Astronomy 330

Lecture 5

17 Sep 2010

Outline

- Review & conclude: ISM
- Review: Stellar Nucleosynthesis
- Chemical Evolution of Galaxies

Review

- Gas content of disk galaxies
  - Note the table ➔ phases of the ISM, filling factors, major diagnostics
  - Example ➔ ionized H
- Neutral Hydrogen
  - Spin-flip transition ➔ 1.4 GHz
  - Radiative transfer ➔ intensity of radiation field is a function of optical depth and temperature ➔ optical depth is a function of number of atoms
  - $M = 2.36 \times 10^5 D^2 \int S(V)\, dV$, where $S(V)$ is in Jy km s^{-1}

Star-formation rates continued

- Recall Stellar IMF
  - $N_o \int dM\ M\ \xi(M)$ = total mass of burst/episode, $\xi(M)$ goes as $(M/M_\odot)^{-2.35}$
- Young, massive stars (on MS) producing nearly all ionizing radiation
- On MS there is a mass-T relationship
- Integrate IMF weighted by ionizing luminosity per star of mass M to get N_{Lyc}
- Extrapolate integral over full mass of IMF to get total mass
- Current best estimates: K98
  - SFR ($M_\odot$ year^{-1}) = 7.9×10^{-42} L(Hα) (ergs s^{-1}) = 1.08×10^{-53} Q(H^0) (s^{-1})
    - Case B for T_e = 10,000 K
  - SFR ($M_\odot$ year^{-1}) = $(1.4 \pm 0.4) \times 10^{-41}$ L[OII]$_{\lambda 3727}$) (ergs s^{-1})
    - empirical
  - In all cases, must correct for extintcion

Can extend to Paschen series where extinction is smaller; see Calzetti et al. (2005)

- Why not measure N_{Lyc} directly?
- What about UV continuum at wavelengths longer than the Lyman limit?
- What about the FIR (what heats the dust)? Radio continuum?

- See: Kennicutt et al.: 1983 1984, 1989, 1998, 2003, 2009; Lee et al. 2009

Line diagnostics

- Redenning:
  - Use recombination coefficients for different lines compared to measured flux ratios, e.g., Hα/Hβ
    - Recombination coefficients depend in detail on knowing T_e and n_e
    - Must correct emission for stellar photospheric absorption which is, e.g. larger in Hβ than Hα
- Temperature: T_e
  - Flux ratios of forbidden-lines from ions with different ionization potentials, e.g.,
    - H+,S+,N+,O+,O++
    - Metallicity and shock-heating effects
- Density: n_e
  - Flux ratios of some forbidden-line doublets, e.g.,
    - [OII]λλ3726,3727 , [SII]λλ6717,6731
    - Limited sensitivity to large dynamic range in density

Hot Gas

- Gas heated to 10^6 K (probably by SNe)
  - Powerful probe of mass distribution in galaxy clusters
- Detected via X-ray emission
  - Point source population
  - Diffuse hot gas
- Emission via
  - Brehmstrahlung
  - Emission lines of highly ionized species

Diffuse Hot Gas: Soft X-Ray Background

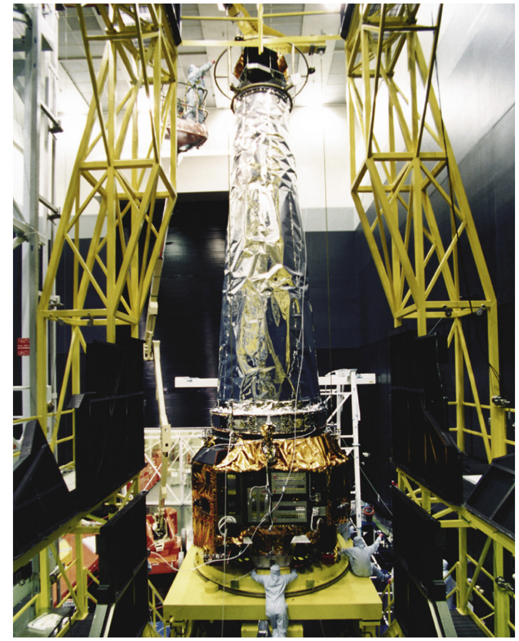
- McKee & Ostriker (1977): diffuse hot phase of the ISM with a filling factor of ~100%
- Early detection of X-ray emitting "superbubbles" in the Milky Way: Sco-Cen, Orion-Eridanus (McCammon et al. '83, McCammon & Sanders '90)
- Origin of Soft X-Ray background
  - MWG: local ISM + hot galactic halo
  - Local Group: hot intergalactic medium
  - Extragalactic: (un)resolved AGN + E galaxies

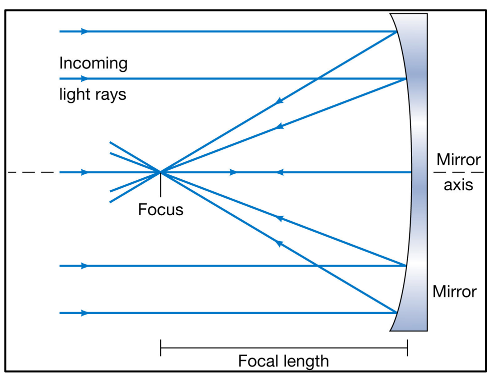
The Local Bubble

- Radius: 100-200 pc
- Temperature: ~2 x 10^6 K
- Thermal pressure: p/k = 10^4 cm^{-3} K
- N(HI) = 6 x 10^{18} cm^{-2} (derived from soft X-ray absorption)
- Origin of the Local Bubble
  - hot gas w/ 100% filling factor?
  - diffuse gas reheated by recent SNe?
  - a series of 2-5 SNe a few million years ago?
  - an extension of nearby superbubble?

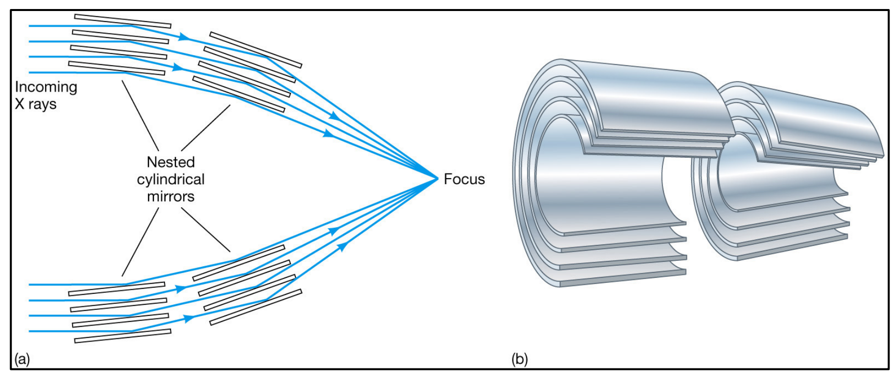
Comparison of X-Ray Observatories

- Einstein: 1' resolution
  - M101 (McCammon & Sanders 1984)
  - L_X(diffuse) ~ 10^{38}-10^{40} erg s^{-1}
- ROSAT (PSPC): 1.'8 resolution, 0.1-2 keV
  - M101, N3184, N4395, N5055, N4736 (Cui et al. 1996)
- CXO (Chandra): <1" over 8 arcminutes
- XMM/Newton: 15" over 30 arcminutes

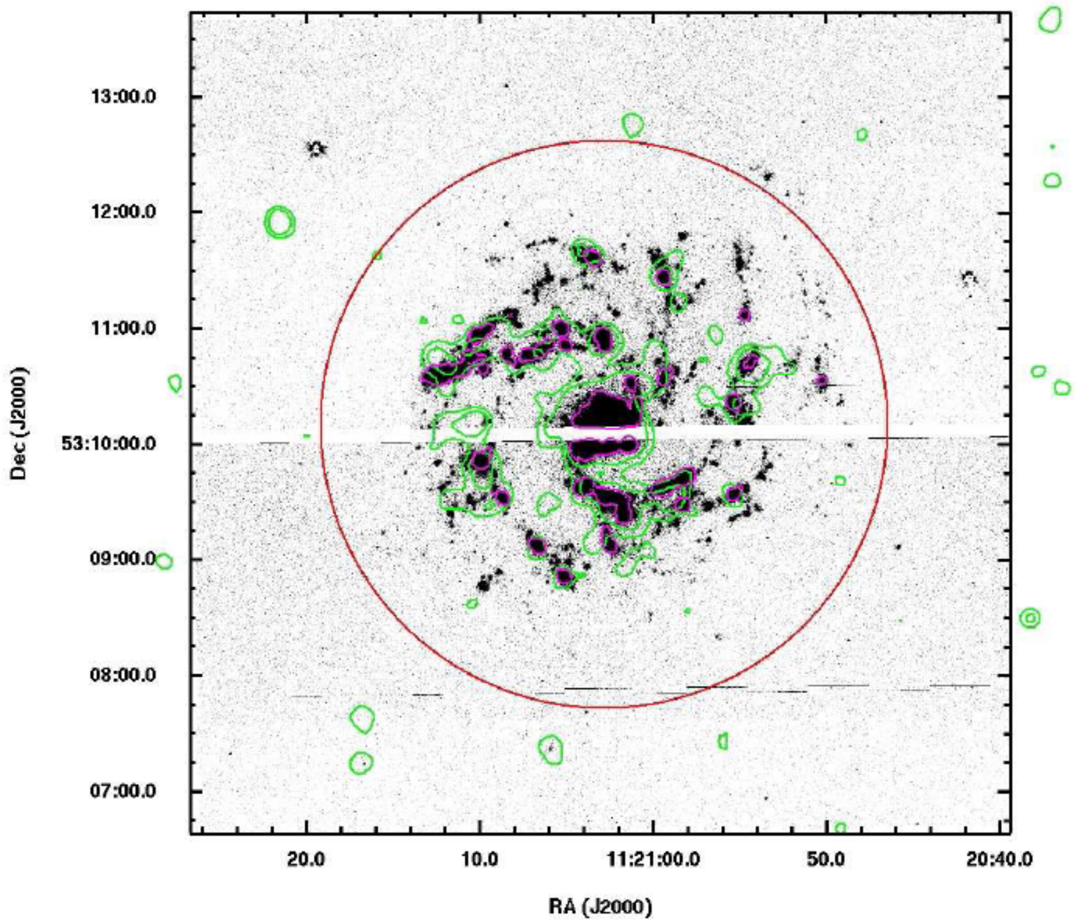




Mirrors:
←Optical
X-ray→



X-ray vs HII region comparison NGC 3631



X-ray emission

Hα emission (WIYN)

(Doane et al. 2007)

Temperature Comparison (10^6K)

- LMC Superbubbles: 1.7-9
- Orion-Eri.: 3.3
- N. P. Spur: 3.0
- Sco-Cen: 4.6

- NGC3631: 1, 3
- NGC6946: 2, 7
- M101: 2 ,8
- N253(halo): 4
- M82(halo): 3, 4

Spirals are best fit with two temperature models of hot gas, but there is variation in the high temperature and surface brightness.

Summary of X-Ray Results

- Diffuse emission is highly correlated with both spiral arms and HII regions
- Bulk of the diffuse emission arises from less than 25% of the area of the disk
- X-ray spectra are best fit with a two temperature model
- There is variation in the surface brightnesses between galaxies and variation in the temperature of the hot component

- Diffuse X-rays in Galaxies
  - Related to SNe production

Feedback: Impact of Massive Stars

- Stellar winds + SNe dump $10^{53.5}$ ergs into ISM
- Creates hot bubble surrounded by swept up ISM and circumstellar matter
  - gas heated by inward moving shock
- X-ray emission should be aligned with HI holes
- growth of chimneys
  - means of getting hot gas into the halo

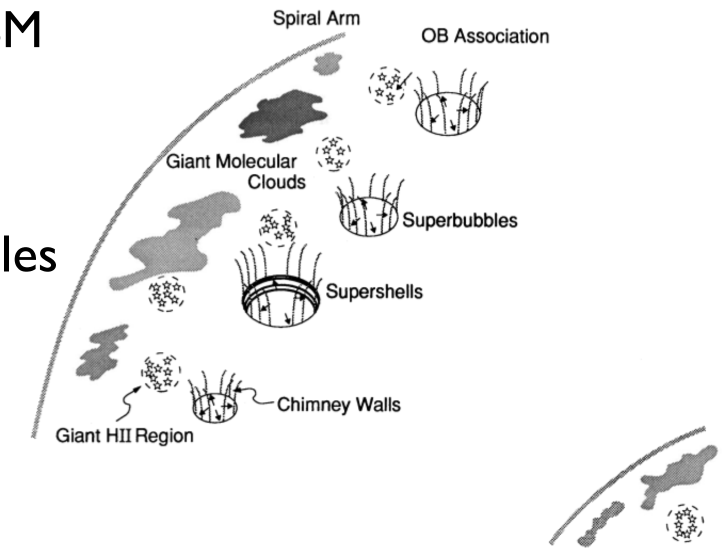
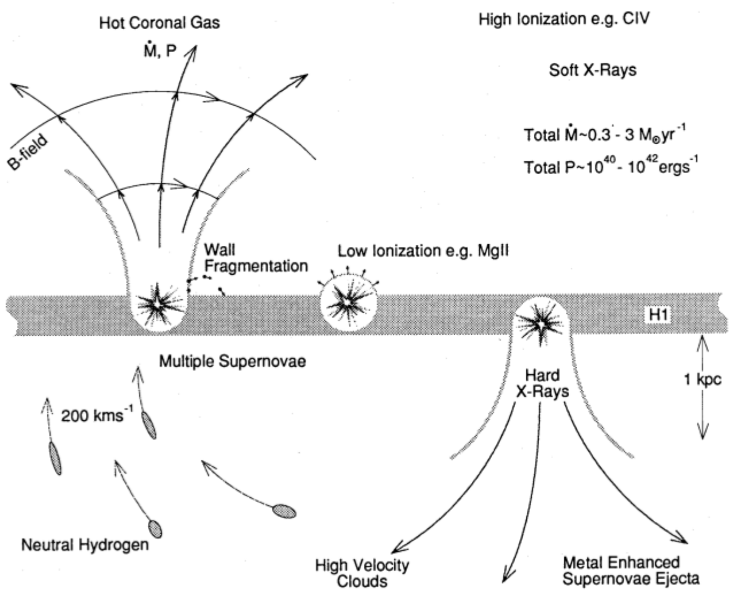
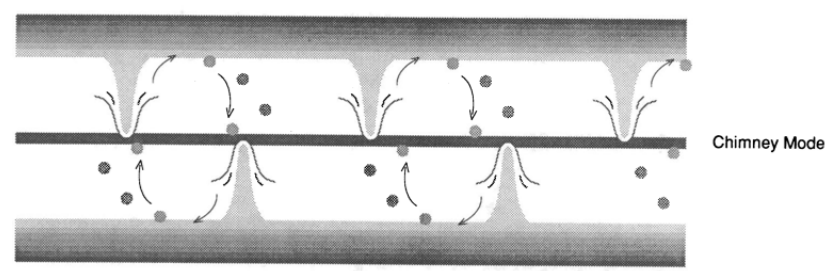


FIG. 4a





Norman & Ikeuchi 1989

Feedback: Bubbles

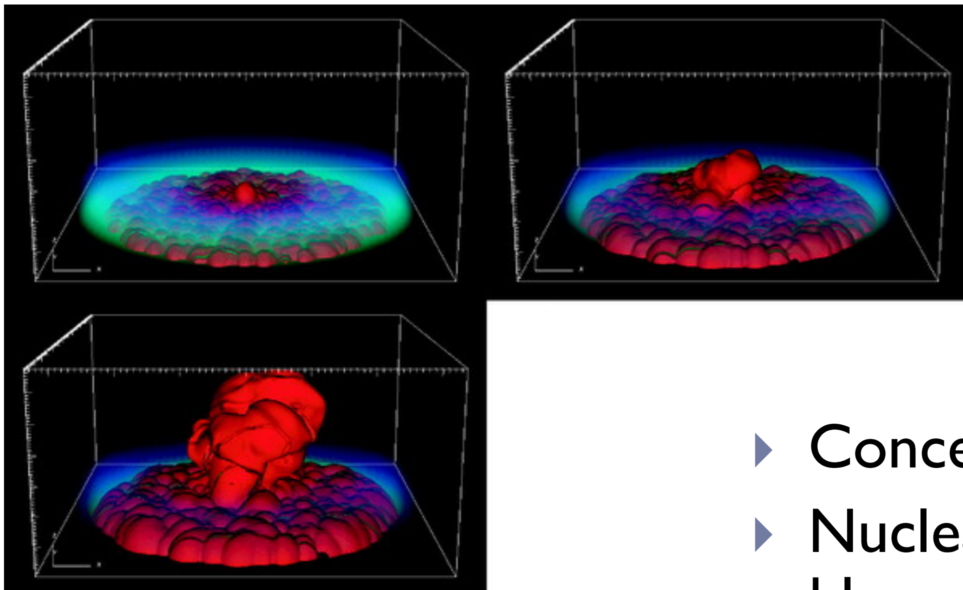
- Stellar winds/SNe drive expanding bubbles into ISM
  - $R_s \sim 100\ (N_* E_{51}/n_0)^{1/5} t_7^{3/5}$ pc (McCray & Kafatos 1987)
  - $V_s = L_W^{1/5} n_0^{-1/5} t_7^{-2/5} \sim 6\ (N_* E_{51}/n_0)^{1/5} t_7^{3/5}$ km s^{-1}
  - Reverse shock heats bubble to 10^6-10^7 K → X-ray emitting
  - Shell includes swept up ISM, dense neutral gas, possibly accelerated particles

R_s – shell size
N_* - number of stars formed with $M > 7 M_\odot$
T_7 – time-scale in 10^7 yr
E_{51} - SN energy / 10^{51} ergs
n_0 – intial electron density cm^{-3}
V_s – shell speed
L_W – mechanical luminosity of winds

- Ultimate fate
  - Shell/bubble expands until $P_{bubble} = P_{ISM+IGM}$
  - Breaks out of disk if

    $P_{bubble} > P_{ambient}$, $V_{shell} > V_{escape}$
  - Shell accelerates in density gradient

Extreme "Feedback"



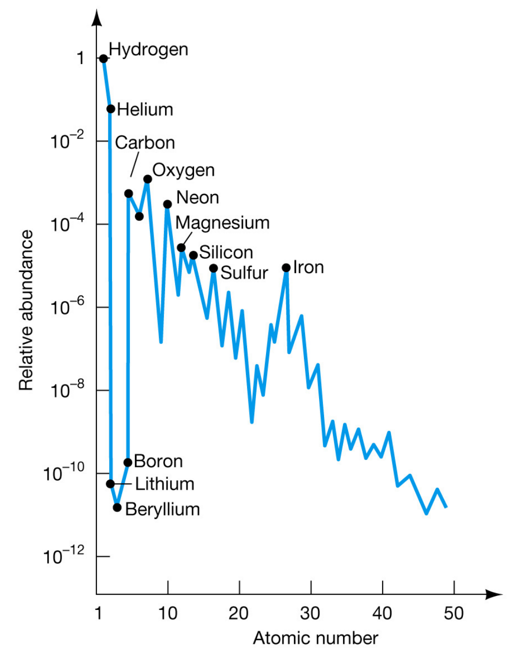
- Concentrated SNe
- Nuclear starburst → complete blowout of the ISM
  - What will M82 look like in 10^7-10^9 years?
  - Bursting dwarfs?

Nucleosynthesis

- Hydrogen Burning (main sequence)
  - P-P chain:
    - H + H ➔ ^{2}D + e^{+} + ν + 0.42 MeV
    - ^{2}D + H ➔ ^{3}He + γ
    - ^{3}He + ^{3}He ➔ ^{4}He + 2H + 12.86 MeV
    - Or step through ^{8}Be (only 14% of the time)
  - CNO bi-cycle (if T > 20 million K)
    - ^{12}C+ H ➔ ^{13}N + γ ….
    - ^{14}N + H ➔ ^{15}O…..^{17}O + H ➔ ^{14}N + ^{4}He
    - N can be brought to surface via dredge-up; majority of ^{14}N is produced this way ➔ "secondary" product
- Giant Branch (T ~ 10^{8} K)
  - 2 α ➔ ^{8}Be; ^{8}Be + α ➔ ^{12}C
  - Causes core expansion for M > $2M_{\odot}$

Nucleosynthesis – later stages

- Higher mass stars ➔ past He burning
  - $^{12}C + \alpha \rightarrow {}^{16}O$ + energy $(M < 8M_\odot)$
  - $^{16}O + \alpha \rightarrow {}^{20}Ne$ + energy $(M > 8M_\odot)$
  - $^{20}Ne + \alpha \rightarrow {}^{24}Mg$ + energy
- More complex reactions:
  - $^{14}N \xrightarrow{\alpha} {}^{18}F \xrightarrow{\alpha} {}^{18}O \xrightarrow{\alpha} {}^{22}Ne \xrightarrow{\alpha} {}^{25}Mg + n$ (α reactions)
  - $^{12}C + {}^{12}C \rightarrow {}^{23}Mg + n$
    - *Free neutrons!*
- Highest mass stars
  - $^{24}Mg + \alpha \rightarrow {}^{28}Si$
  - $^{16}O + {}^{16}O \rightarrow {}^{32}S$
  - Leads to Fe peak ➔ Type-II SNe (core collapse, bounce)



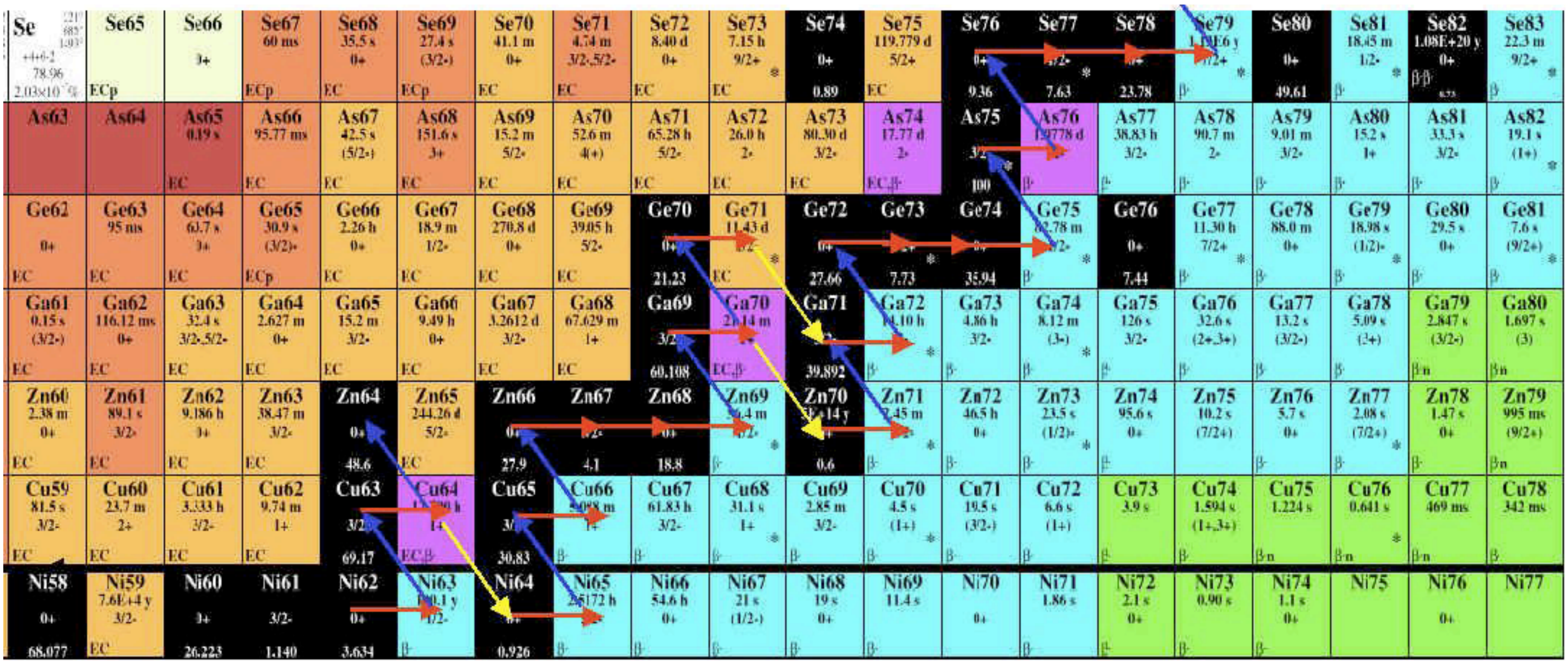
Dispersing the Elements

- Intermediate mass stars
  - $M < 2.5\ M_\odot$ ➔ CO degenerate core, PN, some He output
  - $2.5\ M_\odot < M < 8\ M_\odot$
    - Convective overshoot ➔ dredge-up of CNO cycle products (e.g., ^{14}N)
    - Dredge-up can reach He-burning products on AGB ➔ C, O
    - Pulses drive mass loss (10^{-7} to $10^{-5}\ M_\odot yr^{-1}$)
      - PN enriched in C,O,N, "s-process"
      - AGB shells good place to form molecules (CO)
- High mass stars
  - Dispersal via SNe
  - Primary products are α elements
  - Some "r-process"

Neutron Capture Elements

- Certain elements are rich in neutrons
- Formation can't be explained by standard nucleosynthesis
- Neutron capture
  - $(t_{1/2})^{-1} \sim \sigma \Phi$ (cross section x neutron flux)
  - (Z,A) + n ➔ (Z,A+1); is this stable?
    - Yes: sits around and waits for another n
    - No: decays to (Z+1,A+1); is this stable?
  - Stable isotopes have higher abundances
- "Valley of Stability"

s-Process Valley of Stablity



Slow Neutron Capture

- "s-process"
  - Neutron densities ~ $10^5 cm^{-3}$
  - Neutrons originate in minor He-burning reactions
    - $^{13}C + \alpha \rightarrow {}^{16}O + n$
    - $^{22}Ne + \alpha \rightarrow {}^{25}Mg + n$
  - Where?
    - H, He shells where burning takes place
  - Example elements (Tc, Ba, La, Zr)
    - Tc is the lightest element with no stable isotopes; lifetime < stellar lifetime so presence of Tc implies in situ production and confirmation of s-process
- Nice review: Busso et al 2001, ApJ, 557, 802

Rapid Neutron Capture

- "r-process"
  - Neutron capture rate > β -decay rate (hours)
  - Neutron densities ~ $10^{23}cm^{-3}$ → only see this in SNe
  - Same fundamental process → n capture to stable nuclei
  - Example products: Eu, Ur, etc

- Mixed origins
  - Rb, Pr, Nd → 50/50 s/r
  - Ba, La, Ce → 85/15 s/r
  - Eu → 3/97 s/r

Type Ia Supernovae (SN Ia)

- CO white dwarf + companion
- Companion fills Roche lobe, dumps matter onto WD until electron degeneracy is overwhelmed:
  - Chandrasekhar mass = 1.4 $M_{\odot}$
- Collapse and deflagration:
  - Explosive nucleosynthesis ➔ whole thing goes
- Produces burning up to iron:
  - Mg, Si, Cr, Ni, Fe (main production of Fe)

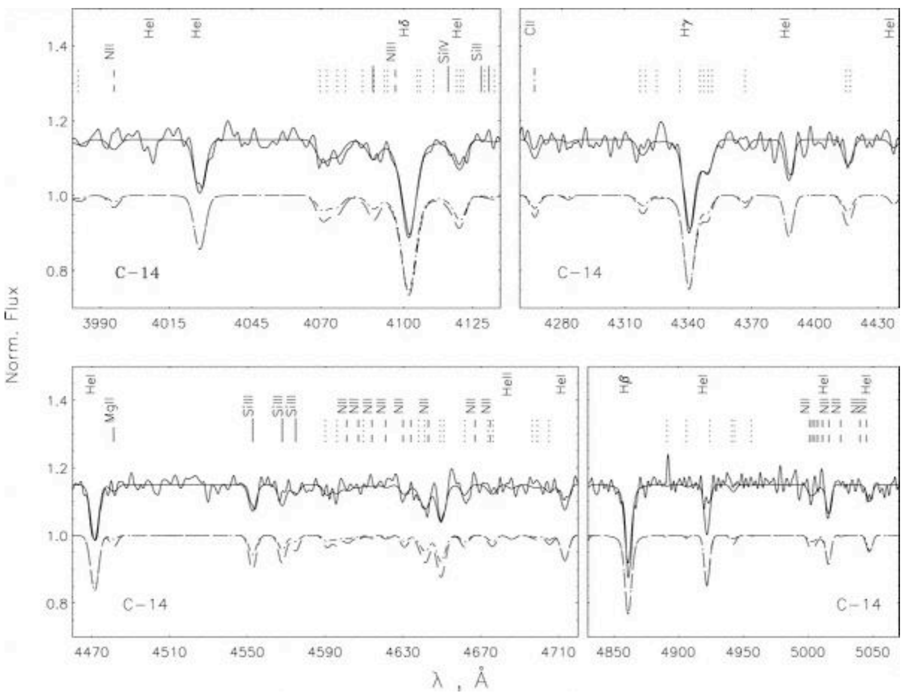
Abundance patterns in galaxies

- SFH reflected in abundances…
- Stellar lifetimes
  - $M > 20\ M_\odot$ ➔ $t < 10$ Myr
  - $1.5M_\odot < M < 5M_\odot$ ➔ $1.4 > t > 0.1$ Gyr
  - $M > 1.5\ M_\odot$ ➔ $t > 1.4$ Gyr
- Single massive stars produce
  - Little Fe (it's locked up)
  - Lots of α-elements, r-process elements
    - $40\ M_\odot$ star produces $7\ M_\odot$ of O
- Intermediate mass stars produce
  - O,C,N, plus s-process elements
    - $0.1\ M_\odot$ of N

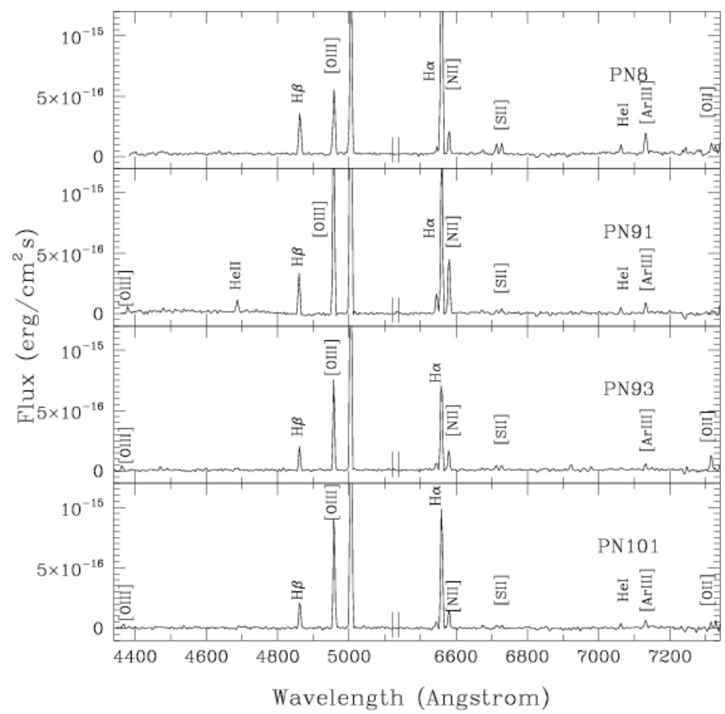
What are the implications for the SFH for finding stars and gas that is α-element rich?

Measurement Techniques

- (a) Stellar spectra: bright stars
- (b) Emission line spectra: HII regions and Planetary Nebulae (PN)
- (c) QSO absorption lines



(a) NGC 300



(b) M33 PN

Extragalactic Abundances: Definitions

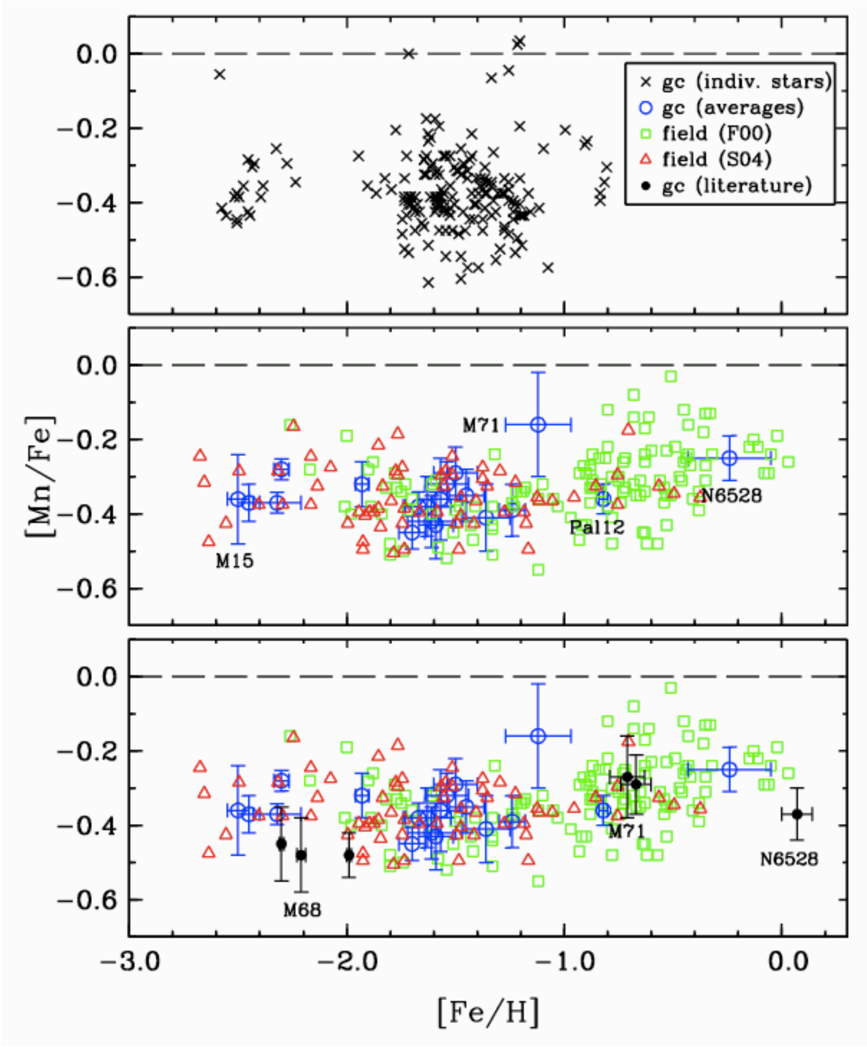
- Relative Abundances
  - $[X/H] = \log_{10}(n(X)/n(H)) - \log_{10}(n(X)/n(H))_\odot$
    - where X is any element
  - Doesn't have to be H
    - $[O/Fe] = \log_{10}(n(O)/n(Fe)) - \log_{10}(n(O)/n(Fe))_\odot$
- Absolute abundances
  - $12 + \log_{10}(O/H)$ (small numbers!)

Solar/Orion Context

- Sun
  - $\log_{10}(He/H) = -1.0$
  - $\log_{10}(O/H) = -3.1$
  - $\log_{10}(C/H) = -3.4$
  - $\log_{10}(Fe/H) = -4.5$
  - $\log_{10}(Ne/H) = -3.9$
  - $[N/H] = -4.0$
  - $[Z/H] = -8.5$
- Orion
  - $\log_{10}(O/H) = -3.3$
  - $\log_{10}(C/H) = -3.5$
  - $\log_{10}(Fe/H) = -4.52$

- Sun is slightly more metal rich than Orion!
  - (remember the local bubble?)
- LMC is 50-70% solar
  - $[O/H] = -0.3$ to -0.15
- SMC ~ 20-25% solar
  - $[O/H] = -0.7$ to -0.65

Sample Abundance Patterns: MW Stars



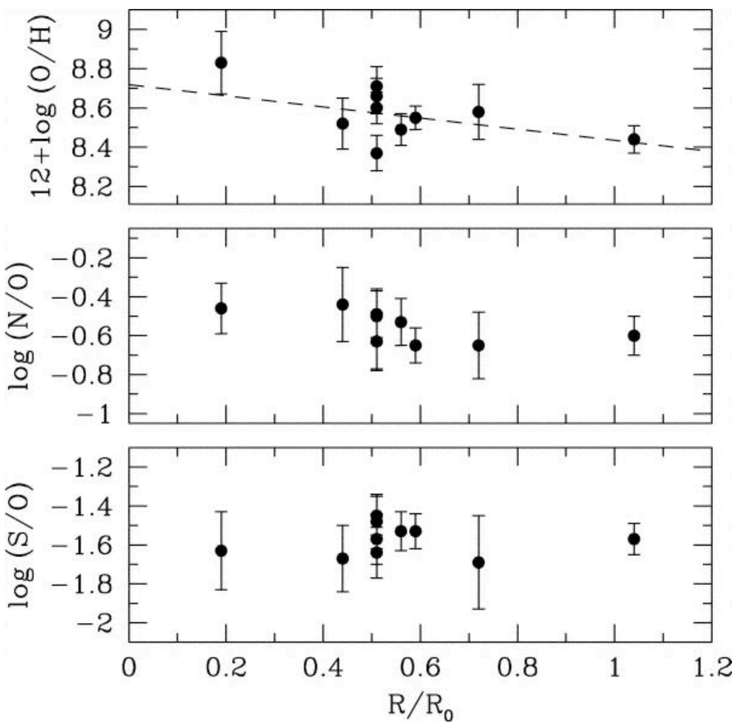
What does this tell us?
(Mn produced in massive stars)

Abundance Patterns in the Milky Way

- Solar neighborhood
  - [Fe/H]-age relationship
  - [O/Fe] vs [Fe/H] correlation
    - Decreases with [Fe/H]
    - Similar for Mg, Si (α process)
  - [Ni/Fe], [Ba/Fe] flat with [Fe/H]
  - [s-process/Fe] correlates with [Fe/H]
    - e.g., [Ni/Fe], [Ba/Fe]
    - Why?
- Halo stars generally metal poor
  - [Fe/H] ~ -1.6 → -2.4
  - [α/H] ~ 0.25-0.30
  - [Fe/H] decreases with R (0.07 dex kpc^{-1})
- Thick disk
  - [O/Fe], [Mg/Fe] enhanced
  - Eu enhanced
  - [α/Fe] enhancement decreases with [Fe/H]
  - Looks like metal-poor halo, but kinematics of a disk

Abundance Gradients in Disk Galaxies

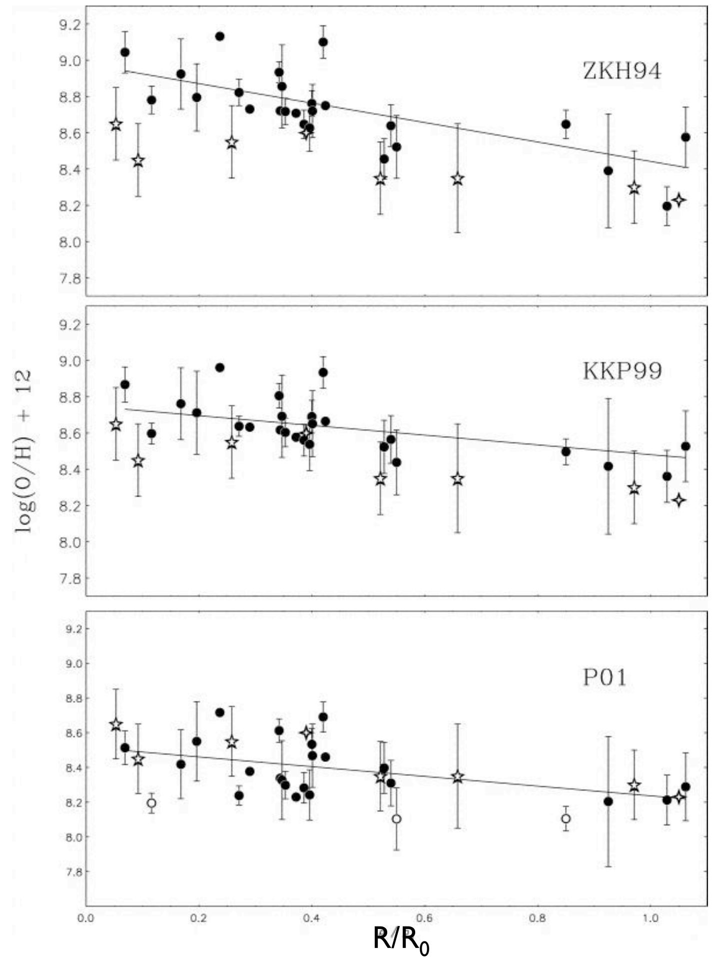
- HII regions in M51



$\log(O/H)_\odot = -3.1$ ➔

$12 + \log(O/H)_\odot = 8.9$

- HII regions in N300



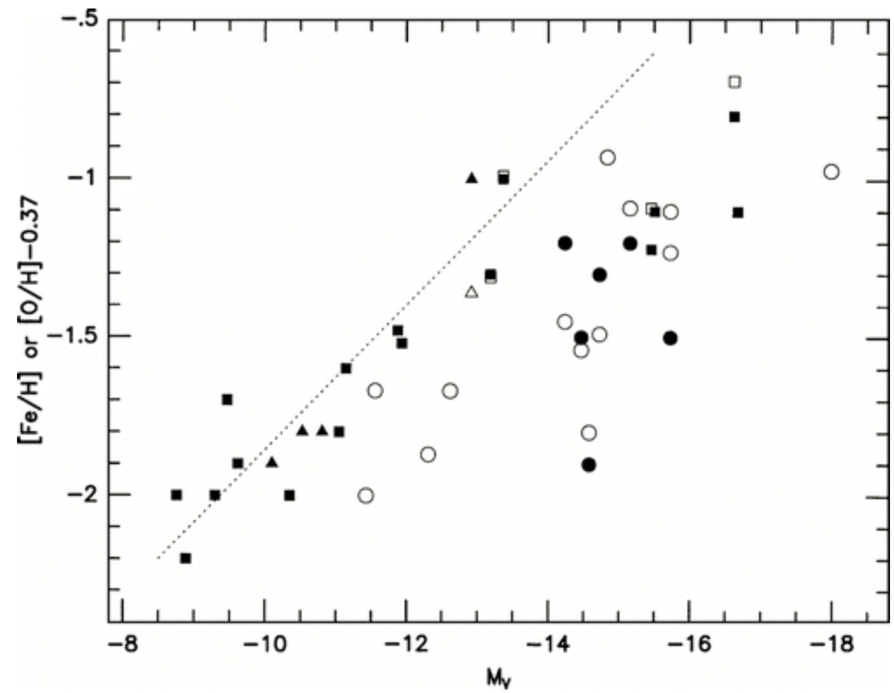
Disk Gradients (continued)

- General characteristics
  - 12 + log(O/H)+12 = 8.58 - 0.32 R/R_0
  - Generally: -0.04 to -0.07 dex/kpc
  - Flatter in late-types, steep in barred galaxies
- Why are there gradients?
  - Radial dependence on SFR/SFH?
  - Radial gas flows?
  - Radial dependence on yield?
  - Radial dependence on infalling gas?

Stopped here

Extragalactic Abundances: Dwarfs

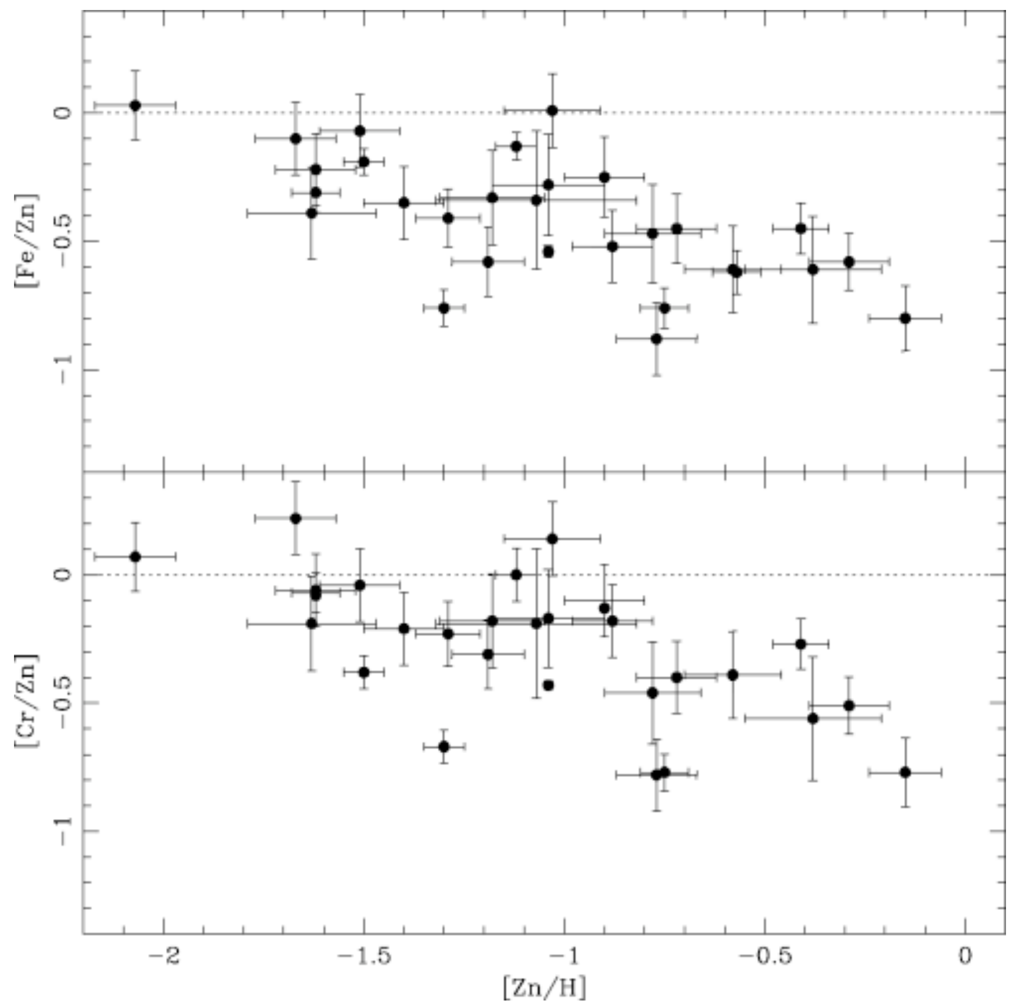
- LMC is 50-70% solar
  - [O/H] = -0.3 to -0.15
- SMC ~ 20-25% solar
  - [O/H] = -0.7 to -0.65
- Some dwarfs extremely metal poor (1/10 solar)
- Why?



Decreasing luminosity

QSO Absorption Lines

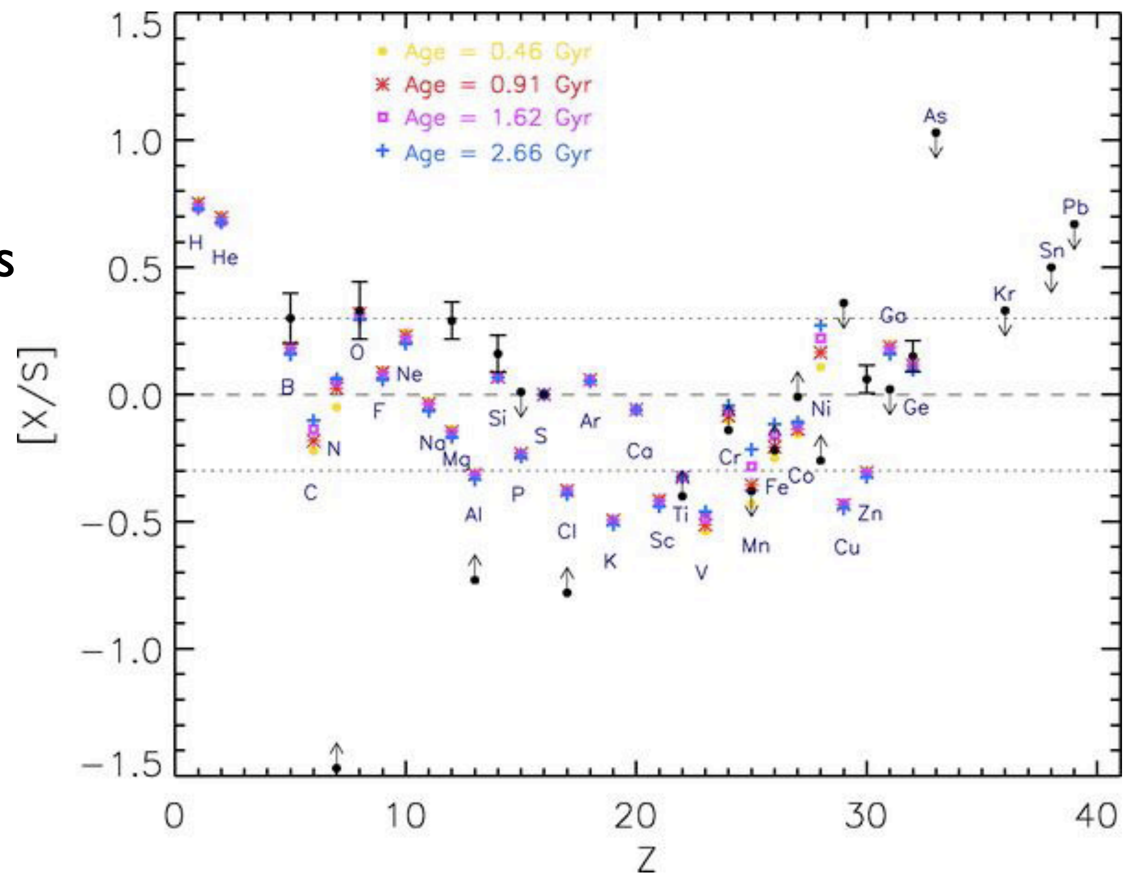
- Absorption line systems detected against background quasars
- Gas phase abundances can be measured via absorption lines
- Most metal-poor gas systems ever found
- Enrichment histories vary from solar



Lanfranchi & Friaca 2003

QSO Absorption Lines

- Damped Ly-α systems have high column, high velocities ➔ correlated with galaxies
- Thought to be progenitors of today's massive galaxies
- Consistent with:
  - young ages
  - 1/3 solar
  - Enrichment dominated by massive stars
    - few Type Ia Sne



Fenner, Prochaska, & Gibson 2004 ApJ

Chemical Evolution of Galaxies

- Simple models
  - $M_g(t)$ = gas mass
  - $M_r(t)$ = remnant mass
  - M_s= mass in stars
  - $M_h(t)$ = mass in heavy elements
  - $Z(t) = M_h/M_g$= metallicity
  - ΔM = change in mass
  - p = fractional yield of heavy elements

➔

$$\Delta M_h = p\Delta M_s - Z\Delta M_s$$
$$= (p-Z)\Delta M_s$$
$$\Delta Z = \Delta (M_h/M_g)$$
$$= [p\Delta M_s - Z(\Delta M_s + \Delta M_g)]/M_g$$

- In a closed box $\Delta M_s + \Delta M_g = 0$…..
  - $Z(t) = p \ln [M_g(t)/M_g(0)]$
  - Implies gas-rich things should have lower Z
  - Also: $M_s(<Z(t)) = M_g(0)[1-e^{-Z(t)/p}]$ ➔

- We should see lots of really low metallicity G stars
- Something like 50% of G dwarfs should have $z < 0.25Z_\odot$!
- But we don't: closer to 25% for Fe and <1% for O
- ➔ so-called G-dwarf problem