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STELLAR FEEDBACK FROM SUB-PARSEC TO GALACTIC SCALES

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Abstract. In this review talk, I discuss a number of open questions concerning the impact of stellar feedback from sub-parsec to galactic scales. In particular, we will focus on the relative impact of stellar winds and ionizing radiation from massive stars on the disruption of molecular clouds. Other feedback mechanisms such as supernovae, protostellar outflows, and radiation pressure will be only briefly discussed. For the simplified case of a spherical, virialized molecular cloud, I will compare the mass loss driven by stellar winds in the energy-driven and momentum-driven limits. One can easily show that stellar winds can substantially reduce the star formation efficiency of a molecular cloud only if they are energy-driven, i.e. in the limit that radiative cooling is negligible, which is typically not the case. Radiation seems to be the dominant feedback mechanism overall. Yet, this result remains to be confirmed on different spatial scales (from small scales such as cores within molecular clouds to large, galactic scales) and for different galactic environments (as quantified by e.g. different gas surface densities and metallicities).

1 Feedback by massive stars

Massive stars ($M_\star > 8\,\mathrm{M}_\odot$) are rare: on average, per 100 $\mathrm{M}_\odot$ of gas that is converted into stars only one massive star is formed. This estimate is based on the stellar initial mass function (IMF) by Chabrier (2003), but the stellar IMF by Kroupa (2001) gives a very similar estimate. The high-mass slope of both, the Chabrier and Kroupa IMFs, is steep and follows the result of Salpeter (1955). Massive stars are special because they have short life times of only a few million years. Stars with masses of more than $\sim 100\,\mathrm{M}_\odot$ can only sustain nuclear fusion for less than 4 million years. Upon their death, they explode as a core-collapse supernova, releasing about $E_\mathrm{SN} \approx 10^{51}$ erg into the surrounding medium (Janka, 2017), or they collapse into a stellar-mass black hole.

In Fig. 1 (taken from Brugaletta et al., in prep.), we show example stellar evolution tracks for massive stars with different zero-age main sequence (ZAMS) masses and different metallicities normalized to solar metallicity ($\mathrm{Z}_\odot$). For the case of 1 $\mathrm{Z}_\odot$, we show the commonly used Geneva tracks (Ekström et al., 2012) as well as the so-called BoOST stellar evolution tracks (Brott et al., 2011; Szécsi et al., 2022), which are also available for lower metallicities. The Geneva models are less luminous than the MW ones, with the exception of the last Myr of their evolution. The massive stars in the Geneva models seem to live longer. Partly the explanation for the apparently prolonged life time is that the Geneva models are evolving the massive stars until the end of the core carbon–burning phase, while the BoOST models are already stopped when the core is depleted of helium. However, there is still a discrepancy at earlier stages, which can be explained by different overshoot parameters, which determine the size of the convective core and hence the efficiency of mixing fresh hydrogen from the outer layers into the burning zone. The difference is most apparent for long-lived, relatively low-mass massive stars.

The left panel depicts the bolometric luminosity in units of solar luminosity ($L_\odot$) as a function of time and the right panel shows the ratio of wind luminosity to bolometric luminosity, where the wind luminosity, L_w is computed as

$$L_\mathrm{w} = \frac{1}{2} v_\mathrm{w}^2 \dot{M}_\mathrm{w}, \tag{1}$$

where v_w is the wind terminal velocity and $\dot{M}_\mathrm{w}$ is the wind mass loss rate. Both quantities are time-dependent. Generally, more metal-poor stars have weaker winds and higher bolometric luminosities. The ratio of wind to bolometric luminosity is small: depending on the ZAMS mass and metallicity, the ratio

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is between $\sim 10^{-6} - 10^{-2}$. If all energy available in the form of photons would be fully absorbed by the surrounding gas, the stellar winds would be unimportant. However, only a small fraction $\sim 10^{-3}$ of the available radiative energy is generally converted into thermal and kinetic energy of the surrounding gas (see e.g., Walch et al., 2012), although the exact fraction is quite uncertain and depends on the properties of the surrounding gas (e.g., Haid et al., 2018). Hence, stellar winds could provide an important contribution to dispersing the surrounding gas, in particular for quite massive stars.

The relative importance of the feedback by stellar winds also depends on whether the wind bubble is subject to radiative cooling. In the following section, we discuss this in more detail.

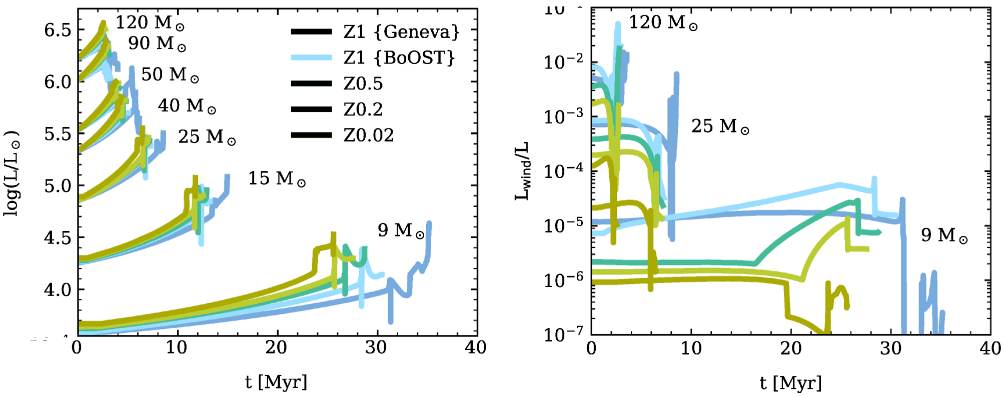

Figure 1: *Left panel:* Time evolution of the bolometric luminosity for massive stars with different initial masses and metallicities. For solar metallicity, we show the commonly used Geneva tracks as well as the BoOST model results (see text for references). *Right panel:* Time evolution of the ratio of stellar wind to bolometric luminosity for three initial stellar masses. The figure is taken from Brugaletta et al. (2023).

2 Energy-driven vs. Momentum-driven Winds

In this section we will estimate the efficiency of outflows driven by wind-blown bubbles which come in two flavours: energy-driven (essentially no cooling case) and momentum-driven (essentially maximum cooling case). The two will be compared with respect to unit stellar mass, respectively star formation rate.

In galaxy formation, a quantity that is often calculated and measured is the so-called mass loading, ζ, the ratio of mass outflow rate to star formation rate

$$\zeta = \frac{\dot{M}_{\rm w,MC}}{\dot{M}_{\rm SFR}}. \tag{2}$$

Here we are concerned with the outflow from molecular clouds and we will therefore use the index "MC" to indicate mass loss from the cloud overall.

Here we assume that the molecular clouds are virialized and that the balance of gravity and kinetic motions determines their escape velocity and we will use that to estimate how much mass may be unbound. This assumption is not necessarily true as we see in simulations that the MCs are not globally bound.

The viral theorem gives us

$$\frac{3}{2}\sigma^2 \sim \frac{1}{2}v^2 = \frac{3}{5}\frac{GM_{\rm MC}}{R_{\rm MC}}, \tag{3}$$

where σ is the velocity dispersion, $M_{\rm MC}$ is the cloud mass, $R_{\rm MC}$ is the cloud radius, and we have assumed a homogeneous, spherical cloud. This implies, that the escape velocity is essentially given as

$$v_{\rm esc} \sim \sqrt{\frac{GM_{\rm MC}}{R_{\rm MC}}}. \tag{4}$$

For a typical MC with a mean number density of approximately $n \sim 100\,{\rm cm}^{-3}$ and surface density of $\Sigma \sim 130\,{\rm M}_\odot{\rm pc}^{-2}$, which we get when plugging in $M_{\rm MC} = 10^6$ M$_\odot$ and $R_{\rm MC} = 50$ pc, we assume $v_{\rm esc} \sim 10\,{\rm km\,s}^{-1}$.

Further, we know from integrating over the whole IMF, that of the order of 1 massive star is formed per $100\,M_\odot$ of gas that is turned into stars. This means that there is an efficiency for the number of stars that produce a significant wind with respect to all stars

$$\eta_\mathrm{w} = 0.01\,\mathrm{M}_\odot^{-1}. \tag{5}$$

2.1 Energy-driven case

The energy provided by the stellar wind is

$$\dot{E}_{\mathrm{w},\star} = L_\mathrm{w} = \frac{1}{2}\dot{M}_\mathrm{w} v_\mathrm{w}^2 \tag{6}$$

The wind of a $60\,\mathrm{M}_\odot$ star delivers about 10^{51} erg over his lifetime, similar to the energy input by the final supernova.

However, the average wind energy input is about 2 orders of magnitude lower because lower-mass stars have significantly weaker winds. We assume an average integrated wind energy input of $\bar{E}_w = 10^{49}$erg.

Hence, the feedback in the form of stellar winds that is provided by a stellar population of mass $M_\star$, which we assume to follow a fully sampled IMF (so this breaks down for low-mass clouds), is

$$E_\mathrm{fb,w} = \epsilon_\mathrm{w}\eta_\mathrm{w}\bar{E}_w M_\star, \tag{7}$$

where we have introduced $\epsilon_\mathrm{w} \leq 1$, the fraction of the wind energy that is cooled away.

The energy in mass that is unbound and ejected from the MC is given as

$$E_\mathrm{fb,ej} = \frac{1}{2}v_\mathrm{esc}^2 M_\mathrm{fb,ej}, \tag{8}$$

where $M_\mathrm{fb,ej}$ is the total mass that can be unbound from the MC.

Now equating the two energies, we can derive the ratio of unbound mass by stellar wind feedback to stellar mass

$$\frac{M_\mathrm{fb,ej}}{M_\star} = 2\epsilon_\mathrm{w}\eta_\mathrm{w}\frac{\bar{E}_w}{v_\mathrm{esc}^2} = \epsilon_\mathrm{w} \times 0.02\mathrm{M}_\odot^{-1}\frac{10^{49}\,\mathrm{erg}}{10^{12}\,\mathrm{cm}^2 s^{-2}} = 100\epsilon_\mathrm{w}. \tag{9}$$

This implies that in the case of $\epsilon_\mathrm{w} = 1$, the star formation efficiency in such a cloud would be reduced to $\sim$ 1% due to the feedback from winds alone.

However, it is unlikely that $\epsilon_\mathrm{w} = 1$ because the hot wind bubbles are subject to efficient cooling if they interact with dense material. The exact cooling rate per unit time however is difficult to compute as it depends on small-scale turbulent mixing layers near the wind bubble shell, while the cooling of the bubble by expansion is rather weak.

Based on a fractal description of the bubble surface, Lancaster et al. (2021a) develop an analytical model to describe how the cooling of stellar wind bubbles in turbulent mixing layers affects the wind bubble expansion and momentum input. They find that the momentum delivered by a wind bubble with a fractal, cooling surface is a factor of 10 - 100 smaller than the values predicted by the Weaver et al. (1977) solution for the same bubble radius. In the case where substantial energy is lost by radiative cooling, which is a rather likely case (see e.g., Lancaster et al., 2021b), the wind bubble becomes momentum-driven.

2.2 Momentum-driven case

We can now compute the case of a momentum-driven wind, where thermal effects are ignored and hence this corresponds to the case of maximum cooling.

In this case, the momentum input by stellar winds of a stellar population is equated with the momentum required to unbind gas from the molecular cloud.

$$\dot{p}_\mathrm{fb,w} = \dot{p}_\mathrm{fb,ej}. \tag{10}$$

The individual terms read

$$\dot{p}_\mathrm{w} = \sum_{N_\star}\dot{M}_\mathrm{w} v_\mathrm{w} \sim \sum_{N_\star} 5\times 10^{20}\,\frac{\mathrm{g\,cm}}{\mathrm{s}}, \tag{11}$$

where the sum goes over all $N_\star$ massive stars that are active at a given evolutionary time of the stellar cluster. For a cluster that is forming stars according to a fully sampled IMF, the mean momentum input per unit time is given. The momentum input by the wind can then be formulated using the probability that a massive star will form as

$$\dot{p}_{\mathrm{fb,w}} = \dot{M}_{\mathrm{w}} v_{\mathrm{w}} \eta_{\mathrm{w}} M_{\star} \epsilon_{\mathrm{mom}}, \tag{12}$$

where we introduced an additional factor $\epsilon_{\mathrm{mom}} \geq 1$, which considers the possibility of additional momentum driving due to the expansion of the hot bubble rather than intrinsic momentum input by the massive stars.

On the other side, we have

$$\dot{p}_{\mathrm{fb,ej}} = \dot{M}_{\mathrm{fb,ej}} v_{\mathrm{esc}}. \tag{13}$$

Equating the two gives us

$$\frac{\dot{M}_{\mathrm{fb,ej}}}{\dot{M}_{\mathrm{star}}} \approx \epsilon_{\mathrm{mom}} 0.01\,\mathrm{M}_{\odot}^{-1} \frac{100\,\mathrm{M}_{\odot}\mathrm{kms}^{-1}}{10\,\mathrm{kms}^{-1}} = 0.1\epsilon_{\mathrm{mom}}. \tag{14}$$

Matzner (2002) give a number of $38\,\mathrm{M}_{\odot}\mathrm{kms}^{-1}$ rather than $100\,\mathrm{M}_{\odot}\mathrm{kms}^{-1}$, but the two numbers are reasonably close.

Overall, we can see that this process is very inefficient and that momentum-driven winds are not strong enough to cause significant mass blow-out and/or reduce the SFR of this molecular cloud, which could still be as high as 90% if only wind feedback would be taken into account.

3 The impact of ionizing radiation

Overall, assuming that we are in a cold and dense molecular cloud environment, stellar winds seem to be less efficient in dispersing molecular clouds than ionizing radiation. On scales of several hundred parsec, this has been shown by Rathjen et al. (2021), who compare the evolution of the multi-phase interstellar medium in galactic discs with different feedback mechanisms. The simulations are carried out within the SILCC collaboration (Walch et al., 2015; Girichidis et al., 2016). In Fig. 2, we show the resulting star formation rate surface density as a function of the gas surface density for these runs. It is apparent that runs with stellar winds but without ionizing radiation have much higher star formation rates. These simulations also demonstrate that supernovae alone do not regulate the star formation efficiency down to the observed level. The reason is that supernova feedback starts late with respect to the free-fall time of a molecular cloud (see section 1), and hence too much gas has already collapsed into stars before the first supernova explodes.

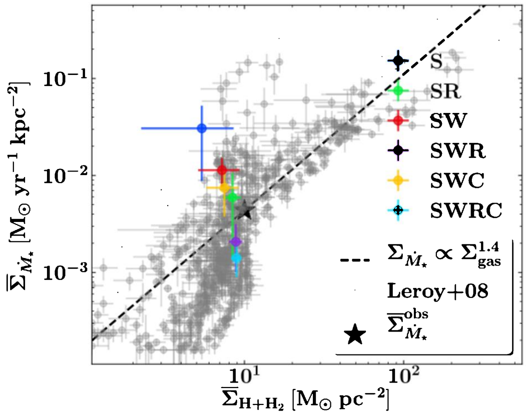

Figure 2: The Kennicutt-Schmidt relation (Kennicutt, 1998) for SILCC simulations of the multi-phase interstellar medium with solar neighbourhood conditions testing the effect of different combinations of stellar feedback. The grey points show the observational results from Leroy et al. (2008). The models include the following feedback processes: "S" - only supernova feedback; "SR" - supernovae and ionizing radiation; "SW" - supernovae and stellar winds; "SWR" - supernovae, winds, and ionizing radiation; "SWC" - supernovae, winds, and cosmic rays which are presumably accelerated when supernovae explode; "SWRC" - all processes combined. Clearly, models with stellar winds but without ionizing radiation show too high star formation rates, thus demonstrating that stellar winds cannot reduce the star formation efficiency to the observed level. The figure is from Rathjen et al. (2021), their Fig. 6.

Also on scales of individual molecular clouds, simulations demonstrate that ionizing radiation can efficiently disperse molecular clouds with moderate surface densities and masses. This has been shown, e.g., by Walch et al. (2012); Geen et al. (2015); Fukushima et al. (2020) for isolated clouds and by Haid et al. (2019) for molecular clouds that have formed self-consistently from the multi-phase interstellar medium. The star formation efficiency in these models can be reduced to 10% - 15% by ionizing radiation alone. Further, also for isolated molecular cloud simulations, Dale et al. (2014) demonstrate that stellar winds have a weak impact on the clouds. In particular momentum-driven winds are ineffective (Dale et al., 2013) as expected from the analytical derivation from above. The combination of winds and ionizing radiation, however, is more effective than only ionizing radiation (see also the review by Dale 2015). That the combination of both processes does lead to reduced star formation efficiencies has also been pointed out by the so-called Warpfield models (Rahner et al., 2019). Yet, all of these simulations (apart from Haid et al., 2019) start with cold, basically spherical, turbulent clouds. But the relative impact of winds and ionizing radiation depends on the environment with which the star interacts. This has been shown by Haid et al. (2018), who find that stellar winds become the dominant source of momentum input if the massive star's environment is already hotter than $\sim 10^4$ K and largely ionized. Generally, this environment would be called the warm ionized medium (WIM).

In Fig. 3, we show the analytical estimate on the relative impact of stellar wind and ionizing radiation in different environments. In the WIM, the momentum gain caused by the expansion of the HII region which, in cold environments, is largely driven by the work done by the pressure-gradient term which is high across the interface of the hot HII region and the surrounding cold gas, is negligible. In such an environment, the radiative cooling of the turbulent wind bubble shell is also reduced, as the gas density of the surrounding medium is reduced compared to cold molecular cloud environments. Hence, the expansion of the wind bubble provides the dominant source of momentum input in the WIM.

As a star-forming molecular cloud evolves, it is likely that ionizing radiation dominates the early phases of the cloud's evolution after star formation has begun. As the forming star cluster becomes more exposed, the importance of stellar winds might increase.

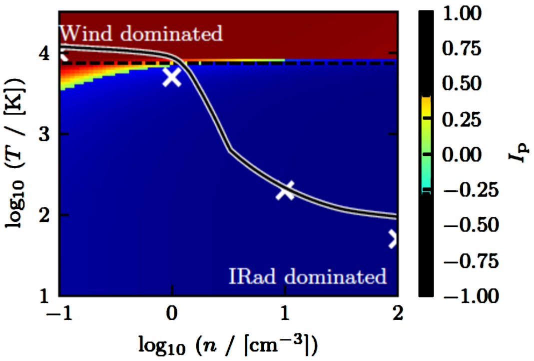

Figure 3: Temperature-density phase space representing the environmental conditions of a massive star that provides momentum input by ionizing radiation and stellar winds. The dominating source of momentum input as calculated from an analytical model is colour-coded. The quantity $I_{\rm p} \equiv (p_{\rm wind} - p_{\rm IRad})/(p_{\rm wind} + p_{\rm IRad})$ gives the relative impact of wind and ionizing radiation. Clearly, momentum input in the WIM is dominated by stellar winds, while cold environments are dominated by ionizing radiation. The white crosses indicate the results of numerical simulations which we carried out to test the analytical model. This figure is from Haid et al. (2018).

4 Towards a full account of stellar feedback

So far we have discussed the role of ionizing radiation and stellar winds in shaping the dispersal of a molecular cloud before the first supernova explodes. Yet, all these processes require the presence of massive stars.

If massive star formation has not yet taken place or is not happening (e.g. in the case of a low-mass molecular cloud), observations still show that the star formation efficiency is low. Therefore, the role of feedback by accretion heating and protostellar jets and outflows, which is feedback provided by young and low-mass stars, has been considered. Simulations of collapsing isolated turbulent clouds show that mostly the stellar accretion-powered radiative feedback and the associated local heating and increase in thermal pressure regulates star formation on small scales (see e.g. Cunningham et al. 2018; but also Price & Bate 2009). This process seems to be important for setting the peak of the stellar IMF.

Lately, the STARFORGE simulations (Grudić et al., 2021) aim to take full account of all feedback processes, including all of the above, plus radiation pressure. They study the relative impact of the different processes on star formation in an isolated, weakly magnetized molecular cloud with an initial mass of

$2 \times 10^4\,\mathrm{M}_\odot$. They find that the energy input is dominated by stellar radiation and that the accretion luminosity is only important in the first phases of star formation. Jets and winds seem to be of subordinate importance, but also ionizing radiation is not that effective in their simulations because they study a rather low-mass molecular cloud which does not host a high number of massive stars. In this case, protostellar jets do overall add more momentum to the environment than stellar winds. Radiation pressure is suggested to become more important for more massive clusters as the amount of trapped infrared radiation increases with the cloud's surface density (Jumper & Matzner, 2018).

5 Concluding remarks

This review does by no means cover the vast amount of available literature on the subject. But it aims to convey the notion that theory and simulation results tell us that there is a clear winner in the run for the most effective feedback process with respect to regulating star formation in molecular clouds: radiation. On small scales and in newly star-forming clouds, radiation released by accretion luminosity limits stellar mass growth. On larger scales and after massive stars have been born, ionizing radiation can disperse molecular clouds, thus locally stopping further star formation. The question is whether this is still the case for massive clouds with high surface densities or not. Models of massive clouds with all the different feedback processes remain to be carried out. Only then the relative importance over a whole cloud lifetime can be measured. Stellar wind bubbles are not energy-driven because the limit of "no cooling" is unrealistic. They are not purely momentum-driven either, but a bit more efficient than that. The exact impact requires studies with very high resolution as the turbulent mixing layers between the hot wind bubble and the surrounding gas are the main regions of radiative energy loss.

What is missing? At the moment we are lacking an account of feedback across entire galaxies, hence in very different environments (e.g. surface density and gas metallicity). Further, we need good tools and methods to compare simulations and observations in order to reconcile the theoretical results with the real data. Third, a closer interaction between the local and the high-redshift communities is needed to understand the role of stellar feedback across cosmic time.

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