EFFICIENCY OF THE DYNAMICAL MECHANISM

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Abstract
The most extreme starbursts occur in galaxy mergers, and it is now acknowledged that dynamical triggering has a primary importance in star formation. This triggering is due partly to the enhanced velocity dispersion provided by gravitational instabilities, such as density waves and bars, but mainly to the radial gas flows they drive, allowing large amounts of gas to condense towards nuclear regions in a small time scale. Numerical simulations with several gas phases, taking into account the feedback to regulate star formation, have explored the various processes, using recipes like the Schmidt law, moderated by the gas instability criterion. May be the most fundamental parameter in starbursts is the availability of gas: this sheds light on the amount of external gas accretion in galaxy evolution. The detailed mechanisms governing gas infall in the inner parts of galaxy disks are discussed.

Keywords: Galaxies, Dynamics, Bars, Spirals, Star formation

1. Introduction

The most spectacular evidence for dynamical triggering of starbursts is that ULIRGs are all mergers of galaxies (e.g. Sanders & Mirabel 1996). They have much more gas, dust and young stars then normal spiral galaxies, but they are quite rare objects in the nearby universe. On the contrary, interacting galaxies do not show intense starbursts (e.g. Bergvall et al 2003, but see Barton et al 2000, Nikolic et al. 2004), or only in their centers. From many observational studies, it appears that galaxy interactions are a necessary condition, but not a sufficient condition to trigger a starburst. Another necessary condition of course is the presence of large amounts of gas.

For small systems, interactions are even not necessary, since spontaneous star-formation can occur intermittently in bursts. Starbursting dwarf galaxies have no excess of companions (Telles & Maddox 2000, Brosch et al 2004, except Blue Compact Dwarfs according to Hunter & Elmegreen 2004). So
for dwarf galaxies, tides are not very important. It is possible instead that the
gas in these objects, having been accreted recently, is not yet in dynamical
equilibrium: observed asymmetries could be due to sloshing gas inside dark
haloes.

It is possible today to trace the star formation and chemical enrichment history
of nearby galaxies, by studying their stellar populations in detail and their
metallicity. The star formation history in the Small Magellanic Cloud reveals
some bursts corresponding to pericenters with the Milky Way (Zaritsky & Harris 2004). The tidal-induced fraction of star formation could be between 10 and
70%. A good fit is impossible however without large amounts of gas infall, at
least 50%. For two local dwarfs, Skillman et al (2003) conclude also that the
bulk of star formation is recent, unlike the predictions of an exponentially de-
creasing star formation history, if the system had acquired most of its mass in
early times (Fig. 1).

![Figure 1](image)

*Figure 1.* Star formation and metal enrichment histories derived for IC1613 and Leo I dwarfs by Skillman et al (2003). It is remarkable that the bulk of the star formation and metal enrichment has occurred since $z=1$. 
2. Dynamical Processes

Empirically, star formation is observed to obey a global Schmidt law, where the rate of SF per unit surface is a power $n=1.5$ of the average gas surface density in a galaxy (e.g. Kennicutt 1998). It is remarkable that this law holds with the same slope and is continuous, for interacting and non-interacting objects, pointing to the gas supply as the main factor.

This empirical law can be interpreted through several processes: Jeans instability, since the SFR is then proportional to the density $\rho$ and inversely proportional to the dynamical time in $\rho^{-1/2}$, or cloud-cloud collisions (Elmegreen 1998), contagious star formation, associated with feedback (generating chaotic conditions), etc. These processes are able, without dynamical trigger, to yield episodic bursts of star formation, and this is well suited to dwarf galaxies, see Fig. 2 (Koppen et al 1995, Pelupessy et al 2004)

For larger systems, large-scale dynamical instabilities must be invoked. Density waves, in creating shocks and concentrations of mass in spiral arms, can favor star formation, but starbursts require to gather large amounts of gas in a small area. Radial gas flows due to bars, or spirals torques are then at work, leading to molecular gas concentrations, and circumnuclear starbursts (e.g. Buta & Combes 1996, Sakamoto et al 1999, Knapen 2004). In galaxy clusters, star formation could be induced by shocks with the intra-cluster medium (Bekki & Couch 2003).

ULIRGS

Ultra-Luminous InfraRed Galaxies have not only more gas and star formation, but also an enhanced star formation efficiency (SFE) defined as the ratio of SFR traced by the far infrared luminosity to the available fuel, traced by the CO emission (for the H$_2$ gas). More generally, in interacting galaxies, the CO emission relative to blue luminosity is multiplied by 5 and more concentrated (Braine & Combes 1993). This certainly means that the H$_2$ content is larger; the interpretation in terms of a lower CO-to-H$_2$ conversion factor would lead to an excessive star formation efficiency $\text{SFE}=L_{\text{FIR}}/M(\text{H}_2)$.
These enhanced gas amount and concentration can be explained by the gravitational torques of the interactions driving gas very quickly to the centers. Gas in ULIRGs is concentrated in central nuclear disks or rings (Downes & Solomon 1998). The condition to have a starburst is to accumulate gas in a time short enough that feedback mechanisms have no time to regulate. Also, the tidal forces are generally compressive in the centers, which favors cloud collapse.

**Compressive tidal forces**

For a spherical density profile, modelled as a power-law \( \rho(r) \sim r^{-\alpha} \), the corresponding acceleration is in \( r^{1-\alpha} \), so the gravitational attraction can increase with distance from center, if \( 0 < \alpha < 1 \). Therefore the tidal force is then compressive: \( F_{\text{tid}} \sim (1 - \alpha)r^{-\alpha} \), in particular, for a core with constant density (\( \alpha = 0 \)). The rotation curve \( V_{\text{rot}} \) in \( r^{1-\alpha/2} \), would then be almost rigid rotation. Molecular clouds inside the core are then compressed, and star formation can be triggered.

This phenomenon can also explain the formation of nuclear starbursts and then young nuclear stellar disks in some barred galaxies. Decoupled stellar nuclear disks are frequently observed in double-barred Seyfert galaxies (Emsellem et al 2001). The observed velocity dispersion reveals a characteristic drop in the center. The proposed interpretation invokes star formation in a decoupled nuclear gas disk (Wozniak et al 2003).

**Star formation recipes**

Numerical simulations use recipes for star formation and feedback phenomena, since this is sub-grid physics (Katz 1992, Mihos & Hernquist 1994, 96). These recipes include the Schmidt law with exponent \( n=1.5 \), together with a gas density threshold. The star formation rate is however generally decreasing exponentially with time, in isolated system, even taking into account stellar mass loss (see Fig. 3). When comparing the star formation history in an isolated galaxy with respect to a merger, the exponential law dominates, unless the SFR is normalised to the isolated case.

According to the detailed geometry, mass ratios or dynamical state of the merging galaxies, star formation can be delayed until the final merger, but the availability of gas is the main issue.

**Importance of gas accretion**

Galaxies in the middle of the Hubble sequence have experienced about constant SFR along their lives (Kennicutt et al 1994, SDSS: Brinchmann et al 2004). The study of stellar populations in the large SDSS sample has shown that only massive galaxies have formed most of their stars at early times, while
dwarfs are still forming now (Heavens et al 2004). Only intermediate masses have in average maintained their star formation rate over a Hubble time.

Even taking into account the stellar mass loss, an isolated galaxy should have an exponentially decreasing star formation history. Galaxies must therefore accrete large amounts of gas mass along their lives, to fuel star formation.

Large amounts of gas accretion is also required to explain the observed bar frequency today (Block et al 2002). Numerical simulations reveal that bars in gaseous spirals are quickly destroyed, and only gas accretion can trigger their reformation (Bournaud & Combes 2002). To have the right frequency of bars at the present time, gas accretion must double the galaxy mass in 10Gyr. This gas cannot come from dwarf companions: they can provide at most 10% of the required gas and their dynamical interactions heat the disk. What is required is continuous cold gas accretion, which could come from the cosmological filaments in the near environment of galaxies.

3. Conclusion

Star formation depends essentially on the gas supply. External gas accretion is essential for the efficiency of dynamical triggering. Galaxy interactions, and the accompanying bars and spirals, help to drive the accreted gas radially inwards and trigger central starbursts.

\textbf{Figure 3.} Star formation history during a major merger of two Sb spiral galaxies: \textbf{Left}, the star formation rate versus time, showing the global exponential decline; \textbf{Right}, the ratio between SFR in the merger run and the corresponding control run with the two galaxies isolated.
Gas accretion regulates not only the star formation history in galaxies, but also their dynamics (bars, spirals, warps, m=1...), since bars require gas to reform, in a self-regulating process.

According to the environment, hierarchical merging or secular evolution prevail. In the field, accretion is dominant, and explains bars and spirals, and the constant star formation rate for intermediate types. In rich environments, galaxy evolution is faster, interactions and mergers are much more important; secular evolution of galaxies is halted at $z \sim 1$, since galaxies are stripped from their gas reservoirs.

References

Barton, E., Geller, M., Kenyon, S.: 2000, ApJ 530, 660
Bekki K., Couch W.: 2003 ApJ 596, L13
Bergvall, N., Laurikainen, E., Aalto S.: 2003, A&A 405, 31
Block D., Bournaud F., Combes F., Puerari I., Buta R.: 2002, A&A 394, L35
Bournaud F., Combes F.: 2002, A&A 392, 83
Braine J., Combes F.: 1993, A&A 269, 7
Brinchmann, J., Charlot, S., White, S. D. M. et al.: 2004, MNRAS 351, 1151
Brosch, N., Almoznino, E., Heller, A. B.: 2004, MNRAS 349, 357
Buta R., Combes F.: 1996, Fund. Cosmic Phys. 17, 95
Downes D., Solomon P.M.: 1998, Apj 507, 615
Elmegreen B.G.: 1998, in "Origins of Galaxies" ed. C.E. Woodward et al. (astro-ph/9712352)
Emsellem E., Greusard D., Combes F. et al: 2001, A&A 368, 52
Heavens, A., Panter, B., Jimenez, R., Dunlop, J.: 2004, Nature 428, 625
Hunter D.A., Elmegreen B.G.: 2004, AJ 128, in press (astro-ph/0408229)
Katz, N.: 1992 ApJ 391, 502
Kennicutt R.C., Tamblyn, P., Congdon, C. E.: 1994 Apj 435, 22
Kennicutt R.C.: 1998, ARAA 36, 189
Knapen J.: 2004, A&A, in press, (astro-ph/0409031)
Koppen, J., Theis, C., Hensler, G: 1995, A&A 296, 99
Mihos J.C., Hernquist L.: 1994 ApJ, 437, 611
Mihos, J.C., Hernquist, L.: 1996, ApJ, 464, 641
Nikolic, B., Cullen, H., Alexander, P.: 2004, MNRAS 501, (astro-ph/0407289)
Pelupessy, F. I., van der Werf, P. P., Icke, V.: 2004, A&A 422, 55
Sakamoto K., Okumura S.K., Ishizuki S., Scoville N.Z.: 1999 ApJ 525, 691
Sanders D., Mirabel I.F.: 1996, ARAA 34, 749
Skillman, E. D., Tolstoy, E., Cole, A. A. et al.: 2003, ApJ 596, 253
Telles, E., Maddox, S.: 2000, MNRAS 311, 307
Wozniak H., Combes F., Emsellem E., Friedli D.: 2003, A&A 409, 469
Zaritsky D., Harris J.: 2004, ApJ 604, 167