PART I

The destruction of bars by central mass concentrations

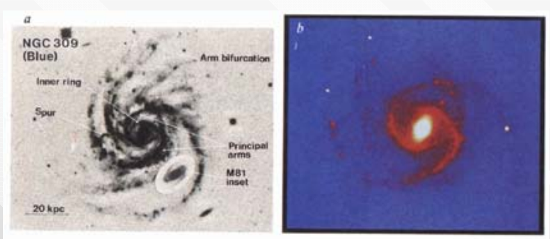
(Shen & Sellwood 2004, ApJ)

Barred galaxies

- A few examples
- General properties of bars
  - mainly composed of stars
    easier to see in near IR band
  - bar pattern rotates rapidly (Aguerri et al. 2003)
  - elongated streaming of material within the bar
- Bars affect dynamical evolution of galaxies
  - Drive gas flow inward; ignite circumnuclear starburst.
  - Bars: important drivers of secular evolution (Kormendy + Kennicutt 2004)

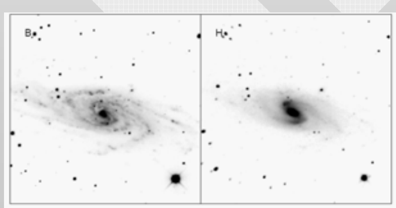
Bars easier to see in NIR

- Block & Wainscoat 1991



2.1 μm

- Eskridge et al. 2000 – NGC 5161



Motivation

- Bars are very common, ~2/3, (Eskridge et al. 2000)
- Central mass concentrations (CMCs)

"soft" – massive gas concentrations:
10^8 --$10^9 M_\odot$, R ~ a few hundred pc to 2kpc

"hard" – Supermassive BHs (+ surrounding stellar cusp)
10^6 --$10^8 M_\odot$, ~ 0.001 M_{bulge}

- How will a CMC affect the bar?
  - The general belief
  - Our main motivation

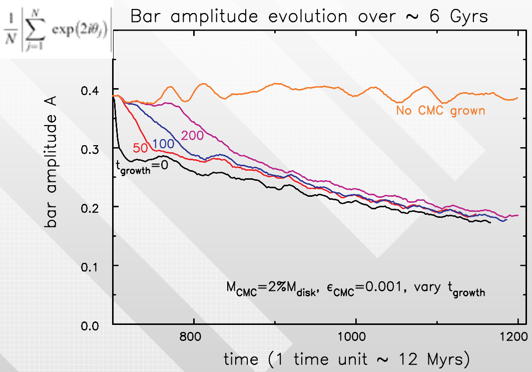
Simulation method and model

- *N*-body collisionless simulation, *N*=1.2~2.8million; particle-mesh code with a 3-D cylindrical polar mesh
- Create a disk galaxy with a fast-rotating bar embedded in a rigid/live halo
- CMC potential $\Phi_{CMC} = -\frac{GM_{CMC}(t)}{\sqrt{r^2+\varepsilon_{CMC}^2}}$

Main Results

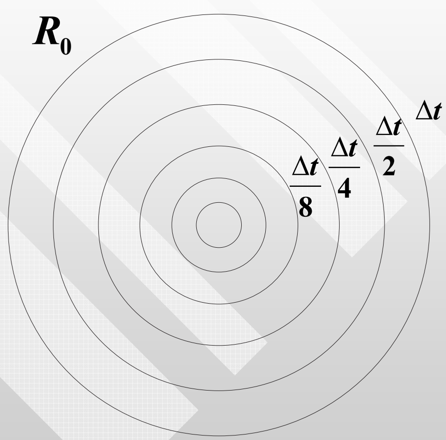
- Bars are robust against CMCs
- *Bar-ampl.* **A vs.** ***time*** for a "hard" CMC
  - growth time makes little diff.
- *Bar-ampl.* **A vs.** *CMC compactness* ε_{CMC}
  - Compact CMCs cause much more damage to bars
- *Bar-ampl.* **A vs.** M_{CMC}
  - The CMC has to be at least ~ **4%** M_{disk} to completely destroy the bar on short time-scale.

$$A(t) = \frac{1}{N}\left|\sum_{j=1}^{N}\exp(2i\theta_j)\right|$$



Checks and Parameter tests

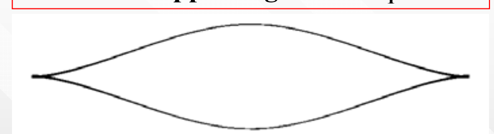
- Tested numerical parameters: *N;* grid size; particle softening ……
- Tiny time steps needed
  - "Guard Shells" scheme
  - large time step might give erroneous fast bar decay
- Rigid halo → a responsive "live" halo
  - Similar bar-decaying behavior
  - A denser live halo stimulates the growth of a bar (Debattista & Sellwood 2000; Athanassoula 2003)



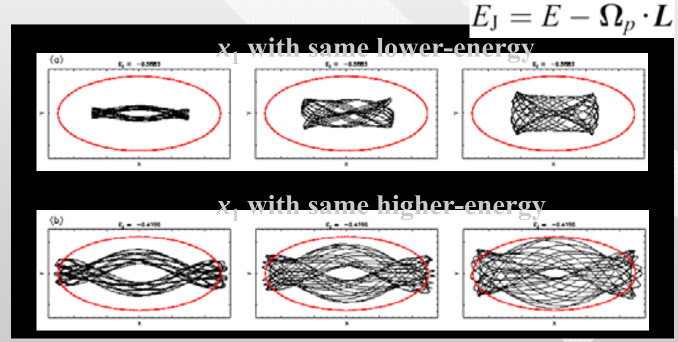
Bar dissolution mechanism

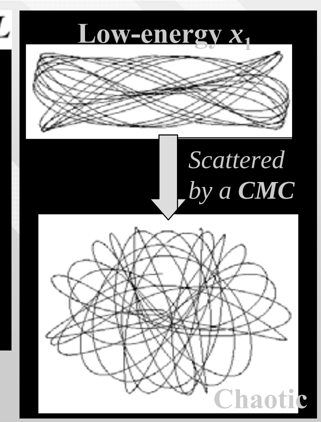
- Why is a bar robust against a CMC?

Main bar-supporting orbits: x_1 orbits



$$E_J = E - \Omega_p \cdot L$$





Bar evolution with a CMC

- 1st phase: low-E_J x_1 particles get scattered into chaotic orbits by a CMC
- 2nd phase: secular changes to the global bar potential further diminish the number of bar-supporting orbits.
  - A collective effect
  - timescale >~ 0.5 t_{Hubble} for a modest CMC

Recent development on bar robustness

- Consensus: bars are robust against typical CMCs.
  - Collisionless simulations.
    - » Athanassoula et al. 2005; confirmed our results; a dense live halo makes the bar even more stronger.
  - with gas
    - » Debattista et al. 2005; Bournaud et al. 2005
- But can other gaseous effects destroy bars?
  - Bournaud et al. 2005
    - » Bars are fragile with gas included; multiple lives in a Hubble time.
    - » gravity torque from gaseous arms destroys the bar
    - » Not verified in other studies yet
  - Debattista et al. 2005: bars are *still robust* with gas included.

Implications

- Bars are common! despite the ubiquity of CMCs
  - No genuine paradox; bars are not required to be regenerated
- Bars drive large amount of gas into galaxy centers, yet bars ***can*** survive such mass concentrations
  - Sakamoto et al. 1999, Regan et al. 2001: barred galaxies have a much higher concentration than unbarred galaxies.
- Bars are probably long-lived features
  - GEMS survey by Jogee et al. (2004): roughly similar fraction of strong bars out to z~1 (8Gyr).
  - ACS survey of Tadpole galaxy field: Elmgreen et al. (2004)

Conclusions

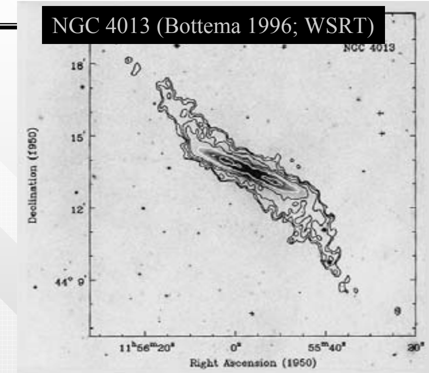
- Bars are more ***robust*** than previously thought.
  - Even for the most destructive SBH-like CMCs, a CMC has to be > a few % of M_{disk} to completely destroy the bar
  - The bar-dissolution time scale is long(~ 6Gyrs even for a hard 2% CMC)
- "Hard" CMCs (SBH-type) cause more damage to the bars than the "soft" ones (gas concentration like).
- The current masses of SBHs (~0.1% M_{bulge} or so), even when dressed with a stellar cusp, are probably too small to affect the bars of their host galaxies.
- The molecular gas concentrations found in some barred galaxies are also too diffuse to weaken the bar significantly.
- Consistent with Jogee et al. (2004): large bar fraction in earlier universe (2~8 Gyr ago)
- Latest more realistic studies have confirmed that bars are robust against typical CMCs.

PART II

Galactic Warps

Warps

- HI warps; mostly $\int$-shape
  - Optical/stellar warps much smaller amplitude
- Warps are extremely common
  - 20/26 edge-on spirals are warped! (e.g. Garcia-Ruiz et al. 2002); Perhaps all warped
  - Long-lived or repeatedly regenerated
- Briggs's rules (1990)
  - Coplanar inside R_{25}, warped beyond
  - $R_{25}<R<R_{26.5}$, straight line of nodes (LON)
  - $R> R_{26.5}$, LON forms a *leading* spiral

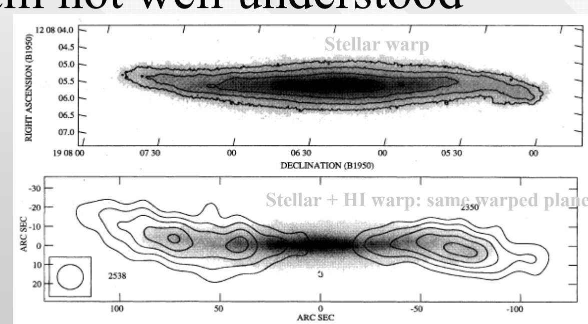


NGC 4013 (Bottema 1996; WSRT)

UGC 10034 [B+R composite] (Matthews & de Grijs 2004)

Theories on warp formation

- A gravitational phenomenon (Cox et al. 1996)
- Still not well understood



UGC 7170 Cox et al. (1996)

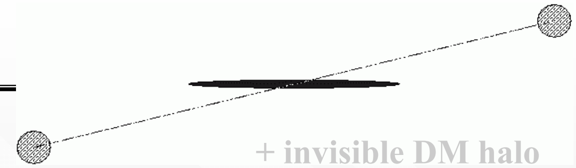
Warp Theories (II)

- Warp formed through "cosmic infall"
  - Proposed by Ostriker & Binney (1989)
    - » CDM: mergers; accretion of material w/ misaligned *L*
    - » Halo *L* must shift within a Hubble time. (Quinn & Binney 1992)
  - Jiang & Binney (1999)
    - » Accreting torus
    - » Warps with reasonable amplitude
    - » Still not well demonstrated

Our work

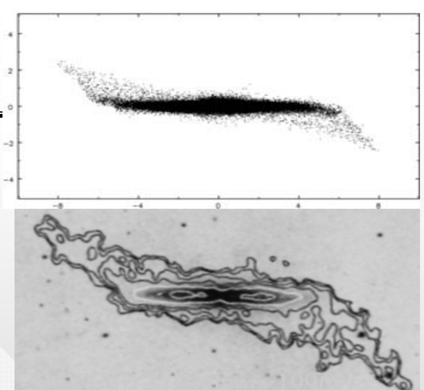
- Try to improve on Jiang & Binney (1999)
  - Self-consistent simulations
  - Study LON in a more extended disk
  - Try to understand this warp-forming scenario better

Setup



- Initial geometry
  - Disk + nearly spherical halo; M_{disk}/M_{halo}=1:9
  - Grow an accreting torus until M_{torus}=2.5 M_{disk}
  - Uniform torus: a clean quadrupole field
    - » mimics the quadrupolar perturbation of a misaligned outer oblate halo flattened by its angular momentum.
- Self-consistent *N*-body
  - Cylindrical polar grid + surface harmonics expansion on a spherical grid
  - *N* > ~ 1 million
  - All components can be live/responsive

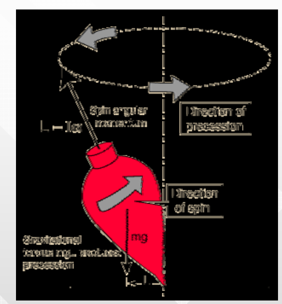
Typical simulations



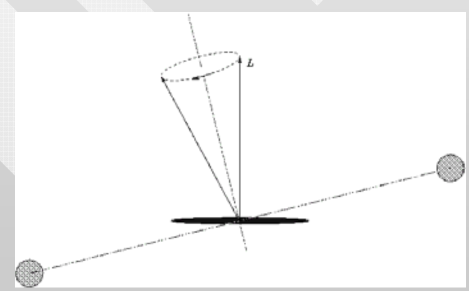
- Formation of warps
  - Movie1: projections
  - Movie2: 3-D view

  of warp at t=400
- The morphology compared with observation
- LON: always ***leading***
- Largely consistent with Briggs's Rules

Detail of warp formation



- Precession of a tilted spinning test ring
  - Retrograde
- Differential prec. → warp



- Inner disk rigid
  - Self-gravity
  - Random motion

Main conclusions

- Fully self-consistent *N*-body
- We demonstrate that warps formed in cosmic infall resembles both amplitude and morphology of observed ones, at least in some idealized models.
- Largely consistent with Briggs's rules; the massive inner disk is primarily responsible to the *leading* spiral of warp LON.