# Course outline

<table>
<thead>
<tr>
<th>1. Introduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Phases of stellar evolution</td>
</tr>
<tr>
<td>- Simple Stellar Populations</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. Resolved Stellar Populations</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Cluster CMDs</td>
</tr>
<tr>
<td>- SSP fitting: age, metallicity, IMF</td>
</tr>
<tr>
<td>- Complex populations: SFH, MDF</td>
</tr>
<tr>
<td>- Exotica</td>
</tr>
<tr>
<td>- Limitations</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. Population synthesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Principles and caveats</td>
</tr>
<tr>
<td>- Temperature, metallicity and gravity effects on stellar spectra.</td>
</tr>
<tr>
<td>- Flux contributions</td>
</tr>
<tr>
<td>- Colours</td>
</tr>
<tr>
<td>Optical age-metallicity degeneracy</td>
</tr>
<tr>
<td>Beyond the optical</td>
</tr>
</tbody>
</table>

- Spectral synthesis
  - Empirical and theoretical stellar libraries
  - Spectroscopic age/metallicity indicators
  - IMF indicators

<table>
<thead>
<tr>
<th>4. Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Abundance ratios and chemical evolution.</td>
</tr>
<tr>
<td>- Star-formation histories and stellar masses.</td>
</tr>
</tbody>
</table>
Integrated light: spectra vs colours

\[ F_\lambda(t, Z) = \int_{M_{\text{lo}}}^{M_{\text{up}}(t)} S_\lambda(T_{\text{eff}}(M), g(M) \mid t, Z) \cdot N(M) \, dM \]

The \( S_\lambda \) could be either total flux in two or more bandpasses, or detailed spectra. Spectra carry much more information, but colours are much cheaper to measure.
Trends from optical continue into IR:
By K-band (2µm), RGB + AGB contributing ~80% of total flux.

In UV, new component from old-but-hot stars: post-AGB (central stars of planetary nebulae), blue HB stars.

Of course, this includes only the components present in the model...
Luminosity contributions: UV-to-IR

Trends from optical continue into IR:
By K-band (2µm), RGB +AGB contributing ~80% of total flux.

In UV, new component from old-but-hot stars: post-AGB (central stars of planetary nebulae), blue HB stars.

Of course, this includes only the components present in the model...
Optical age-metallicity degeneracy

Classic problem in understanding “old-ish” populations like elliptical galaxies.

Because both age and metallicity cause the population to redden, a given measured colour doesn’t distinguish an old-but-metal-poor vs young-but-metal-rich stellar population.
The age-metallicity degeneracy

Because both age and metallicity cause the population to redden, a single measured colour is not enough to disentangle the parameters.

Models of Maraston (2005)
The age-metallicity degeneracy

A pair of (optical) colours is no help either!

An observed galaxy with these colours could be 3Gyr, 2x solar, or 15Gyr 0.5x solar!
Beating the Age-Z degeneracy in the IR?

In the IR, more of the light comes from the RGB (affected more by metallicity) and less from the MS/TO (affected more by age).

So the IR colours have greater metallicity dependence...

**larger “spread” between lines (metallicity effect), relative to “slope” of each line (age effect)**
Beating the Age-Z degeneracy in the IR?

In principle, this is possible, but clearly requires very accurate photometry in the IR.
Younger ages in optical/IR

Good news: parts of this colour grid “unambiguously” signal 0.5-2 Gyr populations.

Bad news: this behaviour due to poorly-understood stellar physics!! (TP-AGB stars)
Maraston (2005):

At age $\sim$1 Gyr, stars on AGB are of masses which take them into very luminous “thermally pulsing” phase.

This phase very hard to model, since non-equilibrium state, explosive He shell ignitions at $\sim$1000 yr intervals, dredge-up of processed material etc.

In Maraston’s models $\sim$80% of the IR luminosity from a 1 Gyr SSP arises from the AGB.

Most modern models indicate more modest, but still substantial contributions.

[NB: relevance to stellar mass estimates for z$\sim$2 galaxies!]
Thermally pulsing AGB stars

Different modelling groups do not agree closely on the impact of the TP-AGB on isochrones...

(Naturally, this also translates into integrated SSP properties.)

Marigo et al. (2017)
Based on MS+RGB alone, we would expect the UV to be dominated by the MSTO.

MSTO stars hotter and brighter at early times, so expect good age sensitivity.

But still have some degeneracy effect from Fe/H dependence of isochrone...

...And have to worry about exotic old-but-hot star contributions: e.g. BHB, EHB, BS.


Ratio of energy distribution for two populations that are indistinguishable in “optical”

Space UV
ground-based UV
optical

Beating the Age-Z degeneracy in the UV?
A cautionary (resolved) case

3.5 Gyr, ~solar metallicity galactic open cluster M67 (cf E galaxy at z~1?)

Landsman et al. 1998

Optical: V

UV: 1500 Ang
A cautionary (resolved) case

An old-ish, ~solar metallicity stellar population.

Blue stragglers dominate the UV emission.

BS content of M67 is extreme within MW...

But we don’t know how to predict incidence of BS in a given population. So how much can we learn from UV in old galaxies...?
Colours of unresolved populations: Summary

THE BAD NEWS:
Optical colours, which are easy to measure, can tell us very little about ages of unresolved stellar systems, after ~1 Gyr from their formation.

(They can, however, readily distinguish 1-10 Gyr galaxies from those with current star formation, where high-mass stars dominate the flux.)

THE NOT-MUCH-BETTER NEWS:
Colours involving the near infra-red and ultra-violet spectral regions, which are harder to measure, are only a little better than the optical. Sensitivity of the IR colours is poor (at least after the AGB-dominated phase), while the UV certainly tells us something, but maybe not what we hoped to learn.

THE GOOD NEWS:
In the next section we will look at narrow spectroscopic indices (which are expensive to measure), and show that these are much more effective at distinguishing age and metallicity effects.
Spectral synthesis

Where do we get the stars?

\[
F_{\lambda}(t, Z) = \int_{M_{\text{lo}}}^{M_{\text{up}}(t)} S_{\lambda}(T_{\text{eff}}(M), g(M) | t, Z) \cdot N(M) \, dM
\]
OBSERVED SPECTRA OF STARS

Need to cover large range in $T_{\text{eff}}$, log $g$ (=“gravity” i.e. dwarf vs giant) and Fe/H.

And to know the atmospheric parameters of the stars.

The spectra need to be “good”: i.e. very high S/N, carefully flux-calibrated, corrected for atmospheric absorption etc.
Empirical spectral libraries

Dwarfs

- $T_{\text{eff}}=8560$ K, HD 74721, A0 V (logg=3.57)
- $T_{\text{eff}}=5727$ K, HD 4307, G2 V (logg=4.07)
- $T_{\text{eff}}=4570$ K, CD-26 10417, K5 V (logg=4.50)
- $T_{\text{eff}}=3344$ K, HD 1326, M1.5 V (logg=5.30)

Giants

- $T_{\text{eff}}=7325$ K, HD 2628, A7 III (logg=3.57)
- $T_{\text{eff}}=5013$ K, HD 2865, G5 III (logg=2.35)
- $T_{\text{eff}}=4731$ K, HD 221345, K0 III (logg=2.63)
- $T_{\text{eff}}=3467$ K, HD 184786, M4.5III (logg=0.60)
Empirical spectral libraries

IRTF library is state-of-the-art in the IR.

Much smaller than MILES (210 cool stars).

Restricted to near-solar metallicity.

(Update: Now with enlarged with broader metallicity coverage — Villaume et al. 2017)
Empirical spectral libraries

Space observations necessary to build empirical library in the rest-frame UV.
(Recall we might want such a library to interpret observed optical spectra of higher-redshift galaxies.)

HST NGSL: UV-optical spectral library with 374 stars.

Nascent GALEX library? Bertone & Chavez (2011)

Russell Smith

Stellar Populations 2019 / III
MILES coverage - currently the best published optical library.

Missing low-metallicity dwarfs at $T_{\text{eff}} > 8000$ K, required to synthesise ages <1 Gyr.

Unavoidable: young stars in solar neighbourhood are all metal-rich!
Empirical spectral libraries

Need to *know* the temperatures to match spectrum to correct point on the HRD. And to know the metallicities, to attach to correct isochrone.

Fundamentally, the temperature scale is derived from interferometric measurements of stellar radius, via $L_{\text{bol}} = (4\pi R^2) \sigma T_{\text{eff}}^4$

Metallicities from comparison of library spectra to stellar model spectra, or through high-resolution spectra to measure individual lines. Difficult for cool stars.
Theoretical spectral libraries

Fundamental limitation of empirical libraries is poor coverage of stellar parameter space by local-neighbourhood stars in the MW.

Alternative possibility: build stars from scratch in a computer.

Model the absorption by all the possible spectral lines of all the species (atoms, ions, molecules) present, and compute expected spectrum.

Advantages obvious: can compute for arbitrary set of atmospheric parameters, and densely sample the parameter space.

Coelho et al. (2005)
But: in detail, the theoretical spectra do not match perfectly...

Problem is that there are literally millions of atomic/molecular lines to include.

E.g. Current Kurucz line-lists include >37M lines for TiO alone.

Many lines are not measured in the lab, but are predicted by QM.

QM predictions for wavelengths and oscillator strengths have large uncertainties.

A “good” model for high-resolution stellar analysis may not be a good model for broad-band fluxes.

Problems are worst in the blue (atomic line blanketing) and at low temperatures (molecular line lists).