Lecture 11:
Ages and Metallicities from Observations
A Quick Review

Ages from main-sequence turn-off stars

Main sequence lifetime:
lifetime = fuel / burning rate
\[ \tau_{\text{ms}} = 7 \times 10^7 \left( \frac{M}{M_\odot} \right)^{-1} \frac{L}{L_\odot} \text{ yr} \]
\[ \tau_{\text{ms}} = 7 \times 10^9 \left( \frac{L}{L_\odot} \right)^{1/2} \text{ yr} \]
(since \( L \propto M^4 \Rightarrow \tau \propto M^{-1/4} \))

Luminosity at the top of the main sequence (turn-off stars) gives the age \( t \).

Ages from main-sequence turn-off stars

\[ M_V(\text{TO}) = 2.70 \log (t / \text{Gyr}) + 0.30 [\text{Fe/H}] + 1.41 \]

Globular Cluster in Halo
Open Clusters in Disk

47 Tuc: 12.5 Gyr
M67: 4 Gyr
NGC188: 6 Gyr

Multiple Ages of stars in Omega Cen

Star Formation Rates

- Star-formation can be measured in many ways:
  - \( 10^5 \text{Ha} \)
  - Optical indices e.g., [A]-
  - \( M_\odot \), [I]-[OIII]
  - \( \text{H}\alpha \)
- See review by Kennicutt (1998), AR&A
- Here we look at one: The \( H\alpha \) recombination line.
- FUV rad from recent star-form ionises cloud which recombined and cascades
- Only stars with \( M=10M_\odot \), with lifetimes <20Myr produce FUV

\[ SFR(M_\odot \text{yr}^{-1}) = 7.9 \times 10^{-23}L(\text{H}\alpha) \text{ergs s}^{-1} = 1.08 \times 10^{-10}Q(H\alpha) \text{cgs} \]
\( Q(H\alpha) \) is the ionising photon luminosity
constants are derived from evol. synthesis models (e.g., Kennicutt 1982)

Cosmic Star Formation History
Abundance Measurements
- Star spectra: absorption lines
- Gas spectra: emission lines
- Galaxy spectra: both
- Metal-rich/poor stars: stronger/weaker metal lines relative to H.

HII region spectra

Stellar spectra
- Lab measurements: Unique signature (pattern of wavelengths and strengths of lines) for each element.

High-Resolution Spectra
Measure line strengths (equivalent widths) for individual elements.
- Equivalent Width measures the strength (not the width) of a line.
- EW is width of a 100% deep line with same area.

Abundance Measurements
- Spectra ⇒ Line strengths (equivalent widths)
- Astrophysics ⇒ Stellar atmosphere models
- Physics ⇒ Laboratory calibrations
  Abundances: $\frac{Fe}{H}$ etc.
  (Temperature, surface gravity, and metal abundances in the stellar atmosphere models are adjusted until they fit the observed equivalent widths of lines in the observed spectrum. Full details of this are part of other courses)

Bracket Notation
Bracket notation for Fe abundance of a star relative to the Sun:
$$\frac{Fe}{H} = \log\left(\frac{n(Fe)}{n(H)}\right) - \log\left(\frac{n(Fe)}{n(H)}\right)_{\text{Sun}}$$
And similarly for other metals, e.g. relative to Fe:
$$\frac{Mg}{H} = \log\left(\frac{n(Mg)}{n(H)}\right) - \log\left(\frac{n(Mg)}{n(H)}\right)_{\text{Sun}}$$

Star with solar Fe abundance: $\frac{Fe}{H} = 0.0$
Twice solar abundance: $\frac{Fe}{H} = \log(2) = +0.3$
Half solar abundance: $\frac{Fe}{H} = \log(1/2) = -0.3$

Metallicity vs Abundance
Metallicity (by mass):
$$Z = \sum A_n \frac{n(A)}{n(H) + 4 n(He)} = \sum A_n \frac{n(A)}{n(H) + 4 n(He) + 4 n(He)}$$
$$X = \sum A_n \frac{n(H)}{n(H) + 4 n(He) + 4 n(He)}$$
To infer $Z$ from a single line:
$$Z = f \frac{n(Mg)}{n(H)} \frac{Z_{\text{Sun}} X_{\text{Sun}} f_{\text{Sun}}}{X_{\text{Sun}} f_{\text{Sun}}} = 10^{f \frac{n(Mg)}{n(H)}}$$
Primordial: $X_p = 0.75, Y_p = 0.25, Z_p = 0.00$
Solar: $X_{\odot} = 0.70, Y_{\odot} = 0.28, Z_{\odot} = 0.02$
Solar Abundances

Primordial He/H measurement
- Emission lines from H II regions in low-metallicity galaxies.
- Measure abundance ratios: He/H, O/H, N/H, ...
- Stellar nucleosynthesis increases He along with metal abundances.
- Find Yp by extrapolating to zero metal abundance.

Enhancement of α-elements
α-elements = multiples of He, more stable, produced by Type II Supernovae (high-mass stars, M > 8M☉).
Stars with high α elements must have formed early, e.g. before a less α-enhanced mix added to ISM by Type Ia SNe (WD collapse due to accretion from binary companion).
Most MW bulge stars are α-enhanced => Bulge must have formed early.

Some Key Observational Results
- Gas consumption: Z = -log(μ) for Z < y
  More gas used => higher metallicity.
- Radius: more metals near galaxy centre
  Near centre of galaxy: Shorter orbit periods => More passes thru spiral shocks => More star generations => μ lower => Z higher. (Also, more infall of IGM on outskirts.)
- Galaxy Mass: Low-mass galaxies have lower metallicity.
  - Dwarf irregulars: form late (young galaxies), have low Z because μ is still high.
  - Dwarf ellipticals: SN ejecta expel gas from the galaxy, making μ low without increasing Z.
**M31: Andromeda in Ultraviolet Light**

UV light traces hot young stars, current star formation.

Gas depleted, hence no current star formation in the inner disk.

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**More metals near Galaxy Centres**

- Ellipticals (NGC 3115)
- Spirals (M100)

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**Mass-Metallicity relation**

Why are low-mass galaxies metal poor?

- Some are young (not much gas used yet, so ISM not yet enriched).
- Supernovae eject the enriched gas from small galaxies.

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**Less Metals in Small Galaxies**

- Two fundamental parameters seem to determine observed metallicity: mass and SFR.
- This forms a fundamental metallicity relation (FMR).
- Despite extremely complex underlying physics, the relation seems to hold out to $z = 2.5$ and in a huge range of galaxies / environments.
More Metals => More Planets

Doppler wobble surveys find Jupiters orbiting 5% of stars with solar metallicity.
This rises to 25% for stars with 3x solar abundance [Fe/H]=+0.5
Fischer & Valenti 2005

A Quick Review

• Main events in the evolution of the Universe:
  – The Big Bang (inflation of a bubble of false vacuum)
  – Symmetry breaking  ➔ matter/anti-matter ratio
  – Quark + antiquark annihilation  ➔ photon/baryon ratio
  – The quark soup  ➔ heavy quark decay
  – Quark-Hadron phase transition and neutron decay  ➔ n/p ratio
  – Big Bang nucleosynthesis  ➔ primordial abundances
    \[ X_H = 0.75 \quad Y_p = 0.25 \quad Z_e = 0.0 \]
  – Matter-Radiation equality  \[ R \sim t^{1/2} \rightarrow R \sim t^{2/3} \]
  – Recombination/decoupling  ➔ the Cosmic Microwave Background
  – CMB ripples (\( \Delta T/T \sim 10^{-5} \) at \( z=1100 \)) seed galaxy formation
  – Galaxy formation and chemical evolution of galaxies

• Main events in the chemical evolution of galaxies:
  – Galaxy formation  ➔ Jeans Mass (\( \sim 10^6 M_\odot \))
    • Ellipticals  ➔ Initial mass and angular momentum, plus mergers.
    • Spirals  ➔ Star formation history \( S(t) \), gas fraction \( \mu(t) \)
    • Irregulars
  – Star formation  ➔ \( \alpha \) = efficiency of star formation
    • The IMF (e.g., Salpeter IMF power-law with slope -7/3)
      • First stars (Population III) from gas with no metals (none seen)
  – Stellar nucleosynthesis  ➔ metals up to Fe
  – Supernovae (e.g., SN 1987A)  ➔ metals beyond Fe
    • p, s, and r processes
      • white dwarfs (\( M < 8 M_\odot \)) or black holes, neutron stars (\( M > 8 M_\odot \)).
  – Galaxy enrichment models:
    (e.g., \( Z = -y \ln(\mu) \), yield \( y \))
    • Metal abundances rise  ➔ \( X = 0.70 \quad Y = 0.28 \quad Z = 0.02 \)
      \( \text{ (solar abundances)} \)
  – Gas with metals  ➔ Stars with Planets  ➔ Life!