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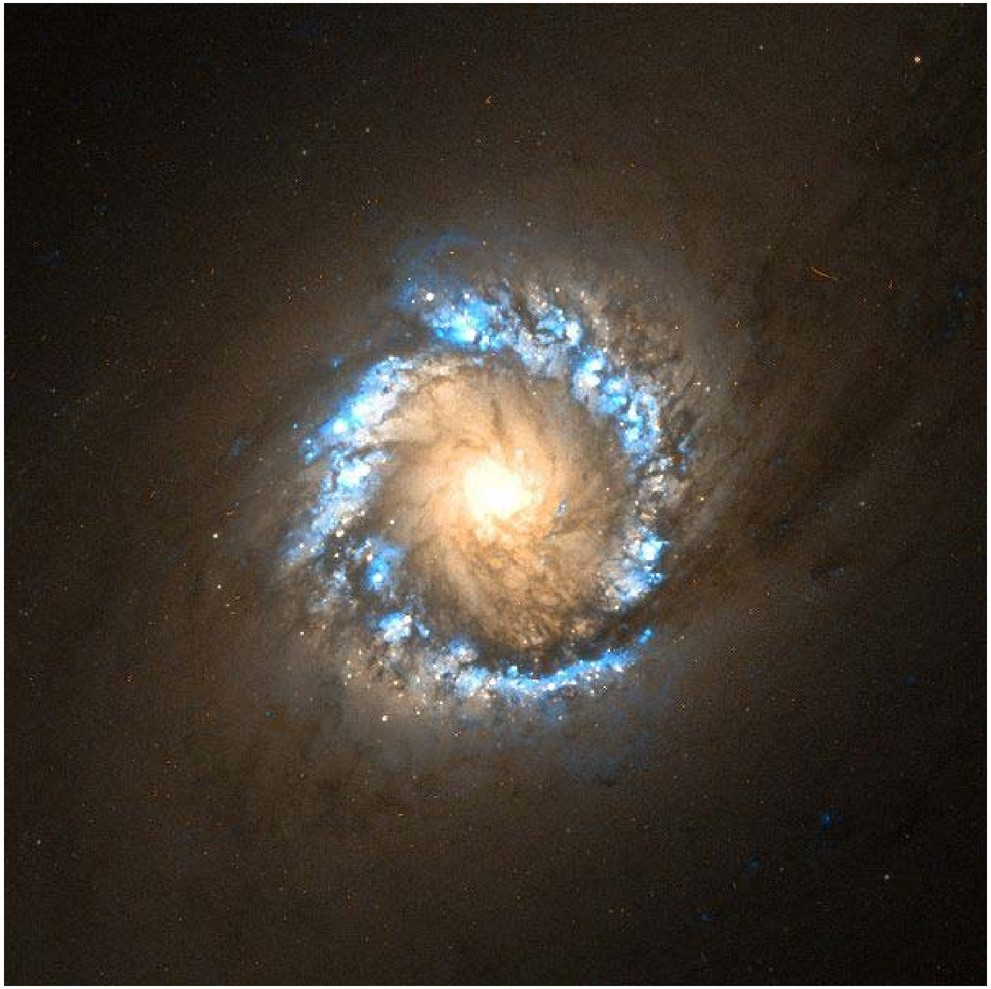
A simulation study of
Star Formation in Nuclear Rings of Barred-Spiral Galaxies

Woo-Young Seo, Woong-Tae Kim
Seoul National University

Nuclear Ring



- Nuclear rings in barred-spiral galaxies are sites of intense star formation.
- Observations indicate that the star formation rate in nuclear rings differs from galaxy to galaxy and widely distributed in the range of 0.1-10 $M_{\odot}$ yr^{-1} .

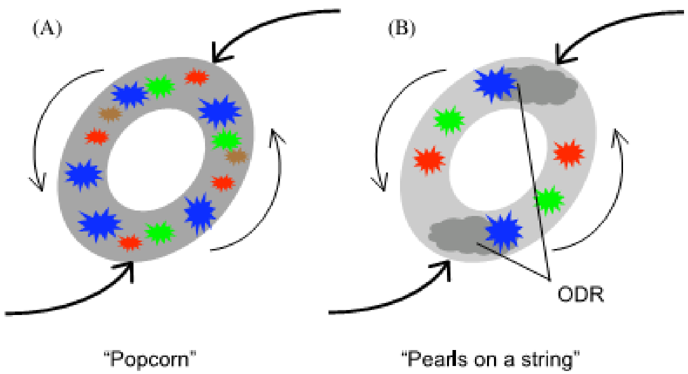
Star Formation History

- Observational estimates
  - Continuous SF
    - van der Laan et al. (2013) find that the circumnuclear ring in NGC 6951 has been forming stars for ~1Gyr.
    - SFR is low (~0.1 $M_{\odot}$ yr^{-1}).
  - Multiple-burst SF
    - Using stellar population synthesis models Allard et al. (2006) estimate SFH of M100(NGC 4321) is multiple-burst type.
    - Sarzi et al. (2007) show two more galaxies (NGC4314 and NGC 7217) also have multiple-burst SF using same method.

Age Gradient

- Observations
  - Some galaxies show an age gradient along the azimuthal direction.
  - Some galaxies do not show a gradient.
    (Mazzuca et al. 2008, Ryder et al. 2010, Brandel et al. 2012)

- Two models of star formation(Böker et al. 2008)
  - Popcorn model
    : SF sites are randomly distributed
    in the whole ring region.
  - Pearls-on-a-string model
    : SF occurs in over dense regions
    located at the contact points.



Issues

- What makes multiple-burst star formation?
- Why the location of star formation differs from galaxy to galaxy?

Galaxy Model

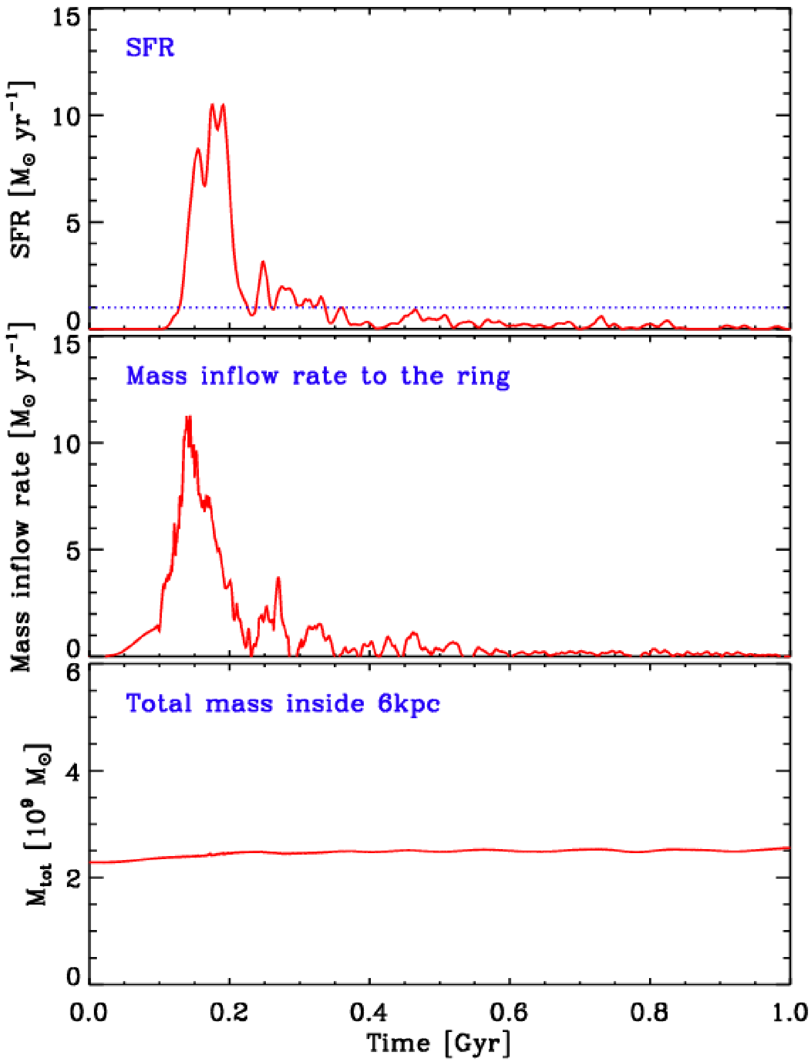
- Consider a 2D gaseous disk that is isothermal (c_s=10 km/s) and self-gravitating.
- Use an exponential gaseous density profile (Bigiel & Blitz, 2012) .

$$\frac{\Sigma_{\rm gas}}{\Sigma_{\rm trans}} = 2.1 \times e^{1.65r/r_d} \qquad (r_d = 16{\rm kpc},\ \Sigma_{\rm trans} = 14 M_{\odot}{\rm pc}^{-2})$$

- Bar potential is modeled by **Ferrers prolate.** (Athanassoula, 1992)
  - Bar fraction f = 30%, Major axis = 5kpc, Axis ratio a/b = 2.5
  - Pattern speed of a bar = 33 km/s/kpc
- Include SF & feedback Prescription.
- Take both models without spirals and with spirals.

Result : Ring SF of Bar-only Model

- SFR is well correlated with the mass inflow rate to the ring.
- The SFR shows a strong primary burst that is caused by the rapid gas infall to the ring due to the bar growth.
- SFR decrease rapidly after strong burst, since gas outside the bar region do not move inward by the bar potential.
- Only the gas inside bar region responds strongly to the bar potential, while the outer region is not much affected.
- Bar-only model cannot explain multiple-burst SF.

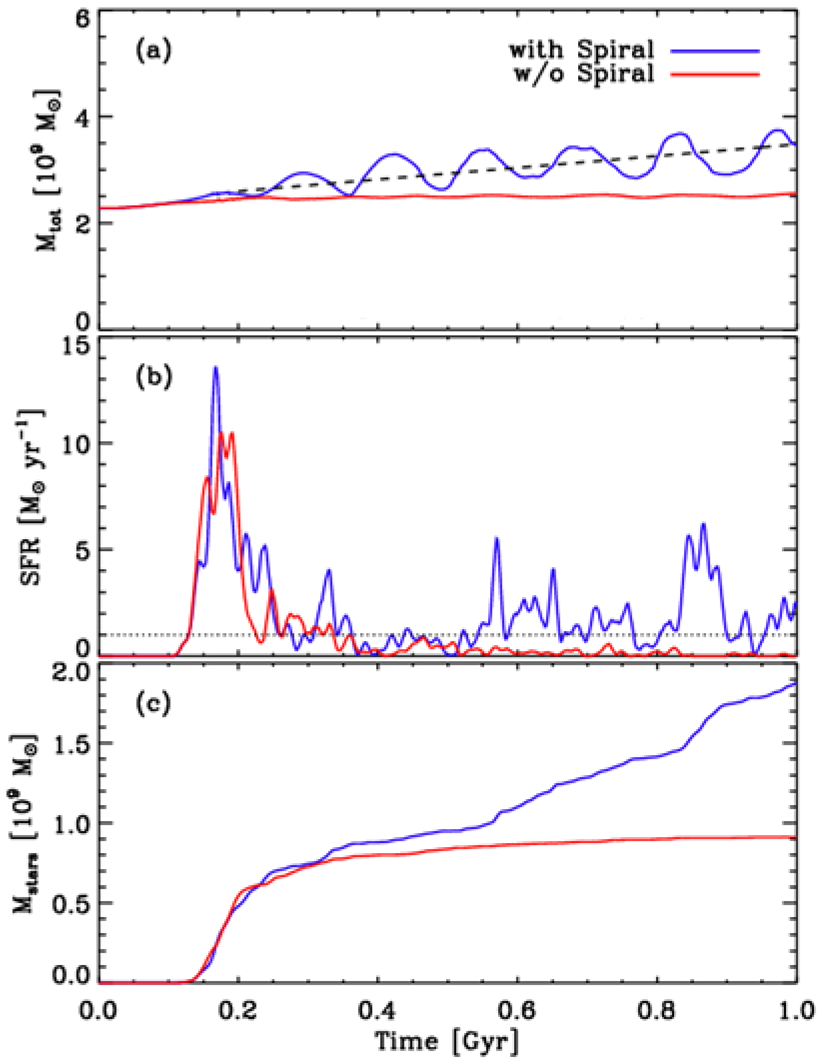


Necessity of Gas Feeding to the Bar Region

- Candidate mechanisms for gas feeding :
  - Angular momentum dissipation by spiral arms (Roberts & Shu 1972; Lubow et al. 1986; Hopkins & Quataert 2011)
    - inside the co-rotation radius, gases move inward after passing spiral shock.
  - Galactic fountains (Fraternali & Binney 2006, 2008).
  - Cosmic accretion of primordial gas (e.g., Dekel et al. 2009)
    - HVCs, ~ 0.7 $M_{\odot}$ yr^{-1} for M31/Milky-Way-type galaxies (Richter 2012)

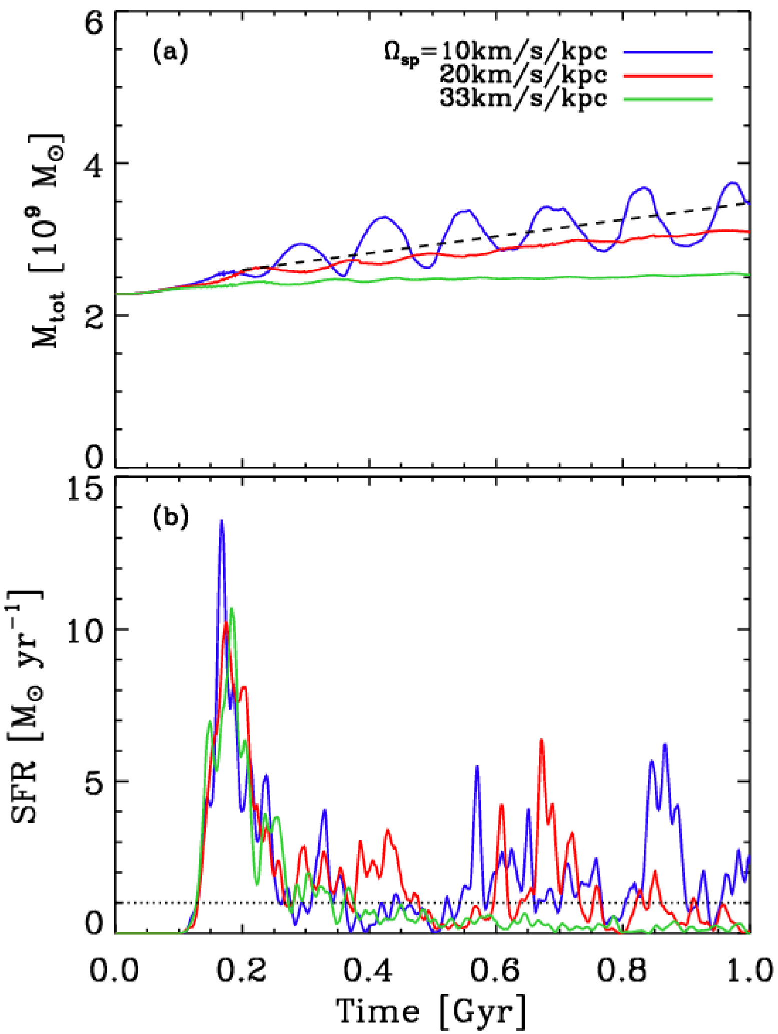
- Add spiral arm potential
  - F = 10%
  - Pattern speed of arms = 10, 20, 33km/s/kpc (Co-rotation Radius : 20, 10, 6kpc)

Result : Effects of spiral arms



- Ω_{sp} of spiral model is 10km/s/kpc
- In model without arms, the total mass inside 6kpc does not increase after 200 Myr.
  - No active star formation in the ring
- In model with spirals, the total mass increase continuously.
  - Exhibits episodic bursts of star formation at late time.
  - The total mass of the gas transformed into stars also increases continuously.

Result : Dependence of Ω_{sp}

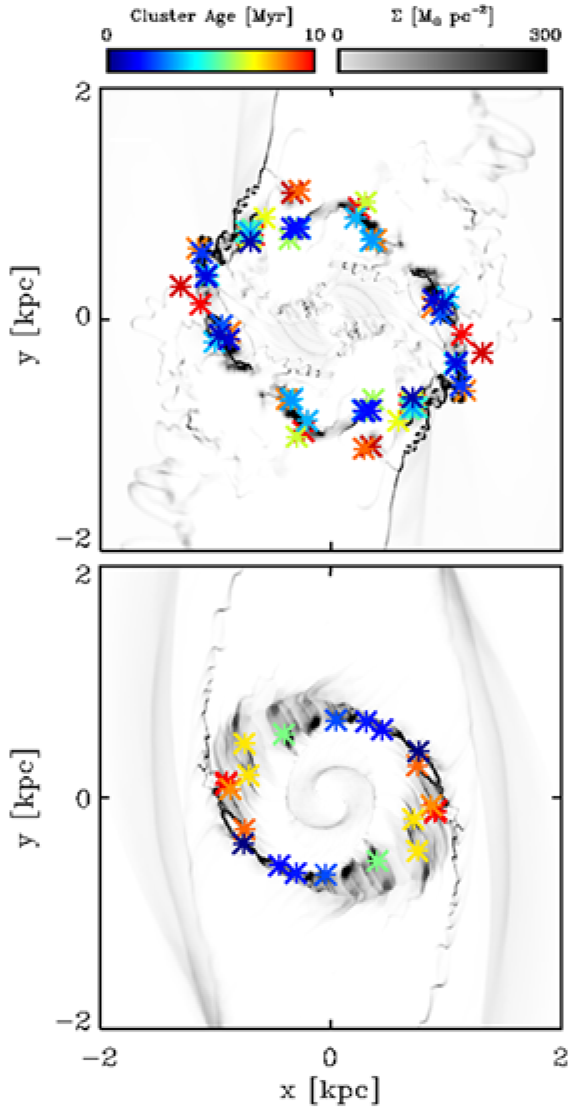


- Spiral shock is stronger when Ω_{sp} is smaller, resulting in a larger inflow rate.
- A model with Ω_{sp} = 20km/s/kpc also shows multiple star burst activities.
- Increase mass and SFR in a model with Ω_{sp} = 33km/s/kpc is almost the same with that in model without spiral arms, since the co-rotation radius is 6kpc.
- Pattern speed of M100 :

  Ω_{sp} =20 km/s/kpc, Ω_{bar} =30 km/s/kpc
  (Hernandez et al. 2005 : TW method)

Result : Age Gradient

- When the SFR is larger than 1 $M_\odot$ yr^{-1} :
  - Star formation is widely distributed throughout the whole length of the ring.
- When the SFR is smaller than 1 $M_\odot$ yr^{-1} :
  - Ages of young star clusters exhibit an azimuthal gradient along the ring, since star formation takes place mostly near the contact points.
- If mass inflow rate to the ring is small, most of the inflowing gas can be converted to stars at contact points.
- If mass inflow rate is large, all inflowing gas cannot be transformed at contact points.



Result : Age Gradient

- The maximum SFR expected from two contact points is simply

$$\dot{M}_{*,\mathrm{CP}} = \frac{2\epsilon_{\mathrm{ff}}\Sigma_{\mathrm{CP}} r_{\mathrm{NR}} \Delta r \Delta \phi}{t_{\mathrm{ff}}}$$

  - Roughly 1 $M_{\odot}$ yr^{-1} in our models.

- NGC 6951 (van der Laan et al. 2013)
  - SFR ~ 0.1 $M_{\odot}$ yr^{-1}
  - SF type : pearls on a string model

Summary

- Bar-only model can not explain multiple-burst SF.
- Spiral arms transport gas from outside region to the bar region, and that makes multiple-burst SF at nuclear ring.
- An azimuthal age gradient of star clusters is expected when SFR is low (less than 1 $M_{\odot}$ yr^{-1} in our models).