ASTR 520 Lecture 15: Star Formation

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Quote from Kennicutt & Evans 2012 ARAA :

Star formation encompasses the origins of stars and planetary systems. As a principal agent of galaxy formation and evolution, however, it is also a subject at the root of astrophysics on its largest scales.

large-scale SFR is determined by a hierarchy of physical processes spanning a vast range of physical scales: the accretion of gas onto disks from satellite objects and the intergalactic medium (megaparsecs), the cooling of this gas to form a cool neutral phase (kiloparsecs), the formation of molecular clouds (10100 pc), the fragmentation and accretion of this molecular gas to form progressively denser structures such as clumps (1 pc) and cores (0.1 pc), and the subsequent contraction of the cores to form stars (solar radius) and planets (astronomical units).

1 Integrated Star formation rate Measures

Table 1 from Kennicutt & Evans Why IMF matters – tracers are for a specfiic stellar population. if you know the IMF then you can use the mass of stars in that mass bin to determine the mass in all.

Measures: UV (direct) , IR, Halpha/Emission Line. (both re-processed). See diagram.

- The **near-ultraviolet (UV)** emission of galaxies longward of the Lyman-continuum break directly traces the photospheric emission of young stars and, hence, is one of the most direct tracers of the recent SFR. For a conventional IMF, the peak contribution to the integrated UV luminosity of a young star cluster arises from stars with masses of several solar masses. Consequently, this emission traces stars formed over the past 10200 Myr, with shorter timescales at the shortest wavelengths

  FUV continuum traces the young stars directly but must be corrected for dust obscuration - primary disadvantage.

  Galex mission revolutionized this field. It imaged approximately two-thirds of the sky in far-UV (FUV; 155nm) and near-UV (NUV; 230 nm) . Provided integrated UV fluxes.

  If the intrinsic color of the emitting stellar population is known a priori, the FUV-NUV color or the UV spectral slope (usually denoted by) can be used to estimate the dust attenuation, and numerous calibrations have been published (e.g., Calzetti, Kinney & Storchi-Bergmann 1994) – but FIR missions showed that there is a LOT of scatter in this relation, and need other methods of determining dust attenuation.

- **Nebular Emission lines** (optical and NIR) traces PDR (photo dissociation regions forming around young, massive stars). For a conventional IMF, these lines trace stars with masses greater than 15 $M_{\odot}$, with the peak contribution from stars in the range 3040 $M_{\odot}$. As such, the lines (and likewise the free-free radio continuum) represent a nearly instantaneous measure of the SFR, tracing stars with lifetimes of 310 Myr.

  The Hα emission line remains the indicator of choice for observations of both local and distant galaxies, but for moderate redshifts, the bluer visible lines have been applied, in particular the [OII] forbidden-line doublet at 372.7 nm. This feature is subject to severe systematic uncertainties from dust attenuation and excitation variations in galaxies. Systematics on OII baed SFRs are larger than for Hα (Recall OII and OIII ratios - density and ionization bounded nebulae).

  For Halpha - Balmer decrement for dust attenuation works reasonably well. but fails for starbursts.

could use Lyα line as SFR measure if knew escape fraction. Really only used for highest redshift galaxies (much stronger than Halpha).

BUT this may break down at low masses. See Lee+2009. Different IMF? Systematic depletion of massive stars in low-SFR environments. This missing unattenuated component varies from essentially zero in dusty starburst galaxies to nearly 100% in dust-poor dwarf galaxies and metal-poor regions of more-massive galaxies.

- **IR tracing the thermal dust emission**. Dust surrounding young star forming regions. Measures total energy input from deeply embedded sources. (gas is not dense enough to reach equilibrium with the radiation field to emit thermal radiation). Interstellar dust absorbs approximately half of the starlight in the Universe and re-emits it in the IR, so measurements in the IR are essential for deriving a complete inventory of star formation. Spitzer, Herschel, AKARI, WISE and Planck

  Just as the UV and visible tracers miss radiation that has been attenuated by dust, the IR emission misses the starlight that is not absorbed by dust (e.g., Hirashita et al. 2001). (Starbursts absorbs all, dwarfs loses all).

  Because starbursts largely young, IR traces totally different stellar population than for older galaxies. So Conversion factor from dust luminosity to SFReven in the limit of complete dust obscurationis not fixed, but rather changes as a function of the stellar population mix in galaxies

  best way to overcome these systematic biases is to combine the IR measurements with UV or visible-wavelength SFR tracers to measure the unattenuated starlight directly and to constrain the dust-heating stellar population

- **radio**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

- **X rays**Over the past decade, the integrated hard X-ray emission of galaxies has been increasingly applied as an SFR tracer. The component of X-ray emission that does not arise from AGN accretion disks is dominated by massive X-ray binaries, supernovae and supernova remnants, and massive stars, all associated with young stellar populations and recent star formation. Furthermore, the observed 210 keV fluxes of galaxies are observed to be strongly correlated with their IR and nonthermal radio continuum fluxes (e.g., Bauer et al. 2002; Ranalli, Comastri & Setti 2003; Symeonidis et al. 2011), thereby strengthening the link to the SFR. Because the relation between X-ray luminosity and SFR cannot be calibrated from first principles, this calibration is usually bootstrapped from the IR or radio.

Kennicutt 1998 gives theoretically derived linear relationships between luminosity in a given waveband and the SFR, using stellar population models with solar abundances and a Salpeter IMF (0.1-100 M$\odot$). Seem to work pretty well, get linear relationship between LIR, LUV etc that tells you things are working ok.

1.1 IMF

Since essentially all techniques measure the total (or ionizing) luminosity of massive stars we need to transform to ALL the stars

These have been updated in Kennicutt & Evans 2012 Nearly all these calibrations are based on evolutionary synthesis models in which the emergent SEDs are derived for synthetic stellar populations with a prescribed age mix, chemical composition, and IMF. Kennicutts (1998a) calibrations employed a mix of models from the literature and assumed a single power-law IMF (Salpeter 1955) with mass limits of 0.1 and 100 $M_\odot$. This IMF gave satisfactory SFR calibrations relative to those of more realistic IMFs for H, but for other wavelengths, the relative calibrations using different tracers are sensitive to the precise form of the IMF. Today, most workers calibrate SFR tracers using a modern IMF with a turnover below $\sim 1\mathrm{M}_\odot$, for example, the IMF of Kroupa & Weidner (2003), with a Salpeter slope ($\alpha = 2.35$) from 1 to 100 $M_\odot$ and $\alpha =$ 1.3 for 0.11 $M_\odot$. The calibrations presented here use this IMF, but the IMF fit from Chabrier (2003) yields nearly identical results (e.g., Chomiuk & Povich 2011). The past decade has also seen major improvements in the stellar evolution and atmospheric models that are used to generate the synthetic SEDs. The results cited here use the Starburst99 models of Leitherer et al. (1999), which are regularly updated in the online version of the package.

NOTEAge estimates These were estimated using the Starburst99 models in the approximation of constant star formation.

All results were calculated for solar metal abundances, and readers should beware that all the calibrations are sensitive to metallicity

2 Spatially Resolved SF

Challenge: First, when the SFR in the region studied drops below $\sim$ 0.0010.01$M_\odot$ year1 (depending on the SFR tracer used), incomplete sampling of the stellar IMF will lead to large fluctuations in the tracer luminosity for a fixed SFR. These begin to become problematic for luminosities of order $10^{38}10^{39}$ ergs s1 for emission-line, UV, or IR tracers, and they are especially severe for the ionized-gas tracers, which are most sensitive to the uppermost parts of the stellar IMF.

A second measuring bias exists because, when the spatial resolution of the SFR measurements encompass single young clusters, such as Orion,

Need to make sure that are covered is large enough.

3 SFR controlled by amount of Dense Gas

Ultimately we want to understand how SF proceeds.

Molecular clouds form in densest gas regions. It follows that SFR should scale with the amount of dense gas.

Gao & Solomon find a *linear* fit with HCN - very dense gas .

But what is the best tracer of this dense gas?

3.1 H2

From Krumholz

Hydrogen is most abundant element. H2 molecular form would follow as the best tracer of the amount of dense gas.

But H2 is really hard to observe.

A diatomic molecule (2 atoms) like H2 has three types of excitation: electronic (corresponding to excitations of one or more of the electrons), vibrational (corresponding to vibrational motion of the two nuclei), and rotational (corresponding to rotation of the two nuclei about the center of mass).

Rotational are lowest in energy (see diagram). First excited state (J=1) is 175 K above ground state. But GMCs are cold (T 10 K) so almost no molecules will be in this excited state.

Homonuclear molecule (molecule made of one element) and for reasons of symmetry can't turn odd J (orthoH2) into one with even J (para-H2) So cant switch within J=1.

So there is no J=1 to 0 emission. Lowest lying transition is J=2 to 0 (quadrupole) This is very weak and is at 510 K above ground state. So for population in equilibrium at a temp of 10 K fraction of molecucles in the J=2 state is $e^{-}510/10 \sim 10^{-22}$.

So no H2 molecules capable of emitting.

The levels of H2 are much further apart than the levels of other diatomic molecules (CO,)2, N2) Level spacing varies with reduced mass ($m^{-1/2}$) − Hydrogen has a low mass.

Very rare to see H2 directly - need a really bright background UV source (see it in absorption rather than in emission). (maybe in forming galaxies)

3.2 CO

Need to observe H2 by proxy.

After H2 Co is the single most abundant molecule in the ISM. CO line emission represents the most accessible and widely used tracer of the molecular interstellar medium.

CO J=1 state is only 5.5 K above the ground state. Its excitation sets the molecular gas temperature. J=2-1 line is also used.

This renders the translation of observed CO intensity into total H2 gas mass critical to understand star formation and the interstellar medium in our Galaxy and beyond.

CO is converted to a total mass. X factor depends on the volume density, temperature.

3.3 Problems with CO

Kennicutt & Evans 2012

CO emission traces column density of molecular gas only over a very limited dynamic range.

At the low end, CO requires protection from photodissociation and some minimum density to excite it, so it does not trace all the molecular (in the sense that hydrogen is in H2) gas, especially if metallicity is low. (see Figure; Narayanan+2012)

At the high end, emission from CO saturates at modest column densities. Becomes optically thick at very low total columns densities

The isotopologues of CO (13CO and C18O) provide lower optical depths, but at the cost of weaker lines.

Using CO and 13CO you can infer the total integrated intensity of CO (or total column density). Because studies of other galaxies generally have only CO observations available, the common practice has been to relate H2 column density N(H2) to the integrated intensity of CO

You can then relate that to the true total column density of H2 using the following:

$$N(H_2) = X(CO)I(CO) \tag{1}$$

I(CO) integrated line intensity.

$$XCO \sim N(H_2)/(T \times \sigma) \tag{2}$$

see diagram.

$X(CO) \sim 2 - 4 \times 10^{20}$ cm$^-2$ (K km s^{-2})$^{-1}$

X factor is defined in terms of a velocity-integrated brightness temperature. The brightness temperature corresponding to a given intensity at frequency ? is just defined as the temperature of a blackbody that produces that intensity at that frequency.

******** DOn't cover Given that the cloud is optically thick, why should there be a relation between column density and intensity at all?

"Using CO intensity to estimate the column density of a cloud is akin to using the presence of a brick wall to estimate the depth of the building behind it. "

$$N = M/\mu\pi R^2 \qquad N = XCOICO \tag{3}$$

so rearranging

$$XCO = 10^5 \frac{(\mu m_H ln\tau_{v0})^{-1/2}}{T} \sqrt{\frac{5n}{6\pi\alpha_{vir}G}} \tag{4}$$

τ_{v0} = optical depth at frequency ν. α_{vir} = 5 σ^2 R / GM (virial ratio) typically 1 if in equilibrium.

XCO depends on n the number density of the cloud (all clouds have roughyl comparable volume densities on large scale and are virialized). Suggests that there should be aroughly constant X factor.

T = 10 K, n = 100 /cm^3, α_{vir} = 1, τ_{v0} = 100 get $XCO = 5 \times 10^{19}$ cm^{-2}(K km s^{-1})$^{-1}$

The value of the conversion factor $X(CO)$ isn't well known, and could change in different density environments, metallcity, cloud temperature (Maloney & Black 1988).

XCO is lower for starbursts and higher for metal-poor galaxies We only know it fairly well in the MW, where it seems to be pretty uniform throughout the entire galaxy.

Uncertainties could cause errors of order 50% in mass estiamtes

4 Kennicutt-Schmidt Relation: SFRs Over Whole Galaxies

Tracing the dense gas requires significant observational resources/resolution. SF "Laws" for global galaxy evolution

A star formation law should predict the SF efficiency from local conditions (physics).

4.1 KS Law

Broadly speaking there is a relationship where larger galaxies, which have more gas, have higher star formation rates.

But if galaxy is resolved you can normalize out the projected area.

Schmidt 1959 : introduced the conjecture that there is a scaling between gas density and star formation rate.

Kennicutt 1998 (one of most cited papers in astrophysics) acutally showed that there is a Scaling relation between the Σ_{SFR} SFR per unit area and the total (HI and molecular) gas surface density averaged over the entire galaxy.

$$\Sigma_{SFR} \propto \Sigma_{gas}^{1.4} \tag{5}$$

In Kennicutt 98 SFR determined from Halpha and IR.

Total gas surface density But assumed a single XCO factor for all galaxies/ You might think this shouldn't be too big of deal, since gas density largely HI. But the H2 fractions might be huge.

XCO is lower for starbursts and higher for metal-poor galaxies.

Correcting for this might make the slope steeper (1.7-1.8) but lots of uncertainty Naryanan+2012

These scaling relations are really useful for calibrating simulations - globally the SFR needs to obey these relations

5 Low Surface Brightness Galaxies

There were few dwarfs in Kennicutt's original sample. Issue is that dwaefs have little dust, and so IR emission is low.

GALEX is the game changer (UV mission launched in 2003) From space, background in FUV is nearly zero.

CO to H2 factor is almost certainly different than in spirals. but HI dominates in dwarfs, so XCO is likely not a big problem.

Find the dwarfs generally lie below the linear extrapolation of the kennicutt relationship.

6 Starbursts & ULIRG/LIRGs

Section 7.1

Starburst: gas compression causes stars to form so rapidly as to exhaust the gas supply within a a few hundred million years.

Period of unsustainably high star formation.

the most extreme cases: Most of the energy released by newly formed stars will be absorbed by dust and re-radiated in the infrared (star forming regions are very dusty) .

This leads to *ultraluminous and luminous infrared galaxies* called *ULIRGs/LIRGs.*

The relation between the star formation rate and the far-infrared emission is about

$$\dot{M}_\star \approx \frac{L_{FIR}}{6 \times 10^9 L_\odot} M_\odot \text{ yr}^{-1}. \tag{6}$$

- LIRGS: $L_{FIR} > 10^{11} L_\odot$ so SFR $> 20 M_\odot/yr$
- ULIRGS: $L_{FIR} > 10^{12} L_\odot$ so SFR $> 200 M_\odot/yr$ some can have 1000 $M_\odot/yr$

Show Figure 7.7 of SG.

6.1 Gas Consumption

SF in normal galaxies uses about 5% of available gas every 10^8 yrs ! average gas depletion timescale,   is 2.1 Gyr. But Recycling of interstellar gas from stars extends the actual time scale for gas depletion by factors of 23

Starburst use up their gas much faster ¡30%¿ of gas used every 10^8 yr Depletion timescale 0.3 Gyr

7 Origin of Starbursts

1. Gas instabilities.
   - Toomre Q : If Pressure and Shear (angular velocity) counteract Gravitational Force then the disk is stable.
   - Star formation can occur even if the disk is stable, but rate can be higher if it is unstable.
   - At high redshift there is so much gas that instabilities become likely and can likely drive a starburst without a merger.
2. Mergers
   - destruction of galaxy, strong concentration of dust in the center. Strong likelihood of a merger driven model. Sanders+1998
   - Mergers drive inflows.
   - Locally, all ULIRGs (z∼1) LIRGs ($z \sim 0$) are mergers (Duc+1997)
   - Note this doesn't mean that all mergers end in starbursts.
   - Merger-induced star formation consists, for a large part, of nuclear starbursts taking place in the central 100-1000 pc (diameter). But it can be more spatially extended.

So Mergers we believe are responsible for the most intense periods of star formation.

7.1 Do Starbursts, ULIRGS/LIRGS follow K-S Relation?

Do these crazy intense periods of SF still obey the same scaling relations as normal galaxies?

People assume a bimodal value for XCO where mergers have lower conversion factors

Adding high redshift galaxies. Normal galaxies and starbursts seem to occupy different loci on the $\Sigma_{gas} - \Sigma_{SFR}$ plane. See figure.

BUT this assumes a different XCO for starbursts relative to normal galaxies, so this might be an artificial exaggeration. If you use one single XCO factor it is more ambiguous.

7.2 Why do starbursts/ULIRGS/LIRGS matter

Inform us of the physics of how stars form.

produce a significant amount of stars rapidly (explain stellar populations and are responsible for the chemical evolution of a galaxy). Dominate the cosmic SFH at early times.

They drive galactic winds. - launch metals outward and thus allow us to regulate star formation.

Generally, star formation is regulated by the balance between the rate at which cold gas is accreted onto the galaxy and feedback. (Bathtub model)

$$Mdot_{gas} = Mdot_{gas,accretion} - (1 - R) M_* - Mdot_{out} \tag{7}$$

$$Mdot_{gas,accretion} \propto M_{\rm halo}^{1.1}(1+z)^{2.3} \qquad Mdot_{out} = \eta Mdot_* \tag{8}$$

Feedback prevents star formation from being a runaway process. Early disk formation models didn't work because too much star formation created huge bulges in the central regions. feedback can be described as the energy or momentum deposition from a source onto the gaseous component of a galaxy

So can SFR evolution over time in form us about inflow and outflow rates? i.e. the baryon cycle of galaxies?

8 Star Formation Main Sequence

From Whitaker+2012: Galaxies show a strong correlation between their star formation rate (SFR) and stellar mass (M) from z = 0 to the earliest observed epoch, z = 7 (e.g., Brinchmann et al. 2004; Noeske et al. 2007; Elbaz et al. 2007; Daddi et al. 2007; Pannella et al. 2009; Magdis et al. 2010; Gonzalez et al. ? 2010).

On average, galaxies on this "star formation sequence" were forming stars at much higher rates in the distant universe relative to today (e.g., Madau et al. 1996)

For a given mass, the SFR has been decreasing at a steady rate by a factor of $\sim$30 from z $\sim$2 to z = 0 (Daddi et al. 2007), although it appears to be roughly constant from z $\sim$ 7 to z $\sim$ 2 (Gonzalez et al. 2010). The star formation sequence is observed to have a roughly constant scatter out to z $\sim$ 1 (e.g., Noeske et al. 2007).

More starbursting and much more intensely starbursting (ULIRGs, HLIRGs) at high z. **Cosmic downsizing:** massive galaxies no longer forming stars and intense periods of growth are over.

Overall picture: z $\sim$ 2 there is a rapid period of mergers and gas flows and turbulence. This all levels off and dominated by passive SF, but big things used up their gas supply. they can only grow by dry mergers.