NEW TOPIC- Star Formation MBW ch 9

- One of the most important processes for galaxy formation and evolution
- Big questions
  - When and how does star formation occur ?
  - How is it related to the evolution of galaxy properties?
  - What are the physical processes that drive star formation ?
    - star formation is (at least in spirals at low z) almost exclusively associated with molecular clouds
      - what is the rate at which stars form in this cloud
      - what mass fraction of the cloud forms stars
      - what controls the IMF?

- for a review see

The Current Status Of Galaxy Formation

Joseph Silk, Gary A. Mamon

https://ned.ipac.caltech.edu/level5/March12/Silk/Silk_contents.html

Star Formation

- One of the most important processes for galaxy formation and evolution

- What are the general conditions for star formation?
  - in the low z universe star formation in spirals occurs mostly in molecular clouds
  - in ellipticals it is not understood; but is it clear that in some ellipticals stars are forming now.
    - in high z universe ellipticals formed stars rapidly
  - special class of star forming galaxies- star bursts

- General scenario gas cloud collapses, fragments, stars form (somehow).

- Whitaker et al Astrophysical Journal Letters 754:L29 The star formation mass sequence out to z=2.5

Jialu Nov15

Star Formation in Spirals

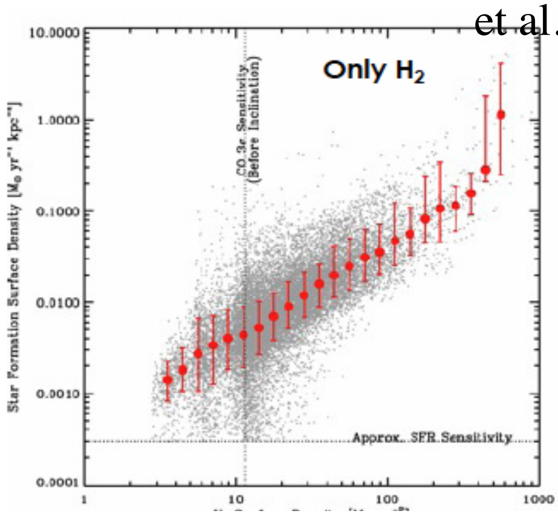
- This is an enormous subject- lots of recent work (see Kennicutt 1989 and Kennicutt and Evans 2012 for reviews)

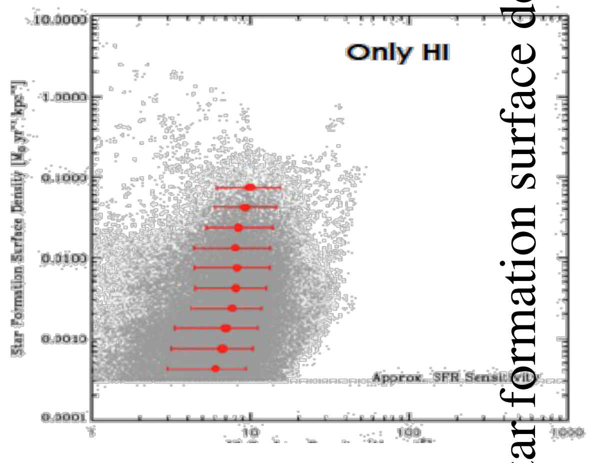
- Broadly.. Observations of nearby galaxies have shown, over a broad range of galactic environments and metallicities, that star formation occurs only in the molecular phase of the interstellar medium (ISM).
  - Star formation is inextricably linked to the molecular clouds
  - Theoretical models show that this association results from the correlation between chemical phase, shielding, and temperature.
  - See MWB sec 9.1.-9.3 for a discussion

- Interstellar gas converts from atomic to molecular only in regions that are well shielded from interstellar ultraviolet (UV) photons, and since UV photons are also the dominant source of interstellar heating, only in these shielded regions does the gas become cold enough to be subject to Jeans instability (Krumholz 2012).
- Shielding due to dust and optically thick gas.

Only H_2 Counts

Bigiel et al. 2008, Leroy et al. 2008





star formation surface density

H_2 Surface density

HI Surface density

stars seem to form only in dense molecular gas…

At Low Z Star Formation Occurs Primarily in Spirals

- HST imaging of low-moderate redshift galaxies shows that star-forming galaxies at all redshifts are *dominated* by disks, while passive (non-star forming) galaxies have spheroidal structures
  - (Eales et al 2015)- estimate that ≈83% of the stellar mass-density formed over the history of the Universe occurred in LTGs (jargon, late type galaxies, aka spirals)
- However since ~50% of all stellar mass lies in passive galaxies- need either to transform spirals into E's or merge them to get the observed population

Eales et al 2015)

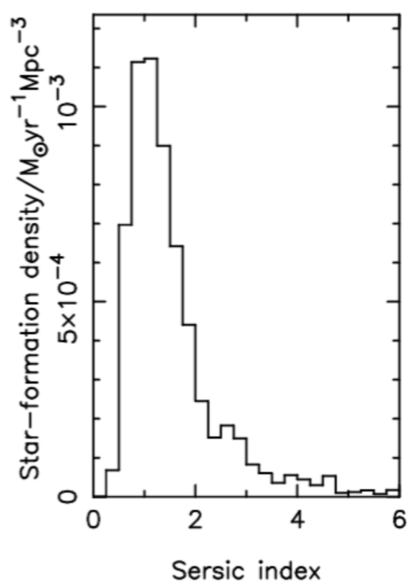


Figure 1. Star-formation rate per unit comoving volume in the Universe today as a function of Sérsic index.

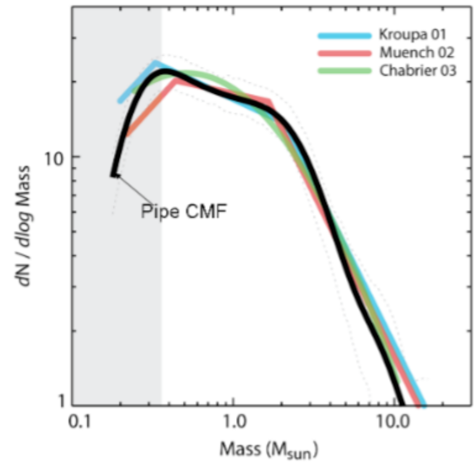
Star Formation in Spirals

In the MW and other well studied nearby galaxies SF occurs mostly in/near

Giant molecular clouds (GMCs, which are predominantly molecular, gravitationally bound clouds with typical masses ~ $10^5 – 10^6\ M_\odot$)- but GMC formation is a local, not a global process

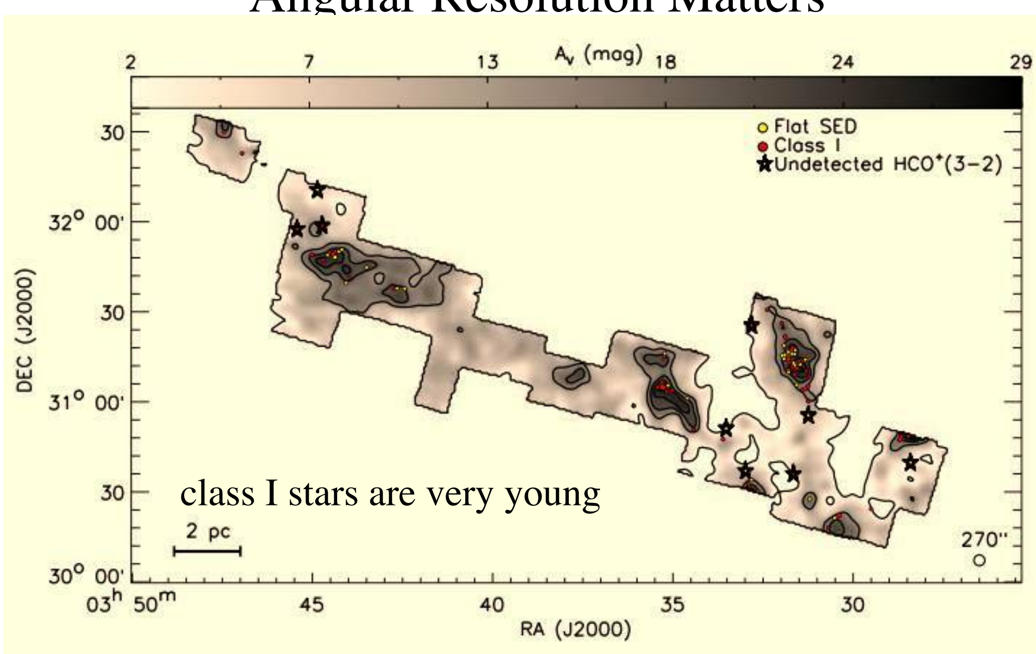
There is a strong correlation between the mass spectrum of molecular clouds and the stellar mass spectrum (Lada 2015 **arXiv:1508.02711**

– Observationally one uses CO as a tracer for H_2 (not perfect but the best we have right now Bolatto, Wolfire, and Leroy ARA&A 2013)). This is time consuming but lots of work has been done (Leroy et al 2008)



3 colored lines are IMF (3 models)
black line is mass spectrum of molecular clouds from a particular molecular cloud complex Lada 2015

Angular Resolution Matters



– Example of the strong concentration of star formation in regions of high extinction, or mass surface density in

In Perseus molecular cloud all the young stars lie in very dusty regions

SFR indicators

- SFR indicators are derived across the full electromagnetic spectrum, from the X-ray, through the ultraviolet (UV), via the optical and infrared (IR), radio, and using both continuum and line emission

(review Kennicutt 1998, Kennicutt & Evans (2012).

- The importance of these indicators change over cosmic time: it seems that most of the star formation at redshift z~1–3 was enshrouded in dust but at z>3 dust was much less important.

Star Formation- How to Measure It

The physics of star formation (what processes produce stars) and the astrophysics (where and when were the stars produced) are two of the dominant issues in astrophysics at present-

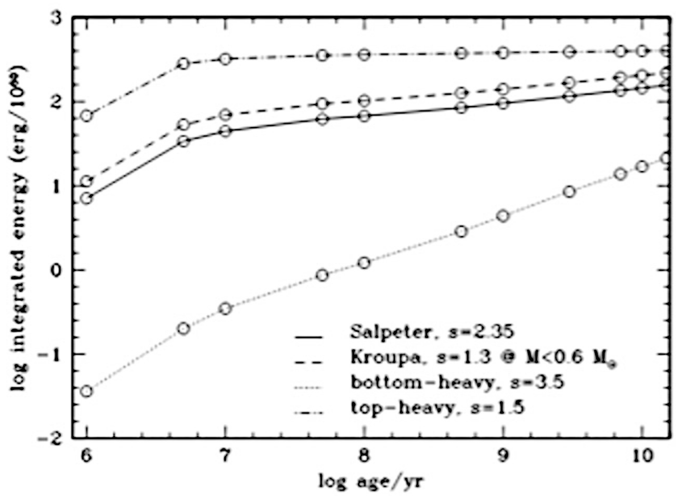
- Stars form from dense, cold gas either in disks or in gas that is violently shock compressed (in mergers)

Current SF can be estimated from a variety of techniques

- Hα observations, which gives the number of ionizing photons if one assumes that all ionizing photons are used and eventually re-emitted - ionizing photons are almost exclusively emitted by massive (hot) stars which have short lifetimes; so the effects of dust can be large
- far-IR flux - this assumes that a constant fraction of the emitted stellar energy is absorbed by dust
- radio continuum emission - this statistically correlated very well with the IR radiation- physics is complex since radio emission comes from synchrotron radiation from relativistic electrons+ thermal bremmstrahlung from hot gas
- far-UV flux (- which is primarily emitted by young (hot) stars- but older /less massive than those responsible for Hα
- X-ray emission- produced by 'high mass' x-ray binaries (a Neutron star or black hole with a massive companion)

How to Normalize SFR

- Since essentially all techniques measure the total (or ionizing) luminosity of massive stars we need to transform to ALL the stars
- Use the IMF (Initial mass function; **please read sec 9.6 of MBW** but not 9.6.2)
- For Kroupa IMF
  - $\Psi(M) \sim M^{-1.4}$ $0.1<M_\odot<1$
  - $\Psi(M) \sim M^{2.5}$ $1<M_\odot<100$
- Integrate Ψ from $10\text{-}100M_\odot$ get 0.16 of all the mass (correction factor)- these are the stars which have short lifetimes and are hot and thus produce the signatures of star formation. Formation of low mass stars can only be detected in MW and Magellanic clouds



total energy emitted by a given IMF with total stellar mass of 10^{11} M as a function of age

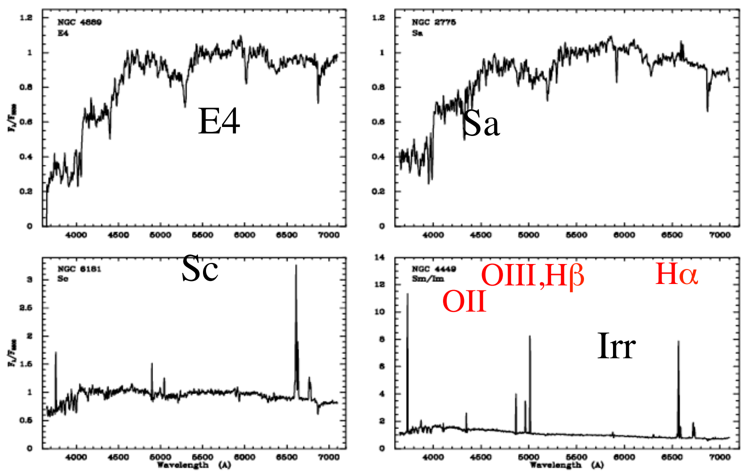
Physics of Various Indicators

- Hα: emitted by gas ionized by stars with T_{eff}>~20,000k ($M>10M_\odot$) which emit photons that can ionized Hydrogen (E_{ioniz}=13.6eV) -t<20Myrs
- IR Continuum- UV light absorbed by dust
- UV continuum- direct signature of massive, young stars
- X-rays: high mass x-ray binaries- massive young star with neutron star companion
- radio emission- due to synchrotron from relativistic particles produced in SNR and hot gas from SN and stellar winds

Importance of Emission Lines

- As one moves on the Hubble sequence the galaxy spectra get more and more emission line dominates and relative prominence of lines changes
- Thus many authors use Hα or OII as SFR indicators
  - these are strong optical lines produced by gas ionized by hot stars ([OIII] is also produced by active galaxies and so it is often difficult to separate AGN from star formation)

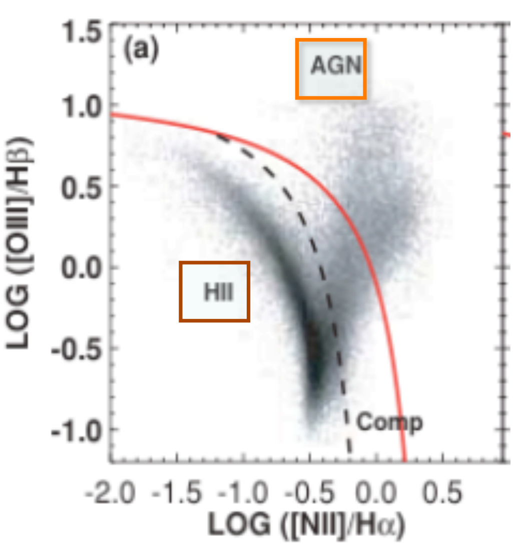
Lines are strong and can be detected at high redshift



Kennicutt 1998

Digression-From spectroscopy how does one classify a galaxy as star forming or an AGN??

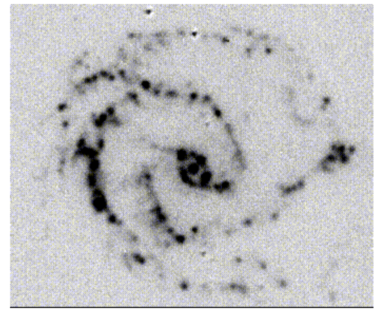
Observe strong lines to make life easier- but these are not necessarily the most diagnostic.



Different lines have different dependences on temperature excitation mechanism (collisions, photoionization)
Ratios of certain lines (chosen to be close in wavelength so reddening is not an issue)

AGN have 'harder' radiation field (higher UV/optical) and collisional excitation less important than in star forming regions.

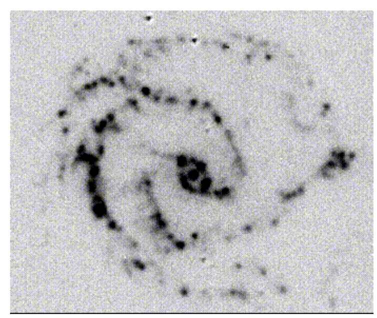
How to Determine SFR from Observables-Hα or Hβ see MBW 10.3.7,10.3.8



Hα image of a star forming galaxy

- The strength of the emission lines is the convolution of the number of ionizing photons, the fraction of them that are absorbed and the physical conditions of the gas.
- Simplifying assumptions: gas of constant temperature, given IMF, gas is internally dust free, Case B (optically thick to ionizing continuum gives Hα/Hβ=2.9) and an analytic approximation to the SFR
  - Hα only comes from ionized gas (HII regions)- very non-uniform images (pearls on a string)
- For a given type of star one can calculate the number of Hα photons e.g (O7)= 10^{38}ph/sec

How to Determine SFR from Observables-Hα or Hβ



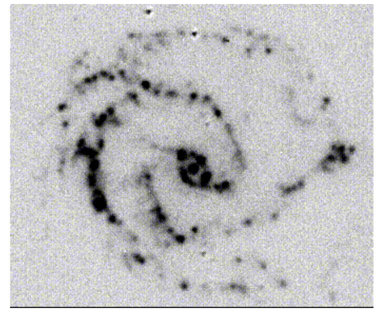
Hα image of a star forming galaxy

- Young, massive stars produce copious amounts of ionizing photons that ionize the surrounding gas.
- Hydrogen recombination cascades produce line emission, including the well-known Balmer series lines of Hα (6563A) and Hβ (4861A), which are strong.
- Only stars more massive than $20M_\odot$ produce an ionizing photon flux.
- In a stellar population formed through an instantaneous burst with a Kroupa IMF *the ionizing photon flux decreases by two orders of magnitude between 5Myr and 10Myr after the burst*.
- So Hα measures the '**instantaneous**' star formation rate

•http://www.astr.ua.edu/keel/galaxies/sfr.html

How to Determine SFR from Observables-Hα or Hβ see MBW 10.3.7,10.3.8

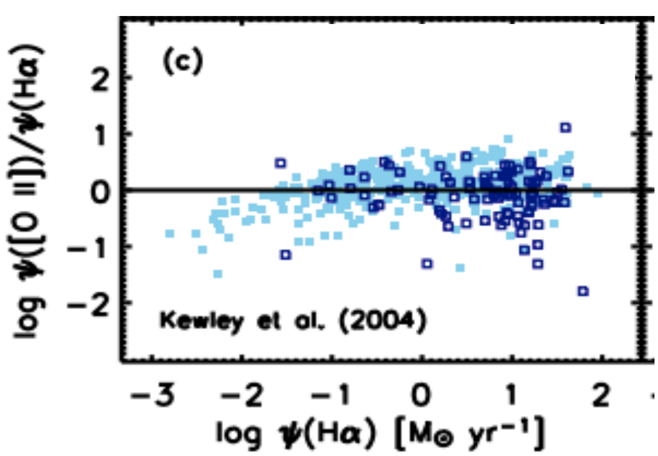
- Using stellar models and the IMF one ends up with SFR($M_{\odot}$/yr)=L(Hα)/7x10^{41} ergs/sec for M>10$M_{\odot}$ stars or
  - SFR($M_{\odot}$/yr)=L(Hα)/1.1x10^{41} ergs/sec for all stars correcting for the IMF
- while this seems great, have to worry about dust, the age of the population- the equation assumes a zero age IMF.
  - The older the population is, the less Hα there is- harder to see how much star formation occurred if it has turned off and the system is more than 20Myrs old (no more O stars).



Hα image of a star forming galaxy

How to Determine SFR from Observables-[OII]

- [OII] (a forbidden line, collisionally de-excited in dense gas) is the next most prominent line and is visible until z~1.4 from the ground (Hα is only visible to z~0.4)
- Calibrate it empirically using Hα since its luminosity is not directly coupled to the ionizing continuum (it is collisionally excited, not a cascade from photoionization) - fairly wide variation in Hα /O[II]makes it noisier.



Ratio of SFR from [OII] to Hα rate vs Hα rate (Moustakas 2006)

UV

- The youngest stellar populations emit the bulk of their energy in the rest frame UV (<0.3μ); in the absence of dust attenuation, this is the wavelength range 'par excellence' to investigate star formation in galaxies over timescales of ≈10–300Myr,
- both O and B stars are brighter in the UV than at longer wavelengths.
  - the lifetime of an O6 star is ~6Myr, and that of a B8 star is ~350Myr.

The luminosity ratio of a O6 to B8 star at 0.16 μ is ~90, but, weighting by a Saltpeter IMF SSP for every O6 star formed, 150 B8 stars are formed.

Thus, at age zero, the UV emission from the collective contribution of B8 stars is comparable to that of O6 stars. And since B8 stars live a lot longer they dominate the UV flux on longer timescales.

(Calzetti 2012)

UV Continuum

- in principle great- direct measure of total luminosity of young massive stars.
- Three big problems
  - DUST- UV extinction is much larger than in optical - light that is absorbed is re-emitted in the IR -the most active and luminous systems are also richer in dust, implying that they require more substantial corrections for the effects of dust attenuation; (MBW-10.3.8(b))
    - effects of dust are BIG- A_V =0.9 produces a factor ten reduction in the UV continuum at 1300Å (see MBW pg 479, S+G pg 33-34 for discussion of reddening- more later in lectures on dust)
  - Observations show that at 'low' SFR dust is not a big effect, at high values critical

UV Continuum

– at low redshift must observe from space – e.g. UV does not get thru the atmosphere
– VERY sensitive to IMF- at best can only constrain 15% of all the stars forming
– For a Kroupa IMF with with constant star formation

SFR(UV)$M_{\odot}$/yr = 3.0x10^{-47} L_{UV}(ergs/sec)(912-3000Å) (eq 10.108)- notice subtle difference due to different UV band assumed and Saltpeter IMF

IR Continuum

- Direct observations show that **~1/2 of total galaxy light in spirals appears in IR**
- This is thermal emission emitted by dust as a grey body

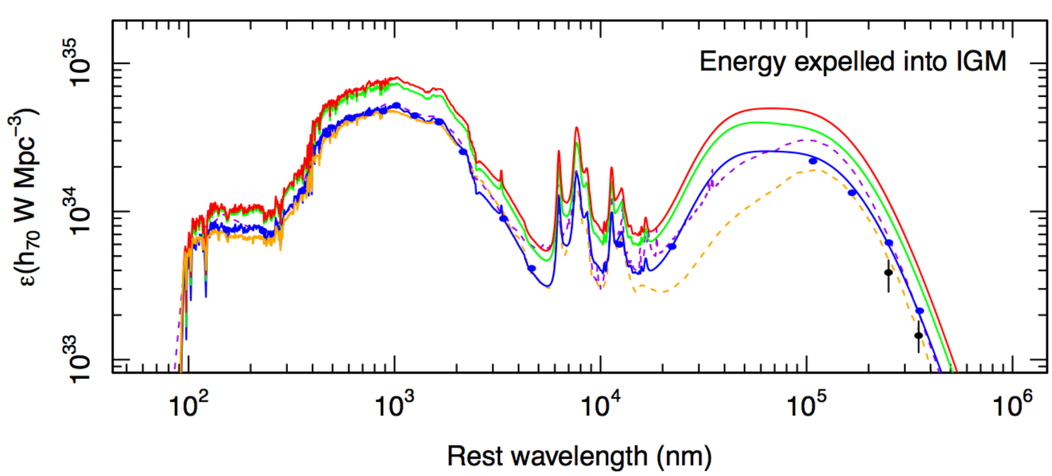


Figure 25. The energy originating (i.e., unattenuated, top), and emanating (i.e., attenuated following dust reprocessing, lower) at intervals equivalent to 0.75, 1.5 and 2.25 Gyr lookback time. The data are normalised to the energy output per Mpc^3 for H_o = 70km/s/Mpc. The data show clear trends in the evolution of the total energy output over this timeline.