Galaxies: Structure, formation and evolution

Lecture 9

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How does starlight from 10^{11} stars add up to form galaxy light?

If you want to construct a galaxy spectrum by summing up the spectra of stars what do you need to know?

How does starlight from 10^{11} stars add up to form galaxy light?

- IMF - mass distribution of stars e.g. Salpeter
- stellar evolution - How do stars evolve *in time* on the main sequence and outside it?
- spectral library (metallicity) - What is spectrum of any particular type of star as a function of age, mass, metallicity? All of the above are very uncertain at high masses and low metallicities. Why?
- Star formation history (SFH) - When did stars form and at what rate?
- dust - attenuation needs to be modeled.

After that, it is just arithmetic to get the galaxy spectrum

Simple Stellar Population (SSP)

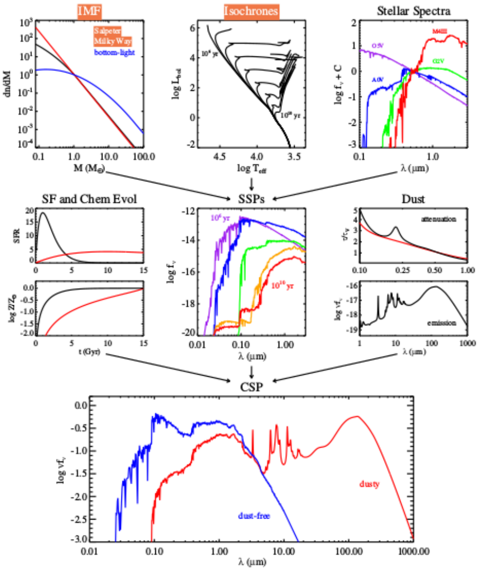
The simple stellar population (SSP) describes the evolution in time of the SED of a single, coeval stellar population at a single metallicity and abundance pattern.

An SSP therefore requires three basic inputs:

1. stellar evolution theory in the form of isochrones
2. stellar spectral libraries
3. IMF

Each of these, may in principle be a function of metallicity and/or elemental abundance pattern.

Stellar population synthesis



If we have a galaxy spectrum, can we determine its star formation history?

Yes, in principle, but the IMF, spectral library, stellar evolution etc. are uncertain.
Biggest uncertainties due to: incomplete isochrone tables, incomplete empirical stellar libraries, poorly calibrated physics
Systematic vs. stochastic uncertainties

Spectrum, star-formation, flux

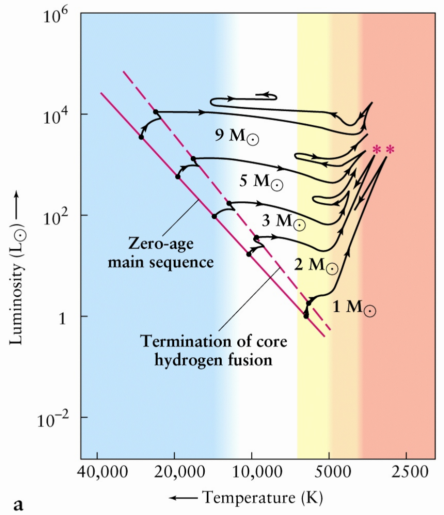
$$S(t, Z) = \int_{M_i^l}^{M_i^u(t)} \Phi(M_i)\Lambda[L(M_i, Z, t), T(M_i, Z, t), Z] \, \mathrm{d}M_i \tag{1}$$

$$M(t) = \int_{M_i^l}^{M_i^u(t)} \Phi(M_i) \, M_{\mathrm{evol}}(M_i) \mathrm{d}M_i \; + \; M_{\mathrm{rem}}(t) \tag{2}$$

The time dependent spectrum

$$F(t) = \int_0^t \Psi(t - t')S(t', Z)e^{-\hat{\tau}_\lambda(t')} \, \mathrm{d}t' \tag{3}$$

Stellar evolution tracks



Well understood at low stellar masses and near-Solar metallicities, but uncertainties grow at high masses and very low metallicities.

Isochrone models

- different ages (masses), chemical compositions, and cover most relevant evolutionary phases.
- Padova models, Geneva (only high mass stars), BaSTI models
- Lyon models from Chabrier's group are very good for low mass stars.
- newer models include Y^2, Dartmouth, Victoria-Regina
- Remarkably, the post-AGB isochrones computed by Schoenberner (1983), Vassiliadis & Wood (1994), and Bloecker (1995) are still widely used in modern SPS codes.
- Implementing isochrones in an SPS model is challenging because no single set spans the necessary range of ages, metallicities and evolutionary phases.

MESA

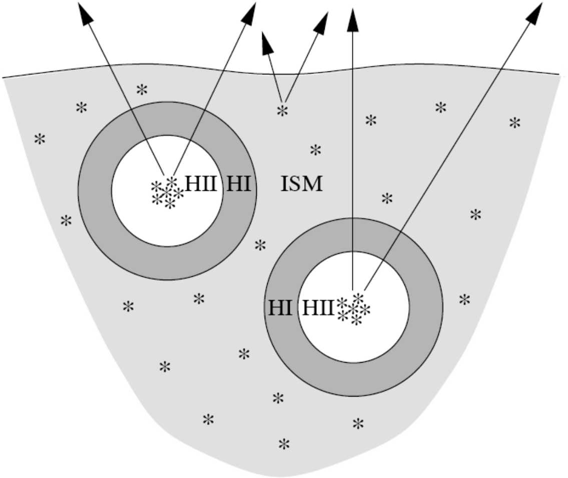
Modules for Experiments in Stellar Astrophysics (MESA) is a new, highly modular and sophisticated stellar evolution code that includes the latest stellar interior ingredients including opacity tables, equations of state, nuclear reaction networks, and surface boundary conditions (Paxton et al. 2011). There is great hope that MESA will be employed to produce high-quality isochrones over the full age and metallicity range and for all evolutionary phases.
See: http://mesa.sourceforge.net/

Stellar spectral libraries

- Theoretical libraries e.g. by Kurucz
- Empirical libraries

see: http://www.phys.unm.edu/ tw/spectra/mk.html

The dust model - Charlot & Fall (2000)



The dust model

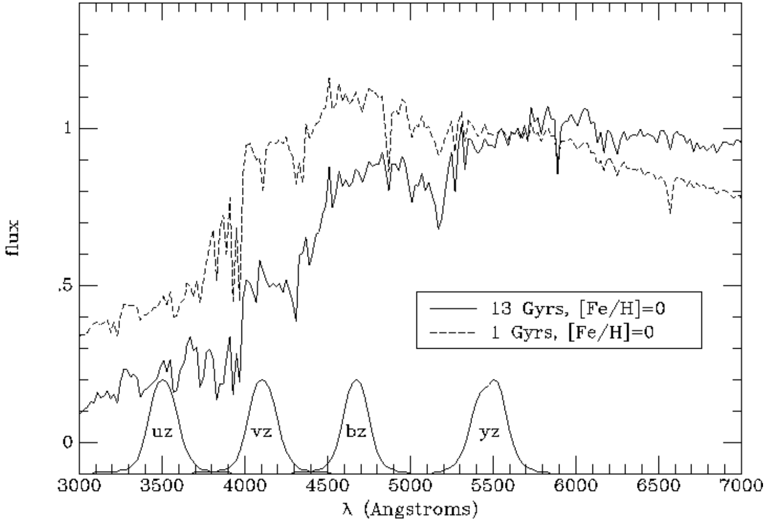
$$\hat{\tau}_\lambda(t') = \begin{array}{ll} \hat{\tau}_V\,(\lambda/5500)^{-0.7} & t' \leq 10^7 yr, \\ \mu\hat{\tau}_V\,(\lambda/5500\,)^{-0.7}\,, & t' > 10^7 yr, \end{array} \quad (4)$$

where $\hat{\tau}_V$ is the total effective V-band optical depth seen by young stars. The characteristic age 10^7yr corresponds to the typical lifetime of a giant molecular cloud. The adjustable parameter μ defines the fraction of the total dust absorption optical depth of the galaxy contributed by the diffuse interstellar medium ($\mu \sim 1/3$ on average, with substantial scatter).

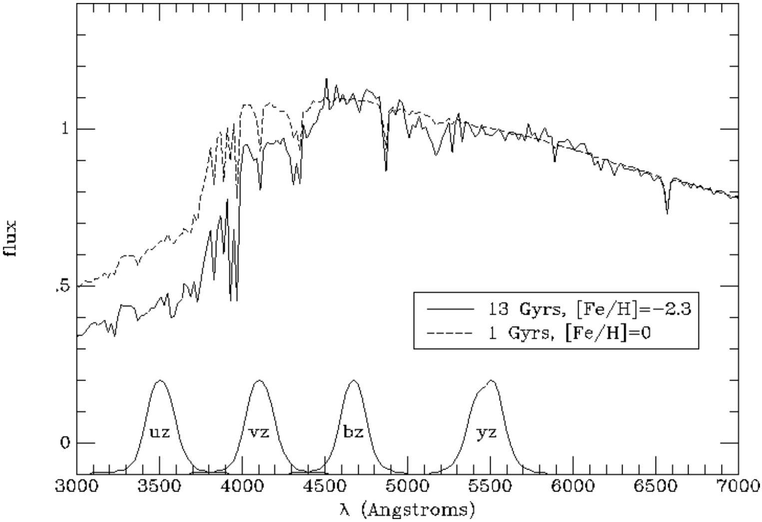
If we have a galaxy spectrum, can we determine its star formation history?

Yes, in principle, within the uncertainties of the IMF, spectral library, stellar evolution etc. are uncertain.
Multiple histories may fit the same observations within the error bars.
We often assume some simple analytic form for the star-formation rate $\psi(t)$. Popular choices include a single burst, exponentially decaying SFR and a constant SFR.

Different age, same metallicity



Different age, different metallicity,similar spectrum

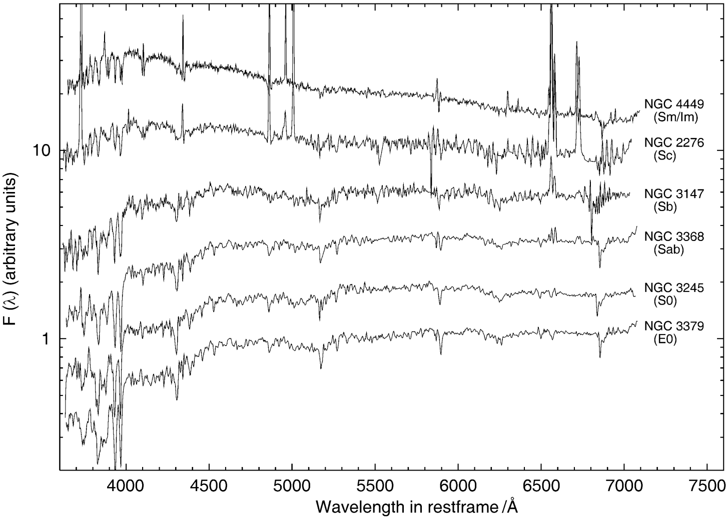


The age metallicity degeneracy

What we have learnt from SPS

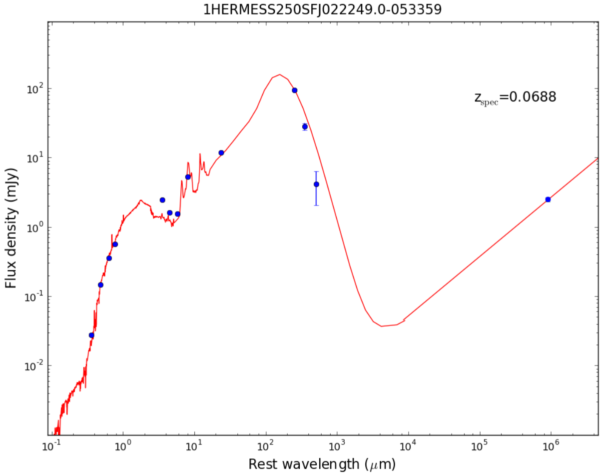
- A simple model of star-formation history reproduces the colors of today's galaxies fairly well.
- (Most of) the stars in elliptical and S0 galaxies are old – the earlier the Hubble type, the older the stellar population.
- Detailed models of population synthesis provide information about the star-formation history, and predictions by the models can be compared with observations of galaxies at high redshift (and thus smaller age).

Spectra of galaxies ordered by Hubble type

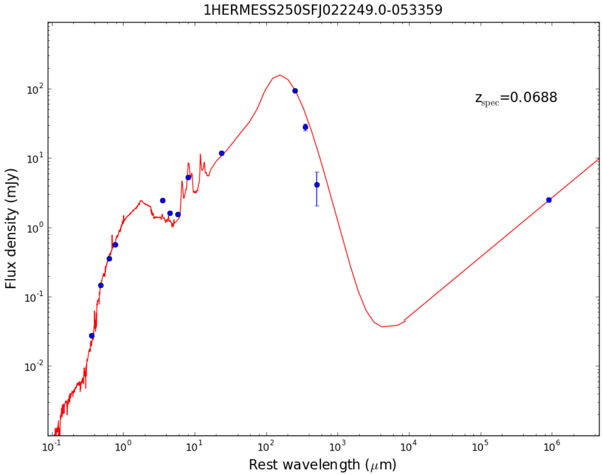


Arbitary normalisation on Y-axis

SED from optical to radio



SED from optical to radio



Bait et al. (2017)

Many SPS codes exist

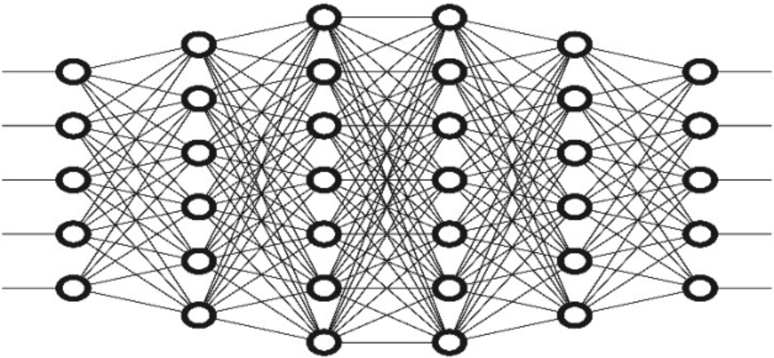
- CIGALE
- MAGPHYS
- FSPS
- LePhare
- Prospector
- STARLIGHT
- FIREFLY
- BAGPIPES

These codes perform a χ^2 fit of SPS models to the data (broad-band fluxes and/or spectra). Outputs are often a posterior PDF obtained by marginalising over all free parameters, except one.

Conroy et al. 2013

Read this article in ARAA for an up-to-date review of the many aspects of SPS that I have not covered.

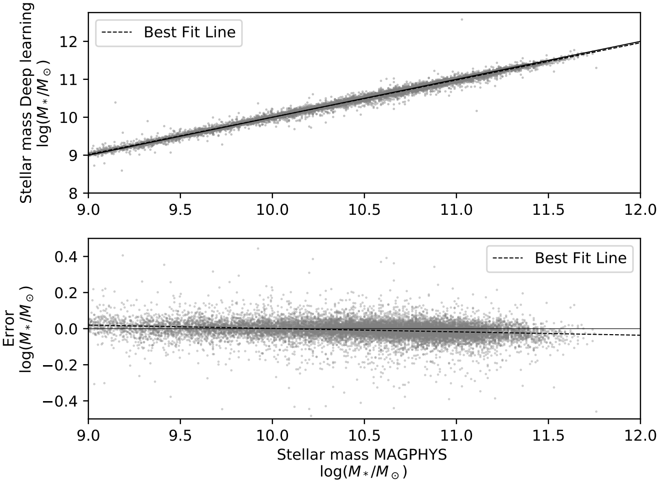
SPS via deep learning



Advantage and disadvantage of the deep learning approach

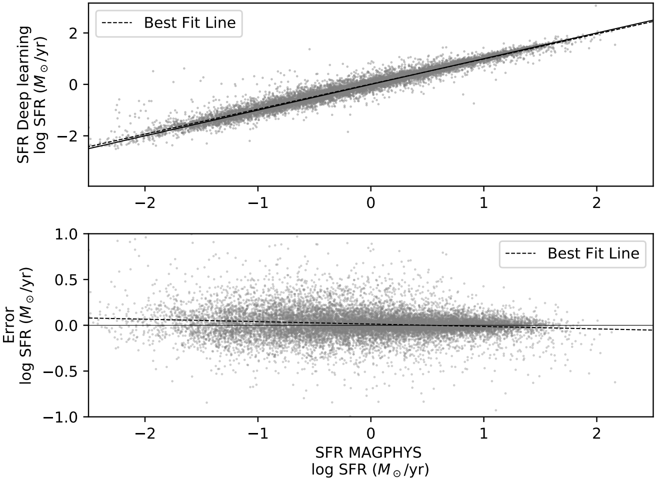
- Once trained, the DL network is very fast. Able to obtain outputs for 20000 galaxies in less than a second.
- Since the deep learning model learns to imitate the SPS model, it can never perform better than the model.
- But the high speed is still useful, given the size of upcoming galaxy surveys - Rubin/LSST will observe $\sim$ 20 billion galaxies.
- A hybrid approach is also possible - use deep learning to narrow down the parameter space and then only fit SPS models only within that restricted space.

Predicting the Stellar Mass



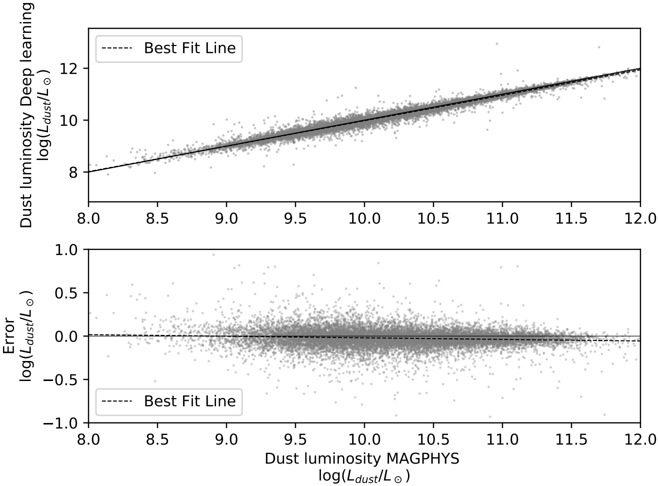
Surana, Wadadekar et al. (2020)

Predicting the SFR



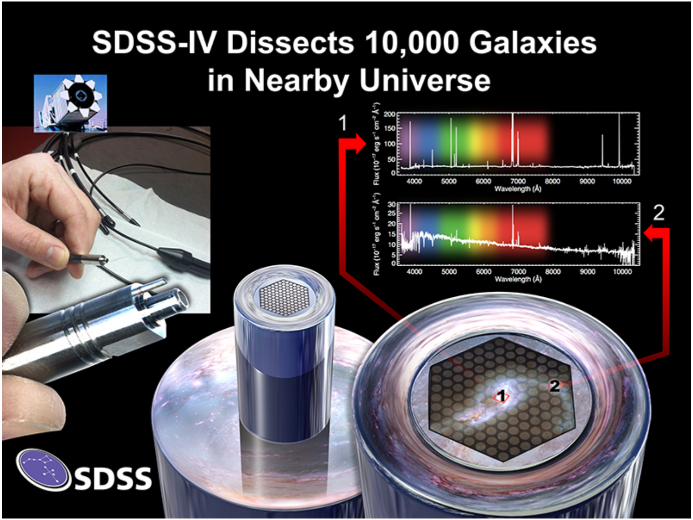
Surana, Wadadekar et al. (2020)

Predicting the dust luminosity

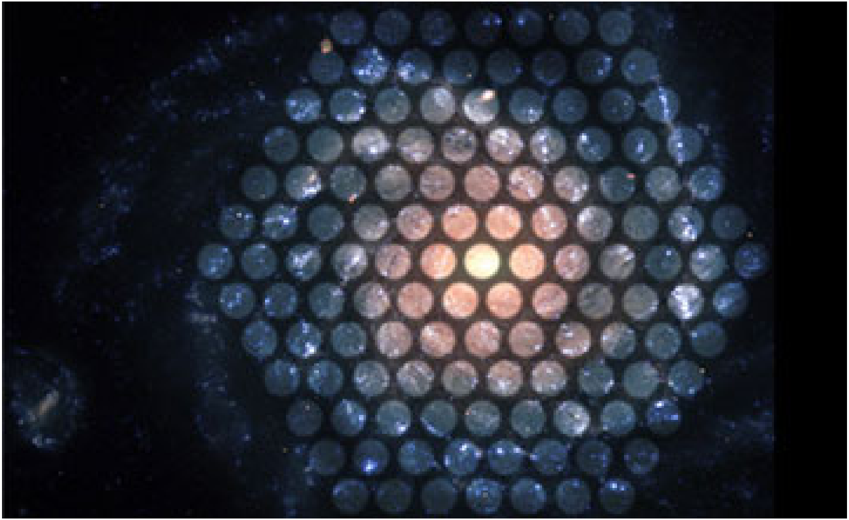


Surana, Wadadekar et al. (2020)

IFU SPS


SDSS-IV Dissects 10,000 Galaxies
in Nearby Universe
1
2
Flux (10^-17 erg s^-1 cm^-2 Å^-1)
Wavelength (Å)
4000
5000
6000
7000
8000
9000
10000
SDSS

IFU SPS



A brief history of the Universe