Plenary Session

FROM GAS TO STARS OVER COSMIC TIME

From Gas to Stars over Cosmic Time

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Abstract. The formation of stars from gas drives the evolution of galaxies. Yet, it remains one of the hardest processes to understand when trying to connect observations of modern and high-redshift stellar and galaxy populations to models of large scale structure formation. It has become clear that the star formation rate at redshifts $z > 2$ drops off rather more quickly than was thought even five years ago. Theoretical models have tended to overpredict the star formation rate at these high redshifts substantially, primarily due to overcooling. Overcooling in galaxies typically occurs because of unphysical radiative cooling. As a result, insufficient turbulence is driven by stellar feedback in galaxies. I show that such turbulence has the net effect of strongly inhibiting star formation, despite its ability to locally promote star formation by compression. Radiation pressure appears less likely to be a dominant driver of the turbulence than has been argued, but supernova and magnetorotational instabilities remain viable mechanisms. Gravity alone cannot be the main driver, as otherwise well-resolved models without feedback would accurately predict star formation rates. Star formation rate surface density correlates well with observed molecular gas surface density, as well as with other tracers of high density material. Correlation does not, however, necessarily imply causation. In this case, it appears that both molecule formation and star formation occur as a consequence of gravitational collapse, with molecules typically playing an important but not an essential role in cooling. The basic concept that gravitational instability drives star formation remains a true guide through the thickets of complexity surrounding this topic. I finally briefly note that understanding ionization heating and radiation pressure from the most massive stars will likely require much higher resolution models (sub-parsec scale) than resolving supernova feedback.

Keywords. ISM: molecules — stars: formation — galaxies: evolution

1. Star Formation History of the Universe

Five years ago, the star formation rate in the Universe was thought to peak at redshifts $z \sim 2$–3, with a rather shallow drop off beyond that era (e.g. Hopkins & Beacom 2006). Recent observations from radio to (rest-frame) UV wavelengths have reached consensus on the star formation history of the Universe dropping rather faster than previously thought (e.g. Behroozi *et al.* 2012; Moster *et al.* 2012), as shown in Figure 1.

The discrepancies between the older and more recent measurements appear to be dominated by two effects (Reddy & Steidel 2009). First, dust corrections to star formation rates derived from rest-frame UV emission probably do not remain constant beyond redshift $z = 2$, but rather drop at higher redshift and for lower luminosity galaxies, which likely have substantially lower metallicities and thus dust abundances. Second, the faint end of the UV luminosity function may be rather steeper than previously thought.

The star formation rate density is dominated at all redshifts by galaxies with stellar masses of a few $\times 10^{10}$ M$_\odot$ (Karim *et al.* 2011), comparable to modern irregular galaxies
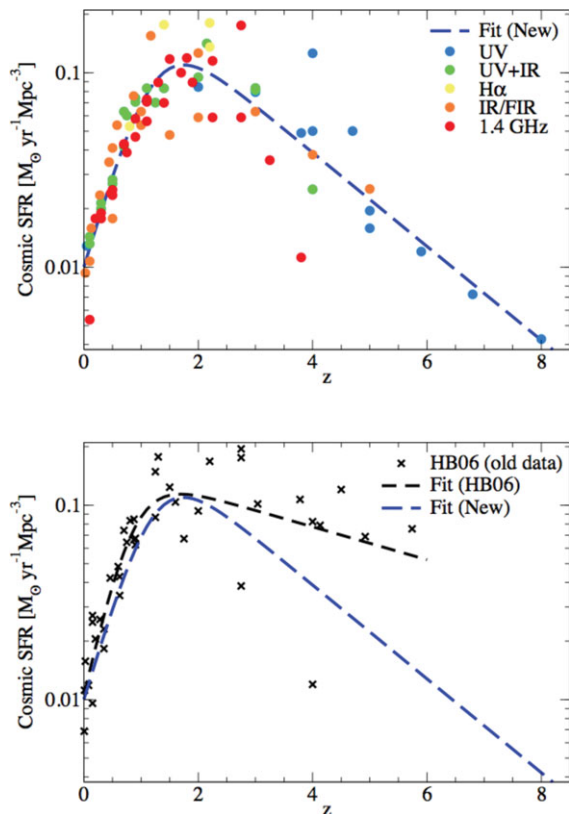
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Figure 1. (a) Star formation rate density as a function of cosmic time, showing a fit to current data coded by observation wavelength range. (b) A comparison to the shallower drop-off at high redshift found by fitting to data reported prior to 2006 shown as crosses (Hopkins & Beacom 2006). Figure from Behroozi *et al.* (2012)

such as the Large Magellanic Cloud. However, high redshift galaxies in this mass range had far higher accretion and star formation rates than modern galaxies of similar masses, so analogies between them cannot always be drawn. Such high-redshift galaxies have by $z = 0$ typically evolved into much more massive galaxies.

2. Overcooling

Theoretical models a decade ago had predicted a rather earlier peak in star formation, at $z \sim 5$–6 (e.g. Springel & Hernquist 2003). This contradiction to the observations reflects a fundamental issue in cosmological models of star formation, that simulations either overproduce stars at early times (White & Frenk 1991), or rely on ad hoc models of strong feedback to suppress that early star formation, in order to agree with the observations. There are two reasons for this requirement. First, accretion onto massive elliptical galaxies is prevented, perhaps by AGN feedback. It is much easier to prevent accretion of diffuse gas that cannot cool easily, than it is to reheat and expel already accreted gas. I will not further discuss this aspect of the problem in this contribution, though.

Second, simulations capturing cosmological scales have been unable to model the interstellar medium with sufficient resolution to follow the energetics of stellar feedback

successfully, leading to the classical overcooling problem. Without sufficiently energetic local feedback, the star formation rate can be an order of magnitude higher than observed, even in models of modern galaxies (Tasker 2011), a conclusion also reached by many previous and current workers, including Katz *et al.* (1996); Somerville & Primack (1999); Cole *et al.* (2000); Springel & Hernquist (2003); Kereš *et al.* (2009); Bournaud *et al.* (2010); Dobbs *et al.* (2011), and Hummels & Bryan (2012).

Feedback models typically fail because of unphysical cooling. The fundamental problems are that the radiative cooling rate of gas in ionization equilibrium $\dot{E} = -n^2 \Lambda(T)$ depends nonlinearly on density, and $\Lambda(T)$ is more than an order of magnitude higher for $T = 10^5$ K gas than for hot 10^6 K or cool 10^4 K gas (Sutherland & Dopita 1993). The elevated cooling around 10^5 K occurs because the strong resonance lines of lithium-like ions of the most common metals carbon, oxygen (and nitrogen) can be excited.

These properties of the cooling function lead to two problems for numerical models. First, if feedback energy is fed into the gas too slowly or over too large a volume, it will only raise the temperature into the 10^5 K range, so that the energy will be promptly be lost to radiation without exerting dynamical effects. Real supernova remnants, on the other hand, produce gas hotter than 10^6 K that only cools with difficulty. Second, in poorly resolved models cool dense gas can numerically diffuse across interfaces with hot, rarefied gas. This can produce large volumes of gas subject to unphysically strong radiative cooling, because they are elevated in density and reduced in temperature compared to the physical solution. Already over 25 years ago, Tomisaka & Ikeuchi (1986) demonstrated that the evolution of superbubbles formed by multiple supernova explosions could not be adequately followed with 5 pc resolution because of such strong numerical overcooling.

For models of the diffuse interstellar medium (ISM) in the Milky Way ($0.1 < n < 100$ cm^{-3}), models by de Avillez (2000); Joung & Mac Low (2006); Hill *et al.* (2012) and others have demonstrated that 2 pc resolution is generally sufficient to resolve interfaces sufficiently to avoid dynamically important loss of energy from hot gas. Models of modern dwarf galaxies at lower average densities can tolerate reduced resolution, as even the dense, swept up supershells have lower densities, and thus induce less cooling in the hot gas (Fragile *et al.* 2004).

3. Turbulent Inhibition of Star Formation

Highly compressible turbulence driven by supernovae and other feedback mechanisms both promotes and prevents gravitational collapse. We can estimate which effect is more important by examining the dependence of the Jeans mass

$$M_{\rm J} \propto \rho^{-1/2} c_{\rm s}^3 \qquad (3.1)$$

on the rms turbulent velocity $v_{\rm rms}$ (Mac Low & Klessen 2004). If we follow the classical picture that treats turbulence as an additional pressure (Chandrasekhar 1951; von Weizsäcker 1951), then we can define an effective sound speed $c_{\rm s,eff}^2 = c_{\rm s}^2 + v_{\rm rms}^2/3$. This increases the Jeans mass by $M_{\rm J} \propto v_{\rm rms}^3$, inhibiting collapse. On the other hand, shock waves with Mach number $\mathcal{M} = v_s/c_s$ in an isothermal medium cause density enhancements $\rho_s/\rho_0 = \mathcal{M}^2$. Thus supersonic turbulent compression decreases the Jeans mass by $M_J \propto \rho_s^{-1/2}$, if we assume that the shocks typically have $v_s \simeq v_{\rm rms}$.

When we combine these two effects, we find that

$$M_{\mathrm{J}} \propto \left(\frac{c_s}{v_{\mathrm{rms}}}\right) \left(c_s^2 + \frac{v_{\mathrm{rms}}^2}{3}\right)^{3/2} \propto v_{\mathrm{rms}}^2 \qquad (3.2)$$

for $v_{\mathrm{rms}} \gg c_{\mathrm{s}}$. Thus, turbulence strongly inhibits collapse. Because it is intermittent however, even though its net effect is to inhibit collapse globally, it can still promote it locally, in shock compressed regions. A region that does not exceed the turbulent Jeans mass globally can therefore still display some gravitational collapse, but at low efficiency (Klessen *et al.* 2000).

This effect can also be demonstrated in the diffuse, stratified interstellar medium. Joung & Mac Low (2006) used the Flash adaptive mesh refinement code (Fryxell *et al.* 2000) to run well-resolved models of supernova driving of turbulence in the ISM, including heating and cooling, but not self-gravity. They indeed found Jeans-unstable regions of cold, dense gas with sizes comparable to observed molecular clouds. However, if the star formation rate expected for those regions is computed, it is an order of magnitude below the rate required to produce the assumed supernova driving. Triggering of star formation by turbulence only occurs at low efficiency, and cannot lead to stochastic propagation waves as once envisioned by Elmegreen & Lada (1977).

At smaller scales, Dale *et al.* (2007) modeled the effect of ionizing radiation on a turbulent molecular cloud. The morphology of the cloud was drastically modified, as the radiation ionized and heated low-density gas that expanded outwards, driving compressive shock waves into the surrounding cloud. However, the actual difference in the star formation rate was small, with the net effect being to accelerate star formation by perhaps $0.2t_{\mathrm{ff}}$, where the free-fall time $t_{\mathrm{ff}} = (3\pi/32G\rho)^{1/2}$.

Quantitative observational studies reveal results consistent with this description. Although triggered star formation clearly occurs, it is a relatively small effect that does not explain most star formation. For example, Getman *et al.* (2012) show that, even under favorable circumstances, less than a quarter of star formation in the Elephant Trunk Nebula is due to triggered star formation. At the galactic scale, in the Large Magellanic Cloud, supergiant shells represent the largest-scale compressive structures in that galaxy. However, they contain only about 10% of young clusters (Yamaguchi *et al.* 2001) and about 5% of the molecular gas (Dawson *et al.*, this volume).

4. Sources of Turbulence

If turbulence controls star formation, then understanding the sources of turbulence, both in the diffuse ISM and in molecular clouds, will help us to understand star formation.

Recently, radiation pressure from the most massive star clusters has been argued to play a dominant role in limiting star formation by a number of groups including Thompson *et al.* (2005); Murray *et al.* (2010); Andrews & Thompson (2011), and Hopkins *et al.* (2011). However, this conclusion depends on how well radiation pressure can couple to gas motions. If each photon only scatters once off of a gas particle, then the strength of the radiative driving from a cluster with luminosity L is proportional to L/c, which is sometimes called the momentum-driven limit. If on the other hand the gas is extremely optically thick, so that photons continue scattering until they lose almost all their energy, then the driving is far higher, proportional to L/v_{rms}, sometimes called the energy-driven limit. Although it is unlikely that this limit is ever reached in star-forming galaxies, the groups mentioned above have argued that it is realistic to expect the number of times photons scatter to be comparable to the infrared optical depth τ_{IR}, which can be substantial. This leads to a strength proportional to $\tau_{\mathrm{IR}} L/c$. On the other hand,

Krumholz *et al.* (2009b) and Fall *et al.* (2010) argued that the momentum-driven limit was more appropriate, leading to radiation pressure being far less important in galactic evolution.

Krumholz & Thompson (2012) performed multi-dimensional simulations of radiation pressure acting on an optically thick layer of gas with optical depth $\tau_{\rm IR} \gg 1$ to resolve this question. As had already been noted in models of individual massive stars (Krumholz *et al.* 2009a), the radiation acts as a light fluid accelerating a heavy fluid, and thus a radiatively driven flow is subject to Rayleigh-Taylor instability. This overturns and fragments the gas, stirring it, but allowing the radiation to escape far more quickly than would be expected from its initial optical depth. They find that, although radiation pressure driving is indeed somewhat more efficient than in the momentum-driven limit, it is typically at least an order of magnitude less efficient than $\tau_{\rm IR} L/c$, calling into serious question results based on that assumption.

The effect of supernova feedback on the diffuse ISM as the supernova rate varies from the Milky Way value to starburst levels of as much as 512 times higher was studied by Joung *et al.* (2009). They varied the midplane gas surface density with the supernova rate following the Kennicutt (1998) relation between surface density and star formation rate. They found that regardless of surface density, the supernovae drove a rather uniform velocity dispersion $v_{\rm rms} = 5\text{–}10$ km s^{-1}, with associated H I linewidths of 10–20 km s^{-1} if single Gaussian components are fit to gas in the atomic temperature range. This agrees with the vast majority of observations of galaxies (e.g. Petric & Rupen 2007; Tamburro *et al.* 2009), aside from extreme starbursts where elevated H I linewidths are observed, possibly from radiation pressure driving (Murray *et al.* 2010, but see comments above).

The driving of turbulence in the ISM of a sample of nearby galaxies observed by the THINGS (Walter *et al.* 2008) and SINGS (Kennicutt *et al.* 2003) surveys was studied by Tamburro *et al.* (2009). They found that the energy input from supernova driving was sufficient to explain the observed kinetic energy density of the ISM within the star-forming region of disks. However, in outer disks, where star formation drops off strongly, they found that some other mechanism was required. Magnetorotational instability (MRI) was shown by Sellwood & Balbus (1999) to be able to drive substantial turbulence in galactic disks. Piontek & Ostriker (2004, 2005, 2007) used simulations to demonstrate that velocity dispersions of the observed magnitudes could be reached if thermal instability allowed a two-phase medium to form. Tamburro *et al.* (2009) in turn showed that the energy input expected from MRI was sufficient to explain the kinetic energy seen in outer disks of galaxies. On the other hand, Elmegreen & Parravano (1994) and Schaye (2004) argue that the transition from a single-phase to a two-phase medium marks the point at which ultraviolet heating can no longer maintain the observed velocity dispersion in outer disks. These two models can be observationally distinguished by the presence or absence of low temperature gas in outer disks. The discovery of finite rates of star formation in these regions by GALEX (Boissier *et al.* 2007), however, seems to lean toward the presence of a two-phase medium, supporting the MRI model.

Gravity itself can drive turbulence even in the absence of other energy inputs. Bournaud *et al.* (2010) demonstrated that gravitationally driven turbulence in unstable disks produces a column density fluctuation power spectrum consistent with observations of neutral gas in the Magellanic Clouds. However, because turbulence decays in a free-fall time (Stone *et al.* 1998; Mac Low *et al.* 1998; Mac Low 1999), such internal gravitational turbulence cannot effectively delay star formation on its own.

On the other hand, accretion from the intergalactic medium onto galaxies brings substantial energy with it. Klessen & Hennebelle (2010) demonstrated that if that energy couples to the ISM with only 10% efficiency, the velocity dispersion of spiral galaxies

could be supported if they accrete gas at the same rate that they form stars. However, dwarf galaxies, which sit in shallower potential wells, and thus have lower energy accretion flows, cannot be explained by this mechanism. As such dwarf galaxies represent the dominant location for star formation (Karim *et al.* 2011), other mechanisms must play an important role in its regulation.

At the molecular cloud scale, accretion from the surrounding interstellar medium can also play an important role in driving observed turbulent motions (Klessen & Hennebelle 2010; Vázquez-Semadeni *et al.* 2010; Goldbaum *et al.* 2011). This results in extended lifetimes compared to isolated clouds. However, other forms of feedback appear necessary to explain the termination of star formation and the disruption of the dense clouds.

Models of galaxy formation do lead us to one simple conclusion: driving of turbulence by either gravitational or accretional sources must be supplemented by other energy sources. Otherwise, simulations without stellar feedback or other energy sources beyond gravity would be sufficient to reproduce observed galaxies. This does not appear to be an effect of insufficient numerical resolution, as workers such as Bournaud *et al.* (2010) have used adaptive mesh techniques to model large ranges of spatial scale without changing this fundamental result. Ultimately, gravity must compete with feedback to determine collapse and star formation.

5. Star Formation Laws

Star formation correlates extraordinarily well with certain properties of galaxies. Perhaps the most well-known of these correlations is the Kennicutt-Schmidt law relating the gas surface density Σ_{gas} averaged over whole disks of normal or starburst galaxies, or entire galactic centers, to the star formation rate surface density $\Sigma_{SFR} \propto \Sigma_{gas}^{1.4}$ (Kennicutt 1998). As observational resolution has improved a similar correlation has now been found for regions of size around a square kiloparsec within galaxies (Bigiel *et al.* 2008). However, as shown in Figure 2*(a)*, very low surface density regions have lower than expected star formation rates, while very high surface density regions have higher than expected rates in comparison to normal galactic star forming regions. It is further worth noting that these relations break down below the kiloparsec scale, with local Galactic star-forming regions showing much more efficient star formation (Heiderman *et al.* 2010).

The star formation rates in these analyses are determined using many different indicators. The most important of these include far infrared emission tracing deeply embedded star formation; Hα emission tracing emerging H II regions; and far ultraviolet emission tracing young, massive stars that have dispersed their natal gas and dust. Different regions emit strongly in different tracers, depending on their stage of development.

The determination of the gas surface density depends on observation of both atomic and molecular hydrogen surface densities. The latter is usually measured by observation of CO emission, followed by the use of a calibrated conversion factor between CO luminosity and H_2 column density, usually denoted X_{CO}. This conversion factor rises sharply in regions with low extinction due to either low metallicity or low column density (Glover & Mac Low 2011; Narayanan *et al.* 2011; Schruba *et al.* 2011; Shetty *et al.* 2011a). Detailed analysis shows that it also may drop in high column-density regions dominated by molecular gas (Narayanan *et al.* 2012) or vary strongly when linewidths increase (Shetty *et al.* 2011b).

Molecular hydrogen surface density correlates linearly with star formation rate over the entire range of observed surface densities, albeit with more than an order of magnitude scatter among individual regions (Rownd & Young 1999; Wong & Blitz 2002; Bigiel *et al.* 2008; Leroy *et al.* 2008; Bigiel *et al.* 2011). This has been interpreted to mean that
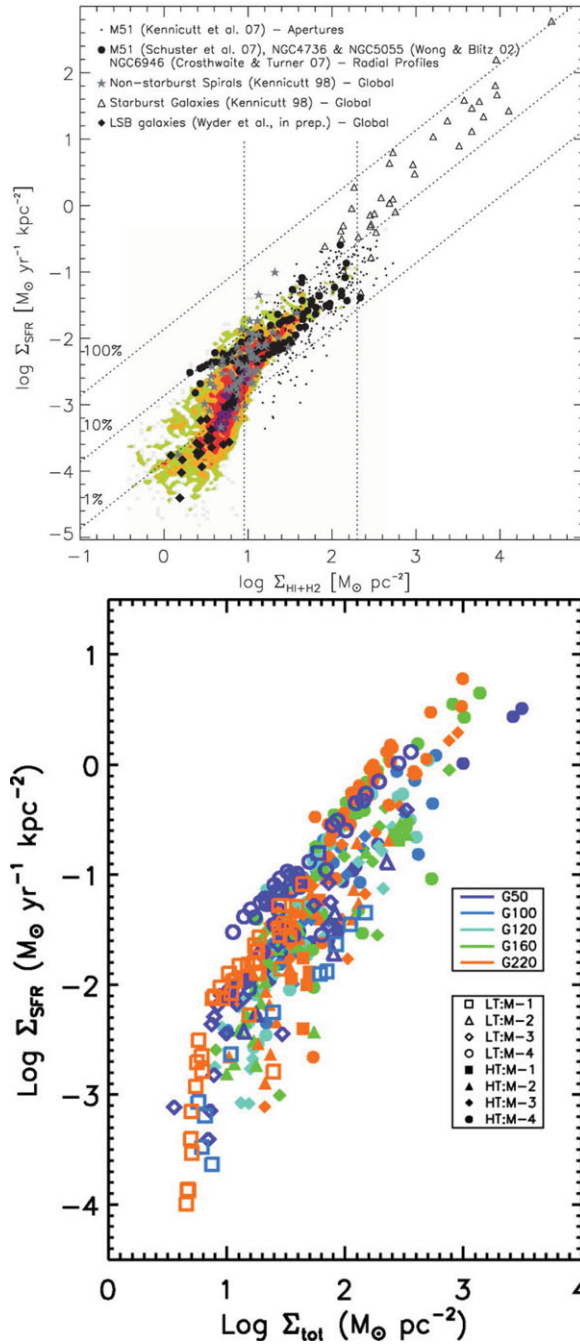
Figure 2. *(a)* A comparison of Σ_{SFR} to Σ_{gas} from Figure 15 of Bigiel *et al.* (2008) showing combined data from that paper in colored contours, along with points from the observations described in the legend on the figure. The dashed lines show what percentage of the gas would be consumed at that star formation rate over a period of 10^8 yr. *(b)* Radial profiles across model disks simulated with isothermal gas and live stellar disks and dark matter halos (Li *et al.* 2005), showing the same drop in star formation efficiency at low gas surface density.

molecular hydrogen formation controls star formation (e.g. Robertson & Kravtsov 2008; Krumholz *et al.* 2009b; Gnedin & Kravtsov 2010; Krumholz & Dekel 2012; Christensen *et al.* 2012). However, one must ask whether correlation implies causation.

Indeed, other measurements of high density gas ($n > 10^4$ cm^{-3}) also yield linear correlations with star formation. Gao & Solomon (2004) demonstrated that observations of HCN emission linearly correlate with Σ_{SFR}, while Lada *et al.* (2010) showed a direct correlation between the number of young stellar objects in a region and the mass of material with K-band extinction $A_K > 0.8$.

The reason for this is that molecules do not appear to control star formation in the presence of metals. Although molecular gas in fact dominates cooling of high density gas, this is coincidental: pure atomic gas at the same densities can cool virtually as effectively so long as it contains even small amounts of metals. Analytic models (Krumholz *et al.* 2011) and numerical experiments (Glover & Clark 2012a) demonstrate that the key to effective cooling is not molecule formation, but rather dust shielding from photoelectric heating. Removing molecular cooling from the models changes the minimum temperature from 5 K to 7 K, while removing shielding increases the minimum temperature by an order of magnitude or more (Glover & Clark 2012a). Indeed, Hopkins *et al.* (2011) demonstrates that well-resolved (parsec kernel size) galaxy formation models produce the same result whether star formation is limited to only occur in molecular gas, or is allowed to occur in all dense gas.

Molecular hydrogen formation occurs quickly at high density (Glover & Mac Low 2007), so as stars form through gravitational collapse, molecules inevitably form. Glover & Clark (2012b) demonstrated that this happens almost independent of metallicity, even though molecule formation depends on metallicity. At solar metallicity, collapse occurs within a free-fall time (Krumholz 2012). However, cooling occurs even more quickly, within a free-fall time even for gas at metallicity $Z > 10^{-4}$ Z$_\odot$. Krumholz (2012) demonstrates that in such low-metallicity gas, cooling occurs within a free-fall time, but molecular hydrogen formation is delayed so severely that star-formation proceeds with molecule formation only occurring in the very densest core of the collapsing region, leading to low integrated molecular fractions despite ongoing star formation.

6. Gravitational Instability

I hypothesize that gravitational instability controls the rate of star formation in galaxies. We can heuristically derive the Toomre (1964) criterion for stability of a rotating, thin disk with uniform velocity dispersion σ and surface density Σ using time scale arguments (Schaye 2004), as described in Mac Low & Klessen (2004). The Jeans criterion for instability in a thin disk, requires that the time scale for collapse of a perturbation of size λ

$$t_{\mathrm{coll}} = \sqrt{\lambda/G\Sigma} \tag{6.1}$$

be shorter than the time required for the gas to respond to the collapse, the sound crossing time

$$t_{\mathrm{sc}} = \lambda/c_{\mathrm{s}}. \tag{6.2}$$

This implies that gravitational stability requires perturbations with size

$$\lambda < c_{\mathrm{s}}^2/G\Sigma. \tag{6.3}$$

Similarly, in a disk rotating differentially, a perturbation will rotate around itself, generating centrifugal motions that can also support against gravitational collapse. This will be effective if the collapse time scale t_{coll} exceeds the rotational period $t_{\mathrm{rot}} = 2\pi/\kappa$, where

κ is the epicyclic frequency, so that stable perturbations have

$$\lambda > 4\pi^2 G\Sigma/\kappa^2. \tag{6.4}$$

Gravitational instability occurs if there are wavelengths that lie between the regimes of pressure and rotational support, with

$$\frac{c_{\rm s}^2}{G\Sigma} < \lambda < \frac{4\pi^2 G\Sigma}{\kappa^2}. \tag{6.5}$$

This will occur if

$$Q = c_{\rm s}\kappa/(2\pi G\Sigma) < 1, \tag{6.6}$$

which is the Toomre criterion for gravitational instability to within a factor of two. The full criterion from a linear analysis of the equations of motion of gas in a shearing disk gives a factor of π rather than 2π in the denominator (Safronov 1960; Goldreich & Lynden-Bell 1965), while a kinetic theory approach appropriate for a collisionless stellar system gives a factor of 3.36 (Toomre 1964).

When collisionless stars and collisional gas both contribute to gravitational instability, a rather more complicated formalism is required to accurately capture their combined action (Gammie 1992; Rafikov 2001). This has been, it should be noted, successfully approximated with simple algebraic combinations of the stellar and gas Toomre parameters (Wang & Silk 1994; Romeo & Wiegert 2011). In the presence of turbulent dissipation, Elmegreen (2011) demonstrates that there is no longer a formal minimum wavelength for gravitational collapse, although finite disk thickness does act to stabilize the smallest wavelengths against collapse.

The relationship between global gravitational instability and star formation can be seen in numerical experiments. For example, Li *et al.* (2006) used models of isothermal, exponential gas disks embedded in live stellar disks and dark matter halos, with gas temperatures fixed near 10^4 K, to study gravitational collapse as the strength of the gravitational instability varied. They fully resolved the Jeans length during collapse up to pressures $P/k = 10^7$ cm^{-3} K^{-1}, and then used sink particles to measure the amount of gas reaching these high densities. This required kernel sizes less than 40 pc and several million particles. They found not only that all their models fell cleanly on the global correlation of Kennicutt (1998), but also, as shown in Figure 2, that an analysis of azimuthal rings predicts the behavior of the local correlation observed by Bigiel *et al.* (2008).

Another example of the strength of this hypothesis lies in the understanding of the unusual morphologies of many high-redshift galaxies. Elmegreen *et al.* (2009) shows that clumpy, irregular galaxies are far more common at redshifts $z \sim 2$ than in modern times. Because accretion rates were far higher then, galaxies tended to be far more gas-rich than now, and as a result were more likely to be strongly gravitationally unstable. Agertz *et al.* (2009) were one group that used well-resolved adaptive mesh computations to show that such conditions naturally lead to the formation of giant, gravitationally bound clumps.

An extended version of the hypothesis has been put forward by Ostriker *et al.* (2010), and developed in subsequent papers (Ostriker & Shetty 2011; Kim *et al.* 2011). They argue that star formation is controlled by the combination of gravitational instability and thermal equilibrium, because feedback increases as instability gets stronger, until it heats the gas sufficiently to reduce the amount of gravitationally unstable gas enough to reach a steady state.

Although resolving feedback in models reaching cosmological scales remains tremendously difficult, computers have become sufficiently powerful and algorithms well developed enough for this to fall within the realm of the possible. Hopkins *et al.* (2011) present one early example of this ability, with SPH models having minimum kernel resolution of only 1 pc. This appears to be sufficient, even with the enhanced numerical diffusivity introduced by the SPH algorithm (Bauer & Springel 2012), to maintain the energy of the hot gas and allow a dynamically realistic interstellar medium to form. These models do use rather stronger radiative pressure feedback than would be recommended by Krumholz & Thompson (2012), but comparison with models completely without radiative pressure suggests that this does not represent a significant error. A major result from these models is that star formation rates agreeing with observed values finally seem to be within reach.

7. Small Scales

The conclusions drawn here have mostly focused on the effects of feedback at scales larger than a few parsecs. This is appropriate for supernova feedback, because most supernovae occur far in time and space from the dense molecular gas in which they formed: because of the steepness of the initial mass function (Salpeter 1955), the vast majority of Type II supernovae have B star progenitors with lifetimes of 10–40 Myr. However, this is not the case for either ionization or radiation pressure, both of which come predominantly from the very most massive stars, with lifetimes of only a few million years: an O4 star, for example, has ten times the ionizing luminosity of an O8 star, and 500 times that of a B0 star (Vacca *et al.* 1996). To understand the effects of these processes on the diffuse ISM, small scale models that capture the interaction of radiation with molecular gas on sub-parsec scales, such as those by Peters *et al.* (2010), will need to be included either directly, or as sub-grid scale models.

8. Summary

In this talk I have discussed how star formation proceeds over cosmic time. I began with the observational evidence that has accumulated over the last five years demonstrating that at redshifts $z > 2$, star formation drops off far more steeply with redshift than had been thought previously (Sect. 1). Theoretical predictions of substantially higher star formation rates at high z seem to have been due to overcooling in small galaxies due to poorly modeled feedback, as well as a lack of quenching of cooling flows onto the most massive galaxies. Focusing on the former problem, I explained why modeling of feedback requires that high temperature ($T > 10^6$ K) gas be resolved with sufficient numerical resolution to avoid artificial loss of energy through unphysical radiative cooling (Sect. 2).

The importance of feedback comes primarily because it drives turbulence that, on average, strongly inhibits star formation (Sect. 3). Although it can locally trigger star formation, this is only a 10–20% effect in the best of cases. The turbulence observed in both galaxies and molecular clouds has many possible sources (Sect. 4). One that has received much recent interest, radiative pressure, may be less effective than first thought because of Rayleigh-Taylor instabilities. Although gravity clearly can play a role in driving the turbulence, it must ultimately be supplemented by other sources. Otherwise, models without or with ineffective stellar feedback would be sufficient to reproduce observed star formation rates.

Observed correlations between gas surface densities and star formation rate can help us to understand how star formation proceeds. However, we must remember that correlation does not prove causation. In Sect. 5 I give evidence that the strong correlation between

the surface density of H_2 and star formation occurs because both trace dense gas, rather than because the formation of H_2 must occur prior to star formation. The key instead appears to be that enough dust shielding must be present to prevent photoelectric heating and allow cooling of the gas to around 10 K. I then argue in Sect. 6 that gravitational instability controls the amount of dense gas, and thus of star formation in galaxies.

Finally, in Sect. 7 I note the complications to be found below the parsec scale. Although they do not affect supernova-driven feedback strongly, they do matter for ionization and radiation pressure, as those are dominated by the very most massive stars, which finish their lifetimes prior to dissipation of their natal dense gas clouds.

Acknowledgements

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