Star Formation in Nuclear Rings of Barred Galaxies

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Outline

• Formation of Nuclear Rings

• Star Formation in Nuclear Rings
NGC 1097

dust lanes

central BH

nuclear ring

nuclear spirals
Some galaxies have relatively straight dust lanes, while others have curved ones.

NGC 6951: $\Delta \alpha = 9^\circ$

NGC 4321: $\Delta \alpha = 73^\circ$

Comeron et al. 2009
• Some galaxies have a relatively large nuclear ring, while others have smaller one.

NGC 1343: $1.2\text{kpc} \times 0.9\text{kpc}$

NGC 1300: $0.3\text{kpc} \times 0.2\text{kpc}$

Mazzuca et al. 2009
• Some galaxies have tightly wound nuclear spirals, while others have loosely wound ones.

Peeples & Martini 2006
Nuclear Rings

• Regarding nuclear rings, it has been widely accepted that rings form via **resonant interactions** of the gas with the bar potential.
  – This notion was driven by the fact that observed nuclear rings are located near the **inner Lindblad resonances** (e.g., Combes & Gerin 85; Knapen+95; Comeron+10).

• Yet, there is no convincing theoretical argument.
  – Bar torque is very weak near the ILRs.
  – Resonance is a secular process, occurring over a very long time scale.
  – Resonance tends to disperse the material, rather than gathering it (e.g., gaps in planetary rings and the asteroid belt).
Bar Strength

• We argue that it is the **bar strength** that controls the properties of bar substructures.

• Bar strength parameter $Q_b$

$$Q_b = \left. \frac{F_T}{F_R} \right|_{\text{max}}$$

where $F_T = \text{tangential force due to a bar}$

$F_R = \text{radial force due to mass distribution}$

– SA($Q_b < 0.1$); SB ($Q_b > 0.15$)  (Buta & Block 2001)
Numerical Models

• To study the effect of bar strength on the properties of bar substructure, we run numerical hydrodynamics simulations.

• Consider a 2D gaseous disk that is isothermal \(c_s=10\) km/s and self-gravitating, and study its response to a non-axisymmetric bar potential.
  
  - Flat rotation curve corresponding to normal disk galaxies.

• Bar potential is modeled by Ferrers prolaters that are characterized by two parameters:
  
  - Bar mass fraction: \(f_{\text{bar}} = \frac{M_{\text{bar}}}{M_{\text{bar}} + M_{\text{bulge}}} \sim 8 \sim 60\%\)

  - Aspect ratio: \(\mathcal{R} = \frac{a}{b} \sim 1.5 \sim 3.5\)

    \(a, b = \text{semi-major and semi-minor axes of the bar}\).

  - Resulting the bar strength is in the range \(Q_b \sim 0.02\sim 0.7\).
Model with $Q_b = 0.23$ ($f_{\text{bar}} = 0.3$, $a/b = 2.5$)

Kim et al. (2012)
larger $f_{bar}$

(a) M08R15N  (b) M15R15N  (c) M30R15N  (d) M60R15N

(e) M08R20N  (f) M15R20N  (g) M30R20N  (h) M60R20N


-5kpc  5kpc
A stronger bar induce stronger shocks and thus removes a larger amount of angular momentum from the gas, resulting in a smaller nuclear ring in size.

The ring position is in general well inside the inner Lindblad resonance of the bar potential.

- Ring formation is not by the resonances but by the centrifugal barrier.
• Observational and numerical results are in good agreement.
  – Stronger bars can possess smaller rings.
Star Formation in Nuclear Rings

- Nuclear rings in barred galaxies are sites of intense star formation.
- Some important observational results that may provide clues as to how star formation occurs in nuclear rings.

1. The present star formation rate (SFR) vs $Q_b$
   - In the range $0.1–10 \, M_\odot \, yr^{-1}$, depending on the bar strength (Mazzuca+08).

![Graph showing star formation rate (SFR) vs $Q_b$](image-url)
2. Longevity of Ring SFR

- Short-lived star formation: single burst
- Long-lived star formation
  - Multiple episodic bursts
  - Continuous SFR

- Population synthesis modeling favors long-lived star formation either with multiple episodic bursts (Allard+06, Sarzi+07) or continuous rates (van der Laan+13) rather than short-lived SF.
3. Azimuthal Age Gradient

- Some galaxies (e.g., NGC 1343, IC 4933, NGC 7552) show an age gradient of star clusters along the azimuthal direction in nuclear rings (Mazzuca+08, Ryder+10, Brandel+12), while a majority of galaxies do not show apparent age gradients.

NGC 1343 (Mazzuca+08)
Ha Equivalent width

Contact points
Two Modes of Ring SF (Böker+08)

- **Popcorn model**: SF occurs in dense clumps randomly distributed along a nuclear ring ➔ no age gradient
- **Pearls-on-a-string model**: SF takes place preferentially at the contact points between a ring and the dust lanes. ➔ age gradient.

- It appears that rings with age gradients have, on average, a smaller SFR than those without noticeable age gradients.
Numerical Methods

- SF Prescription
  - Critical density corresponding to the Jeans condition.
  - Star formation efficiency $\varepsilon \sim 1\%$ (Krumholz & Tan, 2007)
    - SF probability $P = \frac{\varepsilon \Delta t}{t_{ff}}$
    - 90% of gas turns into a particle that represents a star cluster
      - Typical Mass of each star cluster $\sim 10^5 M_\odot$
- Delayed SF feedback via SN events
  - In the form of momentum injection
  - Delay time $= 10$ Myr.
Star Formation In Nuclear Rings

Model with SF feedback included

(Seo & Kim 2013)
Star Formation Rate

- SFR is well correlated with the mass inflow rate to the rings.
- SFR shows a strong primary burst lasting for about 100 Myr and then decays to small values below $\sim 1 \, M_\odot \, \text{yr}^{-1}$.
  - The primary burst is caused by the rapid gas infall due to the bar growth.
  - The secondary bursts are due to re-entry of the ejected gas from the primary burst.
- Contrast to observational results (Allard et al. 2006; Sarzi et al. 2007; van der Laan et al. 2013)
Azimuthal Age Gradient

• The presence or absence of azimuthal age gradients of young star clusters in nuclear rings depends on the SFR.
  – No azimuthal age gradient if SFR > 1 $M_\odot$ yr$^{-1}$.
• The maximum SFR that can be afforded to two contact points

\[
\dot{M}_{*,CP} = 2\epsilon_{\text{ff}} \Sigma_{\text{CP}} r_{\text{NR}} \Delta r \Delta \phi / t_{\text{ff}} \sim 1 M_\odot \text{ yr}^{-1} \left( \frac{r_{\text{NR}}}{1 \text{ kpc}} \right)^2 \left( \frac{c_s}{10 \text{ km s}^{-1}} \right)^3
\]

  – $\epsilon_{\text{ff}}$: SF efficiency (~1%)
  – $\Sigma_{\text{CP}}$: gas surface density at the contact points
  – $r_{\text{NR}}, \Delta r, \Delta \phi$: radius, width, angular extent of a nuclear ring
  – $t_{\text{ff}}$: free-fall time
Necessity of Gas Feeding to the Bar Region

• The gas in the bar regions should be replenished continuously or continually in order to make SF prolonged in nuclear rings.

• Candidate mechanisms for gas feeding
  – angular momentum dissipation by spiral arms (Roberts & Shu 1972; Lubow et al. 1986; Hopkins & Quataert 2011)
  – cosmic accretion of primordial gas (e.g., Dekel et al. 2009)
    • HVCs, \( \sim 0.7 \, M_\odot \, \text{yr}^{-1} \) for M31/Milky-Way-type galaxies (Richter 2012)
• Spiral arms with moderate strength of can drive radial mass inflows of \(~1 \, M_\odot \, \text{yr}^{-1}\), provided the corotation resonance of the arms is at large \(R\).

• Spiral arms can continuously transport fresh gas from outer regions to the bar region, capable of enhancing SFR at late time in the ring.
Summary

• Formation of nuclear rings
  – They form *not by resonances* but by the centrifugal barrier that the inflowing gas cannot overcome.
  – Galaxies with stronger bars host smaller nuclear rings

• Star formation in nuclear rings
  – In bar-only models, SF exhibits a strong primary burst followed by weak secondary bursts, before declining to very small values.
  – An azimuthal age gradient of star clusters is expected when SFR is low (less than 1 \( M_\odot \) yr\(^{-1} \) in our models).
  – The bar potential alone is unlikely to be responsible for the gas supply needed for star formation in real nuclear rings.
    • For prolonged SFR, gas should be supplied to the bar region.
    • Spiral arms can be such a gas feeding mechanism.
The trend of $Q_b$ becoming larger for a more elongated bar in the observational estimates is consistent with the results of our galaxy models.

- $f_{\text{bar}} = 0.25$–$0.35$ for a homogenous bar
Nuclear Rings

larger $Q_{b\dagger}$
The ring SFR has a tight linear correlation with the mass inflow rate $\dot{M}_{NR}$ to the ring, and has a weak dependence on the total gas mass $M_{NR}$ in the ring.
Radial Age Gradient

The star clusters produced exhibit a positive radial age gradient:
- Young clusters are located close to the nuclear ring, while old clusters are found away from the ring.
- Due to a temporal decrease in the ring size