Star formation

1. Basics

Star formation is a fundamental process in forming galaxies. It proceeds through the cooling and gravitational collapse of gas within gas *clouds*. Based on molecular gas measurements, the mass function of clouds has a slope of about $\alpha \sim 1.5$–2 ($\mathrm{d}N/\mathrm{d}M = M^{-\alpha}$) between 10^3 and 10^6 $M_\odot$. During the collapse process, the gas becomes cold enough for molecules to form, and stars form always within molecular clouds. Individual stars form in a range of masses. Light from the most massive forming stars tends to disassociate and then ionize the surrounding gas cloud. Dust in the cloud absorbs and is heated by ultraviolet light from the stars. The *star clusters* that result seem to have a similar mass distribution to the gas clouds (though it is thought that clusters form within isolated *clumps* within the clouds).

At redshift zero, spiral galaxies at Milky Way masses have star formation rates around a few solar masses per year. Most estimates of the dependence on stellar mass find SFR $\propto M_*^{2/3}$. At higher redshifts the typical star formation rates of such galaxies are higher, by about a factor of ten at $z \sim 1$.

1.1. Initial mass function

The stars within the clusters form over a large range of masses. The initial mass function estimated within the Milky Way appears to peak between 0.1 and 0.3 $M_\odot$, and at higher masses decline with a slope close to -2.35 (the *Salpeter* slope). This initial mass function may depend on environment in various ways. Estimates of star formation rate integrate the mass of stars extending down to the hydrogen burning limit (0.08 $M_\odot$) even though the star formation indicators are only directly sensitive to much more massive stars.

1.2. Color-magnitude diagram

For systems whose stars can be resolved from each other, we can estimate the star formation rate by modeling the color-magnitude diagram, sometimes using all the stars or sometimes only the most massive O-type or Wolf-Rayet stars. This method can estimate the star formation rate over the past 100 million years or so. Systems like the Orion Nebula Cluster can be studied in this way, and with Hubble Space Telescope observations nearby galaxies can be mapped in their star formation rate.

1.3. Ultraviolet light

More useful for most galaxies is the integrated ultraviolet continuum light, which (depending on the IMF) traces stars of a few solar masses, and consequently star formation over the past 100 million years.

However, dust attenuates the ultraviolet light strongly. In principle, the slope of the ultraviolet continuum constrains the dust attenuation. Because the dust re-emits in the infrared, this leads to a relationship between the ultraviolet spectral slope β and the ratio of the infrared to ultraviolet light ("IRX"; Overzier et al. 2011; Grasha et al. 2013). However, in practice there appears to be too much scatter in the dust attenuation as a function of reddening for this correction to be sufficient.

1.4. Emission lines

The most massive young stars ($> 15\ M_\odot$) produce large ionized *HII regions* surrounding them. Recombination in these regions produces a sequence of Balmer lines (and also higher wavelength Paschen and Brackett lines) with line ratios that are only a weak function of the gas conditions. To a good approximation, there is one Balmer line produced for every ionized photon. Therefore, Balmer lines can be used to determine the total ionizing flux, which is related to the number of massive stars, which due to their short lifetimes is related to the star formation rate within the past 10 million years. Hα is the usual Balmer line of choice as the brightest and reddest, to minimize dust extinction. The Paschen and Brackett lines are more robust but less accessible with ground-based instruments.

The Hα emission needs to be corrected for dust as well. Typically, we use the *Balmer decrement*, the ratio of the Balmer lines compared to the (unextincted) theoretical expectation. With an assumed extinction curve, the Balmer decrement yields an extinction correction. For low attenuation levels (up to about 1 magnitude at Hα), this method is sufficient but it becomes uncertain when there is large small scale variation in the extinction, which is typical at high extinction.

1.5. Infrared light

Dust extinction of the ultraviolet light leads to reemission at infrared wavelengths. This emission is a mix of lines from polycyclic aromatic hydrocarbons (PAHs) and thermal emission from dust grains at a mix of temperatures. PAHs are typically only $\sim 1\%$ of the dust map but dominate the emission between 5–20 μm. Longward of 20 μm thermal emission from dust grains dominates, though note there are some atomic lines from the gas.

The total infrared luminosity plus the total ultraviolet light traces the total star formation, in principle. However, evolved stars older than a few hundred million years can heat the dust as well.

This heating typically occurs more diffusely throughout the galaxy and is less concentrated in star forming regions; it can contribute to up to half the infrared signal for low specific star formation rate systems.

A number of calibrations have been performed that are useful if one only has infrared observations or only PAH measurements (e.g. for higher redshift systems).

1.6. Radio continuum

The radio continuum of galaxies correlates with other measures of star formation. There are two components, a thermal free-free component which at cm wavelengths is in the optically thin limit so relatively flat, and a synchrotron component with a steeper spectrum. The free-free component should correlate with the ionizing luminosity that heats the plasma. The synchrotron component correlates with other star formation indicators for sufficiently luminous galaxies, but the physical reasons behind this correlation are unknown.

The synchrotron component dominates, so high enough signal-to-noise ratio multifrequency data is necessary to measure the free-free emission. Most radio measurements of star formation are based on 20 cm (1.4 GHz) continuum measurements of the synchrotron.

1.7. Kennicutt-Schmidt Law

The Kennicutt-Schmidt law relates the surface density of atomic and molecular gas to the surface density of star formation, averaged over the galactic disk. Above $\Sigma_{\rm gas} = 10\ M_\odot\ {\rm pc}^{-2}$, galaxies obey $\Sigma_{\rm SF} \propto \Sigma_{\rm gas}^n$ with $n \sim 1.4$, with a scatter of about 0.3 dex. At lower densities, there is less star formation and more scatter than the power law predicts. Note that star formation surface density is linearly related to the total dense molecular gas (as traced by HCN for example). When comparing the star formation locally within galaxies, similar trends are seen, with a similar threshold density.

The physical causes of the Kennicutt-Schmidt law are unclear. The scaling can be derived if the star formation rate is driven by large scale instabilities in the gas, leading the rate to be proportional to the free fall time $t_{\rm ff}$ in the disk, with the depletion time $M_*/\dot{M}_* \sim 100 t_{\rm ff}$. However, there are many intermediate processes between the large scale gravitational collapse of the gas and the production of stars. The Kennicutt-Schmidt law could be explained by an appropriate variation of the fraction of molecular gas as a function of density and a constant conversion rate of molecular gas into stars.

The cause of the threshold at $10\ M_\odot\ {\rm pc}^{-2}$ is also not clear. If star formation is initiated by large scale instabilities, then the *Toomre instability criterion* must be satisfied (Toomre 1964). A

thin gas disk is unstable to large scale perturbations when:

$$Q_{\rm gas} = \frac{\sigma_g \kappa}{\pi G \Sigma_{\rm gas}} < 1 \tag{1}$$

where κ is the epicyclic frequency of the disk, and σ_g is the velocity dispersion of the gas. For higher Q, the Coriolis forces in the disk prevent large scale collapse even above the Jeans mass. If stars dominate the gravitational field (as for a large spiral at $z \sim 0$), then it can be shown that:

$$Q_* = \frac{\sigma_{*,R} \kappa}{3.36 G \Sigma_*} < 1 \tag{2}$$

Under most conditions found in the local universe, both $Q_{\rm gas}$ and Q_* are of order but greater than unity, so clearly this simplified picture is not complete. Observationally, the Qvalue in disks tends to correlate with many other parameters and it is therefore difficult to disentangle whether the observed threshold is due to the Toomre criterion or a different one (Leroy et al. 2008).

Considerations that are "global" like these ones probably only govern the formation, or not, of molecular clouds. Within molecular clouds, fragmentation must occur and collapse of individual cores to form individual stars. This process is complex and involves turbulence, magnetic fields (which supply substantial pressure), as well as cooling physics, all important well below any resolvable scale within a galaxy simulation.

2. Key References

- *Star Formation in the Milky Way and Nearby Galaxies, Kennicutt & Evans (2012)*

3. Order-of-magnitude Exercises

1. Assuming that the observables are unchanged, what is the difference in inferred star formation rate between assuming a Salpeter function all the way to the hydrogen burning limit, and one that turns over to a constant below 0.5 $M_\odot$?

2. For a Milky Way-mass galaxy, what is the typical depletion time for its gas? Is it lower or higher for lower mass galaxies? Given how star formation rates change with redshift, what should we expect about the gas content of higher redshift galaxies?

4. Analytic Exercises

1. The Kennicutt-Schmidt Law says that $\Sigma_{\rm SF} \propto \Sigma_{\rm gas}^{3/2}$. Assuming that gas disks have a uniform thickness, show that this relationship would result if the star formation rate density at all points in the disk was proportional to the gravitational free-fall time multiplied by the gas density.

2. The Jeans instability can be derived for a self-gravitating gas by linearizing the fluid equations:

$$\begin{aligned} \dot{\rho} &= -\nabla \cdot \vec{v} \\ \dot{\vec{\rho v}} &= -\nabla P - \rho \nabla \Phi \\ \dot{\vec{v}} &= -\frac{1}{\rho} \nabla P - \nabla \Phi \end{aligned} \tag{3}$$

5. Numerics and Data Exercises

1. SP models and UV star formation rate
2. Comparing SFRs for a single galaxy from UV, Halpha, IR.
3. Balmer decrement
4. Strongest star formers
5. XUV disks

REFERENCES

Grasha, K., Calzetti, D., Andrews, J. E., Lee, J. C., & Dale, D. A. 2013, ApJ, 773, 174

Kennicutt, R. C., & Evans, N. J. 2012, Annual Review of Astronomy and Astrophysics, 50, 531

Leroy, A. K., Walter, F., Brinks, E., et al. 2008, The Astronomical Journal, 136, 2782

Overzier, R. A., Heckman, T. M., Wang, J., et al. 2011, ApJ, 726, L7

Toomre, A. 1964, ApJ, 139, 1217

This preprint was prepared with the AAS LaTeX macros v5.2.