PLAYING WITH POSITIVE FEEDBACK: EXTERNAL PRESSURE-TRIGGERING OF A STAR-FORMING DISK GALAXY

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ABSTRACT

In massive galaxies, the currently favored model for quenching star formation is via active galactic nuclei (AGN) feedback, which ejects gas from the galaxy using a central supermassive black hole. At high redshifts however, explanation of the huge rates of star formation often found in galaxies containing AGNs may require a more vigorous mode of star formation than is attainable by simply enriching the gas content of galaxies in the usual gravitationally driven mode that is associated with the nearby universe. Using idealized hydrodynamical simulations, we show that AGN-pressure-driven star formation potentially provides the positive feedback that may be required to generate the accelerated star formation rates observed in the distant universe.

Key words: galaxies: active – galaxies: formation – methods: numerical

1. INTRODUCTION

The remarkable universality of the Schmidt–Kennicutt star formation relation, ranging from global fits to star-forming galaxies in the nearby universe (Kennicutt 1998) and local fits to star-forming complexes within galaxies (Kennicutt et al. 2007) and to star-forming galaxies to z ∼ 2 (Genzel et al. 2010) inspires considerable confidence in the theory of gravitational instability-driven star formation in galactic disks (Krumholz et al. 2012). There are exceptions, most notably in molecular complexes with anomalously low star formation rates (SFRs; Rathborne et al. 2014), but simple and plausible additions to the usual density threshold criterion for star formation, most notably by incorporating turbulence, may go far toward resolving these issues, as demonstrated both theoretically (for a review, see Kritsuk et al. 2011) and phenomenologically in well-resolved examples such as NGC 253 (Leroy et al. 2015).

In the high-redshift universe, the accumulation of recent data on remarkably high SFRs poses a fascinating challenge (e.g., Drouart et al. 2014; Piconcelli et al. 2015; Rodighiero et al. 2015). Is it simply a question of turning up the gas fraction or is a new mechanism at work for inducing more efficient star formation?

In this Letter, we reinforce the case for the latter, more radical view by simulating the evolution of a fully self-consistent, gas-rich star-forming disk galaxy that is subject to the overpressurising influence of a vigorous outburst from its central active galactic nuclei (AGNs). Star formation is a complex interplay between gas supply, multiphase interstellar medium (ISM), cloud collapse, and gas ejection from the disk. We will consider two cases, corresponding to gas-poor (gas fraction 10%) and gas-rich (gas fraction 50%) systems at z ∼ 2.

The case for inducing star formation via AGN activity has been made analytically (Silk & Norman 2009) and in simulations (Gaibler et al. 2012; Ishibashi & Fabian 2012; Wagner et al. 2012; Zubovas et al. 2013b) with varying degrees of astrophysical reality. The densities in the ISM of high-redshift clumpy galaxies are high compared to the densities of the jet. The important mechanism of jet feedback is thus the thermalization of the mechanical jet power, which transforms the highly anisotropic momentum of the bipolar, collimated jet into a nearly isotropic thermal pressure. As shown in simulations by Sutherland & Bicknell (2007), the jet initially pressurizes the disk through a central high pressure bubble; later, the entire galaxy is surrounded by a medium with enhanced pressure. Gaibler et al. (2012) simulated a powerful AGN jet within a massive gaseous, clumpy disk and showed that the jet activity causes a significant enhancement of SFR that is due to the formation of a bow shock resulting in the compression of the galactic disk. Generally, the simulations demonstrate that whether the AGN activity is jet or wind-induced is irrelevant: after a few kiloparsecs, both inputs are indistinguishable.

Furthermore, negative and positive feedback are not necessarily contradictory (Silk 2013; Zinn et al. 2013; Zubovas et al. 2013b, 2013a), and AGN activity may both quench and induce star formation in different parts of the host galaxy and on different timescales. Possible observational evidence of both positive and negative feedback is discussed in Cresci et al. (2015). The outflow observed removes gas from the host galaxy (negative feedback) but also triggers star formation by outflow-induced pressure (positive feedback).

Hitherto, however, star formation in the multiphase ISM has not been followed in adequate detail because of the lack of numerical resolution. For the first time, we study the effects of pressurization of the disk by performing simulations in which we fully include self-gravity of the multiphase ISM and thereby trace the evolution of the SFR as well as that of the gas content of the system. Because the effects of feedback on a clumpy media by a wind and by a jet are indistinguishable, pressurization of the disk in the simulation is induced in a general way.

2. SIMULATION SET-UP

To study the effect of an external pressure on a galaxy, we have performed four isolated disk galaxy simulations with two different initial gas fractions of 10% (hereafter gasLow) and 50% (hereafter gasHigh). We allow the galaxies, of one-tenth
the total mass of the Milky Way, to initially adiabatically relax to an equilibrium configuration (with a reasonable disk thickness) over the rotation time of the disk at its half-mass radius. After this first relaxation phase, we turn on the external pressure, gas cooling, star formation, and also feedback from supernovae (SNe), as will be described below.

In the initial conditions, the dark matter (DM) particles are sampled with a Navarro–Frenk–White (Navarro et al. 1997) density profile and a concentration parameter of \( c = 10 \) using the method introduced by Springel & Hernquist (2005). For the DM particles, the virial velocity is set to \( v_{200} = 70 \) km s\(^{-1}\), which corresponds to a virial radius of \( R_{200} \approx 96 \) kpc and a virial mass of \( M_{200} \approx 1.1 \times 10^{11} M_{\odot} \). We use \( 10^{6} \) DM particles with a mass resolution of \( 1.21 \times 10^{5} M_{\odot} \) to sample the DM halo. The stellar disk with a total stellar mass of \( M_{*} \approx 8.1 \times 10^{9} M_{\odot} \) for the \textit{gasLow} simulation and \( M_{*} \approx 4.6 \times 10^{10} M_{\odot} \) for the \textit{gasHigh} simulation was initially sampled with \( 5.625 \times 10^{5} \) particles, of which \( 6.25 \times 10^{4} \) were used to sample the bulge. The stellar particles are distributed in an exponential disk with a scale length of 3.44 kpc and scale height 0.2 kpc, and a spherical, non-rotating bulge with a Hernquist (1999) profile of scale radius 0.2 kpc. The scale length of the disk explores the two regimes of star formation in a Toomre stable and Toomre unstable disk, respectively, in order to show that extra pressure boosts the star formation not only in already star-forming galaxies, but can also trigger the star formation in disks that are initially stable against gravitational collapse (Martig et al. 2009).

The simulations are run with the \textsc{ramses} adaptive mesh refinement code (Teyssier 2002). The box size is 655 kpc with a coarse level of 7, and a maximum level of 14 corresponding to a maximum resolution of \( \Delta x = 40 \) pc. The refinement is triggered with a quasi-Lagrangian criterion: if the gas mass within a cell is larger than \( 8 \times 10^{5} M_{\odot} \) or if more than eight DM particles are within the cell, a new refinement level is triggered.

After relaxation, the origin of time was reset to zero and the base simulations were run further in time with an enhanced and uniform pressure outside the disk (\textit{pressure} simulations) for another \( \approx 0.42 \) Gyr. As mentioned in Section 1 above, the important mechanism of the feedback is the thermalization of the mechanical jet power transforming a highly anisotropic property (momentum of the collimated jet) into a nearly isotropic one (thermal pressure). Additionally, the bow shock in the simulation of Gabler et al. (2012) pressurizes the outer disk only a few Myr after pressurizing the inner disk. We therefore consider the academic case of a disk galaxy on which external pressure is applied continuously (starting at a reference time), throughout the galaxy, in a spherical geometry. The effects of isotropy and the geometry of the enhancement is deferred to a future work (Bieri et al. 2015). The assumption of a uniform positive pressure outside the galaxy is an approximation to the pressurization seen in Gabler et al. (2012). However, it allows us to study the effect of an enhanced pressure outside the galaxy in an isolated and controlled way.

To mimic a large-scale AGN jet that carries on mass down to the disk, a pressure enhancement is applied starting at \( t = 0 \) for a value of \( 3 P_{\text{max}} \) (hereafter pa3) outside the sphere of radius \( r_{1} = 12 \) kpc, where the transition between the two regimes is smooth. \( P_{\text{max}} \) is the maximum radially averaged pressure in the disk at \( t = 0 \) (reached in the central few cells), with \( P_{\text{max}} \approx 9.8 \times 10^{-13} \) Pa for the \textit{gasLow} simulation set and \( \approx 4.7 \times 10^{-12} \) Pa for the \textit{gasHigh} simulation set. The pressures expected can be estimated with some back-of-the-envelope calculations and relations derived by Krause (2003). Given that the jet density is low compared to the high-density ISM, we can assume, to first order, a constant background density. Assuming further that the jet delivers a constant amount of energy to their cocoons, the expansion of the cocoon goes as

\[
 r = \left( \frac{15 P_{\text{jet}} / 12 \pi \rho_{0}}{P} \right)^{1/5},
\]

where \( P_{\text{jet}} \) is the jet power, \( r \) the radius at which one measures the pressure, and \( t \) is the time of measurement. By assuming that the injected jet power \( (E = P_{\text{jet}} t) \) is injected over the volume of a spherical blast wave, we get a rough estimate of the pressure. With \( P_{\text{jet}} = 10^{44} \) erg s\(^{-1}\) and \( \rho_{0} = 1 \) H cm\(^{-3}\), we get an estimate of \( P \approx 5 \times 10^{-11} \) Pa. This is in agreement with the simulation by Gabler et al. (2012), which shows that the bow shock that pressurizes the gaseous disk has a pressure of \( P \approx 8 \times 10^{-11} \) Pa.

Sub-grid models for cooling Sutherland & Dopita (1993) and star formation, as well as SN feedback, were used in the simulations. Gas is turned into star particles in dense cold regions of gas density \( n_{\text{gas}} > n_{0} = 14 \) H cm\(^{-3}\) by drawing a probability from the Schmidt law \( \rho_{\text{gas}} / \rho_{0} = 0.01 \rho_{\text{gas}} / n_{\text{crit}} \) to form a star with a stellar mass of \( m_{*} = n_{0} \Delta V \approx 2 \times 10^{4} M_{\odot} \) (Rasera & Teyssier 2006). The gas pressure and density are evolved using the Euler equations, with an equation of state for a monoatomic gas with \( \gamma = 5/3 \). In order to prevent catastrophic and artificial collapse of the self-gravitating gas, we use a polytropic equation of state \( T = T_{0} (n_{\text{gas}} / n_{0})^{-\kappa} \approx 0.01 \) gas ff to artificially enhance the gas temperature in high gas density regions \( (n_{\text{gas}} > n_{0}) \). Here, \( \kappa = 2 \) is the polytropic index, and \( T_{0} = 270 \) K, chosen to resolve the Jeans length with a minimum of four cells (Dubois & Teyssier 2008). We account for the mass and energy release from SNe II. The energy injection, which is purely thermal, corresponds to \( E_{\text{SN}} = \eta_{\text{SN}} (m_{*} / M_{\odot}) 10^{50} \) erg, where \( \eta_{\text{SN}} = 0.2 \) is the mass fraction of stars going into SNe. We also return an amount \( \eta_{\text{SN}} m_{*} \) back into the gas for each SN explosion that occurs 10 Myr after the birth of the star particle. To avoid excessive cooling of the gas due to our inability to capture the different phases of the SN bubble expansion, we used the delayed cooling approach introduced by Teyssier et al. (2013).

3. RESULTS

3.1. Disk Fragmentation and Star Formation History

The application of external pressure at \( t = 0 \) leads to fragmentation of the gaseous galaxy disks, i.e., accelerated clump formation. This can be seen in Figure 1 for the \textit{gasLow} and in Figure 2 for the \textit{gasHigh} simulations. However, the \textit{gasHigh} case shows more gas between clumps in the enhanced pressure run, as well as more gas ejection from the disk.

Since the star formation recipe depends on the local gas density, we expect an enhanced star formation when more clumps are formed (gas gets more concentrated), assuming that the clumps have sufficient mass. Therefore, if external pressure leads to increased fragmentation and hence increased clump formation, we expect the star formation to be positively enhanced when external pressure is applied on the galaxy.
Figure 3 shows the SFR as a function of time. One can see that generally the SFR is larger when external pressure is applied. In the gasLow simulations, the SFR starts rising almost immediately and gradually after the pressure is applied. In the absence of external pressure, the star formation is at a modest rate ($\sim 0.1 \, M_\odot \, \text{yr}^{-1}$). This value is only reached at late times (after 300 Myr) once the gas has sufficiently collapsed to reach the star formation gas density threshold.

On the other hand, in the gasHigh simulations, star formation sets in at earlier times, even without any forcing by external pressure. This different behavior is related to differences in the Toomre (1964) $Q$ parameter in the galaxies of

![Figure 1](image1.png)  
**Figure 1.** Gas density maps (mass-weighted) for the gasLow simulations for no pressure enhancement (top) and for a pressure enhancement of a factor of 3 (bottom), with time evolving from left to right. The galaxies are shown both face-on (upper portion of the panels) and edge-on (bottom portion of the panels).

![Figure 2](image2.png)  
**Figure 2.** Same as in Figure 1, but for the gasHigh simulations.
the two simulations, such that the gaseous disk is stable in the gasLow case $\langle Q \rangle = 3.29 > 1$ measured at $t = 0$, but unstable in the gasHigh case $\langle Q \rangle = 0.72 < 1$. This demonstrates that the fragmentation of the disk can be driven by the forcing of an external pressure, even though the disk is initially Toomre stable. As we will see later, this is due to the pressure-driven mass inflow that acts as an enhancement of the disk self-gravity and makes the disk more unstable. For the gasHigh simulations, the rise in SFR is, however, significantly faster when external pressure is applied. At later times, the SFR flattens after $\sim 80$ Myr maintaining this rate for the remainder of the simulation. In contrast, for the non-pressure simulation, the SFR keeps rising with time.

This picture is confirmed when looking at the density probability function (PDF) of the gas, which we defer to a future article (Bieri et al. 2015). In summary, one can see that increasing the external pressure allows one to reach higher gas densities faster. For the gasHigh galaxy, the non-pressure simulation catches up with the overpressure simulations after a time delay, similar to the SFR behavior. For the gasLow galaxy, the non-pressure simulation never attains the densities reached by the pressure enhancement simulations.

3.2. Mass Flow Rate

The SFR is sensitive to both the mass flux and to the clump mass distribution. We measure the gas mass flux through a sphere of radius 16 kpc as

$$\dot{M} = \int \int \rho \mathbf{v} \cdot \hat{\mathbf{r}} \, dS = \sum_{i \in \text{shell}} m_i \mathbf{v}_i \cdot \hat{\mathbf{r}}_i \frac{S}{V},$$

where $i$ denotes the index of a cell within a shell of surface $S$ and volume $V$. In all simulations with enhanced pressure, an incoming pressure-driven mass inflow is created at the beginning of the simulation and is followed by a short mass outflow (seen in the edge-on view of the galaxies in Figures 1 and 2), after which it oscillates around zero for the remaining of the simulation (top panels of Figure 4). In the early adjustment phase, the external pressure drives the ambient gas toward the disk, compressing the clouds, and eventually expelling the gas. This is to be expected from the way we set up the pressure, as the pressure wave coming into the galaxy carries momentum causing the galaxy to expel more gas when compared with the non-pressurized case where the mass outflow rate is close to zero.

The bottom panels of Figure 4 show that the cumulative mass flow remains negative for the gasLow pressurized simulation, indicating a greater mass inflow than outflow for this simulation, while the cumulative mass flow is close to zero for the non-pressurized simulations. The mass inflow in the pressurized simulation enhances the mass of the galaxy and makes the disk more unstable leading to more clump formation and, hence, to an enhanced SFR. For the gasHigh simulations, the difference in the cumulative mass flow is small over the whole simulation time, demonstrating that the two galaxies have the same amount of gas to form stars. However, the greater initial gas inflow in the gasHigh pressure simulation causes more instability at the beginning. This instability allows the galaxy to reach higher gas densities faster, leading to an enhanced SFR.

4. CONCLUSIONS

We show that a toy model for AGN-induced overpressurization leads to enhanced star formation in disk galaxies. The effects are dramatic at early times, regardless of the initial gas fraction of the galaxy, although the high gas fraction galaxy, which is Toomre unstable, experiences a very early rapid burst of star formation, followed by a more moderate SFR that remains above the SFR in the non-pressurized case. However, even in the Toomre stable low gas fraction galaxy, external pressure can enforce fragmentation and star formation, albeit on a longer timescale.

One reason for the increased star formation in pressurized galaxies is early pressure-driven mass inflow from the halo and outer disk, on a 10 Myr timescale (Figure 4), especially on the low gas fraction galaxy. This gas inflow feeds cloud/clump growth in the inner parts of the galaxy and eventually leads to enhanced star formation (Figure 3). This can also be seen in the gas density PDF of the simulations: higher gas densities are reached faster, generating a larger star formation rate. The effects of inflow are more dramatic for the high gas fraction galaxy, where the disk is more unstable (Figure 2). The mass inflow due to the pressurization of the disk acts as an effective enhancement of the disk self-gravity, which in turn makes the disk more unstable. We have confirmed this with a detailed
One expects that gas-rich star-forming galaxies should have gravitationally driven SFRs of the order of $100 \, M_\odot \, yr^{-1}$, simply by scaling the gas surface density and maintaining a similar efficiency. Indeed, observations at $z \sim 2$ confirm this trend. The more exotic cases of very high ($\sim 1000 \, M_\odot \, yr^{-1}$) SFRs are more typically found at higher redshift and almost invariably have associated luminous AGNs. While any connection is speculative, and indeed the very direction of possible causality is vigorously debated, our simple tests of the effects of AGN-induced pressure, due to wind-driven or jet-initiated bow shocks that overpressurize the entire inner gaseous disk, suggest that strongly enhanced SFRs are readily achievable.

Similar SFR enhancements are found from increased pressure in the initial stages of ram pressure harassment, although gas loss dominates the long-term behavior (Abadi et al. 1999; Fujita & Nagashima 1999; Bekki 2014). Here, however, the gas is retained, and the SFR enhancement is far more pronounced.

The assumptions made in setting up our simulations will have to be checked in future studies. First of all, we are examining different geometries for the external pressure, depending on the mass and type of galaxy simulated. Nevertheless, we believe that the idea of external pressure triggering star formation within the galaxy should be robust to these details.

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REFERENCES

Abadi, M. G., Moore, B., & Bower, R. G. 1999, MNRAS, 308, 947
Bekki, K. 2014, MNRAS, 438, 444
Bieri, R., Dubois, Y., Silk, J., Mamon, G. A., & Gaibler, V. 2015, MNRAS, submitted (arXiv:1507.00730)
Cresci, G., Mainieri, V., Brusa, M., et al. 2015, ApJ, 799, 82
Drouart, G., De Breuck, C., Vernet, J., et al. 2014, A&A, 566, A53
Dubois, Y., & Teyssier, R. 2008, A&A, 477, 79
Fujita, Y., & Nagashima, M. 1999, ApJ, 516, 619
Gaibler, V., Khochfar, S., Krause, M., & Silk, J. 2012, MNRAS, 425, 438
Genzel, R., Tacconi, L. J., Gracia-Carpio, J., et al. 2010, MNRAS, 407, 2091
Hernquist, L. 1990, ApJ, 356, 359
Ishibashi, W., & Fabian, A. C. 2012, MNRAS, 427, 2998
Kennicutt, R. C., Jr. 1999, ApJ, 498, 541
Kennicutt, R. C., Jr., Calzetti, D., Walter, F., et al. 2007, ApJ, 671, 333
Krause, M. 2003, A&A, 398, 113
Kritsuk, A. G., Ustyugov, S. D., & Norman, M. L., 2011, in IAU Symp. 270, Computational Star Formation, ed. J. Alves et al. (Cambridge: Cambridge Univ. Press), 179
Krumholz, M. R., Dekel, A., & McKee, C. F. 2012, ApJ, 745, 69
Leroy, A. K., Bolatto, A. D., Ostriker, E. C., et al. 2015, ApJ, 801, 25
Martig, M., Bournaud, F., Teyssier, R., & Dekel, A. 2009, ApJ, 707, 250
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Piconcelli, E., Vignali, C., Bianchi, S., et al. 2015, A&A, 574, L9
Rasera, Y., & Teyssier, R. 2006, A&A, 445, 1
Rathborne, J. M., Longmore, S. N., Jackson, J. M., et al. 2014, ApJL, 795, L25
Rodighiero, G., Brusa, M., Daddi, E., et al. 2015, ApJL, 800, L10
Silk, J. 2013, ApJ, 772, 112
Silk, J., & Norman, C. 2009, ApJ, 700, 262
Springel, V., & Hernquist, L. 2005, ApJL, 622, L9
Sutherland, R. S., & Bicknell, G. V. 2007, ApJS, 173, 37
Sutherland, R. S., & Dopita, M. A. 1993, ApJS, 88, 253
Teyssier, R. 2002, A&A, 385, 337
Teyssier, R., Pontzen, A., Dubois, Y., & Read, J. I. 2013, MNRAS, 429, 3068
Toomre, A. 1964, ApJ, 139, 1217
Wagner, A. Y., Bicknell, G. V., & Umemura, M. 2012, ApJ, 757, 136
Zinn, P.-C., Middelberg, E., Norris, R. P., & Dettmar, R.-J. 2013, ApJL, 774, 66
Zubovas, K., Nayakshin, S., King, A., & Wilkinson, M. 2013a, MNRAS, 433, 3079
Zubovas, K., Nayakshin, S., Sazonov, S., & Sunyaev, R. 2013b, MNRAS, 431, 793