Accretion-regulated star formation in late-type galaxies

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Abstract. We develop a four-phase galaxy evolution model in order to study the effect of accretion of extra-galactic gas on the star formation rate (SFR) of a galaxy. Pure self-regulated star formation of isolated galaxies is replaced by an accretion-regulated star formation mode. The SFR settles into an equilibrium determined entirely by the gas accretion rate on a Gyr time scale.

1. Introduction

The galactic star formation process is understood to be self-regulated: An increasing star formation activity leads to an increase of the energetic feedback to the interstellar medium (ISM) by supernovae, stellar radiation and stellar winds heating up the cold gas component from which stars form, suppressing further star formation. After decrease of stellar feedback on-going cooling of the ISM leads to an increase of the cold gas component and star formation rises again. These negative feedback processes lead to a self-regulated equilibrium of star formation \citep{KoppenTheisHensler1995}. The star formation rate (SFR) is correlated with the cold gas density as found by \cite{Schmidt1959} or with the gas surface density \citep{Kennicutt1998}. An isolated galaxy would then be depleted in gas and the SFR decreases continuously.

Indeed large gas reservoirs have been found around star forming galaxies which are able to refuel galaxies. In individual studies of local star forming galaxies gas accretion rates have been estimated by dividing the mass of extra-galactic gas stored in the extended gas reservoirs through the infall time scale. These calculated accretion rates are of the order of the current SFR which has lead to the conclusion that gas accretion can sustain long-term high-level SFRs. This requires that the SFR settles into an equilibrium determined by the accretion rate and that the self-regulated mode of galactic star formation is replaced by an accretion regulated process.

We here quantify with a galactic four-phase model if and how fast the accretion regulated star formation equilibrium is established.

2. Model

The galaxy evolution model used here to study the effect of gas accretion is the four phase model developed in \cite{KoppenTheisHensler1998} for an isolated galaxy
without gas accretion. The four phases are: i) hot gas, \( g \), fed by supernovae, ii) cold and warm gas, \( c \), from which stars form, iii) high-mass stars, \( s \), driving the energetic feedback, and iv) remnants, \( r \), which are long-lived low-mass stars and stellar remnants of high-mass stars, i.e. black holes and neutron stars. The matter and energy cycle in this four phase model is illustrated in Figure 1.

The galaxy evolution model is described by four equations quantifying the time derivatives of the mass density of the four phases,

\[
\begin{align*}
\dot{c} &= -\Psi + E_c + K_g + A_c \quad (1) \\
\dot{g} &= \frac{\eta}{\tau} s + E_c - K_g \quad (2) \\
\dot{s} &= \xi \Psi - \frac{1}{\tau} s \quad (3) \\
\dot{r} &= (1 - \xi) \Psi + \frac{1 - \eta}{\tau} s, \quad (4)
\end{align*}
\]

where \( A_c \) is the accretion rate, \( \Psi \) the star formation rate, \( E_c \) the evaporation rate of cold and warm cloud material, \( K_g \) the condensation rate of gas, \( \xi \) the formation fraction of high-mass stars, \( \eta \) their gas return fraction and \( \tau \) their mean life time.

The exchange of energy between hot gas, \( g \), and cold and warm gas, \( c \), is formulated by

\[
\dot{e}_g = h_{SN} s - g^2 \Lambda_0(T_g) + E_c b T_c - K_g b T_g \quad (5)
\]
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\[ \dot{e}_c = h_{SN} s - c^2 A_0(T_c) - E_c bT_c + K_g b\bar{T}_g - \Psi bT_c + bT_{\bar{A}_c} A_c + \frac{1}{2} v_c^2 A_c , \] (6)

where \( h_{SN} \) is the heating coefficient by supernovae, \( h_{\gamma} \) the heating coefficient by ionising radiation, \( A_0 \) the cooling function, \( T_c \) the temperature of the clouds, \( \bar{T}_c \) temperature of evaporated clouds when entering the hot gas, and \( T_g \) the temperature of the hot gas, \( \bar{T}_g \) the temperature of the hot gas when condensing onto the clouds, \( T_{\bar{A}_c} \) is the temperature and \( v_c \) the infall velocity of the accreted gas.

A full description of the calculation of the parameters can be found in Pflamm-Altenburg & Hensler (in prep.).

3. Constant accretion

In the case of constant accretion it is expected that the SFR will settle into an equilibrium. An expression for the equilibrium can be derived by setting \( \dot{\gamma} = \dot{e} = \dot{s} = 0 \) in eq. 1–4. The equilibrium SFR is then determined by the accretion rate,

\[ \Psi = \frac{1}{1 - \xi \eta} A_c . \] (7)

For typical values of \( \xi \approx 0.9 \) and \( \eta \approx 0.1 \) (Pflamm-Altenburg & Hensler, in prep.) it follows that the accretion rate amounts to \( \approx 90 \% \) of the equilibrium SFR. The remaining \( 10 \% \) is covered by returned material from high-mass stars.

Note that the equilibrium SFR is independent on the local formulation of the star formation law, i.e. the slope of a Schmidt-type or Kennicutt-Schmidt-type description of the star formation rate density or surface density. This implies that star formation, which is locally self-regulated and described by a gas-density dependent formula, is globally described by an accretion regulated mode.

If and how fast this equilibrium is reached can be studied by numerical integration of the set of equations 1–5. Fig 2 (left) shows the evolution of the SFR density for different accretion rates (solid curves). For comparison, the thick solid line shows the case of pure self-regulation without accretion. The dashed lines mark the equilibrium SFRs calculated with eq. 7. It can be seen that in the case of constant accretion the SFR approaches the equilibrium value on a Gyr time scale if the accretion rate drives an equilibrium SFR which is larger than the corresponding self-regulation SFR. If the equilibrium SFR determined by the accretion rate is lower than the self-regulation SFR then the evolution follows the self-regulated star-formation mode.

The evolution of the corresponding gas mass fractions are shown in Fig. 2 (right). It can be seen that the gas mass fractions decrease faster with increasing accretion rate. An isolated galaxy which is purely self-regulated consumes the gas on the longest time scale, whereas galaxies with highest accretion rates experience high SFRs so that the gas mass fractions becomes the lowest.

4. Conclusion

Using a four-phase galaxy evolution model we have shown that in the case of accretion of extra-galactic gas the global star formation process switches from pure self-regulation into an accretion regulated mode. Under these circumstances the accretion-regulated SFR is simply determined by the accretion rate (eq. 7). If large-scale star
formation is accretion-regulated then a varying gas accretion history implies naturally a varying star formation history. Additionally, as star-forming galaxies are extended objects an inhomogeneous infall is expected to cause an inhomogeneous star formation pattern. These issues, how closely the star formation history is linked to the gas accretion history and how an inhomogeneous or radial varying gas infall would lead to an inhomogeneous or radial varying SFR will be explored in future studies.

References

Kennicutt, R. C., Jr. 1998, ApJ, 498, 541. astro-ph/9712213
Köppen, J., Theis, C., & Hensler, G. 1995, A&A, 296, 99
— 1998, A&A, 331, 524
Schmidt, M. 1959, ApJ, 129, 243