Star Formation in Galaxies Along the Hubble Sequence

Kennicutt (1998)

How to measure a galaxy's SFR:

UV continuum:

$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = 1.4 \times 10^{-28} L_\nu (\mathrm{ergs\ s^{-1}\ Hz^{-1}}).$$

Hα:

$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = 7.9 \times 10^{-42}\ L(\mathrm{H}\alpha)\ (\mathrm{ergs\ s^{-1}})$$

[O II]:

$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = (1.4 \pm 0.4) \times 10^{-41}\ L[\mathrm{OII}]\ (\mathrm{ergs\ \ s^{-1}})$$

FIR continuum:

$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = 4.5 \times 10^{-44}\ L_{FIR}\ (\mathrm{ergs\ s^{-1}})$$

UV continuum (125 - 250 nm)

$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = 1.4 \times 10^{-28} L_\nu(\mathrm{ergs\ s^{-1}\ Hz^{-1}}).$$

- Most UV continuum light comes from stars younger than ~100 Myr.
- For a typical IMF, UV continuum is dominated by ~5 M_sun stars.
- Photons are not energetic enough to ionize ground state of hydrogen, so hopefully optically thin.
- Composite spectrum L_v is ~flat in UV, so can measure at any wavelength.

UV continuum: weaknesses

- Sensitive to dust extinction
    - Dust extinction is likely patchy, but most of the light we see comes from the optically thin parts, so it's hard to determine how much dust there is.
- Assumes SFR was constant over last ~100 Myr.
    - E.g., a 10 Myr burst would make us overestimate SFR by a factor of ~2.
- Sensitive to IMF

Hα (656 nm)

Basic idea: Massive stars (> 10 M_sun) produce Lyman continuum photons (λ<91.2 nm) which will ionize any Hydrogen atom they encounter. Eventually, electrons and protons will recombine, producing recombination lines like Hα.

Assume “case B” recombination: ignore recombination directly the ground state, since that will produce another Lyman limit photon, ionizing another atom.*

→ 0.45 Hα photons will be produced per Lyman continuum photon (Osterbrock 1989). Pretty robust result across wide range of density & temperature.

*Caveat is two-photon emission.

Hα: Weaknesses

- We’ve assumed every LyC photon will ionize an atom, but Some LyC photons could escape the HII region.
    - Leitherer et al. 1995: LyC escape fraction is at most 0.03
    - Patel & Wilson 1995: LyC escape fraction is ~99%
    - *#@&???
    - Even if photons escape HII region, (high “local escape fraction”), they probably won’t escape the galaxy (low “global escape fraction”).

Hα: More weaknesses

- LyC photons could be absorbed by dust before they ionize a H atom.
- Hα photons could also be absorbed by dust. Hard to correct for, because dust is clumpy.
    - Can try to measure IR recombination lines.
- Can be contaminated by absorption in stellar atmospheres (but bigger problem from other Balmer lines).
    - Also contaminated by NII
- Assumes SFR is constant over ~10 Myr.
- Very sensitive to IMF

Forbidden lines: [O II] (372.7 nm)

$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = (1.4 \pm 0.4) \times 10^{-41}\ L[\mathrm{OII}]\ (\mathrm{ergs\ s}^{-1})$$

- Approximately the same idea as Hα, but easier to observe at z > 0.5
- Empirically calibrated to Hα in local HII regions

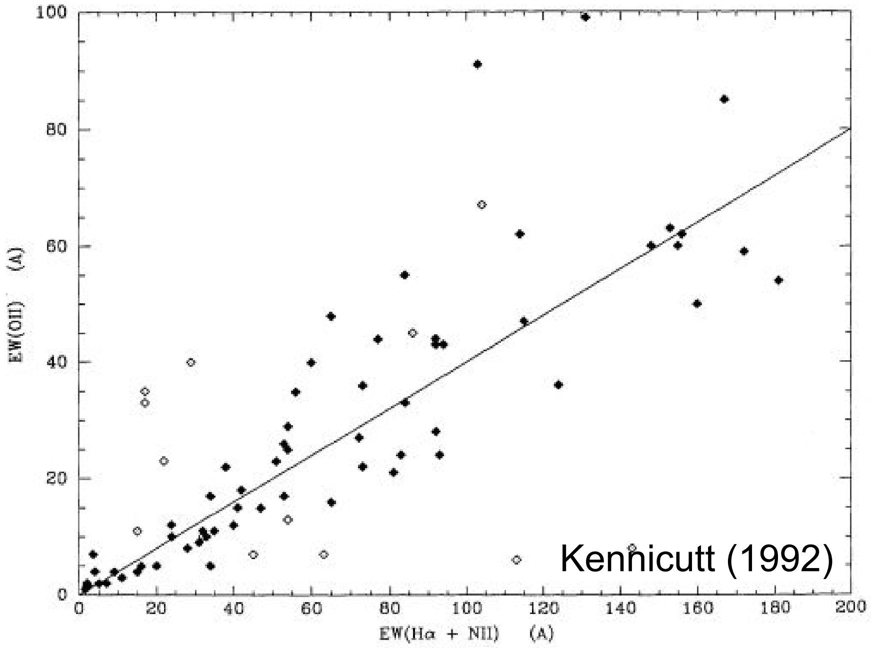


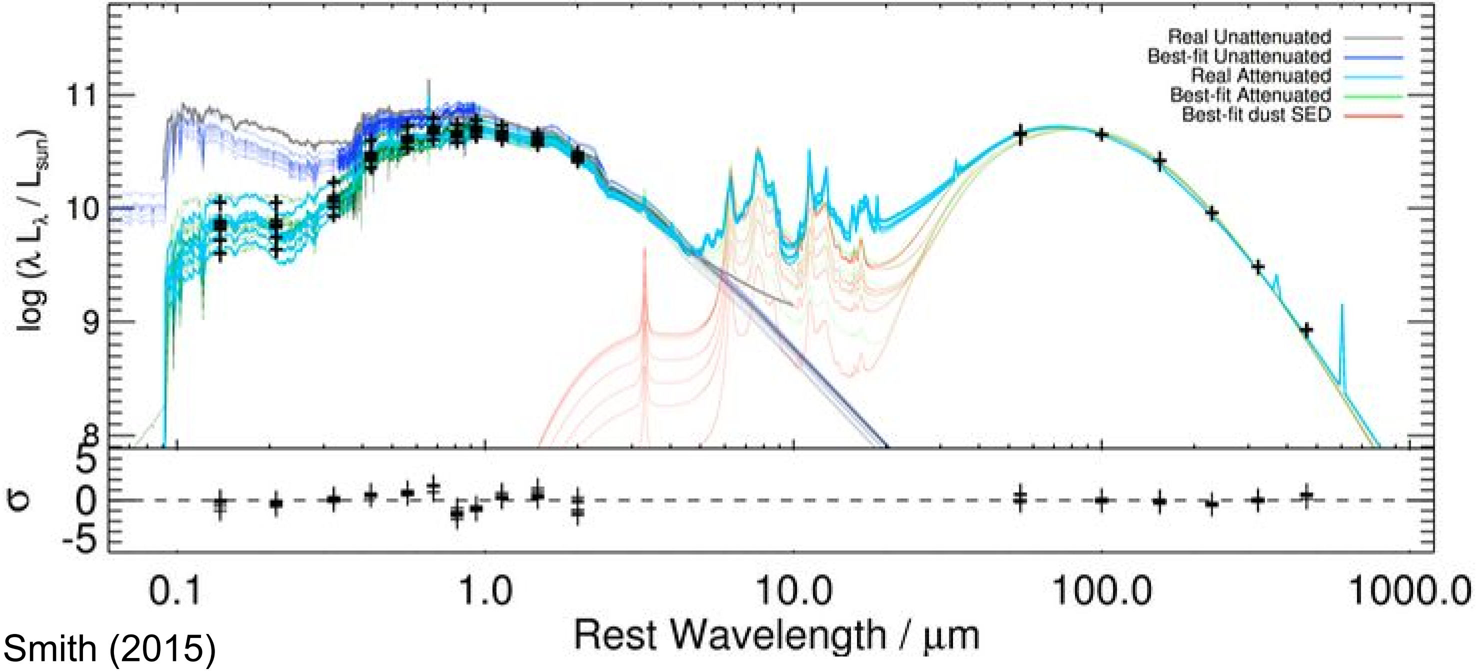
Fig. 6.—Relation between the equivalent widths of the [O II] λ3727 and Hα + [N II] emission lines. Notation the same as in Fig. 4. The line shows a simple model with EW(O II) = 0.4 EW (Hα + N II).

[O II]: Weaknesses

- Not directly coupled to ionizing photon luminosity
  - Relies on empirical calibrations, but these could vary with environment or cosmic time
  - Sensitive to abundance ratios, gas density + temperature, and ionization state.
  - Given all these variables, the Hα/[O II] ratios are surprisingly well behaved.
- Same caveats as Hα regarding IMF, SFR timescales, etc.

FIR continuum (8 - 1000 µm)

Idea: UV photons (and sometimes Hα) get absorbed by dust. The dust reëmits them in the FIR.



Hayward & Smith (2015)

FIR continuum: weaknesses

- Dependent on metallicity, dust geometry, UV escape fraction, grain size, etc.
  - Starburst galaxies tend to be dustier
- Dust is also heated by AGB stars!
  - Dust emission is thus sensitive to SFH over long timescales
  - The contribution of dust heating from old stars will tend to lower the implied SFR.
  - However, the lower optical depth of the dust will tend to *increase* the implied SRR.

Quiz

- Astronomer Bob measures a galaxy's UV continuum emission and infers a SFR of 50 ± 5 M_sun/yr.
- Astronomer Sally measures the same galaxy's FIR continuum and infers a SFR of 35 ± 10 M_sun/yr.

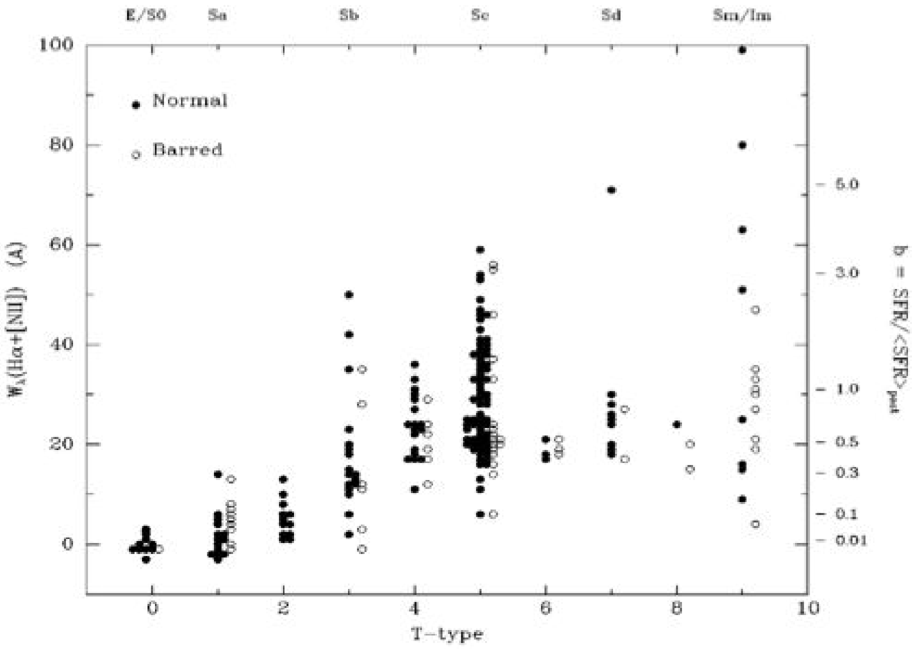
What's the galaxy's true SFR?

Quiz

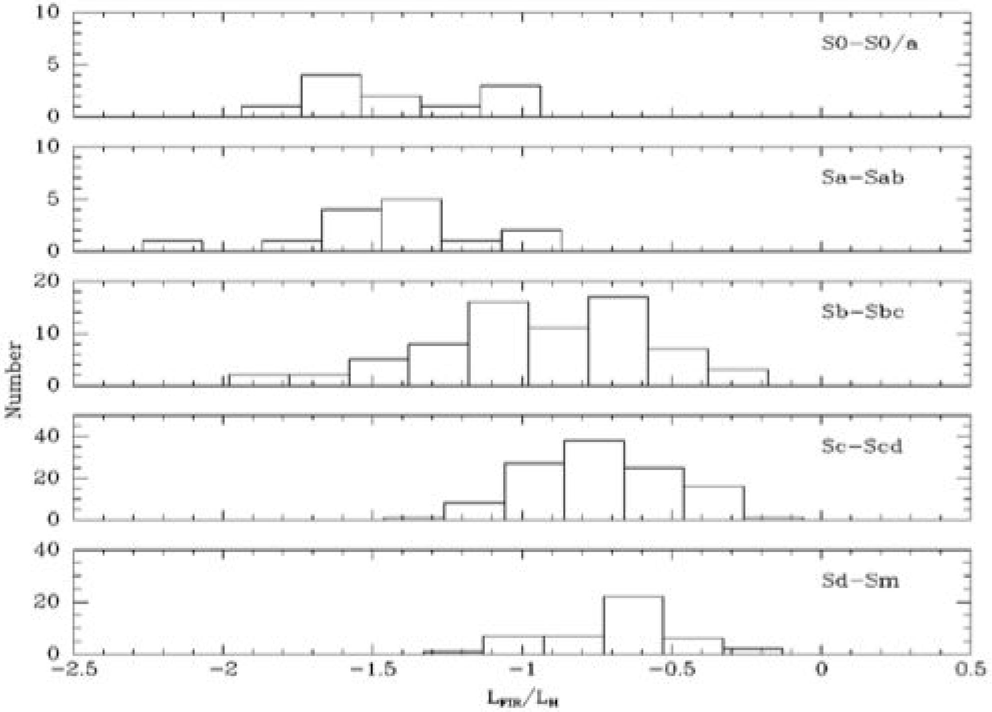
- Astronomer Bob measures a galaxy’s UV continuum emission and infers a SFR of 50 ± 5 M_sun/yr.
- Astronomer Sally measures the same galaxy’s FIR continuum and infers a SFR of 35 ± 10 M_sun/yr.
- Astronomer Jim measures the same galaxy’s Hα emission and infers 70 ± 10 M_sun/yr

What’s going on?

How does SFR vary with galaxy type/morphology?



Less variation across type in FIR emission



Kennicutt-Schmidt law: SFR ~ Σ_gas^(1.4)

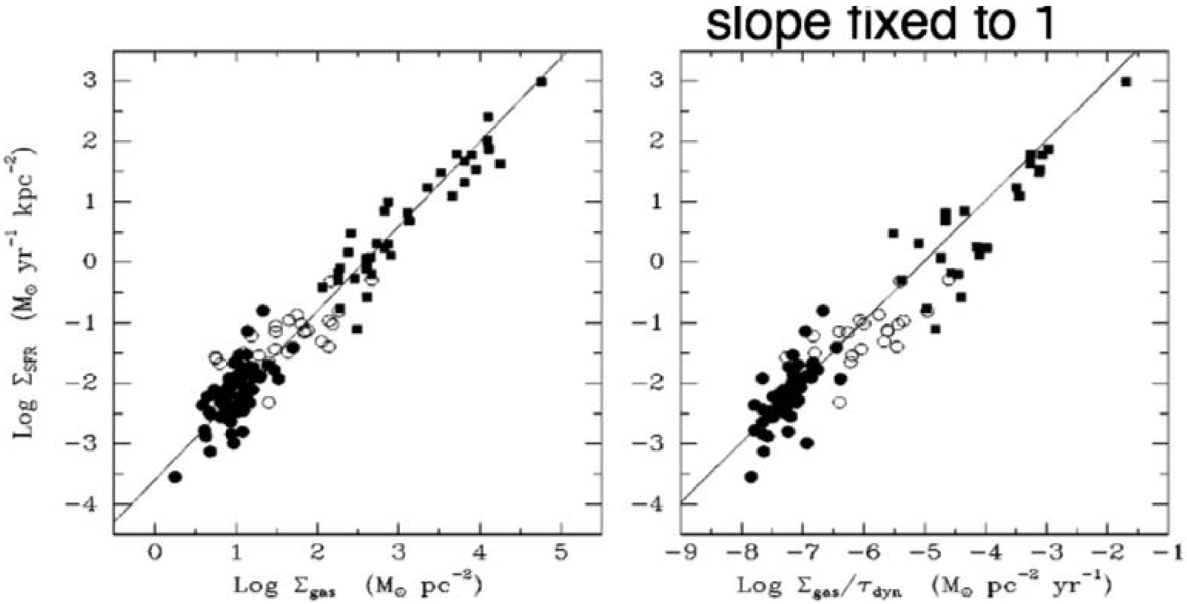


Figure 9 (*Left*) The global Schmidt law in galaxies. *Solid points* denote the normal spirals in Figure 5, *squares* denote the circumnuclear starbursts in Figure 7. The *open circles* show the SFRs and gas densities of the central regions of the normal disks. (*Right*) The same SFR data but plotted against the ratio of the gas density to the average orbital time in the disk. Both plots are adapted from Kennicutt (1998).