This week at Astro 3303

Lecture 12, Oct 07, 2015

• HW#5 is posted; it is due Oct 14

• Today:

  • Star Formation in Galaxies: Tracers and Relations
  • SDSS & Spectroscopy of Galaxies

• Reading: Chapter 3.8 & 5 of textbook
Spectral Energy Distribution of a Galaxy

Aim: understand spectral energy distributions of galaxies.
Virtually all continuum and spectral features at long wavelengths are due to the ISM.

- Dust bump
- FS Lines
- Molecular lines (non-log scale)
- CO Rotational “ladder”
- PAHs
## Known Interstellar Molecules

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Molecular Cooling is Complex...

1.3 mm spectrum of SgrB2(N) near the Galactic Center

(note: numerous unidentified features)

ACMA: 'involuntary line surveys'

NGC 253

IRAM 30m 2mm line scan

Martin et al. 2006
Molecular Cooling is Complex...

1.3 mm spectrum of Arp 220:

28% of the broad-band flux is due to molecular lines

⇒ What is the “continuum flux” of a galaxy at (sub)mm wavelengths?

Martin et al. 2011
Star formation Rate Estimators

Star formation rate indicators:

• count individual stars w/ reliable masses, ages: \( \langle \dot{M}_* \rangle = \sum_{M_*=M_f}^{M_*} N(M_*, t_*) M_*/t_* \)
• \( L(H\alpha) \Rightarrow \) massive (young) stars
• \( L(\text{radio}) \Rightarrow \) thermal HII (free-free) + SNe/SNR (synchrotron)
• \( L(\text{FIR}) \Rightarrow \) dust heated by UV photons
• \( L(\text{UV}) \Rightarrow \) massive (young) stars
• \( L(\text{X-ray}) \Rightarrow \) XRBs, SNe, SNRs, massive (young) stars

**SFR: Indicators of Young Stars**

Observables produced by short-lived population of luminous, massive stars

**Emission from Star Formation Regions**

- **DMCs (Dense Molecular Clouds)**
- **Observed Indicators**
  - Radio Lines: CO
  - HII Regions
  - Ha etc

**Star Formation**

- **SN (Supernova)**
  - Shock waves
  - c. rays

**UV**

- O/B stars
- Ionize
- Age & mix
- Optical colors/spectra
- Radio Synchrotron
- Free-free
- Radio
- FIR

**Sketch:** Whittle

**But:** low-mass stars dominate in mass

⇒ Need to know initial mass function (IMF) to infer how much stellar mass is formed
Two Regimes of Star Formation

- “normal” galaxies (~75% of local SF);
  SFRs: <<1 to few $M_{\text{sun}}\text{yr}^{-1}$
- starburst galaxies (~25% of local SF);
  SFRs: few (starbursts) to ~50 (LIRGs) to >100 $M_{\text{sun}}\text{yr}^{-1}$ (ULIRGs)

Starbursts: intense bursts of short duration (<$10^8$ yr)
  typically circum-nuclear or in interacting systems
  (=> rapid supply/accumulation of gas)
  SF relationships may differ from “normal” galaxies

LIRGs/ULIRGs: (ultra-) luminous infrared galaxies, so defined by $L_{(F)IR}$

CAUTION: we will see significant differences in the early universe
Radio-(F)IR correlation

- exploits tight observed relation between 1.4 GHz radio continuum (synchrotron) and FIR luminosity

- correlation may reflect CR particle injection/acceleration by supernova remnants, and thus scale with SFR

- no ab initio SFR calibration, bootstrapped from FIR calibration

- valuable method when no other tracer is available

Star Formation Laws

“Kennicutt-Schmidt Law”

- **Super-Linear**
- **Linear**

- **Total gas mass (H\(_2\)+HI)**
- **H\(_2\) as traced by CO**

- **Dense Gas Mass (HCN)**

Kennicutt & Evans 2012, ARA&A
Kennicutt 1989, 1998
Gao & Solomon 2004
SF Law shows three general regimes on sub-galactic scales:

- **HI-dominated**
- **H$_2$-dominated**
- **starburst-dominated**

Law holds to few hundred pc scales (but becomes very noisy on smaller scales where cloud-to-cloud variations dominate)

*Kennicutt & Evans 2012, ARA&A*

*Bigiel et al. 2008*
Given the difference in SF properties observed between "normal" galaxies and starbursts, it has been proposed that the KS law is not a single, non-linear sequence, but instead a combination of two, nearly linear sequences, representing two modes of SF: a "quiescent" and a "bursty" mode.
Star Formation “Threshold” and Phases

Moving from high to low gas surface densities or the inner to outer parts of galaxies, the ongoing star formation per unit ISM mass drops.

Color: \( \frac{\text{H}_2}{\text{HI}} \) Ratio

“pile-up” in \( \Sigma_{\text{SFR}} \) at fixed \( \Sigma_{\text{gas}} \)

Schruba et al. (2011)
HI is Most of the Mass, but H$_2$ Forms Stars

- different ISM phases (HI vs. H$_2$) exhibit very different relations to star formation
- even where HI dominates the ISM, star formation correlates with molecular gas
$\Rightarrow$ the varying H2-to-HI ratio closely relates to the ability of the whole ISM to form stars

Azimuthally averaged profiles of 30 disk galaxies (Schruba et al. 2011)
Red sequence & Blue Cloud

Gavazzi et al.: A snapshot on galaxy evolution in the Great Wall

What does this tell us about galaxy evolution?
SDSS Legacy Survey: Photometry & Spectroscopy

Photometry/DR7

Spectroscopy/DR7

2\textsuperscript{nd} generation surveys: SEGUE (SDSS-2), others in SDSS-3.
SDSS Photometric Survey: Goals

- Identify and obtain positions for a uniformly-selected sample of galaxies
- Provide precise colors and approximate morphological information
- Provide database needed for identification of quasars by image structure and apparent color
- Create a reliable photometric catalog of the brightest million stars and galaxies over a large region in 5 color filters

SDSS filters:
- Ultraviolet (u) 3543 Angstroms
- Green (g) 4770 "
- Red (r) 6231 "
- Near IR (i) 7625 "
- IR (z) 9134 "

![Graph of spectral response of SDSS filters]
SDSS Spectroscopic Survey:

- **Redshifts**
  - Distances via Hubble's Law
- **Absorption lines:**
  - Stellar population
- **Emission lines:**
  - HII regions: massive star formation
  - “Active galactic nuclei” (AGN) implies presence of Super Massive Black Hole (SMBH)

Prototype fiber optic cartridge with 20 fibers

- Wide angle shallow survey
- Galaxies should have limiting magnitude $r' = 18.15$ Petrosian
- Fiber diameter $\sim 3''$

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<th>$z$</th>
<th>3'' = 1.6 kpc</th>
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<td>16 kpc</td>
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- Covers 3900-9100 Å range with 2 double spectrographs
- 640 spectra per observation
SDSS Fiber Placement Rules

• Each spectroscopic fiber plug plate, referred to as a “tile”, has a circular field-of-view with a radius of 1.49 degrees, and can accommodate 640 fibers, 48 of which are reserved for observations of blank sky and spectrophotometric standards.

• Because of the finite size of the fiber plugs, the minimum separation of fiber centers is 55''.

• If, for example, two objects are within 55'' of each other, both of them can be observed only if they lie in the overlap between two adjacent tiles.

• The goal of the SDSS is to observe 99% of the maximal set of targets which has no such collisions (about 90% of all targets).
Spectroscopic Targets in SDSS

Fiber Placement

First, we discuss the allocation of fibers given a set of tile centers, ignoring fiber collisions for the moment. Figure 1 shows an example of a distribution of targets and the positions of two tiles we want to use to observe these targets. Given that for each tile there is a finite number of available fibers, how do we decide which targets get allocated to which tile? This problem is equivalent to a network flow problem, which computer scientists have been kind enough to solve for us already.

An optimization problem equivalent to a network flow problem
Have to solve a computer science problem, luckily one that has known solution(s)
Spectra indicate the dominant stellar population and the current rate of star formation relative to the past star formation. Spectra can also show unusual features:

- Higher than expected SFRs (starbursts)
- Ionization by sources other than starlight (accretion by supermassive black holes)
What determines the CMD/spectrum?

Star formation history: **passive** versus **star forming** versus **starburst**

- The *star formation rate* SFR and how it may vary with time, SFR(t)
  - Is SFR constant? Decreasing over time?
  - A “starburst”? Episodic bursts?
- The “*initial mass function*” IMF, which stipulates the number of stars per mass interval per unit volume that are created.
  - \( \xi(M) = \text{Const} \ M^{-(1+x)} \)
  - In the solar neighborhood, we have the “Salpeter” IMF, \( x = 1.35 \) (Salpeter 1955) => Is the IMF everywhere the same?

Active galactic nucleus/QSO:
- High ionization species: need SMBH energy source (population of stars not adequate)
- Broad emission lines implying high velocities => SMBH
Equivalent width

To characterize the strength of a spectral line (emission or absorption), we define the **equivalent width**:

$$ W_\lambda = \int d\lambda \frac{S_1(\lambda) - S_c(\lambda)}{S_c(\lambda)} \approx \frac{F_{\text{line}}}{S_c(\lambda_0)}, \quad (5.7) $$

where $S_1(\lambda)$ is the total spectral flux and $S_c(\lambda)$ is the spectral flux of the continuum radiation interpolated across the wavelength range of the line. $F_{\text{line}}$ is the total flux in the line and $\lambda_0$ is its wavelength.

$W_\lambda$ is the width of the wavelength interval over which the continuum needs to be integrated to obtain the equivalent flux as measured in the line.

The equivalent width is a measure of the strength of the line relative to the neighboring continuum flux.
Let’s look at some actual SDSS spectra so that we can gain a better sense of how classification works.

…but first some quick recap on stellar spectra
Recap: Stellar Spectra

- Stars of different spectral types have different effective temperatures, i.e., peak wavelengths.
- The wavelength of a spectral line is determined by the energy of the corresponding QM transition.
- Stars of different spectral types will be dominated by different lines (typ. absorption in stellar atmosphere).
- Also important: chemical composition.
Recap: Stellar Spectra

Spectral Lines

O: Weak neutral and ionized Helium, weak Hydrogen, a relatively smooth continuum with very few absorption lines

B: Weak neutral Helium, stronger Hydrogen, an otherwise relatively smooth continuum

A: No Helium, very strong Hydrogen, weak Cal I, the continuum is less smooth because of weak ionized metal lines

F: Strong Hydrogen, strong Cal I, weak Na I, G-band, the continuum is rougher because of many ionized metal lines

G: Weaker Hydrogen, strong Cal I, stronger Na I, many ionized and neutral metals, G-band is present

K: Very weak Hydrogen, strong Cal I, strong Na I, and many metals, G-band is present

M: Strong TiO molecular bands, strongest Na I, weak Cal I, very weak Hydrogen absorption, (Note: Hydrogen may be emission lines.)
Recap: Stellar Spectra
Recap: Stellar Spectra

What type of star?
- Blue continuum: K or M unlikely
- Strong H absorption: B, A, or F type
- Significant CaII, some NaI => F type
HII regions: the Stromgren Sphere

In equilibrium in an HII region, there is a balance between ionizations and recombinations: free electrons and protons collide to form neutral HI; however the UV photons from the stars are continuously breaking up these atoms.

- the Stromgren radius:
  \[ r_s = \left( \frac{3}{4\pi\alpha} \right)^{1/3} (N_{UV})^{1/3} n_p^{-2/3} \]

The size of an HII region depends upon the rate at which a star gives off ionizing photons and the density of the gas.

Spectrum: dominated by emission from ionized gas

Typically associated with young, blue, luminous (O, B) stars
⇒ indicator for current/recent star formation
Spectral evolution

Fig 6.18 (B. Poggianti) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007
Galaxy Spectral Energy Distribution (SED)

To calibrate the SFR (in $M_{\odot}\,yr^{-1}$) we need *population synthesis models*:

- evaluate evolutionary tracks for $L_{\text{bol}}$ & $T_{\text{eff}}$ & $R_*$ & $Z$ as functions of Mass and Age
- add stellar atmosphere spectra
- sum over an IMF isochrone spectrum $\rightarrow$ synthesized stellar population
- sum over a chosen star formation history (constant, exponential, short burst) & chemical evolution
- add dust model, ISM components $\rightarrow$ composite stellar population $\rightarrow$ spectral energy distribution

Free parameters:
SF History; IMF; Metallicity.

in practice, the main parameters are:
burst age and/or e-folding decay; plus fraction of old populations; dust

Conroy et al. 2013
Active Black Holes: AGN spectra

- strong blue continuum
- broad lines
- bright high-ionization lines
- very high ionization lines
- [OI], [OII], [OIII],… at the same time
PE #10: Classifying spectra

Let’s look at some actual SDSS spectra so that we can gain a better sense of how classification works.
## SDSS spectral lines

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z=0.15722±0.00002 Class=QSO AGN BROADLINE
No warnings.

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RA=204.85999, Dec=-7.57677, Plate=1801, Fiber=583, MJD=54156
z=0.14730±0.00001 Class=GALAXY STARBURST
Warnings: MANY OUTLIERS

Survey: sdss Program: legacy Target: QSO CAP GALAXY
RA=204.40267, Dec=-8.55226, Plate=1802, Fiber=90, MJD=53885
z=0.00417±0.00001 Class=GALAXY STARBURST
No warnings.

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RA=205.50751, Dec=14.70937, Plate=1776, Fiber=451, MJD=53856
z=0.01535±0.00001 Class=GALAXY STARBURST
No warnings.
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RA=193.17966, Dec=-22.40149, Plate=2849, Fiber=424, MJD=54212
z=1.84212=0.00034 Class=QSO
No warnings.

Survey: sdss Program: legacy Target: QSO_HIz
RA=233.08847, Dec=-7.37966, Plate=1820, Fiber=410, MJD=54206
z=0.59936=0.00006 Class=QSO BROADLINE
No warnings.

z=1.8 quasar

z=0.6 quasar
46,420 Quasars from the SDSS Data Release Three