynamics
- v) magnetic fields will stall the expansion of SNRs (p.282 Tielens)

Also on p.282 Tielens: when SNe stir up the ISM, ..the turbulent pressure dominates the total pressure of the ISM. → Three-phase ISM model

More modern views of a complex, multi-phase ISM: McKee & Ostriker 1977; Ostriker+2010

		T	n	χ
cold neutral medium	(CNM)	80 K	42 cm^{-3}	10^{-3}
warm neutral medium	(WNM)	8000	0.37	0.15
warm ionized medium	(WIM)	8000	0.25	0.68
hot ionized medium	(HIM)	$4.5\cdot10^5$	$3.5\cdot10^{-3}$	1.0

What phases are missing from this list?

Are the phases in pressure equilibrium?

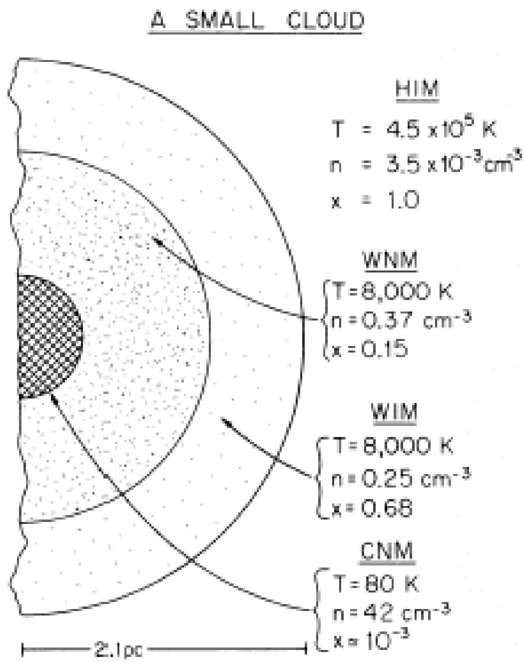


FIG. 1

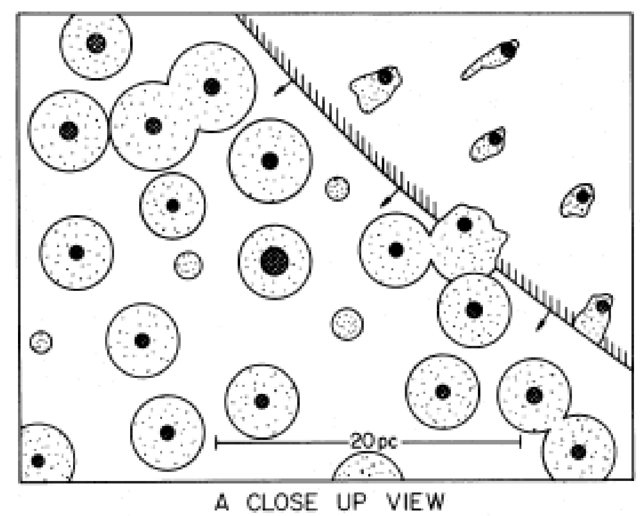


FIG. 2

FIG. 1.—Cross section of a characteristic small cloud. The crosshatched region shows the cold core, which gives the usual optical absorption lines. Next is the warm neutral medium (WNM) with ionization produced by soft X-ray background. The outer layer (WIM) is gas largely ionized by stellar UV background. Typical values of hydrogen density n, temperature T, and ionization $x = n_e/n$ are shown for each component, except that a higher than average value of the soft X-ray flux has been assumed in order to produce a significant amount of WNM at this pressure.

FIG. 2.—Small-scale structure of the interstellar medium. A cross section of a representative region 30 pc × 40 pc in extent is shown, with the area of the features being approximately proportional to their filling factors. A supernova blast wave is expanding into the region from the upper right. The radius of the neutral cores of the clouds (represented by crosshatching) ranges from about 0.4 to 1 pc in this small region; all the clouds with cores have warm envelopes (*dotted regions*) of radius $a_w \sim 2.1$ pc. A few clouds are too small to have cores. The envelopes of clouds inside the SNR are compressed and distorted.

More modern views of a complex, multi-phase ISM: McKee & Ostriker 1977; Ostriker+2010

TABLE 1

INTERSTELLAR CLOUD PROPERTIES FOR TYPICAL CONDITIONS

Average Cloud Properties	Cold Cores	Warm Ionized Component
Hydrogen density, n (cm^{-3}).........	42	0.25
Fractional ionization, x............	...	0.68
Assumed temperature, T (K)........	80	8,000
Filling factor, f....................	0.024	0.23
Intercloud distance, λ (pc)..........	88	12
Cloud radii (pc):		
Largest........................	10.0	10.8
Mean*.........................	1.6	2.1
Smallest.......................	0.38	2.1
Column densities (10^{19} cm^{-2}):		
Largest........................	173	.22
Mean*.........................	27	.22
Smallest.......................	0.5	.22

* Weighted by cloud area.

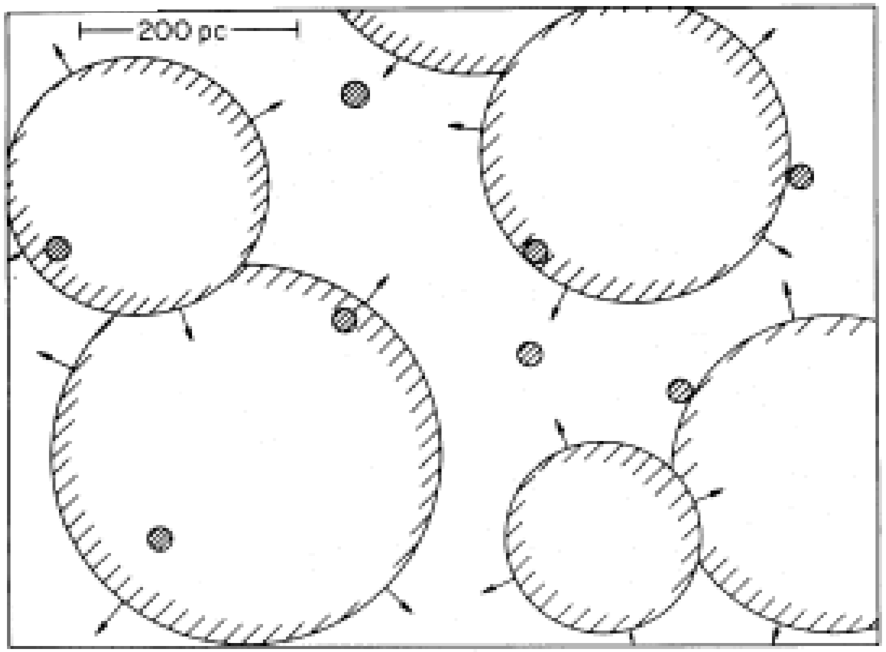
filling factors are approximately

HIM ~

CNM ~

WIM ~

WNM ~



A LARGE SCALE VIEW

FIG. 3.—Large-scale structure of the interstellar medium. The scale here is 20 times greater than in Fig. 1: the region is 600 × 800 pc. Only SNRs with $R < R_c = 180$ pc and clouds with $a_0 > 7$ pc are shown. Altogether about 9000 clouds, most with $a_0 \sim 2.1$ pc, would occur in a region this size.

The Astrophysical Journal, 345:372–383, 1989 October 1

THE DISK-HALO INTERACTION: SUPERBUBBLES AND THE STRUCTURE OF THE INTERSTELLAR MEDIUM

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ABSTRACT

The Type II supernovae in our Galaxy are spatially and temporally correlated and the consequences of such correlations are superbubbles and supershells fed by tens or hundreds of supernovae per bubble. These objects evolve and expand rapidly, and they soon break out of the disk of the Galaxy. The collimated structures formed in this process are called chimneys.

We assume that the interaction between the disk and the halo is dominated by the upward flow of mass, energy, momentum, and magnetic flux convected in the chimneys. As cooling occurs, the cycle is completed by the downward flow, from the halo to the disk, of gas that has cooled and formed clouds. These clouds rain down onto the disk, returning to it both mass and magnetic flux, and some energy and momentum in the resulting shocks, as the clouds strike the disk. This is similar to the galactic fountain model but with a highly concentrated upward energy flow in chimneys rather than over the entire disk.

We make the further simplifying assumption that these superbubbles dominate the energy input into both the disk as well as the halo and examine the consequences of this model for our understanding of the structure of the interstellar medium and the gaseous halo. This admittedly extreme assumption, necessary for our simplified analysis, is motivated by recent observations of the structure of the interstellar medium in our own Galaxy and external galaxies.

Our theory indicates a modification in the understanding of the nature of both the interstellar medium and the halo. The essential difference here from the 1977 McKee-Ostriker theory is that, at least currently, for our own Galaxy, the filling factor of the hot gas in the disk is significantly less than unity. We describe the structure of the interstellar medium using as the fundamental parameters the clumping of the Type II supernovae rate and the mean ambient density. We sketch how, for galaxies of various types, the interstellar medium can be three-phase, chimney, or two-phase. The state of the interstellar medium may also vary within a given Hubble type as a function of galactocentric radius. Temporal variations occur when a galaxy changes its star formation rate, for example, if it is triggered into the starburst mode.

Certain conditions are necessary for chimneys to occur,
e.g., superbubble formation rate vs gas density.

Normal & Ikeuchi (1989):
"To form chimneys from multiple supernovae, the bubble must evolve sufficiently rapidly so that the characteristic dynamical time to reach one scale height is shorter than the cooling time."

Normandeau+1996 Nature article:

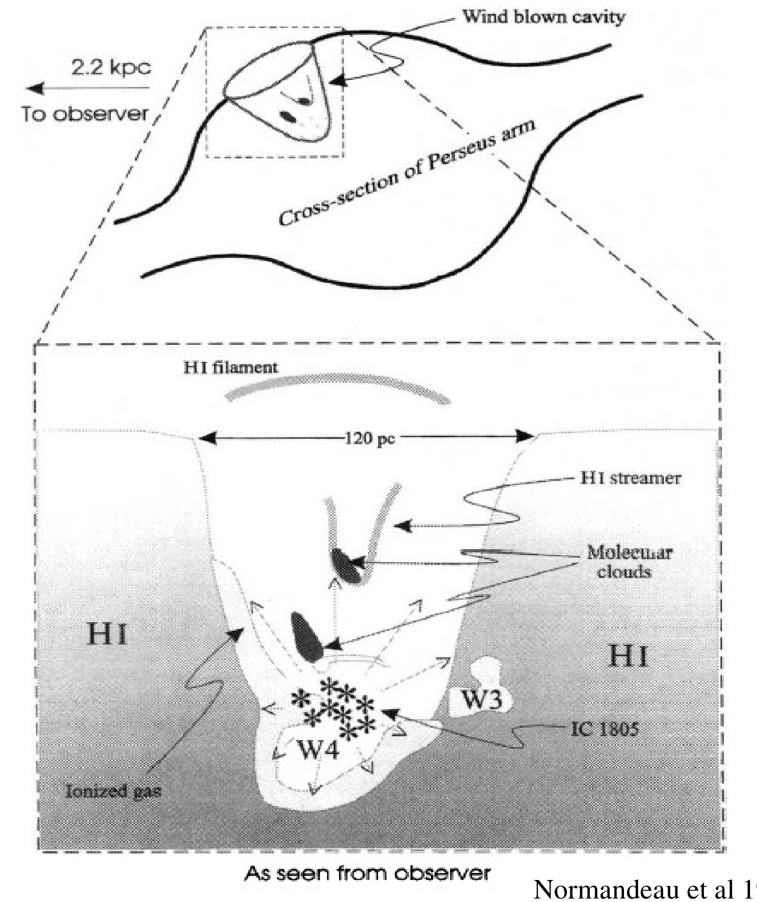
Q: Justify that the KE imparted to the streamers is >6e47 ergs.

Q: Why is the kinematic age <4.5Myr?

Q: Are the lifetimes of the stars long enough to produce the chimney?

Q: Why is the energy outflow rate >9e35 erg/s?

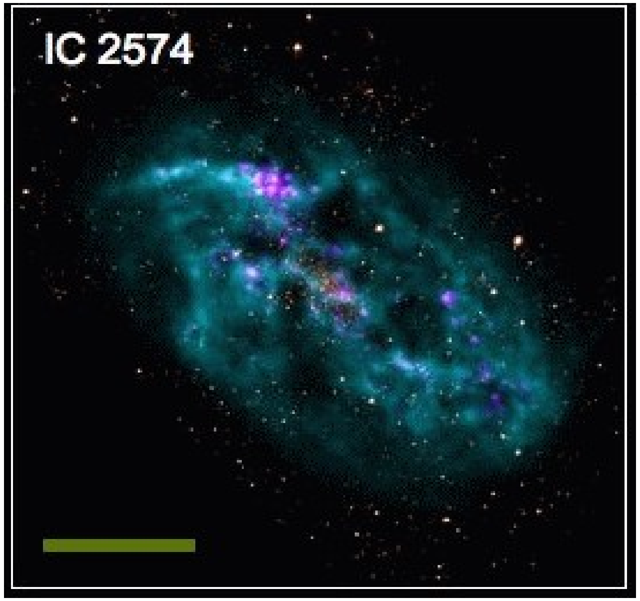
Q: Why is the mechanical wind luminosity >3e37erg/s?



Normandeau et al 1996

Phases of the Interstellar Medium

Walter+2008 and the THINGS survey



Norman & Ikeuchi 1989

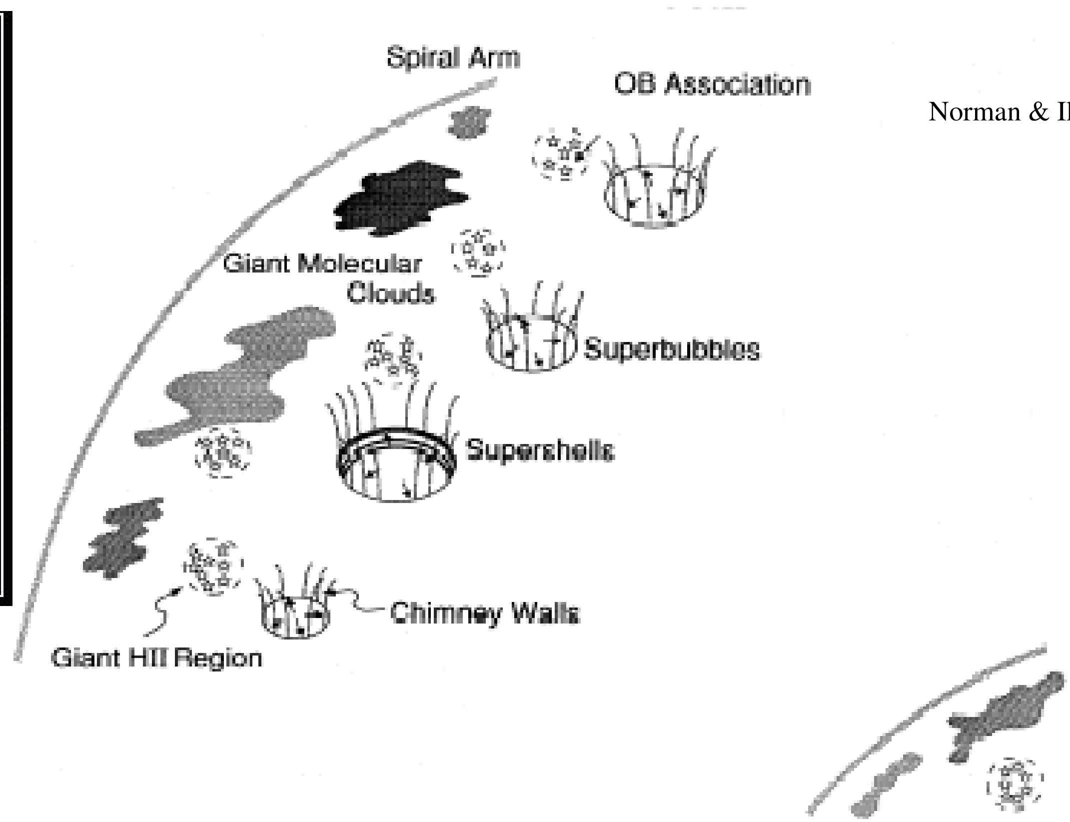


FIG. 4*a*

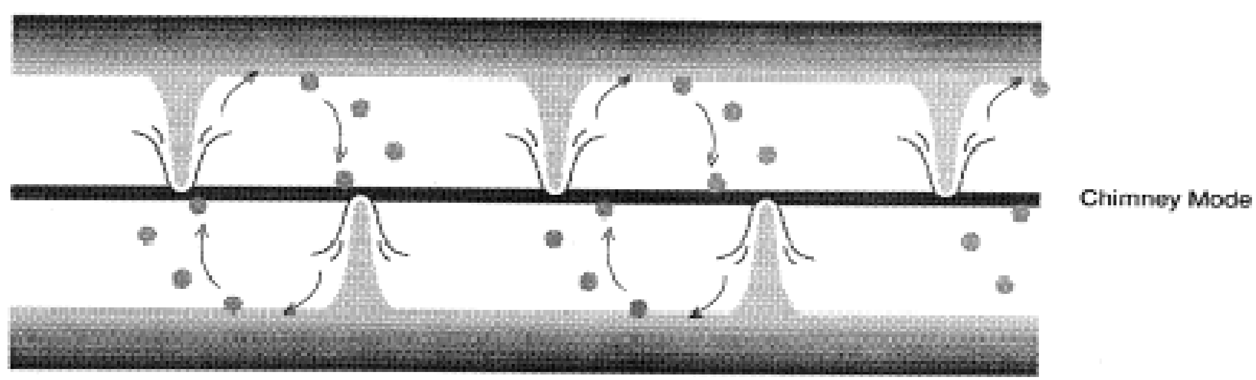
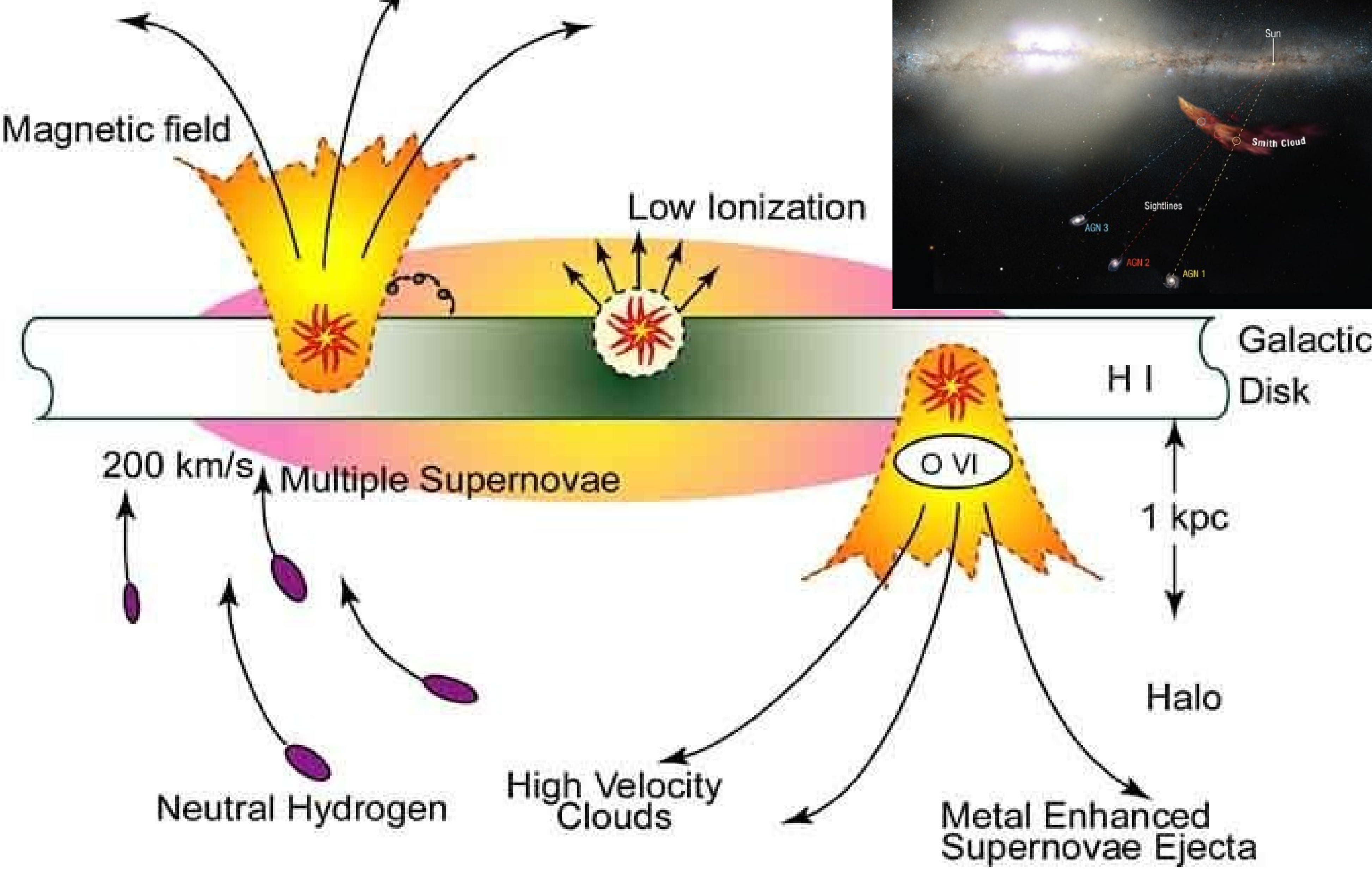


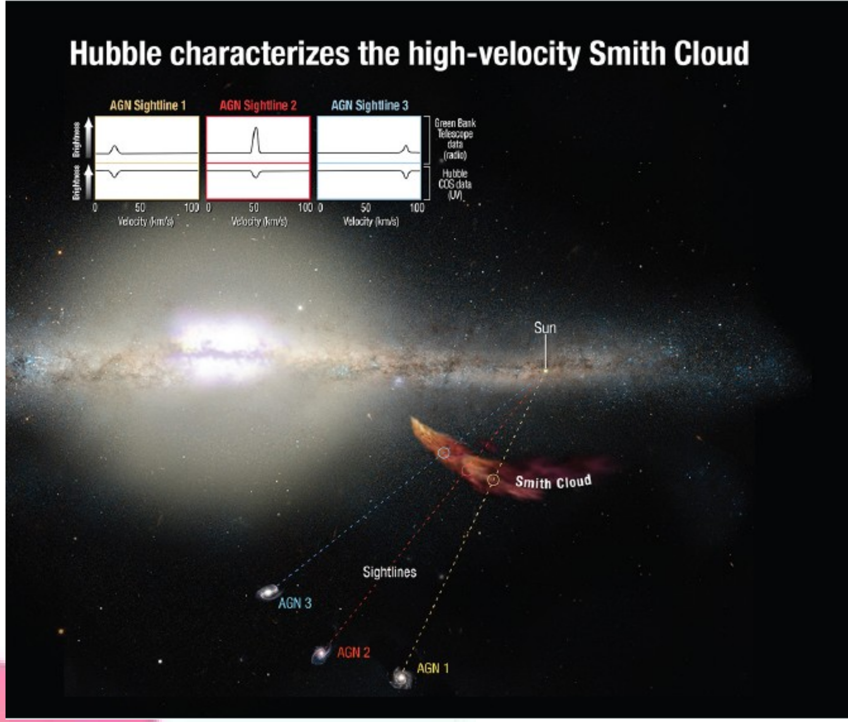
FIG. 4*b*

FIG. 4.—Schematic diagram of (*a*) superbubble formation in the disk powered by massive OB associations formed from giant molecular clouds associated with spiral arms and (*b*) superbubble evolution into the halo and circulation from disk to halo and back again.

Phases of the Interstellar Medium

This is how the halo gets so hot!



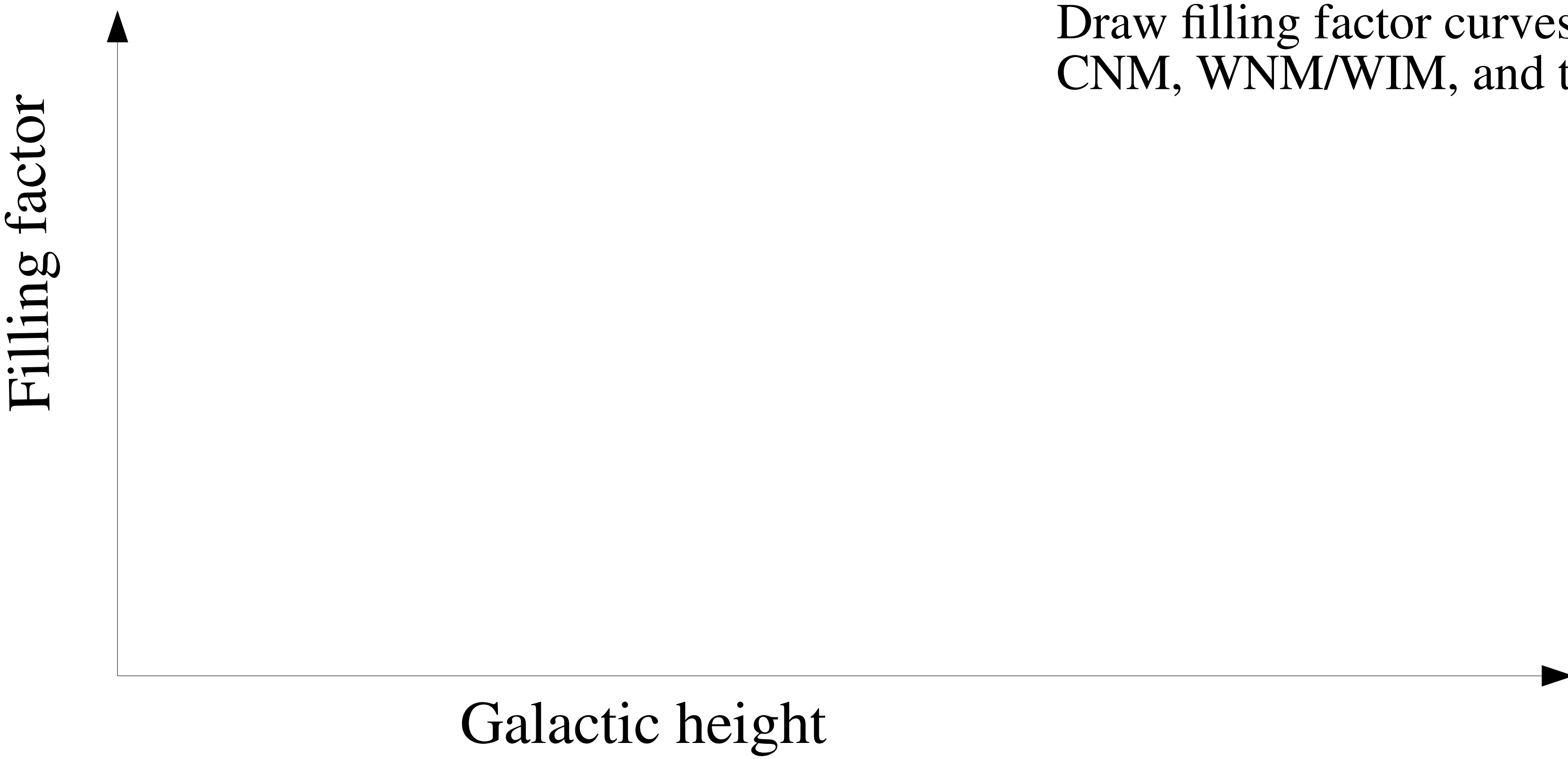


How does H_2 fit into the picture?

- GMCs are self-gravitating, not in pressure equilibrium
- But $M_{H2}/\tau_{\text{free-fall}} \gg$ star formation rate, therefore not in free-fall collapse
- But GMCs form stars, and a young star implies O stars and SN

GMCs form and grow by agglomeration of diffuse gas from ISM and other clouds

Draw filling factor curves for the CNM, WNM/WIM, and the HIM



Extreme UV and X-ray photons in the ISM (Binney & Merrifield 1998, Section 8.1.2)

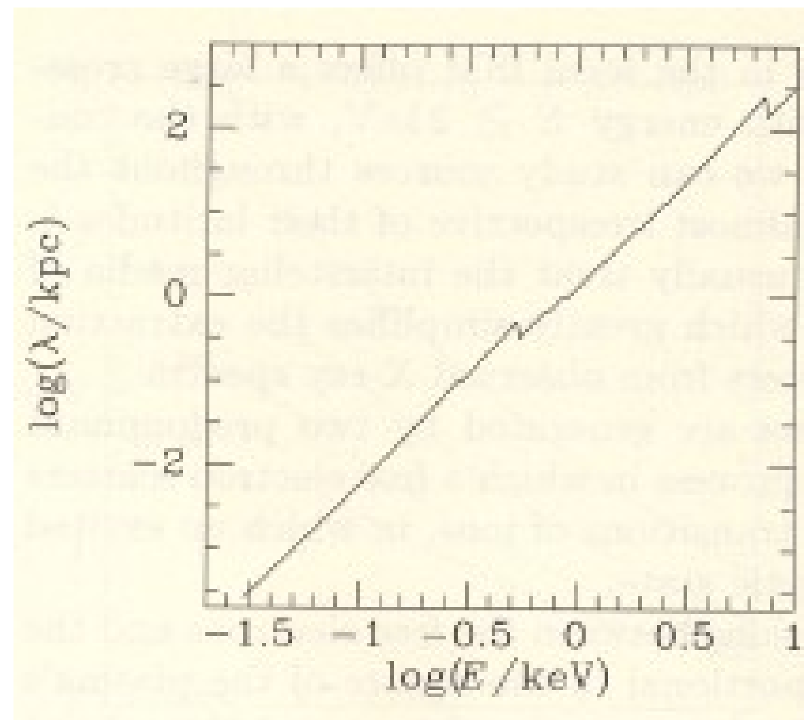
We've seen that the vast majority of the volume of the Milky Way's ISM is extremely hot, and essentially 100% ionized. This plasma emits at Extreme UltraViolet (EUV) and X-ray wavelengths.

Extreme UV:	0.0136-0.1	keV
soft X-ray:	0.1-1	keV
medium X-ray:	1-10	keV
hard X-ray:	>10	keV

Interstellar hydrogen offers a large absorption cross-section for photons of energy 13.6 eV and somewhat higher. Interstellar helium is similarly opaque to photons of ~ 24.6 and 54.4 eV, the binding energies for the first- and second-most loosely-bound helium e^-s.

It is very difficult to observe external galaxies in the EUV, because HI, HeI, and HeII absorb almost all such photons.

The figure to the right shows the mean-free path of a photon of energy E that moves through an ISM of particle density 10^6 m^{-3}. (Binney & Merrifield 1998, p. 459)



Tielens does not cover star formation, so we will supplement this chapter's material with observables related to star formation. Since this is a class on the interstellar medium, we will focus more on the physics of the initial star formation process and the subsequent interactions with the interstellar medium, and less with the specifics of the evolution of a protostar to its eventual position on the main sequence.

See class website for visually appealing examples of star formation, including for:

DR 21
Henize 206 in the LMC
M16 *aka* Eagle Nebula
M8 *aka* Lagoon Nebula
30 Doradus *aka* Tarantula Nebula
Herbig-Haro 46/47

Q: Why is it that when we look at pictures of active star formation we also frequently see examples of stellar death (not just stellar birth)?

When stars form their initial HII region, the natal HII regions expand into the less dense and cooler surrounding ISM. This process can actually work to compress the latter to the point where portions of the surrounding ISM collapse to form another star. This new star will then create its own HII region. It's easy to envision such a 'positive feedback' chain reaction that creates several new stars.

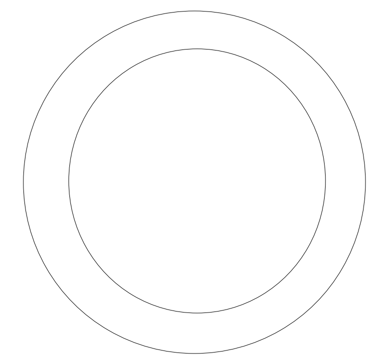
The virial theorem applies for an *isolated* gaseous body in hydrostatic equilibrium:

2 (thermal energy) + (gravitational self-energy) = 0 [$2\Pi + \Omega = 0$]

In the absence of external pressure the critical mass for collapse is

$$M_{\text{critical}} = M_{\text{Jeans}} \geq (3\pi^5/(32G^3\rho_{\text{cloud}}))^{1/2}\, c^3_{\text{cloud}}$$

Consider the effects of external pressure P_{surface} on a shell of radius r, for a spherical cloud of gas with mass M_{cloud}, volume $V_{\text{cloud}}=4/3\pi R_{\text{cloud}}^3$, and central pressure P_{center}. A pressure differential d$P(r)$ must exist across the shell, to balance gravity. The pressure must ___________ outwards.



d$M(r)$=

Including the effects of external pressure results in

$$2\Pi + \Omega - 3V_{cloud}P_{surface} < 0 \quad \text{contraction}$$

$$2\Pi + \Omega - 3V_{cloud}P_{surface} = 0 \quad \text{equilibrium}$$

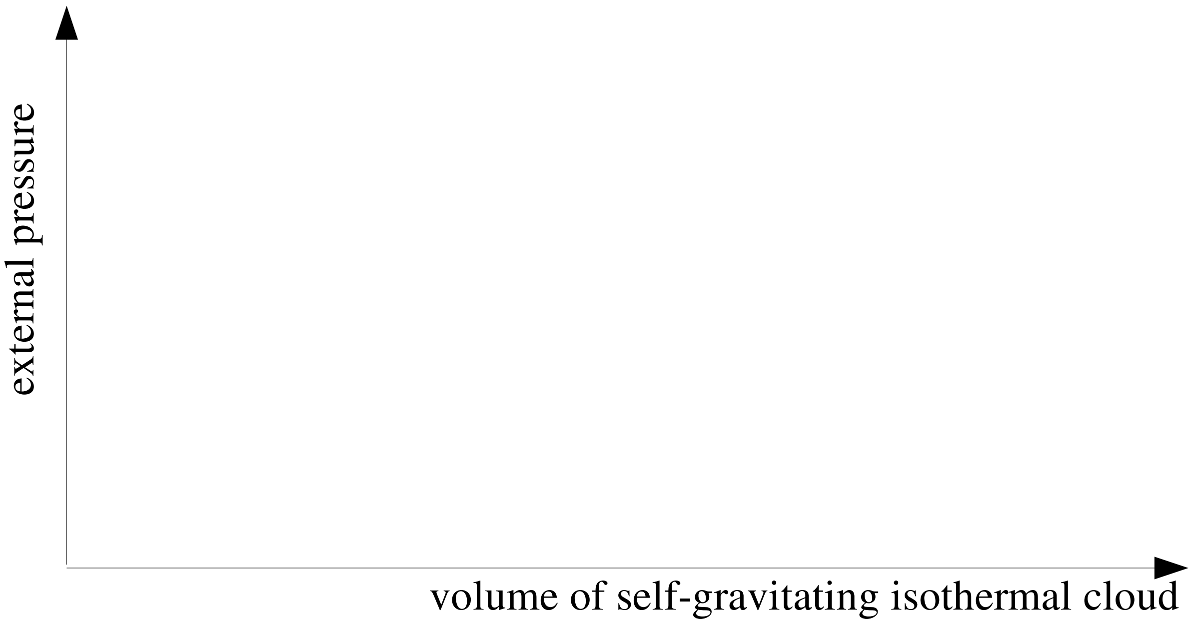
$$2\Pi + \Omega - 3V_{cloud}P_{surface} > 0 \quad \text{expansion}$$

So pressure can be an additional concern when it comes to cloud collapse. Consider a spherical, constant temperature cloud that is initially in equilibrium but then starts to collapse. If the pressure gradient is small, why can we consider the collapsing gas to be in free fall?

[$t_{ff} \sim (3\pi/(32G\rho_c))^{1/2}$] Hint: write down an expression for the acceleration of a chunk of gas at a distance r from the cloud center.

Plot the relation between the volume of a hypothetical self-gravitating isothermal gas cloud and the external pressure exerted on its surface. Hint: start at the location in the diagram where the cloud is initially uncompressed and embedded within a typical interstellar environment (e.g., a typical HI cloud), then suppose a neighboring SN event or HII region expansion pushes on the cloud.

Fermi qualitative plot 'technique'



HI Cloud A is three times as extensive as Cloud B. Since they have the same average density, Cloud A is 27 times more massive. In terms of the time it takes the respective clouds to shrink their radii by a factor of 2, Cloud A will collapse ___________ Cloud B.

a) substantially faster than
b) slightly faster than
c) substantially slower than
d) slightly slower than
e) as fast as

Adapted from Shu p. 250:

Imagine a spherical globule whose temperature remains constant as long as the gas and dust remain transparent enough to their own cooling radiation. As this globule is compressed by an external pressure P_{ext}*, the cloud volume V will decrease. Since the cloud is expected to behave like a perfect gas when the volume is large, V will at first decrease with increasing* P_{ext}*. As V decreases, however, self gravity will become increasingly important. Past a certain critical radius, the self-gravity becomes strong enough that further decreases in V result regardless of* P_{ext}*. The globule is now dynamically unstable to gravitational collapse.*

Adapted from Dyson & Williams p. 147:

To the right of the peak in P_{ext} *vs V: If the external pressure is raised incrementally, the cloud contracts. The internal pressure within increases to balance the external pressure. The cloud is stable to collapse.*

To the left of the peak in P_{ext} *vs V: If the external pressure is raised incrementally, the cloud would have to grow in radius, which is unphysical. Hence, the cloud cannot stay in equilibrium and it starts to collapse. Furthermore, if enough external pressure is applied, a cloud initially larger than the critical radius can be squeezed to be smaller than the critical radius* $\rightarrow$ *'induced star formation'.*

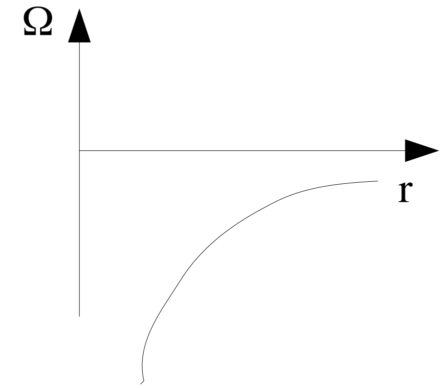
Compressive shocks can trigger collapse, but do not guarantee permanent compression. Unless a compressed cloud can also dissipate energy, it will rebound elastically. In order for the cloud to remain compressed it must cool itself on a timescale comparable to the compression time (Harwit p. 416). Since neither atomic nor molecular hydrogen radiate efficiently at temperatures below 1000 K, we find that compressed molecular clouds are cooled by ____________________________.

Once the cloud is dense enough to absorb spectral line radiation emitted by atoms and molecules, then cooling is dominated by _____________________.

Concept Question

A cloud will collapse if its free-fall time is less than the sound-wave crossing time. The Jeans mass, the critical mass for collapse, is inversely proportional to $\rho^{1/2}$*. Thus, as the cloud collapses, the Jeans mass decreases, meaning that the cloud is increasingly likely to fragment into ever smaller chunklets. What stops the fragmentation from cascading into an infinite regression of fragmentation?*

During the collapse, the gravitational self-energy -3/5 GM^2/r gets more negative. So where does the extra available energy go?



a) kinetic energy due to radial collapse; think of an electron and proton coming together from infinity
b) thermal energy; heating up of cloud
c) radiation
d) to a Denver Broncos playoff game (tickets scalped)

The opacity that ultimately slows the collapse is mostly due to dust grain absorption. The increased pressure that occurs at this point can balance the inward collapse, resulting in a ~5 AU cloud in hydrostatic equilibrium, a 'protostar.' Dust re-radiation implies that such entities are optimally observed in the infrared wavelength regime.

Do the fragments collapse faster, slower, or at the same rate as the parent cloud? Discuss this with a neighbor and be prepared to justify your answer.

For the *homologous* collapse of a cloud with constant density, all the material infalls at the same rate. Since the change in density remains constant throughout, the Jeans mass decreases everywhere at the same rate. If, on the other hand, a cloud were somewhat centrally concentrated, then the collapse would occur ______ closer to the core and the Jeans mass would decrease _______ there as well. In this case, the innermost material will reach hydrostatic equilibrium first and the outerlying material will eventually collapse onto it. The in-falling material smacks into the hydrostatic core, at a speed greater than the local sound speed; this __________ loses a significant fraction of its kinetic energy in the form of heat that 'powers' the cloud and produces much of its luminosity.

When the temperature reaches approximately 1000 K, the dust begins to vaporize and the opacity _________. Thus the radius at which the optical depth is ~unity approaches the core. As the overlying material continues to fall onto the hydrostatic core, the temperature of the core slowly increases until it's high enough (~2000 K) to dissociate molecular hydrogen. This process absorbs energy that could otherwise be used to maintain hydrostatic equilibrium, resulting in a second collapse. Equilibrium is re-established once the core size is ~30% larger than the Sun. After this core collapse, a second shock front is established. But with only a finite amount of mass available from the original cloud, the accretion rate and hence luminosity must eventually ________. Excerpted from Carroll & Ostlie (2017)

Hey, the dissociation energy for H_2 is 4.6 eV: why doesn't that equal $3/2\ k_B T$ where $T = 2000$ K as claimed above? (4.6 eV = $3/2\ k_B T \rightarrow$ _____ K)

Follow-up to the Concept Question

While these fragments are collapsing, what is the motion of the center of mass of each fragment? What should be the final result of the collapse, a few million years later?

In addition to classical gas pressure, *turbulent* pressure (i.e., non-thermal motions of macroscopic parcels of gas within a cloud) may play a role in supporting molecular clouds against collapse. In principle (with very good observational data), how is it possible to tell the difference between thermal and turbulent motions in a gas?

For pure free-fall, the pre-collapse Jeans mass is 10^3-10^4 $M_\odot$ for an HI cloud (i.e., won't likely collapse) and ~10^1 $M_\odot$ for a molecular cloud (can happen). As discussed previously, the Jeans mass decreases as the collapse progresses. Taking into account adiabatic effects, the minimum possible Jeans mass can be expressed as

$M_{crit,min} \propto T^{1/4}\, e^{-1/2}\, M_\odot$ (your homework problem)

where e is the fraction of radiation that escapes the cloudlet

~ 0.01 solar masses for T=10 K and e=1.0

These calculations have assumed

- a perturbation of a static situation at each and every point during the collapse; we haven't considered the initial velocity of the cloud's outer layers
- simplistic radiation transport through the cloud
- no vaporization of dust grains, dissociation of molecules, atomic ionization

Follow-up to the Concept Question

Further caveats:

Would the presence of a magnetic field increase or decrease the Jeans mass? Why?

Would the presence of an external pressure increase or decrease the Jeans mass? Why?

The fragmentation described previously must occur since we know that stars frequently form in close pairs, groups, and clusters. However, the first generation of stars that formed after the Big Bang (the so-called Population III stars) formed from gas with very low heavy-element abundances. Explain why these stars are thought to have been exclusively very high-mass stars.

Determining Star Formation Rates

Star formation rates tell us about the physical mechanisms of cloud collapse and other 'local' issues; the possible origins of the Hubble sequence of galaxies (elliptical→S0→spiral); and plausible scenarios for galaxy formation in the distant Universe.

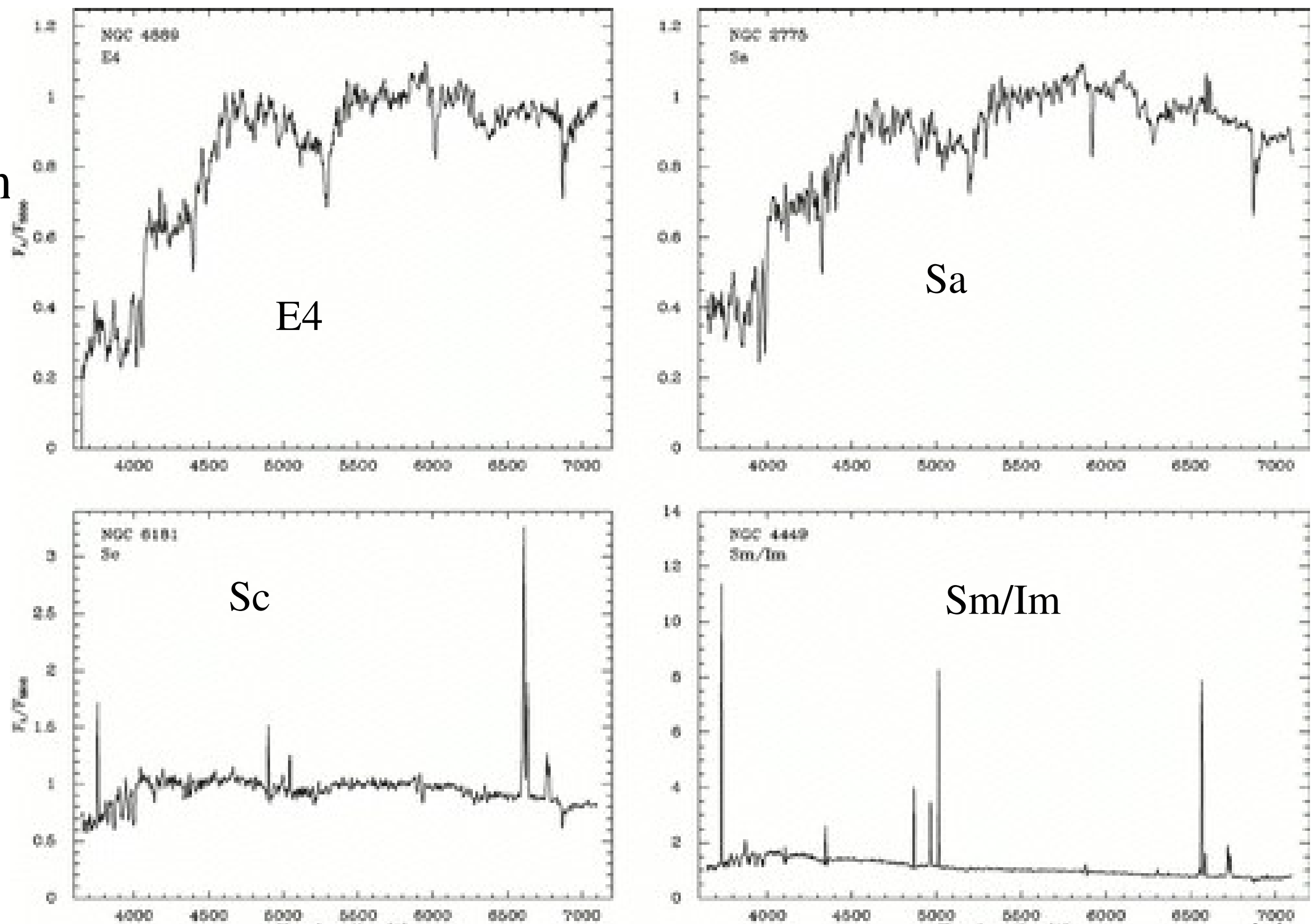
For unresolved objects, we can use (e.g., Kennicutt 1998 review):

- the shape of the ultraviolet continuum (e.g., UV colors)
- far-infrared and radio continuum methods
- recombination lines
- forbidden lines

Changes in the optical spectrum as star formation increases:

- broad rise at blue λ
- stellar absorption changes
    - from *K*-giant to
    - *A*-star dominated
- dramatic rise in nebular
    - line strength

Kennicutt 1998



Determining Star Formation Rates

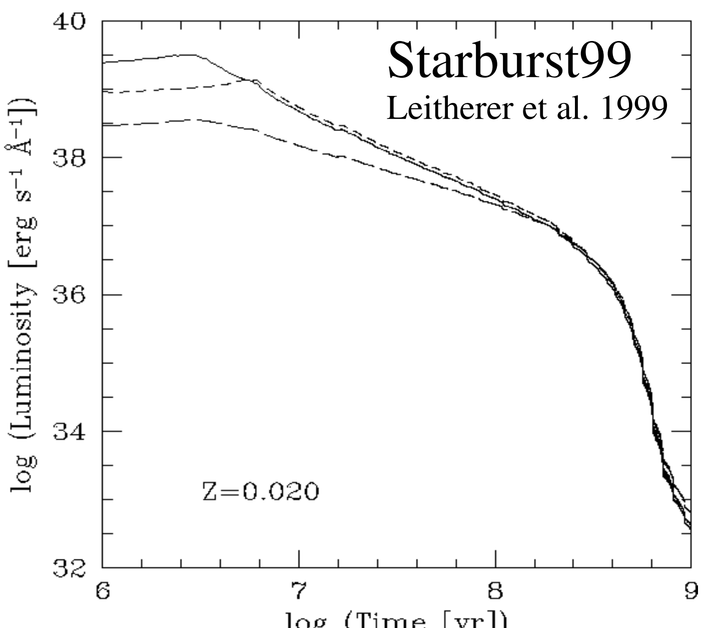
Star Formation Rates from the ultraviolet continuum

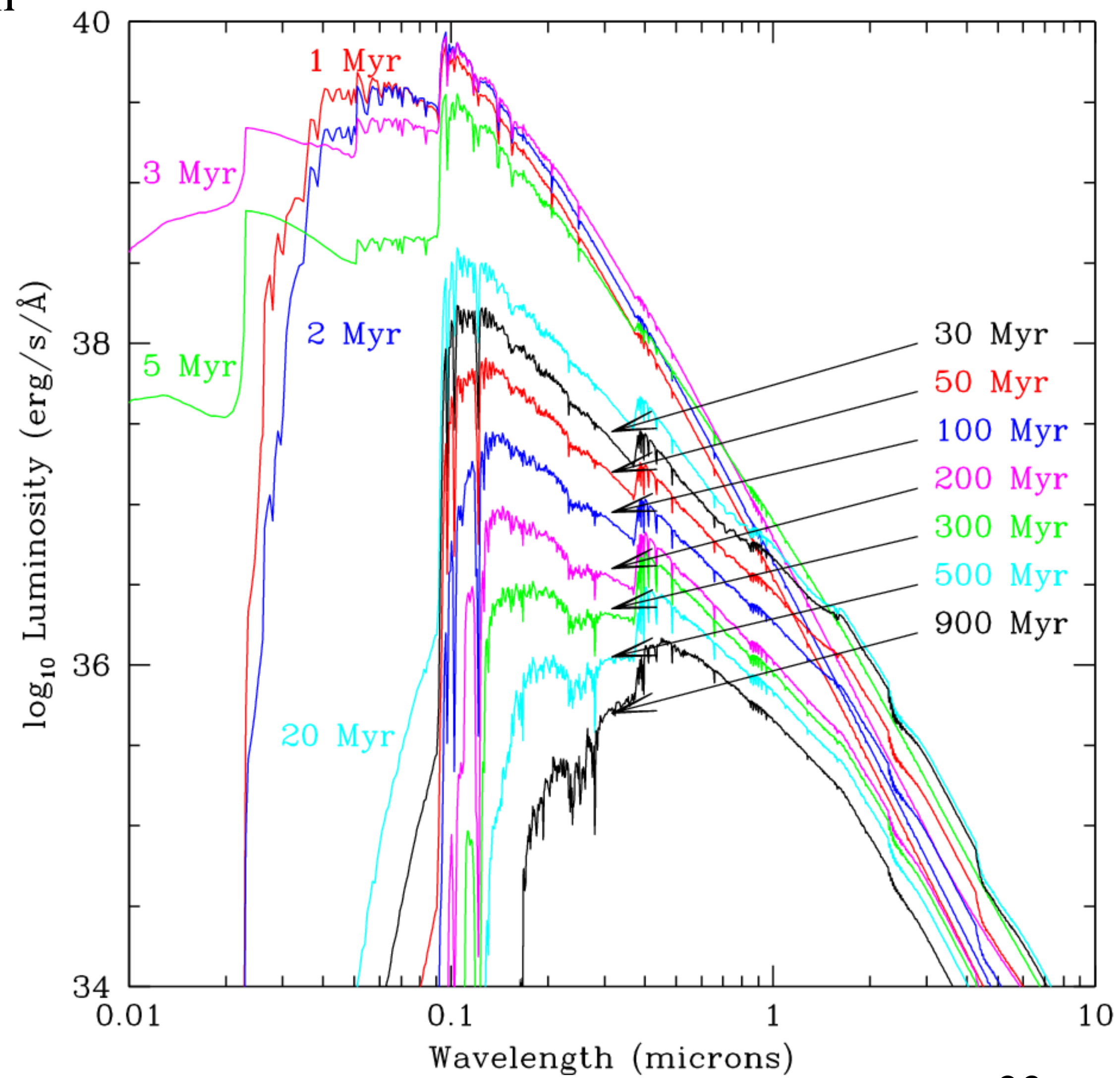
The ultraviolet continuum generally reflects emission from young and massive (e.g., OB) stars. An example metric is

$$SFR\ (\mathrm{M}_\odot\ \mathrm{yr}^{-1}) = 1.4\cdot10^{-28}\ L_\nu\ (\mathrm{erg\ s^{-1}\ Hz^{-1}}) \qquad 1500\ \text{Å} < \lambda < 2500\ \text{Å}$$

These are usually based on calibrations from model predictions. This technique is best pursued from space-based platforms and is particularly sensitive to:

- extinction by dust
- SF history
- Initial mass function (IMF) e.g., $\propto M^{-2.35}$
- M_{upper}, the largest stellar mass in the IMF





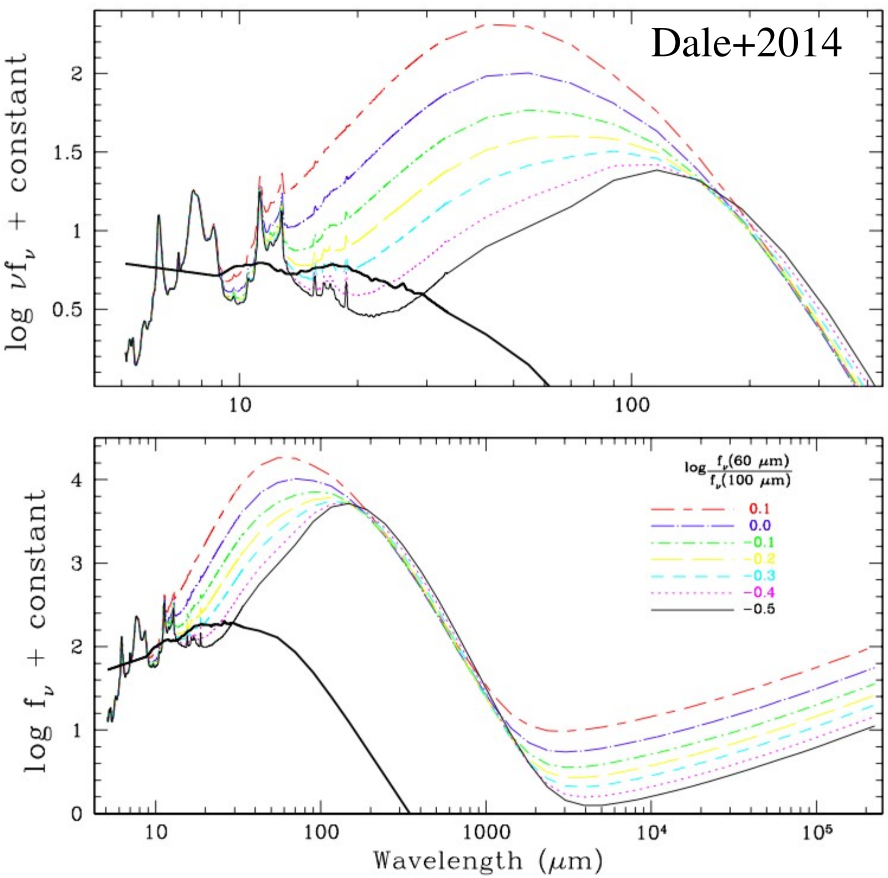
Determining Star Formation Rates

Star Formation Rates from the Far- and Total-Infrared

Much of a galaxy's luminosity is absorbed by dust and re-radiated in the thermal infrared (~ 20μm<λ<1000μm). In the simplest scenario, $L_{TIR} \propto SFR$. Of course this is complicated by the presence of active galactic nuclei, old/cold stars that emit in the infrared, extinction, diffuse dust that is heated by the general interstellar radiation field (and thus not directly related to the current star formation activity). Kennicutt&Evans (2012) give

SFR ($M_\odot$ yr^{-1}) = $3.9 \cdot 10^{-44}$ L_{TIR} (erg s^{-1}) 3μm < λ < 1100μm

TIR ~ 2x the classical definition of *FIR* for 42μm < λ < 122μm: *FIR* (W m^{-2}) = $1.26 \cdot 10^{-14}$ (2.58 f_ν(60μm/Jy) + f_ν(100μm/Jy))



$$L_{\rm TIR} = \eta_1 \nu L_\nu(25\,\mu{\rm m}) + \eta_2 \nu L_\nu(60\,\mu{\rm m}) + \eta_3 \nu L_\nu(100\,\mu{\rm m})$$
(*IRAS*-based),

$$L_{\rm TIR} = \zeta_1 \nu L_\nu(24\,\mu{\rm m}) + \zeta_2 \nu L_\nu(70\,\mu{\rm m}) + \zeta_3 \nu L_\nu(160\,\mu{\rm m})$$
(*Spitzer*-based),

$$L_{\rm TIR} = \xi_0 \nu L_\nu(8\,\mu{\rm m}) + \xi_1 \nu L_\nu(24\,\mu{\rm m}) + \xi_2 \nu L_\nu(70\,\mu{\rm m}) + \xi_3 \nu L_\nu(160\,\mu{\rm m})$$
(*Spitzer*-based),

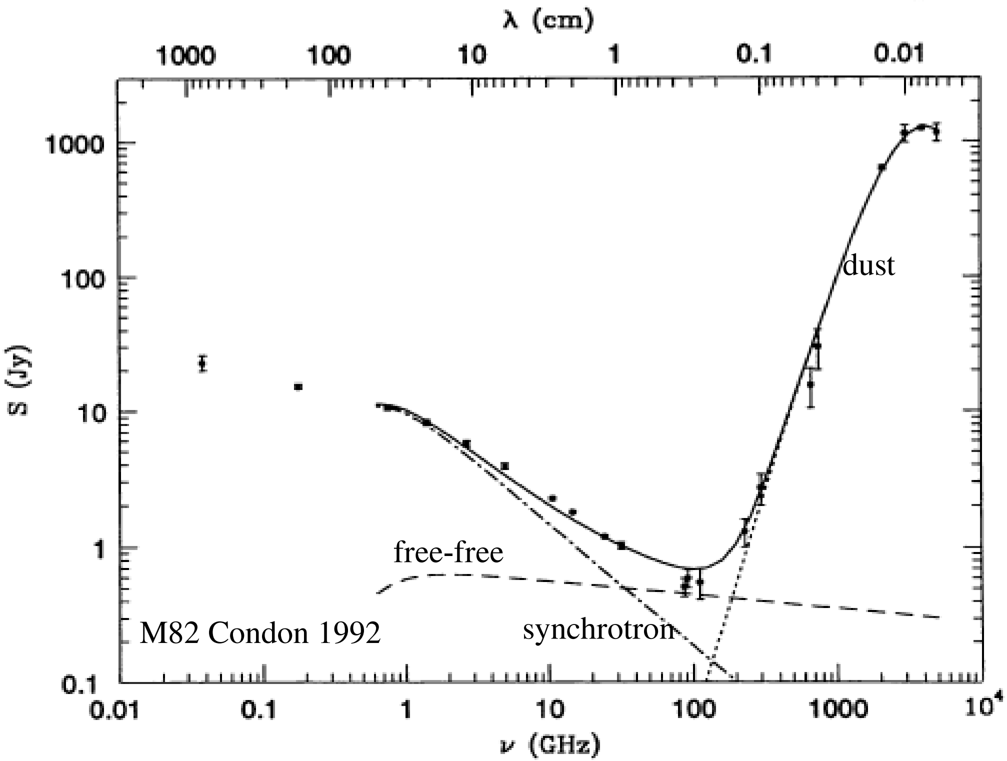
Determining Star Formation Rates

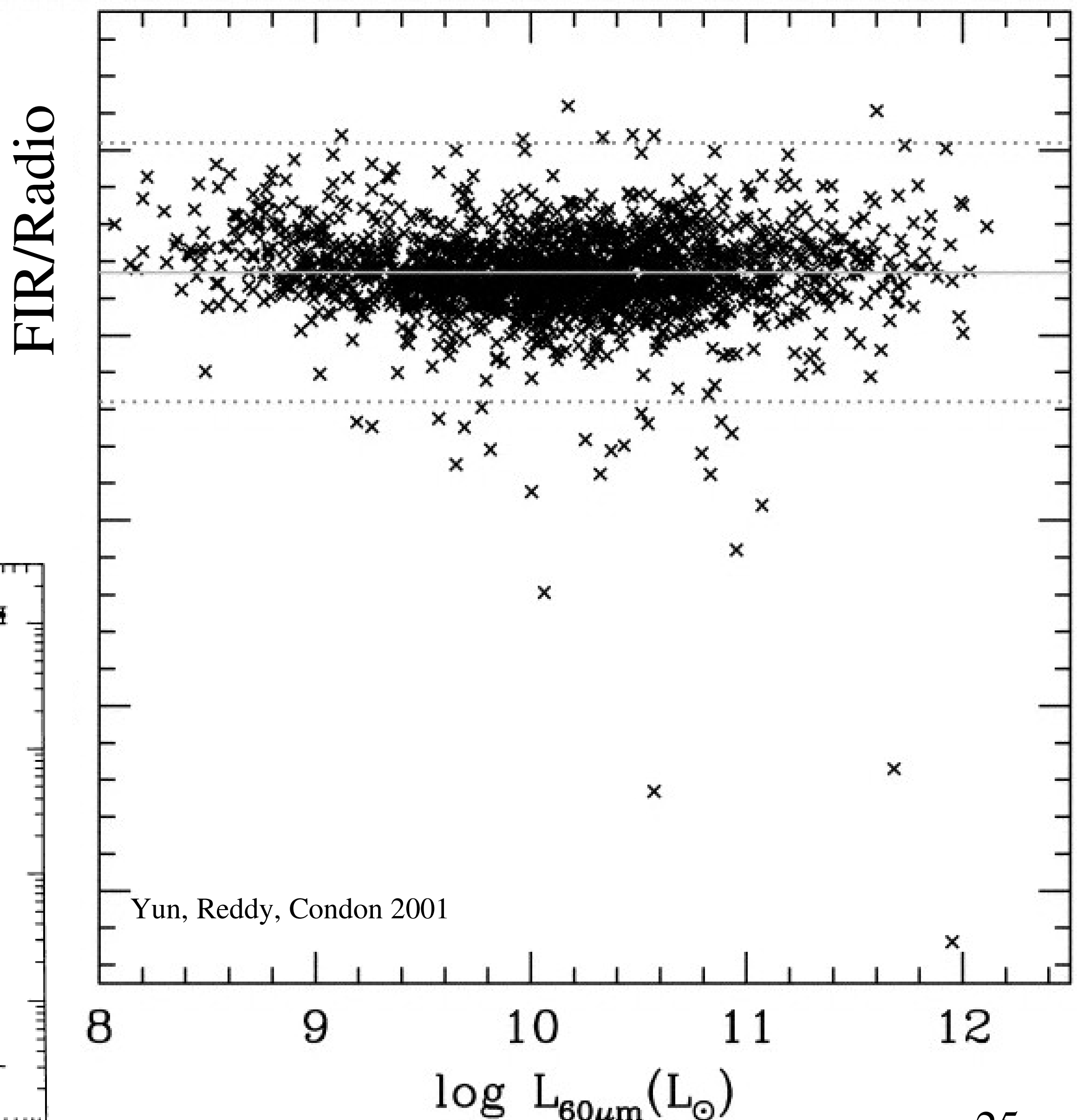
Star Formation Rates from the Radio Emission

Takes advantage of the tight correlation '*q*' between radio and far-infrared emission:

$$q = \log\,[FIR/3.75\cdot10^{12}\ \mathrm{W/m^2}] - \log\,[f_\nu(1.4\mathrm{GHz})/\mathrm{W/m^2/Hz}]$$

This relation holds for normal galaxies (ie. no significant AGN activity) where typically the 20 cm flux is 90% due to synchrotron and just 10% from thermal emission (e.g., free-free).





Determining Star Formation Rates

Star Formation Rates from Recombination Lines

This technique is perhaps conceptually the easiest to understand, since 'hot' photons from star-forming regions excite/ionize atomic electrons.

$$L_{H\alpha}(n{=}3\rightarrow2;\ \text{erg/s}) = 1.361\cdot10^{-12}\ Q_0$$

Q_0 = total number of Lyman continuum (i.e., H-ionizing) photons/second

Calibrations based on stellar synthesis models (probably no better than 30% accurate) give

$$SFR\ (\text{M}_\odot\ \text{yr}^{-1}) = 5.4\cdot10^{-42}\ L_{H\alpha}(\text{erg/s})\ A(\text{H}\alpha) = 7.3\cdot10^{-54}\ Q_0\ A(\text{H}\alpha)$$

A(Hα) ⇒ extinction of the Hα line. Extinction at 6563 Å is typically difficult to estimate! It can be estimated by measuring the flux from other hydrogen recombination lines, and knowledge of relative & intrinsic ratios. (Kennicutt&Evans 2012; Schaerer 1999)

This particular formalism is valid for instantaneous bursts of star formation, or star formation bursts of very short timescales ($\leq 10^6$ yr).

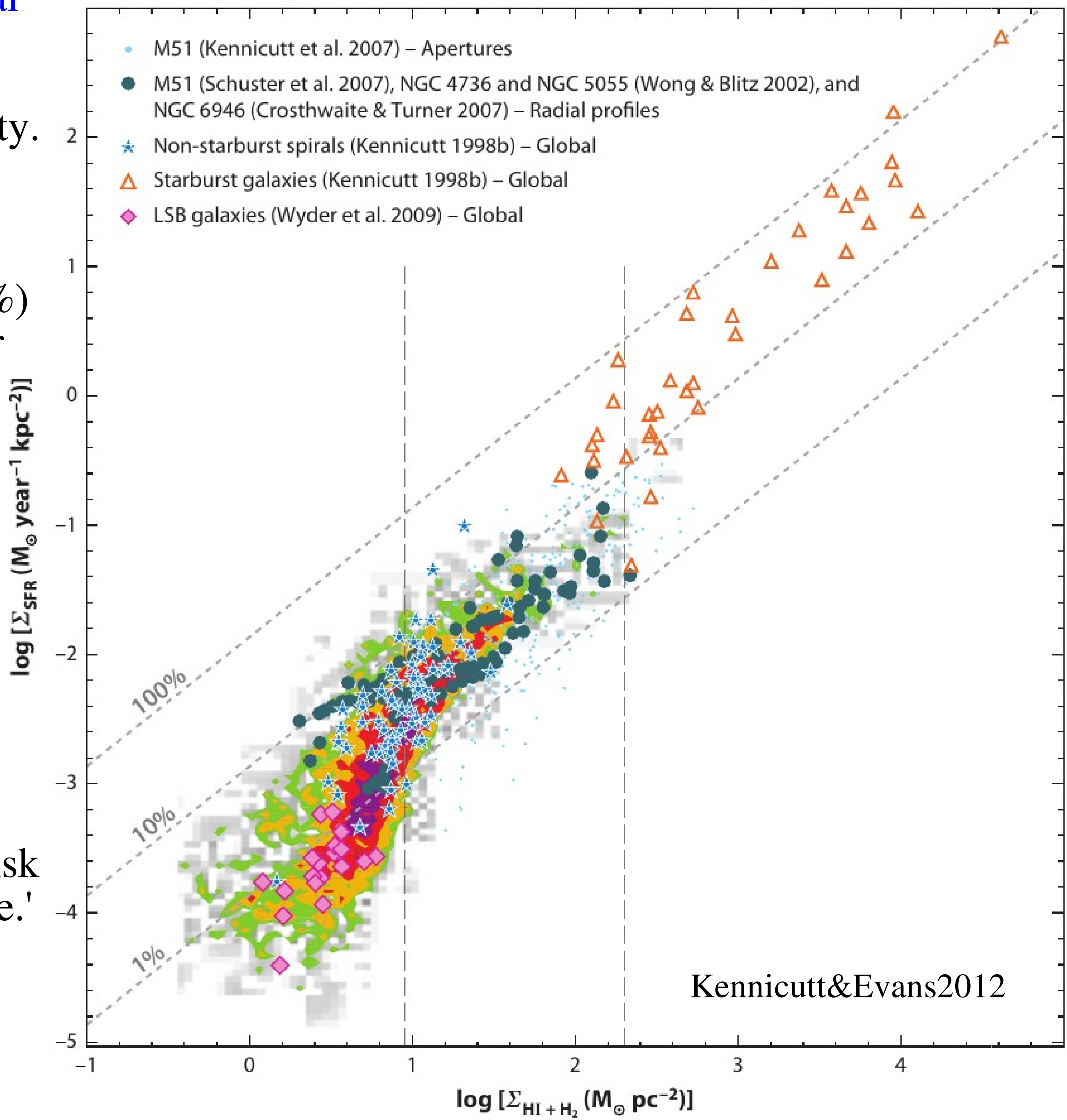
Star Formation: Local and Universal

The star formation rate density is correlated with the (total) gas density. Galaxies show a wide range of star formation rate densities.

Q: What is a typical efficiency (in %) for converting gas mass to stars, for middle-of-the pack systems? The dashed lines indicate efficiencies per 10^8 yr.
A: _____ %

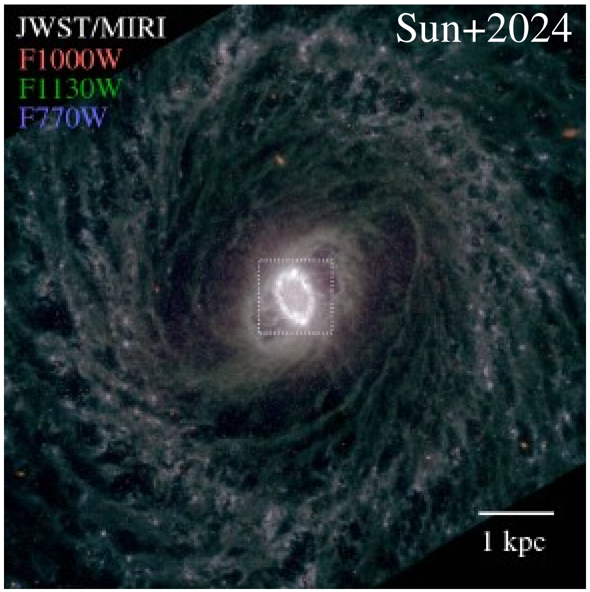
→

'Since the typical gas mass fraction in these disks is 20%, this implies that the stellar mass of a disk grows by about 1% per 10^8 yr … the time scale for building the disk … is comparable to the Hubble time.' (Kennicutt 1998)



Star Formation: Local and Universal

The regions surrounding the nuclei undergo more dramatic star formation episodes. 'The circumnuclear star formation is especially distinctive in terms of the absolute range in star formation rates, the much higher spatial concentrations of gas and stars, its burst-like nature (in luminous systems), and its systematic variation with galaxy type.' (Kennicutt 1998)



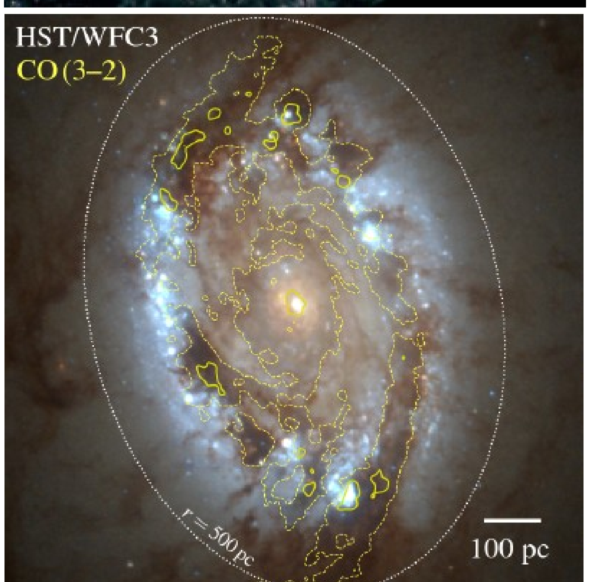


Table 1 Star formation in disks and nuclei of galaxies

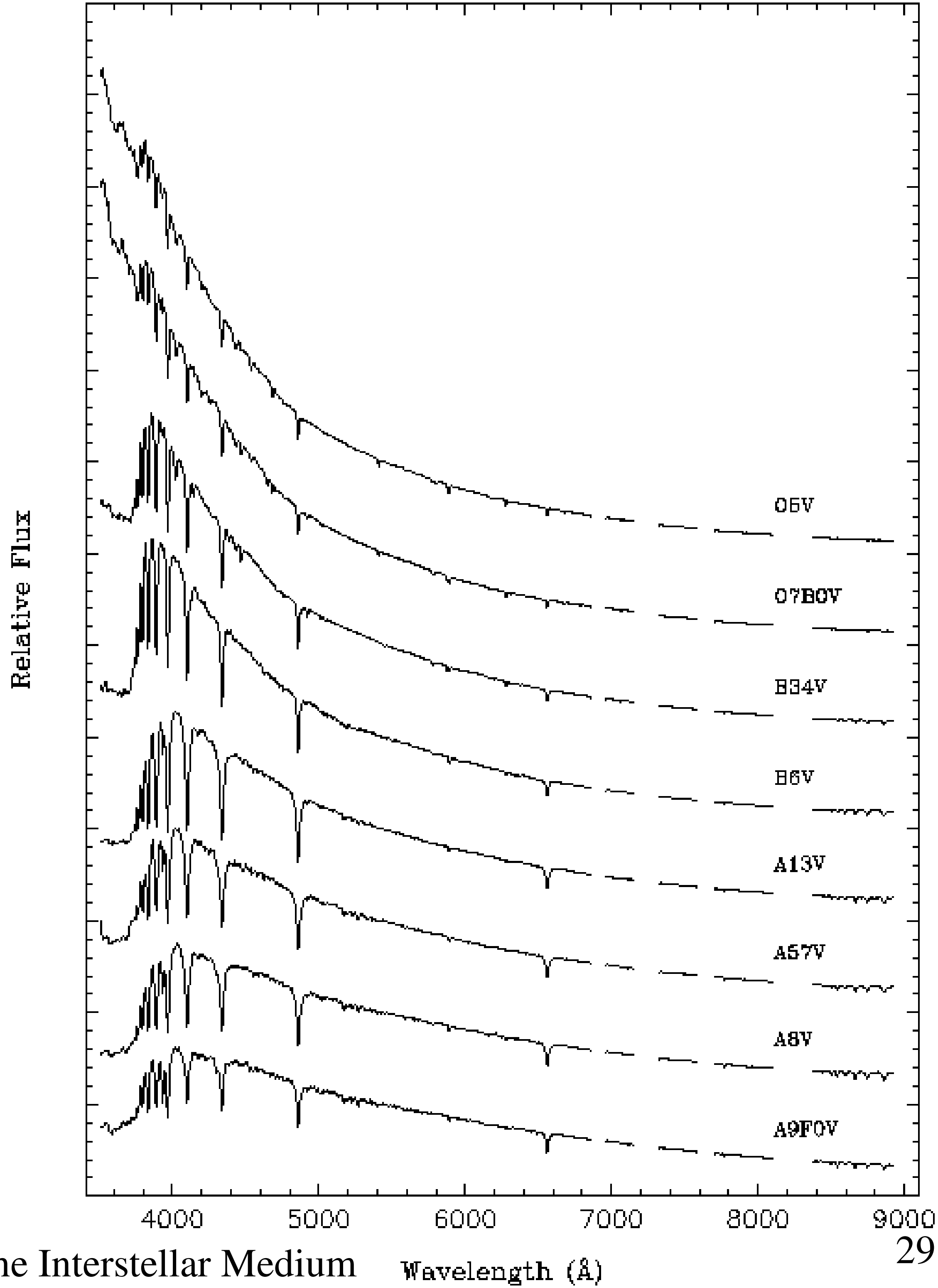
Property	Spiral disks	Circumnuclear regions
Radius	1–30 kpc	0.2–2 kpc
Star formation rate (SFR)	0–20 $M_\odot$ year^{-1}	0–1000 $M_\odot$ year^{-1}
Bolometric luminosity	10^6–10^{11} $L_\odot$	10^6–10^{13} $L_\odot$
Gas mass	10^8–10^{11} $M_\odot$	10^6–10^{11} $M_\odot$
Star formation time scale	1–50 Gyr	0.1–1 Gyr
Gas density	1–100 $M_\odot$ pc^{-2}	10^2–10^5 $M_\odot$ pc^{-2}
Optical depth (0.5 μm)	0–2	1–1000
SFR density	0–0.1 $M_\odot$ year^{-1} kpc^{-2}	1–1000 $M_\odot$ year^{-1} kpc^{-2}
Dominant mode	steady state	steady state + burst
Type dependence?	strong	weak/none
Bar dependence?	weak/none	strong
Spiral structure dependence?	weak/none	weak/none
Interactions dependence?	moderate	strong
Cluster dependence?	moderate/weak	?
Redshift dependence?	strong	?

Hot stars: O, B, and A types

Steeply rising continua to the blue
(T ~ 10,000-30,000 K)

Dominated by absorption lines of Hydrogen (to the n=2 state)

The Balmer break at 3646Å marks the termination of the hydrogen Balmer series and is strongest in A-type stars. The break strength does not monotonically increase with age, but reaches a maximum in stellar populations of intermediate ages (0.3 - 1 Gyr).



Cool stars: F, G, and K types

Hydrogen absorption is less prominent, and ionized metals begin to appear (H and K lines of Ca II 3933, 3968Å).

The 4000Å break arises because of an accumulation of absorption lines of mainly ionized metals. As the opacity increases with decreasing stellar temperature, the 4000Å break gets larger with older ages, and it is largest for old and metal-rich stellar populations.

The Balmer break and the 4000Å break are often treated as one feature, due to their similar locations and the fact that they partially overlap. However, the breaks originate from different physical processes and behave differently as populations age.