RevMexAA (Serie de Conferencias), **6**, 177–179 (1997)

NUCLEAR AND CIRCUMNUCLEAR BAR-INDUCED STARBURSTS

Daniel Friedli[1] and Louis Martinet[1]

RESUMEN

La formación de una barra estelar en un disco gaseoso induce flujos de gas hacia las regiones centrales y formación de estrellas, cuya intensidad depende de la relación de ejes de dicha barra. Los indicadores de la formación estelar en el lejano IR muestran que las galaxias aisladas con mayor nivel de actividad tienen barras prominentes. En ausencia de ILRs, la formación estelar se concentra en el núcleo. Cuando hay dos ILRs, o están presentes dos barras con diferentes velocidades de rotación, la mayor parte de la formación estelar ocurre en la región circumnuclear.

ABSTRACT

The formation of a stellar bar in a gas-rich disk triggers central gas fueling and star formation whose intensities critically depend on the bar axis ratio. Far-IR indicators of star formation activity show that the most active isolated galaxies have strong bars. In absence of inner Lindblad resonances (ILR's), the central burst of star formation is concentrated in the nucleus. When two ILR's or two nested bars with two different pattern speeds are present, the bulk of the star formation occurs in the circumnuclear region.

Key words: **GALAXIES: STARBURST — INSTABILITIES — STARS: FORMATION**

1. INTRODUCTION

Triaxial deformations like stellar bars are known to be very efficient engines for extracting angular momentum (via gravitational torques) and increasing dissipation of cold gaseous components (via shocks). Although a significant bar-driven central gas fueling as well as a subsequent nuclear starburst are highly expected, the role played by bars in inducing starburst galaxies is somewhat controversial (e.g., reviews by Hawarden et al. 1996; Ho et al. 1996). Also, the detailed processes of the formation and evolution of nuclear rings are still poorly understood although some recent progress have clearly been obtained (e.g., Elmegreen, these proceedings). In order to clarify the overall picture and investigate these highly non-linear, non-axisymmetric, time-dependent, and dissipative processes, we have performed various 3D self-consistent numerical simulations with stars, gas, radiative cooling, and star formation (for technical details see Friedli & Benz 1993 1995).

2. INTENSITY OF THE STARBURST

Numerical simulations indicate that the intensity of the gas fueling phenomenon mainly depends on the strength of the bar. As the bar axis ratio (b/a) decreases, much faster gas accumulation into the center occurs (Friedli & Benz 1993). In less than one Gyr, strong bars (approximately with $(b/a) < 0.6$) have nearly pushed all the gas initially inside the bar region into the center whereas weak bars have only accreted a small fraction of it. In the strong bar case, the starburst phase typically lasts $\approx 0.1 - 0.2$ Gyr with a peak star formation rate (SFR) of $\approx 8 - 16$ $M_\odot$ yr^{-1} depending on the initial amount of gas and the various parameters of the star formation "recipe" (Friedli & Benz 1995). In particular, the SFR observed near the center is strongly influenced by the amount of mechanical energy (ME) released into the system as well as by the assumed star formation efficiency ϵ. If the ME release increases or ϵ decreases, then the mean global SFR decreases. If the ME injection or ϵ are very high, then no star formation occurs near the center since all the gas is turned into stars along the bar before reaching the center!

In a sample of 32 observed late-type isolated galaxies, the relation between the FIR star formation indicator S_{25}/S_{100} and the deprojected bar axis ratio $(b/a)_d$ strongly suggests that all the most star-forming galaxies have strong bars (for details see Martinet & Friedli 1996). Weakly star-forming galaxies have both weak and strong bars. These results are summarized by the histogram of Fig. 1. Note that the most luminous galaxy in this

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[1] Geneva Observatory, CH-1290 Sauverny, Switzerland.

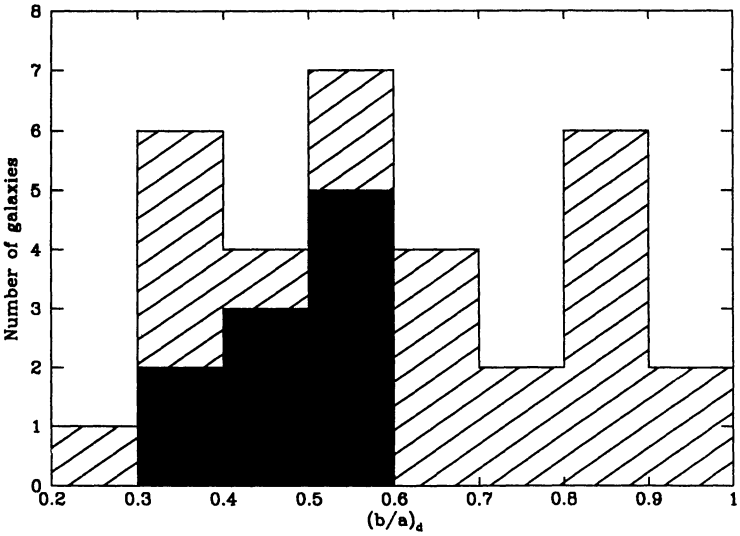

Fig. 1. Histogram of the distribution of the deprojected bar axis ratio $(b/a)_d$ for 32 late-type isolated galaxies having either $\log(S_{25}/S_{100}) < -1.2$ (low star formation rate; shaded regions) or $\log(S_{25}/S_{100}) \geq -1.2$ (high star formation rate; filled regions). No weakly barred galaxies harbor significant star formation activity.

sample, i.e., NGC 7479, has $L_{\rm FIR} \approx 4 \cdot 10^{10}$ L$_\odot$. Non-active strongly barred galaxies are supposed to be either in a pre-starburst phase (not yet enough gas in the center, i.e., $\Sigma_g < \Sigma_c(Q)$ corresponding to the critical gas surface density for the onset of star formation) or in a post-starburst phase (gas exhausted or below Σ_c). Martin (1995) had already noticed that the fraction of strong bars is higher in galaxies with nuclear activity than in quiescent galaxies.

3. MORPHOLOGY OF THE STARBURST

The large-scale morphology of massive star formation strongly varies from one barred galaxy to the other (see e.g., Kennicutt 1994). However, only three dominant shapes for powerful star forming regions are observed:

1) *Star formation along the bar major axis.* This shape essentially appears in late-type galaxies like e.g., NGC 3359. In this case, there should be one single young bar without ILR's (Friedli & Benz 1995). The bar is probably young ($\lesssim 0.5 - 1$ Gyr) since the gas cannot survive for a long time in a strong bar due to the presence of large-scale shocks. Subsequent supplies of gas coming either from the disk or from stellar evolution mass loss could also occur and lead to the formation of stars along the bar. However, large amounts of gas should be involved in order to exceed Σ_c. The bar cannot have ILR's to produce straight shocks nearly along the bar major axis (Athanassoula 1992).

2) *Star formation in the nucleus.* This morphology occurs for instance in NGC 5643. The nucleus can be nearly circular or elongated along the bar major axis. Again there should be one single bar devoided of ILR's (Telesco et al. 1993) but the bar is supposed to be older than in the previous case ($\gtrsim 0.5 - 1$ Gyr) since some time is required to concentrate large amounts of gas into the nucleus. Note that in many galaxies (e.g., NGC 7479) intense star formation is simultaneously observed along the bar major axis and in the nucleus. This can be interpreted as an intermediate step in the evolution from pure star formation along the bar major axis to pure star formation in the nucleus or in the circumnuclear region.

3) *Circumnuclear star formation.* Two mechanisms can induce the bulk of the star formation to preferentially occur around the nucleus, usually along a more or less patchy nuclear ring: (I) One single bar with two ILR's (e.g., NGC 6951). In this case, nuclear rings are generally located close to the inner ILR; this possibility has been known for a long time and will not be developed here (for details see e.g., Combes 1988; Knapen et al. 1995). (II) Two nested bars with two different pattern speeds (e.g., NGC 6782). Contrary to the case (I), it has only recently been demonstrated that such systems can exist and that nuclear gaseous rings can be formed between the two bars (Friedli & Martinet 1993). To distinguish mechanism (I) from mechanism (II) in real galaxies, it is necessary to infer the presence of a trailing misaligned secondary stellar bar inside the circumnuclear star forming region. Without kinematics, the case of leading misaligned secondary stellar bars

is ambiguous since these could also be formed by mechanism (I) (Shaw et al. 1993). The respective fraction of these two mechanisms in operation is completely unknown but neither of them seem to be marginal.

Circumnuclear star formation in galaxies with bars within bars. Many misaligned secondary bars within primary bars have been observed (Wozniak et al. 1995; Friedli et al. 1996; and references therein). No preferred angle between the two bars θ is found, and both leading and trailing secondary bars exist. These are strong arguments in favor of the existence of two different pattern speeds. Both bars are very often separated by blue nuclear rings (9 over 13 in the sample of Wozniak et al. 1995) indicating that circumnuclear star formation is very common in these systems. The number of Seyfert nuclei is also high (6 over 13).

Numerical simulations (Friedli & Martinet 1993) indicate that the ILR of the primary bar approximately coincides with the corotation of the secondary bar. Gas is accumulated just inside this region leading to the formation of the nuclear ring. The shape and the orientation of this gaseous nuclear ring are strongly time-dependent and are mainly controlled by the secondary bar as can be observed in Fig. 2 (Plate 4). In particular, when both bars are nearly perpendicular, the gas is accumulated in the leading edge of the secondary bar showing a clear "twin peaks" morphology. The "ring" is very elongated with an axis ratio close to 0.5 and a short nuclear gaseous bar is also apparent. On the contrary, when both bars are close to parallel, the gas shape is that of a nearly circular, very patchy, ring. Concerning the H II regions (which correspond here to all stars created less than 10 Myr ago), they also have widely different morphologies depending on θ, e.g., two hotspots ($\theta \approx 90°$), a circular ring ($\theta \approx 0°$), or two trailing spiral arms ($\theta \approx -45°$). The time-scale to change from one morphology to the other is very short $\approx$ 10 Myr, and could explain why such a huge shape diversity is observed in the circumnuclear Hα emissions. In this model, the gas mass involved in the ring is $M_g^{\rm ring} \approx 2 \cdot 10^9\, M_\odot$ which corresponds to about 20% of the total gas mass (initially $M_g^{\rm tot}/M_* = 0.1$). Only a weak fraction of gas has been pushed into the nucleus, i.e., $M_g^{\rm ring}/M_g^{\rm nucleus} \approx 10$. During this phase with two bars, some nuclear star formation occurs as well but is surpassed by that in the ring, i.e., ${\rm SFR}^{\rm ring}/{\rm SFR}^{\rm nucleus} \approx 4$.

4. MAIN CONCLUSIONS

The formation of a spontaneous or induced strong bar in a gas-rich Sc-like disk triggers a starburst of intermediate power and duration. Bars alone cannot trigger short and ultraluminous starbursts.

In isolated barred galaxies, the central gas fueling and the star formation rate are much higher in the case of strong forming bars than in weak ones. This could explain why significant star formation activity does not seem to occur in weakly barred galaxies.

The starburst occurs in the nucleus (i.e., $R \lesssim 200$ pc) in absence of ILR's whereas a circumnuclear starburst (typically near $R \approx 0.5 - 1.0$ kpc) can be generated both by a single bar with two ILR s or by two embedded stellar bars. In the latter case, various morphologies of the circumnuclear star forming regions are observed (hotspot-like; ring-like; spiral-like; etc.) and the alteration time-scale is typically $\approx$ 10 Myr.

This work has been supported by the Swiss National Science Foundation (FNRS) and the Swiss Society of Astronomy and Astrophysics (SSAA). We thank Isabel Márquez for the Spanish translation of the abstract.

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