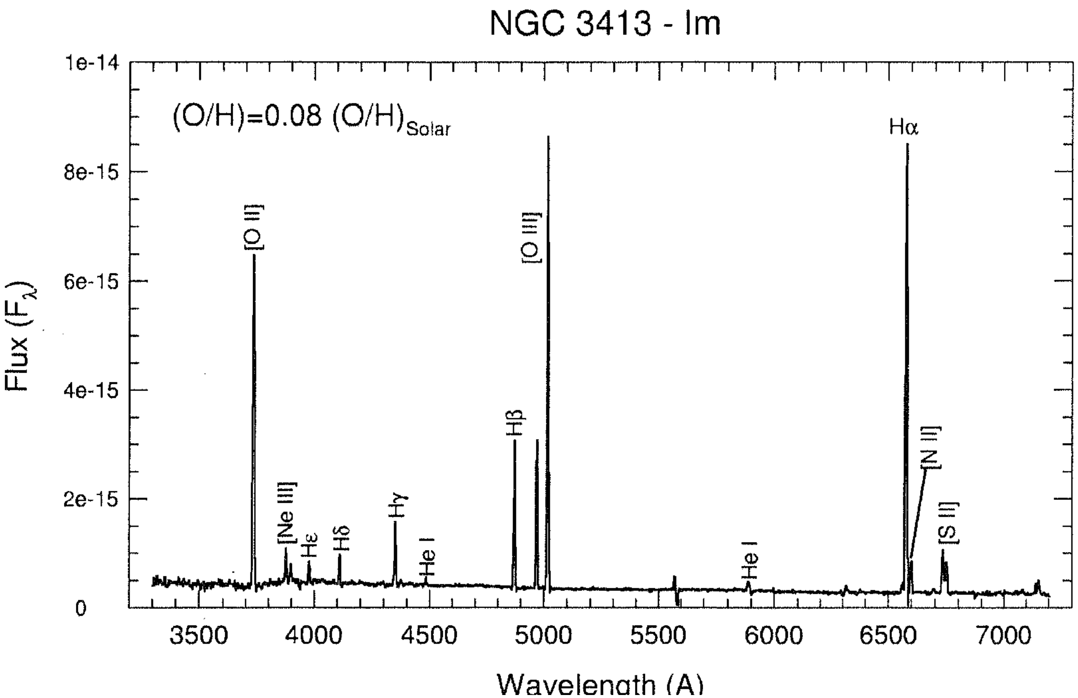
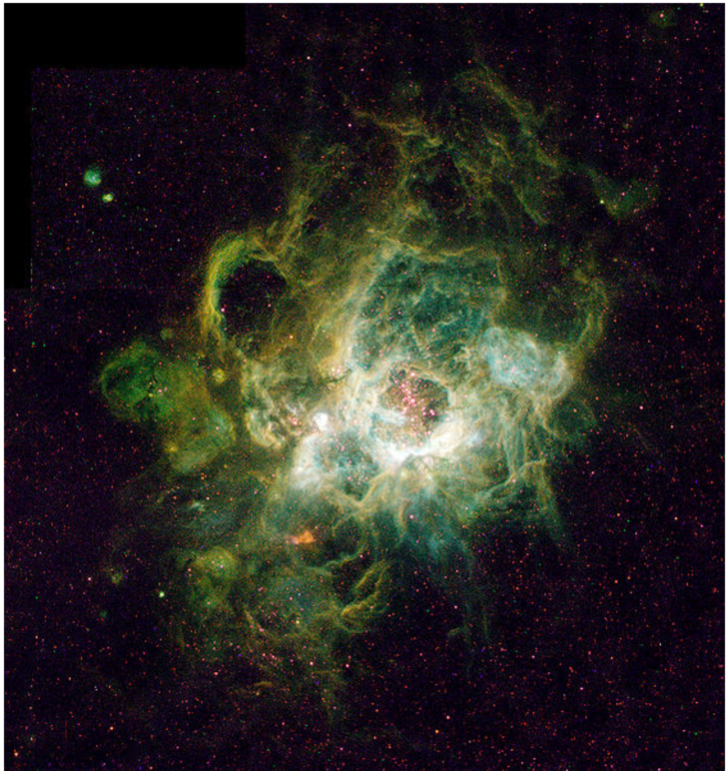
Astr 5465 February 24, 2020
Abundances in Late-type Galaxies

- **Spectra of HII Regions Offer a High-Precision Means for Measuring Abundance (of Gas)**
  - **Emission lines arise from permitted (recombination) and forbidden lines (collisional excitation)**
  - **Simple model: Stromgren sphere**
  - **High S/N measurements make possible abundance determination**
  - **Lines of a given species originating from different collisionally excited levels constrains temperature (Boltzman equation)**
  - **Lines of a given species originating from similar levels with different lifetimes constrains electron density.**





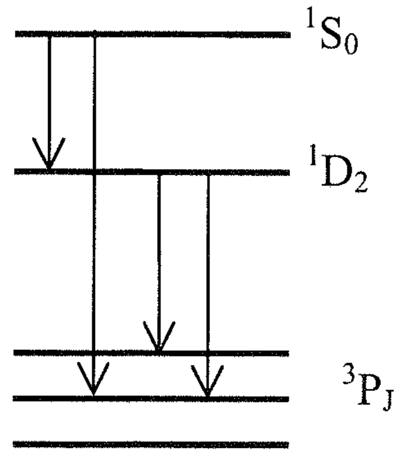
Some Physics of HII Regions

- **Ionizing γ with λ < 912 A° can ionize H out of ground state**
- **Electrons interact with atoms and loose energy such that recombination occurs.**
- **Free electrons can also excite other elements into states that for which radiative transitions are "forbidden."**
  - **The level populations should reflect the collisional energy and follow a Boltzman distribution:**

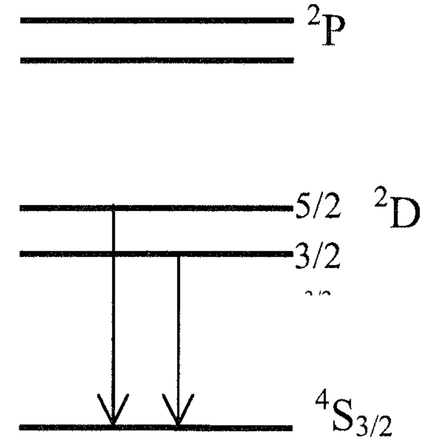
    $N_2/N_1 = g_1/g_2\ e^{-h\nu/KT}$
- **These excited states can have long lifetimes (low spontaneous emission probabilities: Einstein coefficients)**
- **Sulfur has two excited levels with small energy difference (low temp. sensitivity) but different transitional probabilities**
  - **Some collisional de-excitation occurs so [SII] line ratio depends on N_e**
- **Oxygen has two excited levels with similar probabilities separated in energy so the populations depend on the Boltzman factor., hence Temp. sensitivity.**
- **Figure at right shows sensitivity to Temperature and Density. So measure flux relative to Hβ and determine ion abundance. Repeat for other ionization states and sum for elemental abundance. Oxygen has lines in the visible for [OI], [OII], and [OIII] so it is most commonly used.**

  See Rick Pogee's monograph for a detailed description of how its done: http://www.astronomy.ohio-state.edu/~pogge/Ast871/Notes/Ionized.pdf

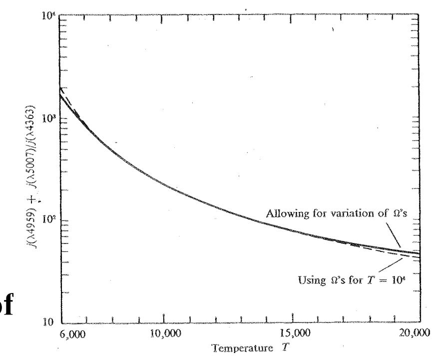
$$\frac{I_\lambda}{I_{H\beta}} = \frac{\int \varepsilon_\lambda(T_e,N_e)N_iN_e\,ds}{\int \varepsilon_{H\beta}(T_e,N_e)N_iN_e\,ds} = \frac{\varepsilon_\lambda N_i}{\varepsilon_{H\beta}N_i}$$

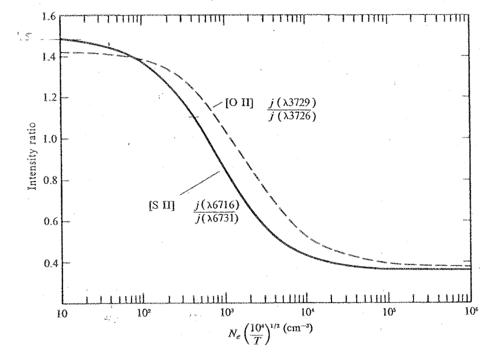


P² ion like[OIII] for Temperature



P³ ion like [SII] for Density

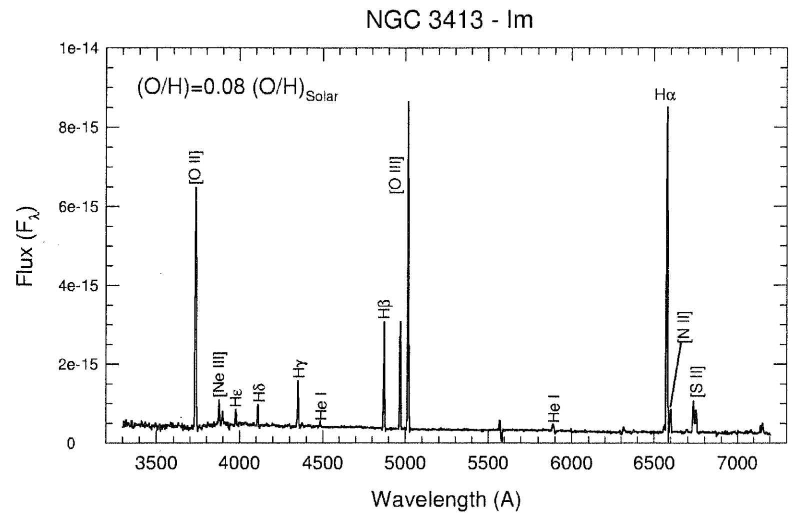


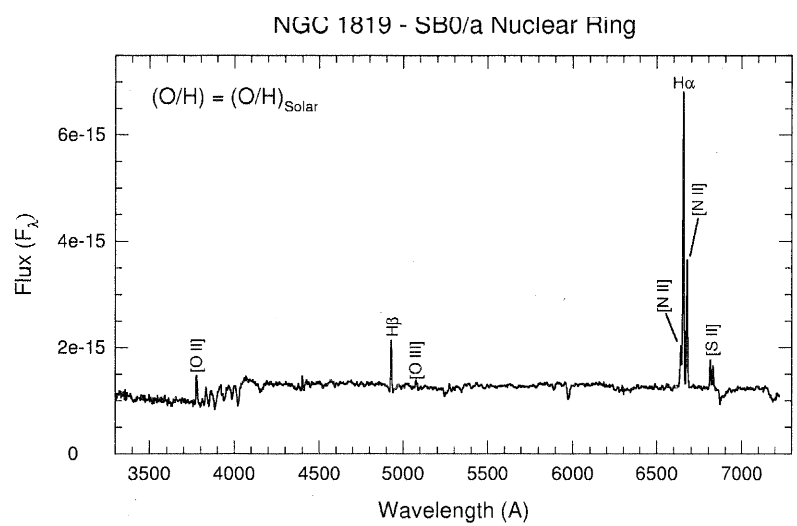


HII Region Abundances and Temperature

- **Far-IR fine structure lines provide most of the cooling**

  [CII] @ 157.7 µm and [OI] @ 63.2 µm and 145.5 µm
- **Radiative transitions are forbidden so there is no absorption.**
- **[OIII] are secondary cooling lines in visible too.**
- **Interestingly, the higher the temperature the fainter the [OIII].**
  - **Less [OIII] means less cooling and a hotter HII region. Metals very inefficient so greater collisional excitation of forbidden transitions.**



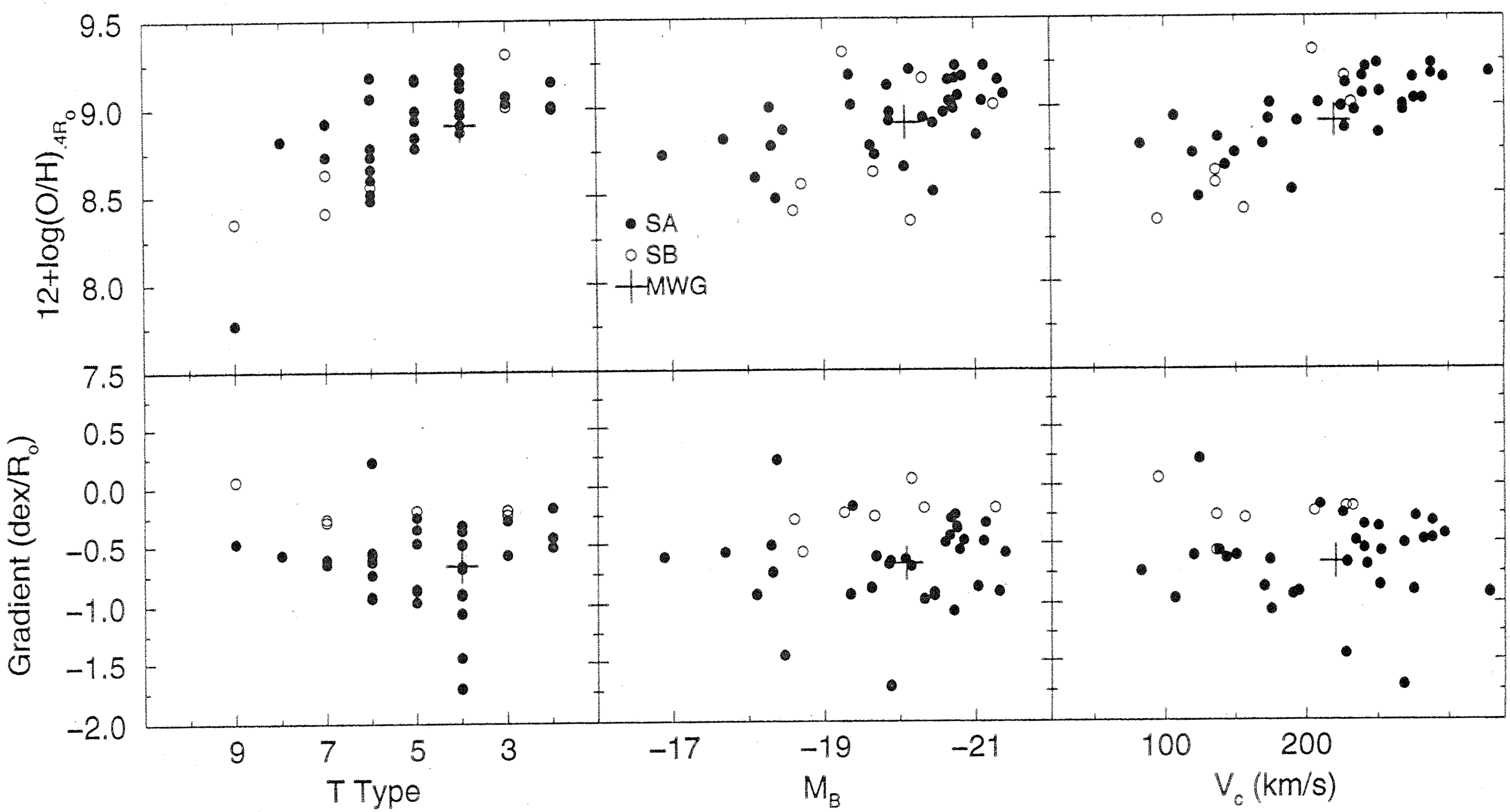


Stromgren Sphere-I

- Size of an HII region depends on the number of ionizing photons and the density of the cloud.
  - Lifetime of an atom in an excited state is ~ 10^{-8} sec.
  - Most Hydrogen either ionized or in ground state.
  - Cloud is optically thick for $\lambda < 91.2$ nm
    - All these photons absorbed
  - Balmer transitions (n = 2 level) are thus optically thin and can escape (generally) so we sum rates for n > 2: $N_R = \sum_2^\infty N_n$
  - Equate number of photoionizations to number of recombinations: $N_n = n_e n_H \alpha_n(T)$ where α is the recombination rate
  - $N(UV) = 4\pi/3\ R_s^3 n_e n_H \alpha(2)$ where n_e is the electron density, n_H is the number of protons, $\alpha(2)$ is the recombination rate for the n = 2 level, and R_s is known as the radius of the Stromgren sphere. If the UV flux from some star is known R_s can be calculated.
  - Thus if the radius and density of the HII region can be estimated we can solve for the number of ionizing photons.

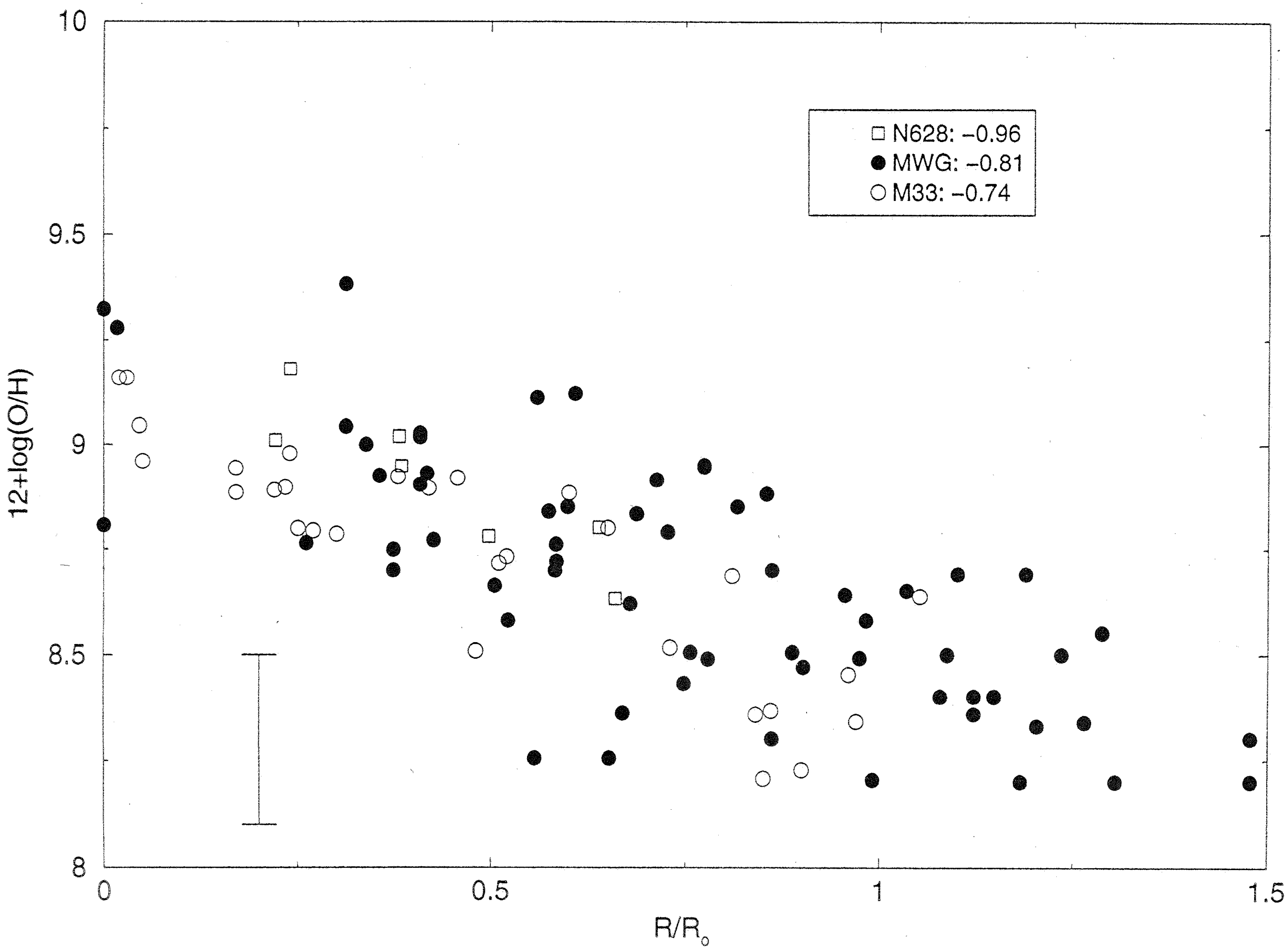
Some Abundance Patterns within Spiral Galaxies

- **Surveys of HII Region Abundances Reveals Enrichment Trends**
  (Zaritsky et al 1994, Apj 420, 87; I need to uptdate this!)



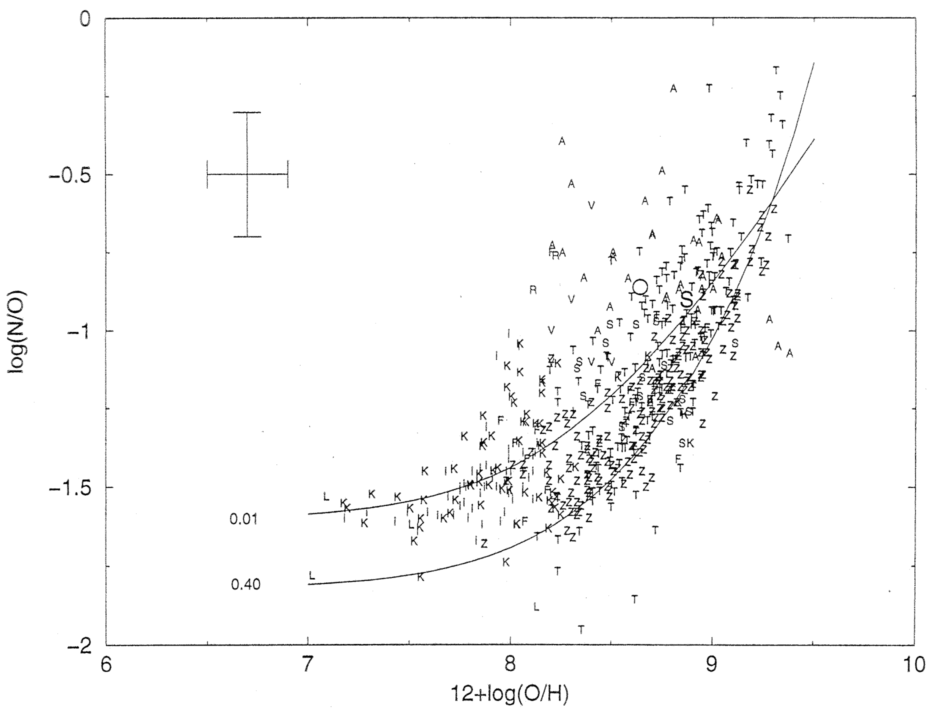
Abundance Gradients within Spiral Galaxies

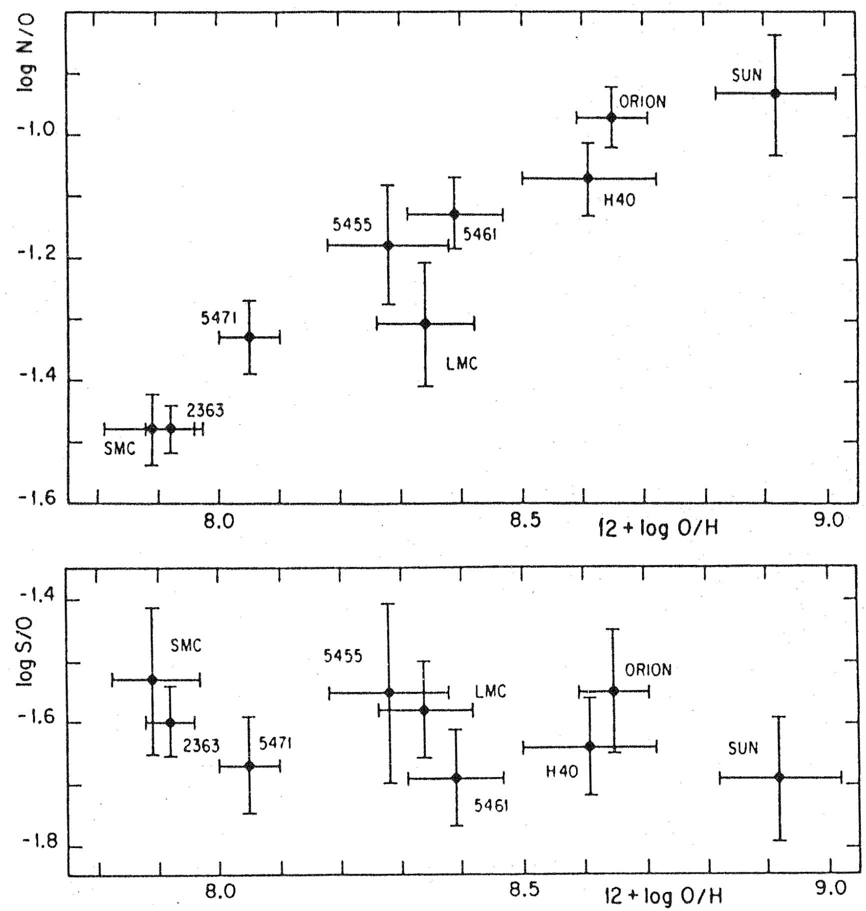
- **All spirals galaxies show abundance gradients**
  - **Star formation progresses faster within the inner regions and more slowly in the exterior**
  - **Lower luminosity spirals are offset in absolute abundance**



Abundance Patterns within Spiral Galaxies

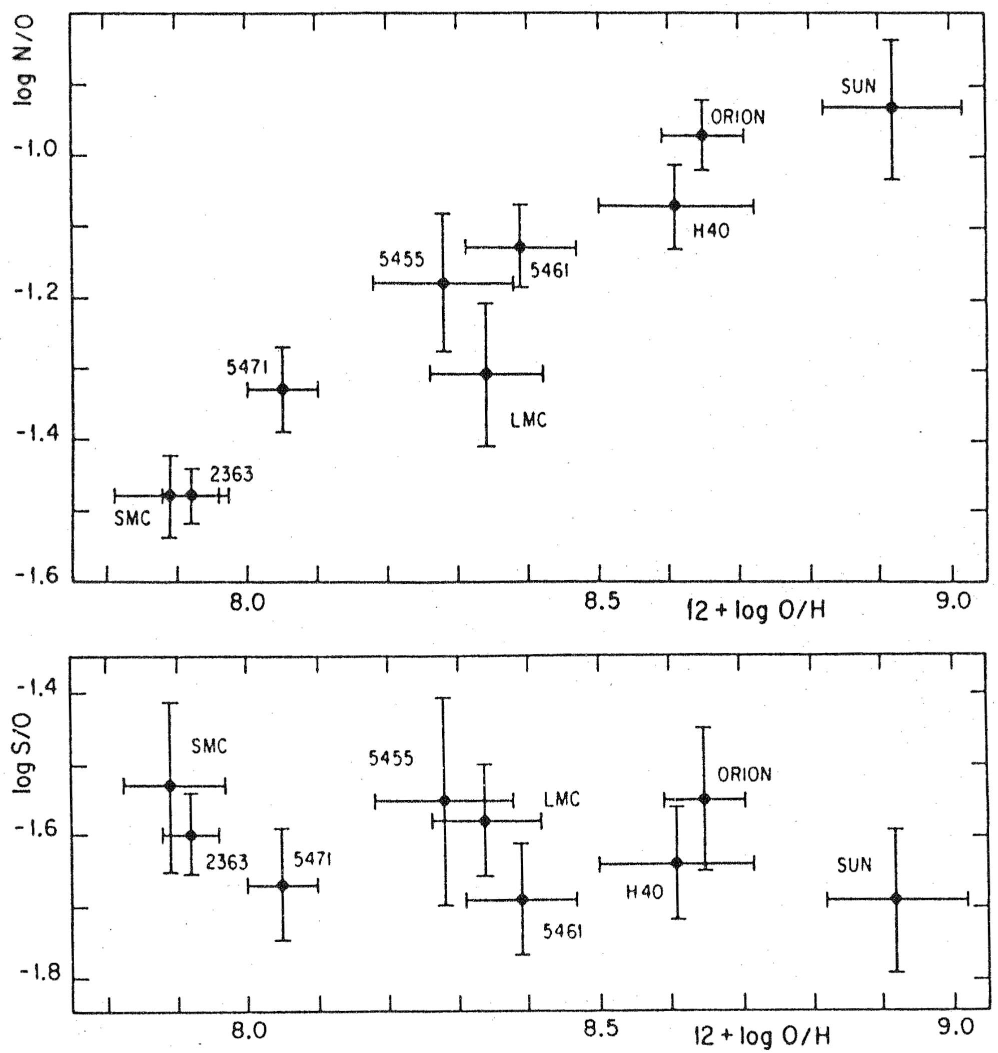
- Nitrogen Correlates with Oxygen
- Ne, Argon and Sulfur do not
- Ne comes from ^{12}C burning (Intermediate mass stars)
- SN II produce O, Ar and S (most massive stars)
  - Evidence for a universal IMF?





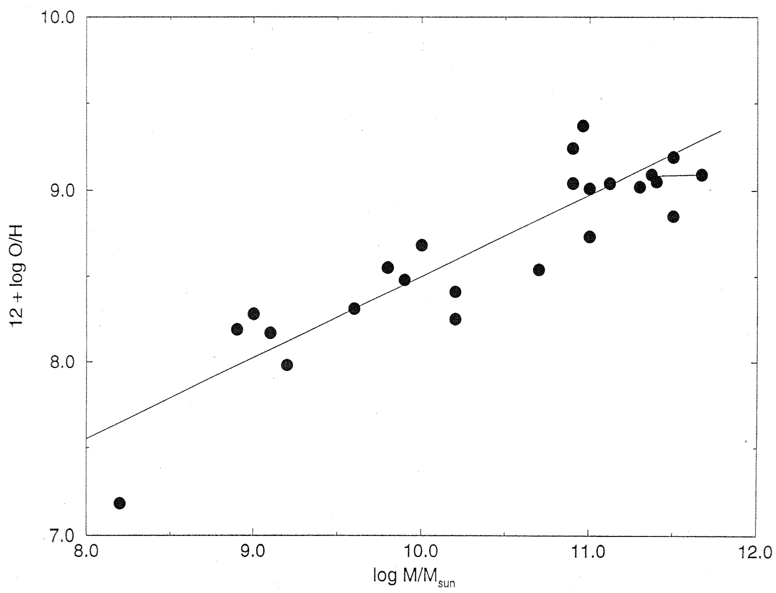
Abundance Patterns within Spiral Galaxies

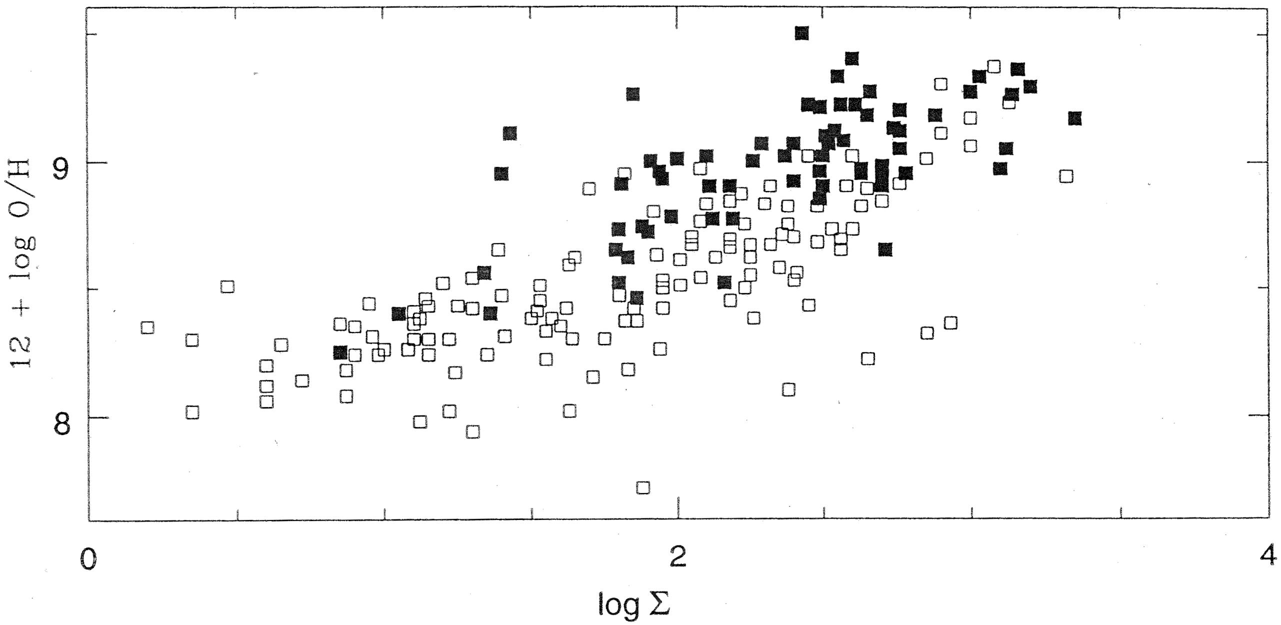
- N and C increase faster than Oxygen due to secondary production from lower mass, AGB stars
- Ne, S, and Ar are in lock step with O but originate in higher mass stars so implication is that IMF is universal.



Oxygen Abundance Correlates with Star Formation History

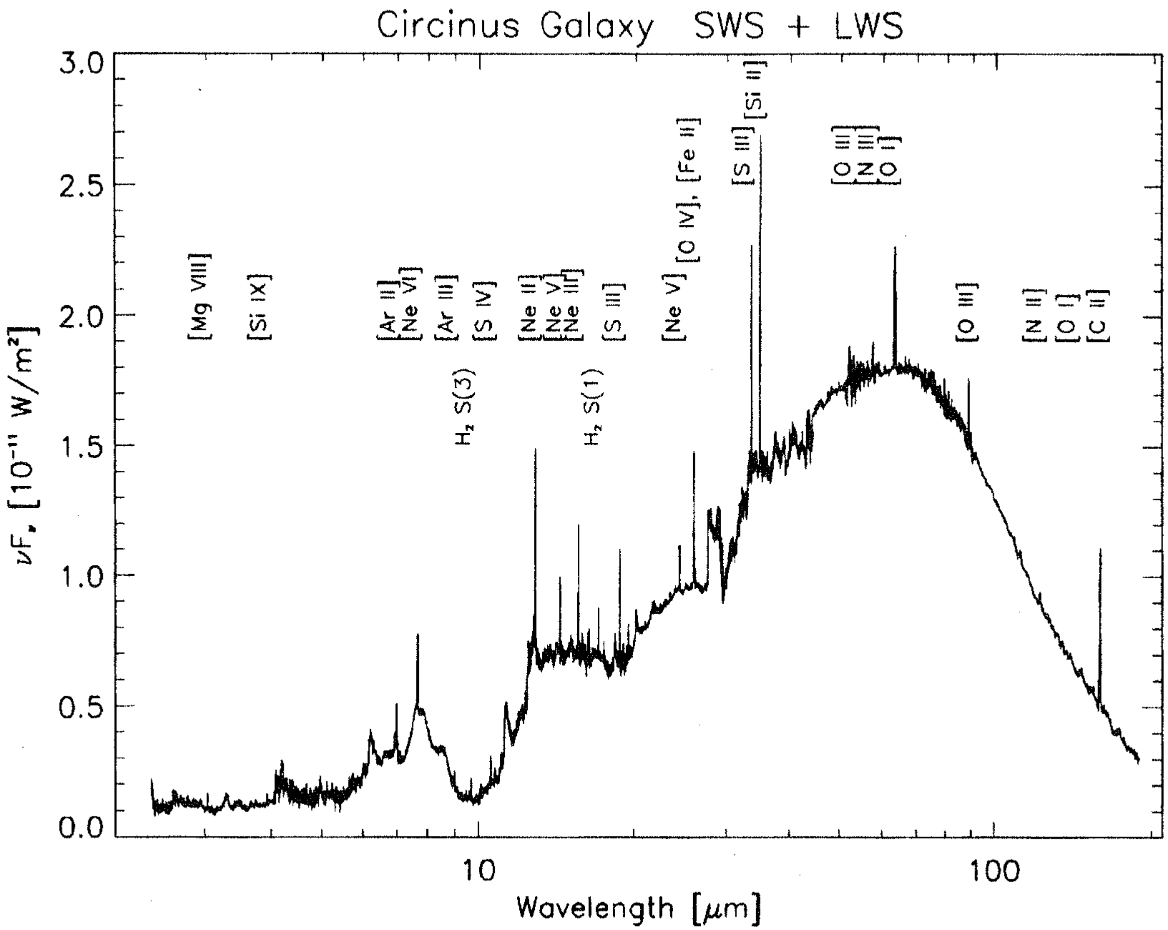
- **All spirals show increasing Oxygen abundance with increasing mass (V^2R/G).**
- **Oxygen abundance correlates with surface brightness.**
- **Massive galaxies form stars earlier and enrich ISM more efficiently than do lower mass galaxies.**
- **Higher stellar surface density means higher historical star formation and greater historical enrichment.**
- **Paradox: star forming galaxies are still forming stars because they are the least efficient. Red and dead galaxies were the most efficient.**





Far Infrared Emission Lines

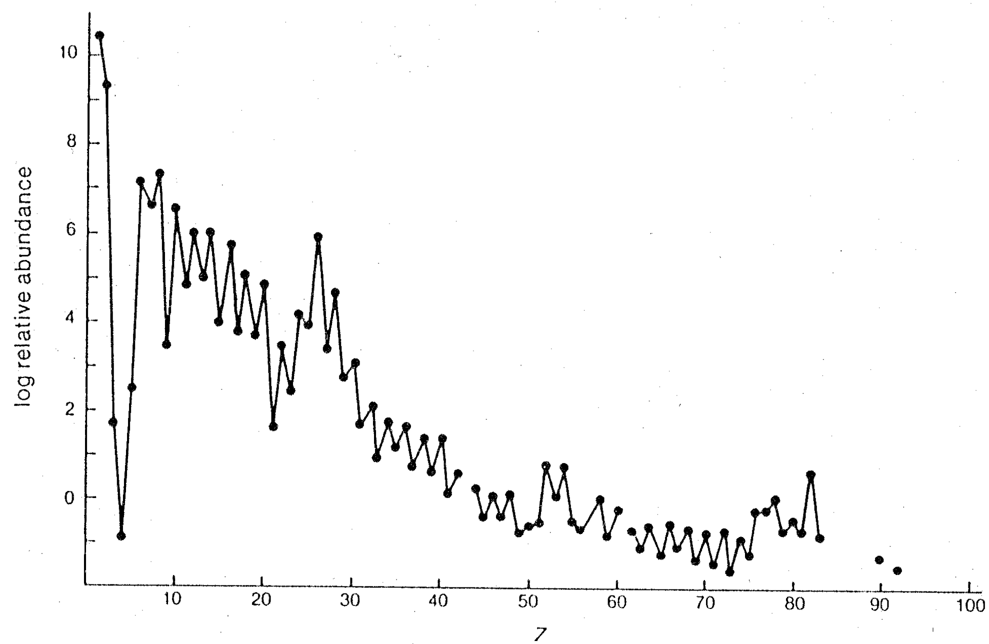
- Far infrared emission lines provide useful diagnostics as well.
- Note the PAH and dust emission

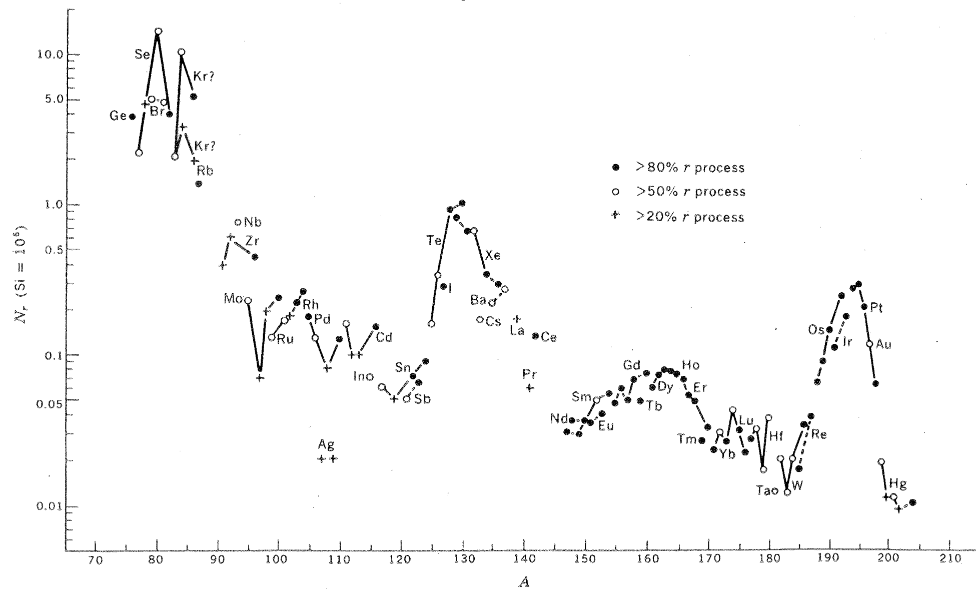


Stars Contain Fossil Record of Milky Way's Enrichment History

- Solar abundance of elements
  - Li, Be, B gap (skipped in p-p chain)
  - Odd-even effect from α-capture
  - Fe peak
  - N > 56 requires neutron capture

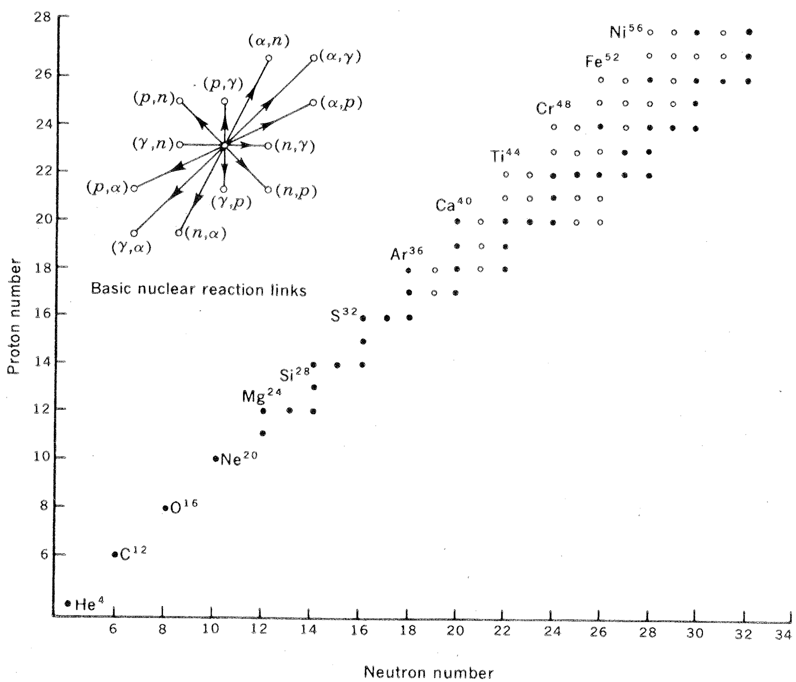
  (see Clayton for a summary of processes)
- Additional peaks and dips from r- and s-process of neutron capture
- R (rapid) process
  - High neutron flux
  - Neutrons captured before radioactive decay
- S (slow) process
  - Low neutron flux
  - Radioactive decay occurs before next neutron absorption
- SN II
  - Nuclear statistical equilibrium yields
  - Low [Fe/H] stars have same r-process ratios as the Sun (Sneden et al 1996)
  - SN II production independent of [Fe/H]?

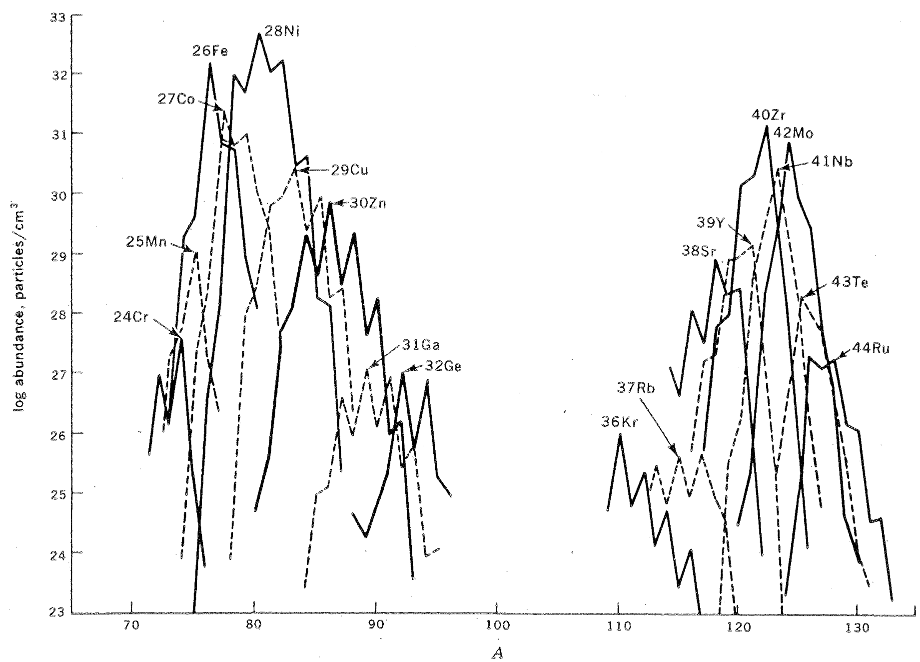




R-process Peak Constrains Physics of SN II

- **Nuclear reaction processes well understood but astrophysical location uncertain**
  - **Historically thought to be SN but Neutron star - Neutron star Mergers appear sufficient (Cote et al. 2018; arxiv.org/pdf/171005875.pdf)**
- **Temp. and density dependence of cross sections also well understood**
- **Model of neutron capture within SNII fireball must reproduce r-process peak**
  - **Eu and AU provide strongest constraints**





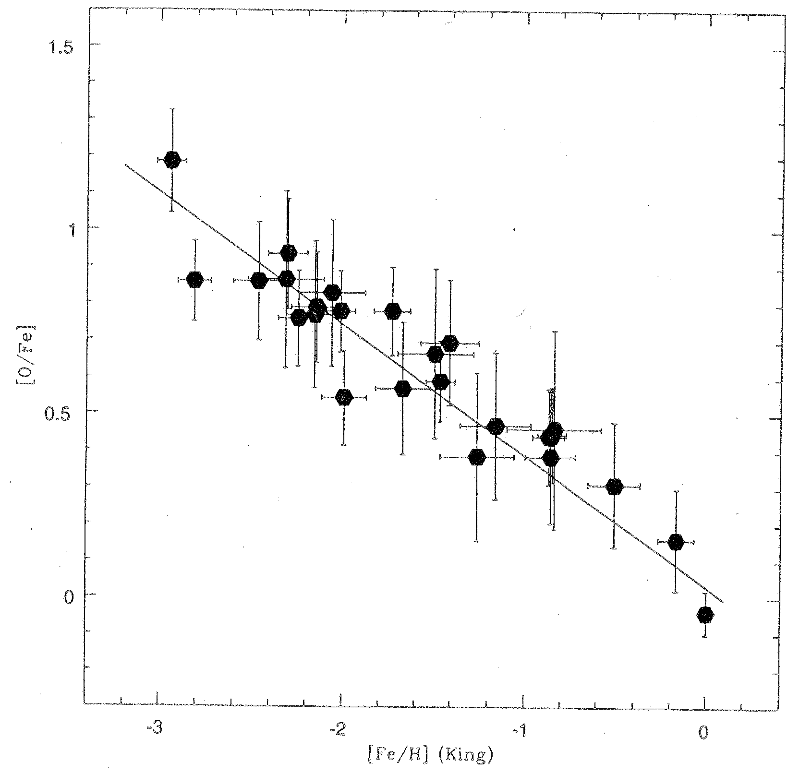
Milky Way's Stars Contain Fossil Record of Enrichment History

- **Oxygen Can Be Easily Measured from HII Regions but It Can Also Be Measured in Stars with High Res. Echelle Spectra**
- **Origin of Oxygen Must be SN II**
  - **Easiest Intermediate Element to Interpret in Stars**
- **Oxygen is enhanced at low [Fe/H]**

  (Boesgaard et al. 1999)
- **If Fe rises with time [O/Fe] traces O production vs. time**

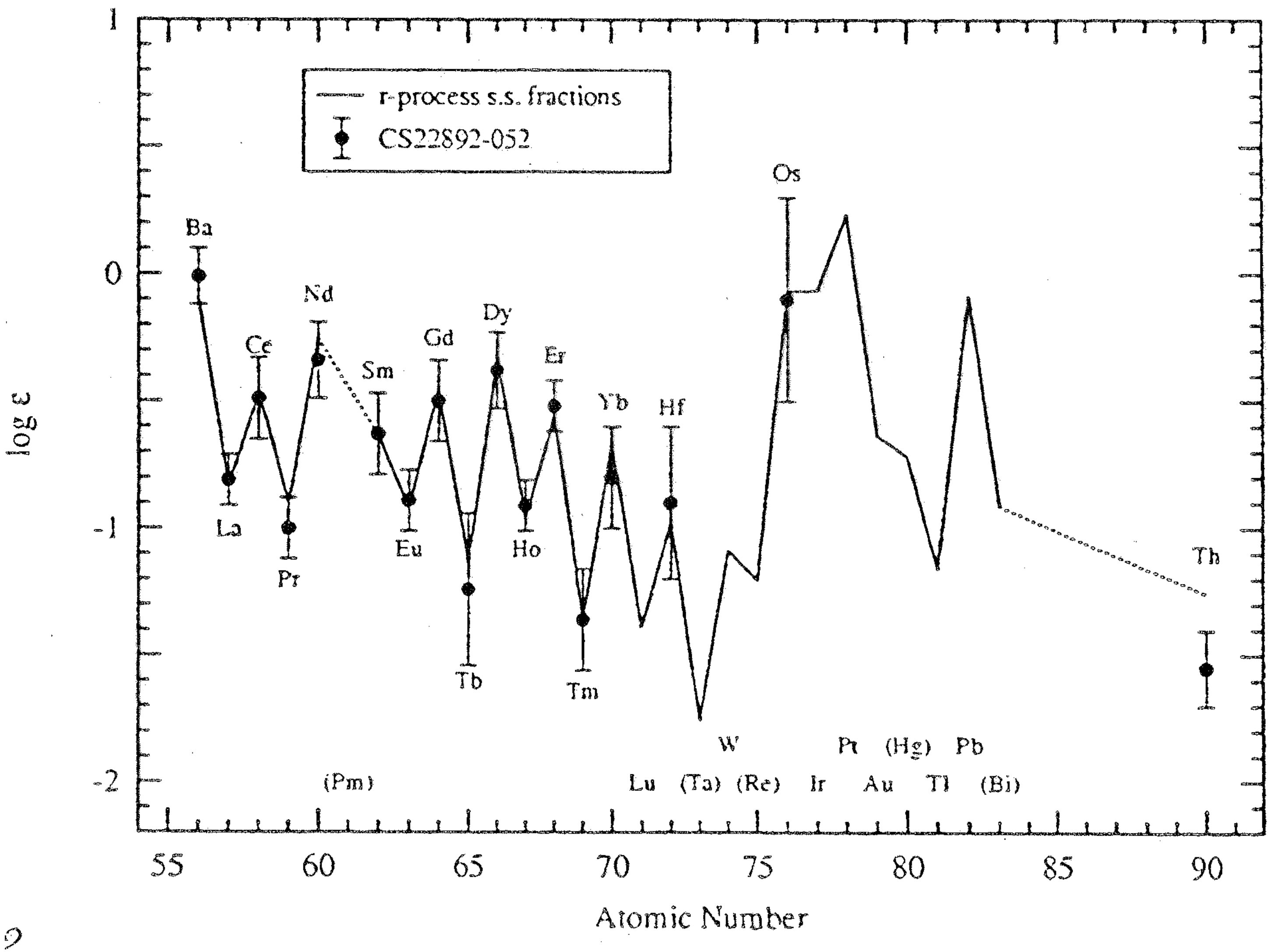
  O: SN II

  Fe: SN Ia + SN II
- **Not clear that Fe rises uniformly with time**
  - **Accretion history of MW implies possibility of a wide variety of formation locations**
- **Nevertheless consensus is that O enhancement at low [Fe/H] is from SN II vs. SN Ia**



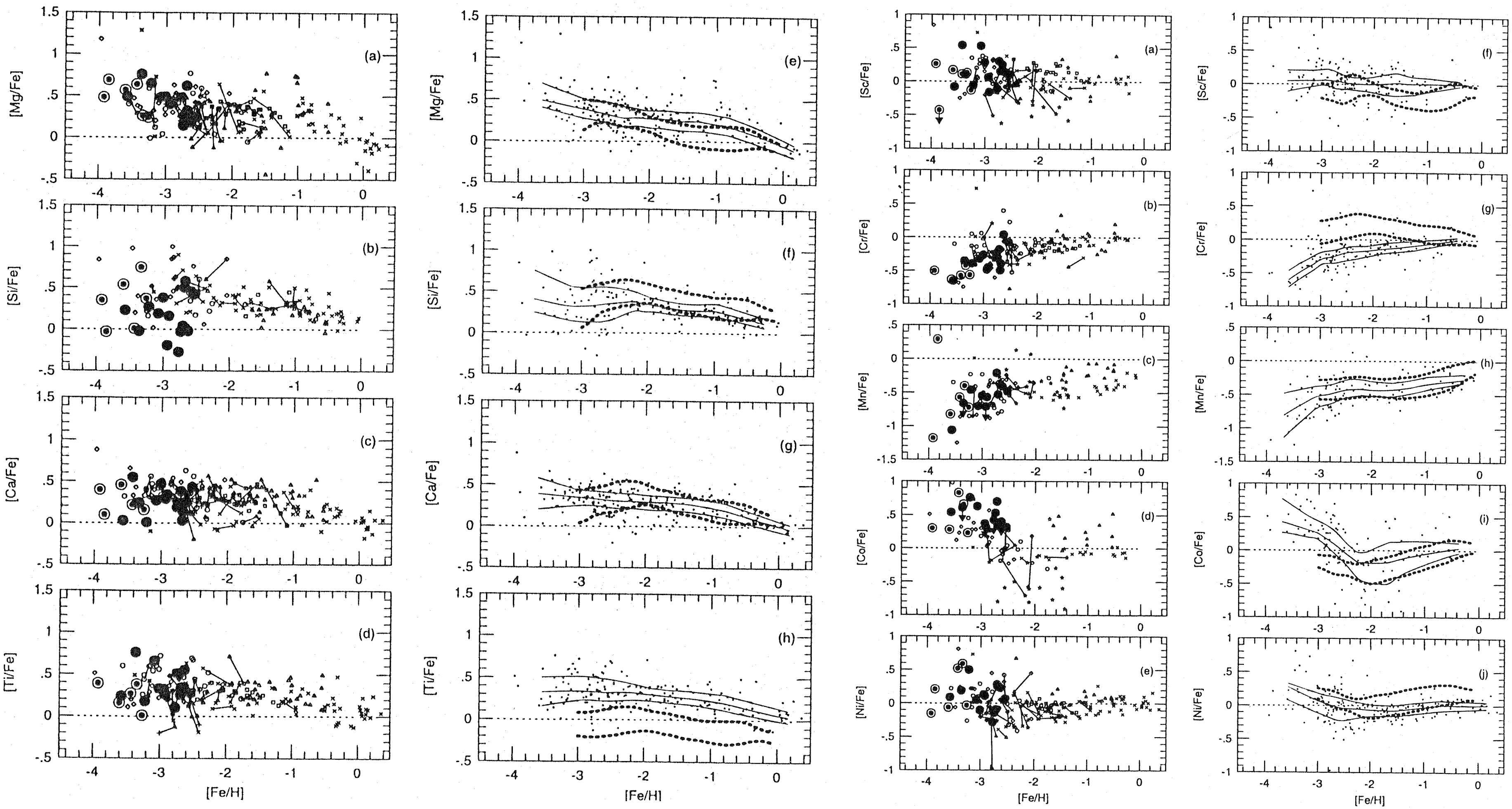
Stars Contain Fossil Record of Milky Way's Enrichment History

- High resolution spectroscopy of low [Fe/H] = -3.5 star (Sneden et al. 1996)
  - R-process production at low [Fe/H] is ~ same as solar: SNII physics independent of initial [Fe/H] (?) or Neutron Star – Neutron Star Mergers (clearly independent of [Fe/H])



Stars Contain Fossil Record of Milky Way's Enrichment History

- **What About Other Elements?**
- **All α-elements appear to be enhanced at low [Fe/H]**
- **Fe-peak elements enhanced at low [Fe/H]**
- **Provides useful constraints on SN II vs SN Ia production and rates**



Models of the Milky Way's Chemical Enrichment

- **Preliminaries**
  - Star formation and evoution produce heavy elements
  - Enriched gas incorporated into subsequent generations so abundance must increase with time
  - As gas is depleted abundance increases
- **Closed Box Model**
- Assumptions:
- Instantaneous Recycling Approximation
- -lifetime of massive stars is so short it is ~ 0
- Gas is uniformly mixed in a dwarf galaxy or an annulus of a large spiral
- Conservation of Mass
- Parameters:
- M_g – the total gas mass
- M_h – the mass of heavy elements
- $Z = M_h/M_g$ ($Z_O \sim 0.02$)
- M_s – the mass in stars at a given time
- dM_s – the mass in stars remaining after the massive stars have evolved
- p – the yield in heavy elements [i.e. $M_h(Dt) = pdM_s(Dt)$]
- Expectations after some time t:
- $dM_h = pd\,M_s - ZdM_s = (p-Z)dM_s$ (1)
- $dZ = d(M_h/M_g) = dM_h/\,M_g - (M_h/M_g^2)dM_g$ (2)
- $= (dM_h - Zd\,M_g)/M_g$
- $dM_s = -\,dM_g$ (conservation of mass) (3)
- Combining (1,2,3) we have:
- $dZ = -p\,(dM_g/M_g)$
- Integrating we obtain:
- $Z(t) = -p\,\ln[M_g(t)/M_g(0)]$

Models of the Milky Way's Chemical Enrichment Cont.

- We can predict metallicity distribution of stars at some given time. Specifically, the mass in stars with $Z < Z(t)$ will be:
- $M_s[Z<Z(t)] = M_s(t) = M_g(0) - M_g(t)$
- $= M_g(0)[1 – e^{-Z(t)/p}]$
- The number of stars with $Z < aZ(t)$, where a is some fraction (like 0.1 corresponding to [Fe/H] < -1), is then:
- $M_s[Z<aZ(t)]/ M_s[Z<Z(t)] = 1 – e^{-aZ(t)/p}/1 – e^{-Z(t)/p}$
- $= (1 – x^a)/(1 – x)$
- where $x = M_g(t)/M_g(0)$ is the remaining gas fraction.
- In the solar neighborhood a reasonable estimate is $x = 0.1$ so we predict:
- $M_s (Z/3) = 0.51\ M_s(Z)$
- Or approximately half the stars in the solar neighborhood should have $Z = Z_{max}/3$. Surveys of G-dwarfs have shown that nowhere near this number of low metallicity stars is seen: the G-dwarf problem. Two possible solutions are a leaky box (enriched gas is lost via SN winds, etc.) or an accreting box (fresh pure hydrogen gas is added to the system over time). Both are reasonably consistent with the observed distribution of metal-poor stars in the solar neighborhood.

Additional Recommended Reading

- **Galactic Chemical Evolution: Gibson et al. 2003, Pub. Astron. Soc. of Australia, 20, 1**
- **Galactic HII Region Abundances: Deharveng et al. 2000, MNRAS, 311, 329**
- **Star Formation: Kennicutt & Evans 2012: https://arxiv.org/abs/1204.3552**
- **Rick Pogge's ISM Notes (these are excellent):**
- **General:** http://www.astronomy.ohio-state.edu/~pogge/Ast871/Notes/Intro.pdf
- **Neutral:** http://www.astronomy.ohio-state.edu/~pogge/Ast871/Notes/Neutral.pdf
- **HII Regions:** http://www.astronomy.ohio-state.edu/~pogge/Ast871/Notes/Ionized.pdf