"Galactic Bridges and Tails"

or

"Simulations-A-Plenty"

Alar Toomre & Juri Toomre

ApJ, Vol. 178, pp. 623-666 (1972)

Natalie R. Hinkel

AST 591: Journal Club

Prof. Rolf Jansen

February 16th, 2007

What to Expect

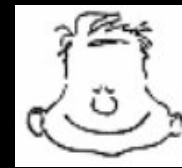
- Why we care
- Five Initial Simulations (to see how tails and bridges are formed)
- Pretty Pictures
- Fun with Parameters
- What we have learned
- Real-life examples of Arp 295, M51 + NGC 5195, NGC 4676, and NGC 4038/9 (complete with more pretty pictures and simulations)
- Wrapping it all up

there are 26 slides - start counting…

Motivation

- Papers previous to this (aka 1972, so I was -11 years old at the time) were hesitant to say that tidal/gravitational interactions were the cause of galactic tails and bridges
- Thought that since tidal forces were spatially gradual, they couldn't produce thin/narrow/filament-like features
- But, boy, were they wrong…
- Counterarm - farside offshoot of galaxy still bound to the disk
- Tail - farside feature that is no longer bound
- Bridge - length of debris/particles that extend to the companion, nearside

Simulation 1



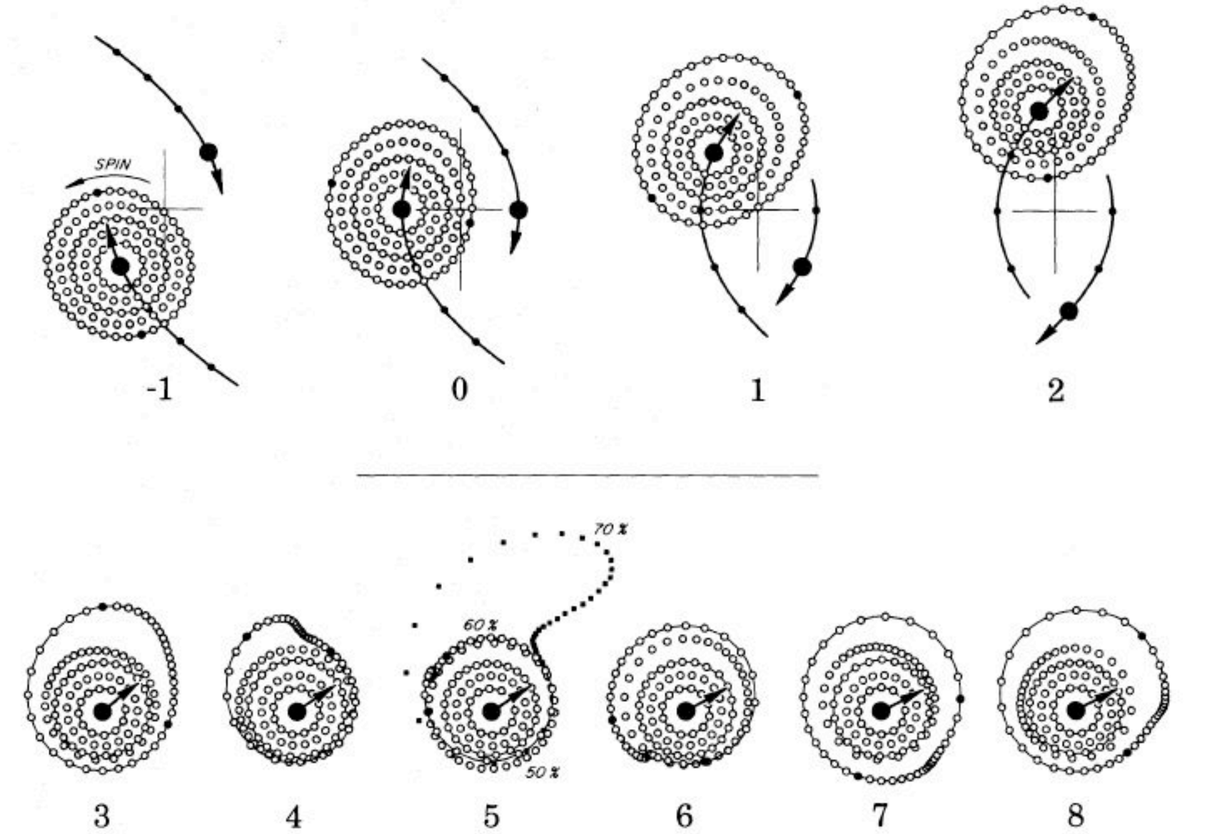


FIG. 1.—A flat retrograde ($i = 180°$) parabolic passage of a companion of equal mass. The two small filled circles denote test particles from the $0.6R_{min}$ ring which, in the absence of the encounter, would have reached positions exactly to the right and left of the victim mass at $t = 0$. The filled squares at $t = 5$ depict additional test particles from $0.7R_{min}$. (Note the partial interpenetrations of the outermost rings at $t = 4$, 5, and 6, and their continuing oscillations thereafter.)

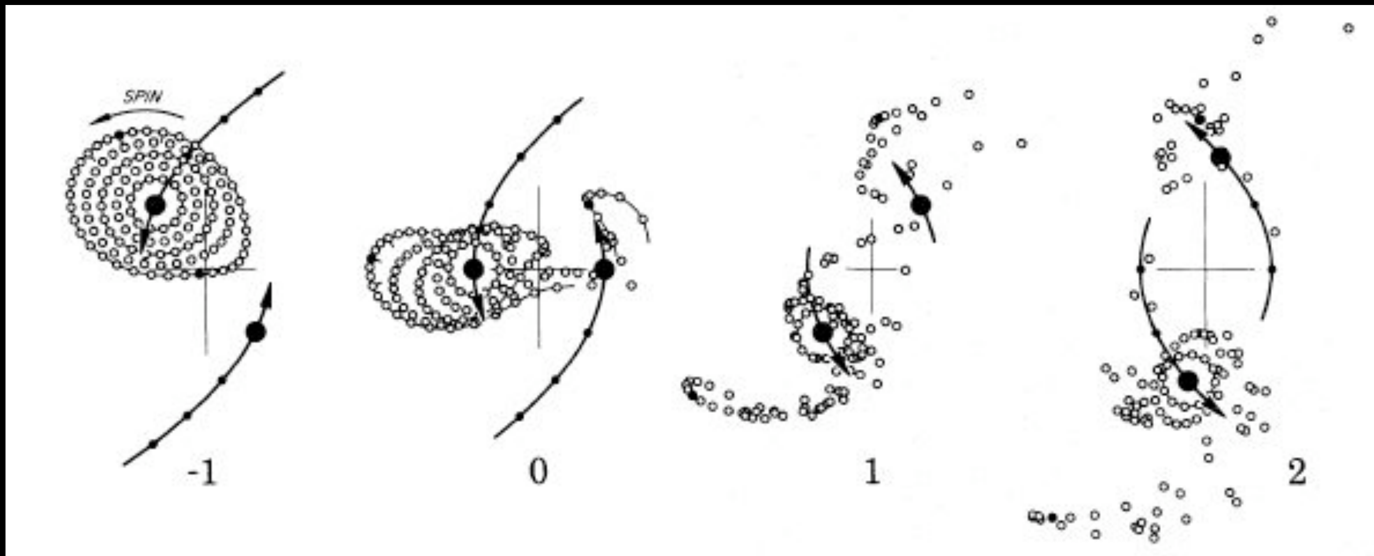
For all models:

- Massless particles make up disk, $1/r^2$ law
- Point sources represent mass bulk of galaxies
- Parabolic passages
- Ignore self-gravity of disk
- See board

Here:

- $M_1 = M_2$, flat, retrograde
- t = [-1, 2] COM frame
  t = [3,8] M_1 frame
- Note black circles

Sim 2



- $M_1 = M_2$, prograde, flat
- much more violent than retrograde motion
- Bridge from outer 3 rings of particles (eventually captured by the companion)
- Tail feature at t = 5 due to escaping particles

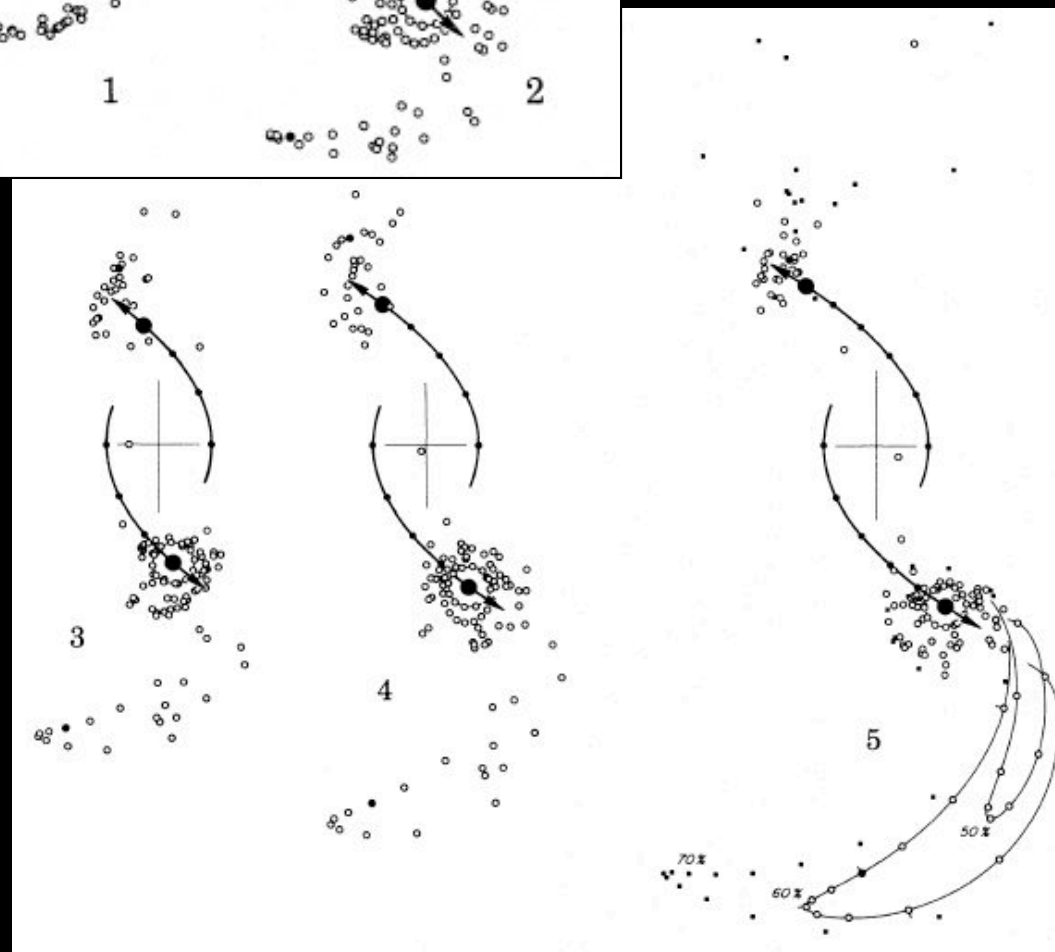
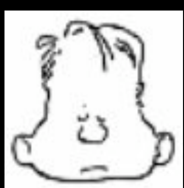


FIG. 2.—A flat direct ($i = 0°$) parabolic passage of a companion of equal mass

Sim 3



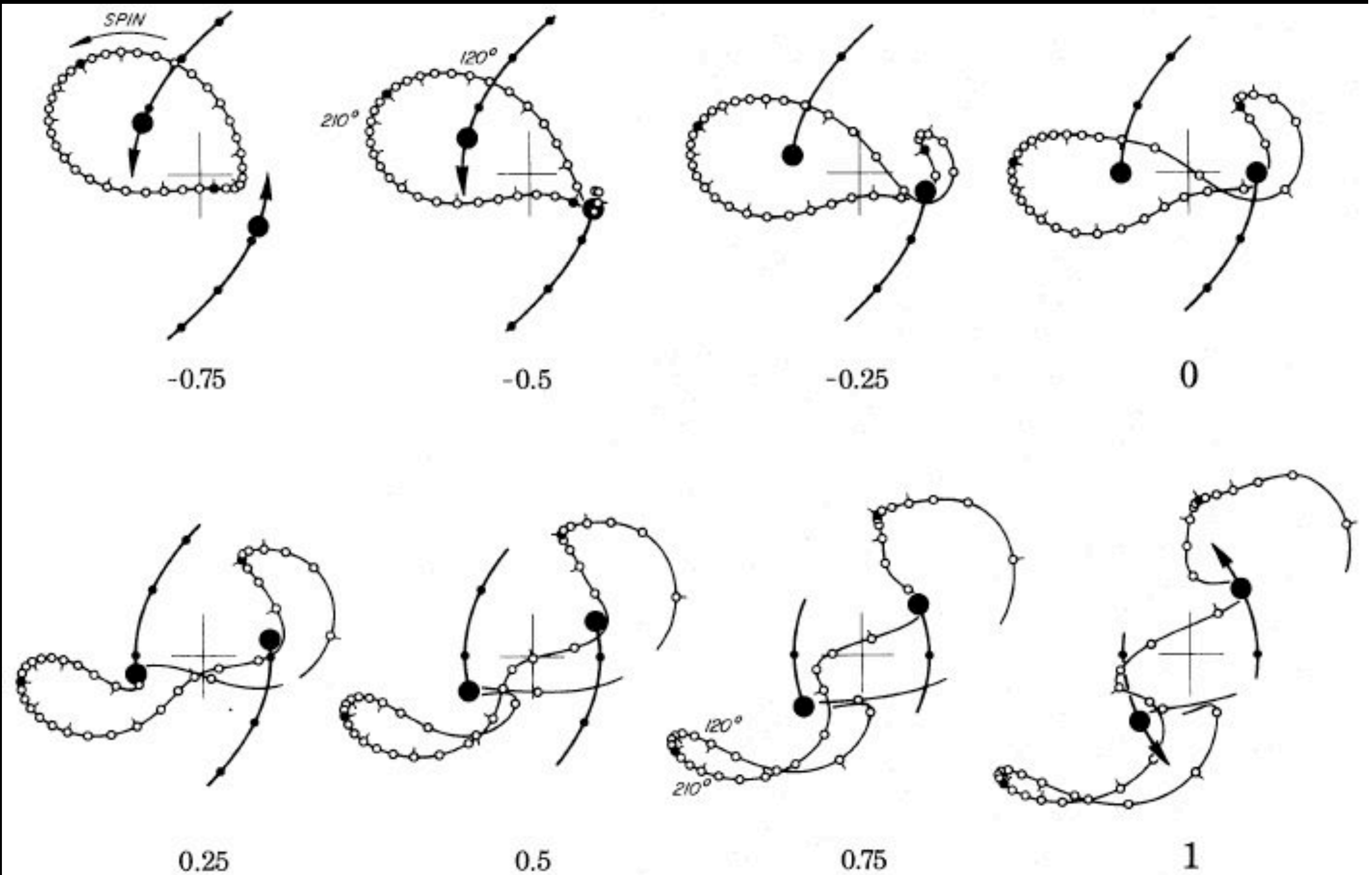
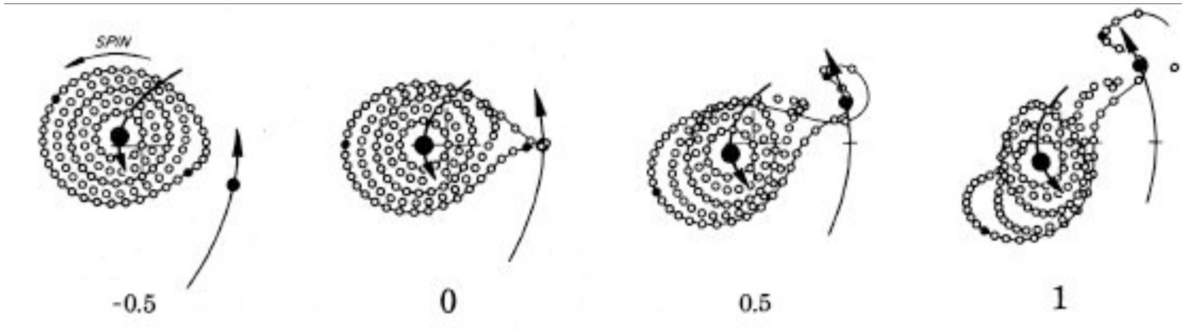
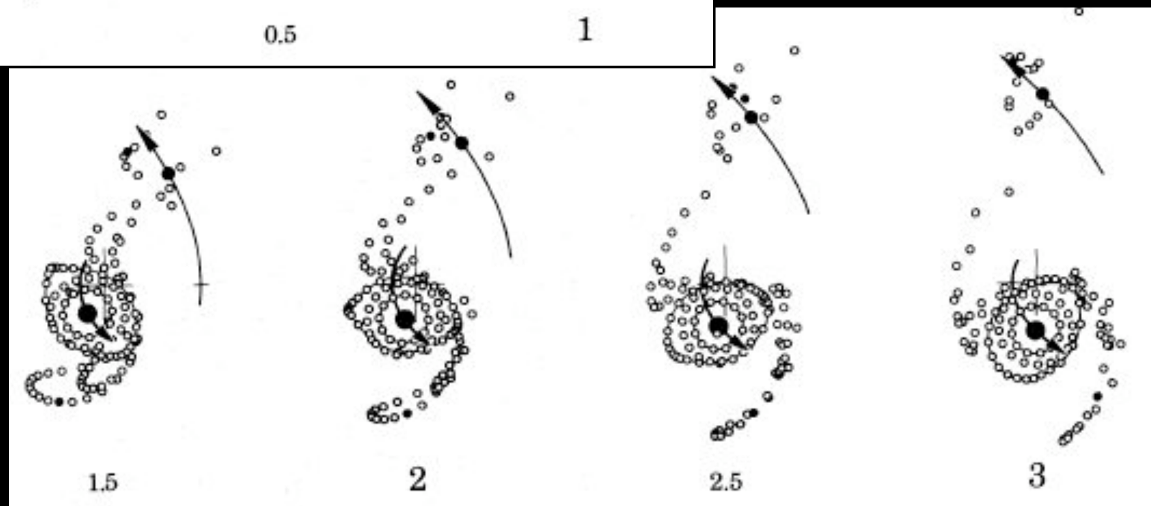


FIG. 3.—A slow-motion study of the distortion of the $0.6R_{min}$ ring during the direct passage of the equal-mass companion. Originally spaced 30° apart in longitude, the tick marks on every third test particle help identify the "inside" of the curve in the later frames.

- Simulation 2 analyzed more closely
- Note that 120^o-particle is inside and eventually overtakes the 210^o-particle

Simulation 4





- $M_1 = 4M_2$
- prograde, flat
- smaller radii modelled since outer rings kept being captured
- longer time to develop bridges than Fig. 2, but they weren't eventually captured
  - Longer/better bridges

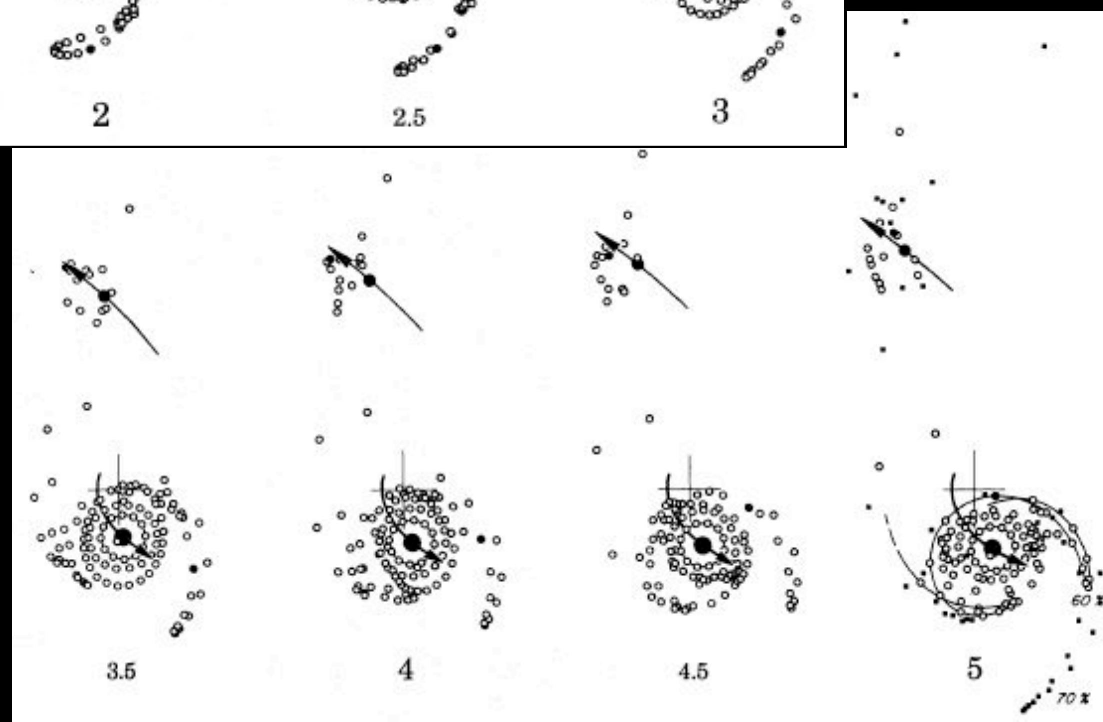
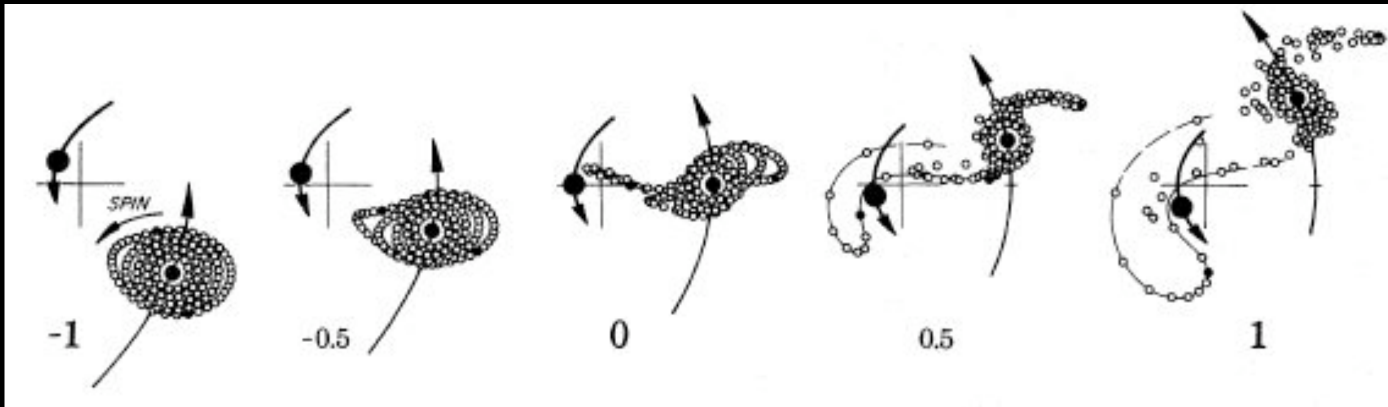


FIG. 4.—A flat direct ($i = 0°$) parabolic passage of a quarter-mass companion

Sim 5



- $4M_1 = M_2$, flat
- Not good bridges - matter captured by companion
- Obvious broad tail formed and disk is distressed

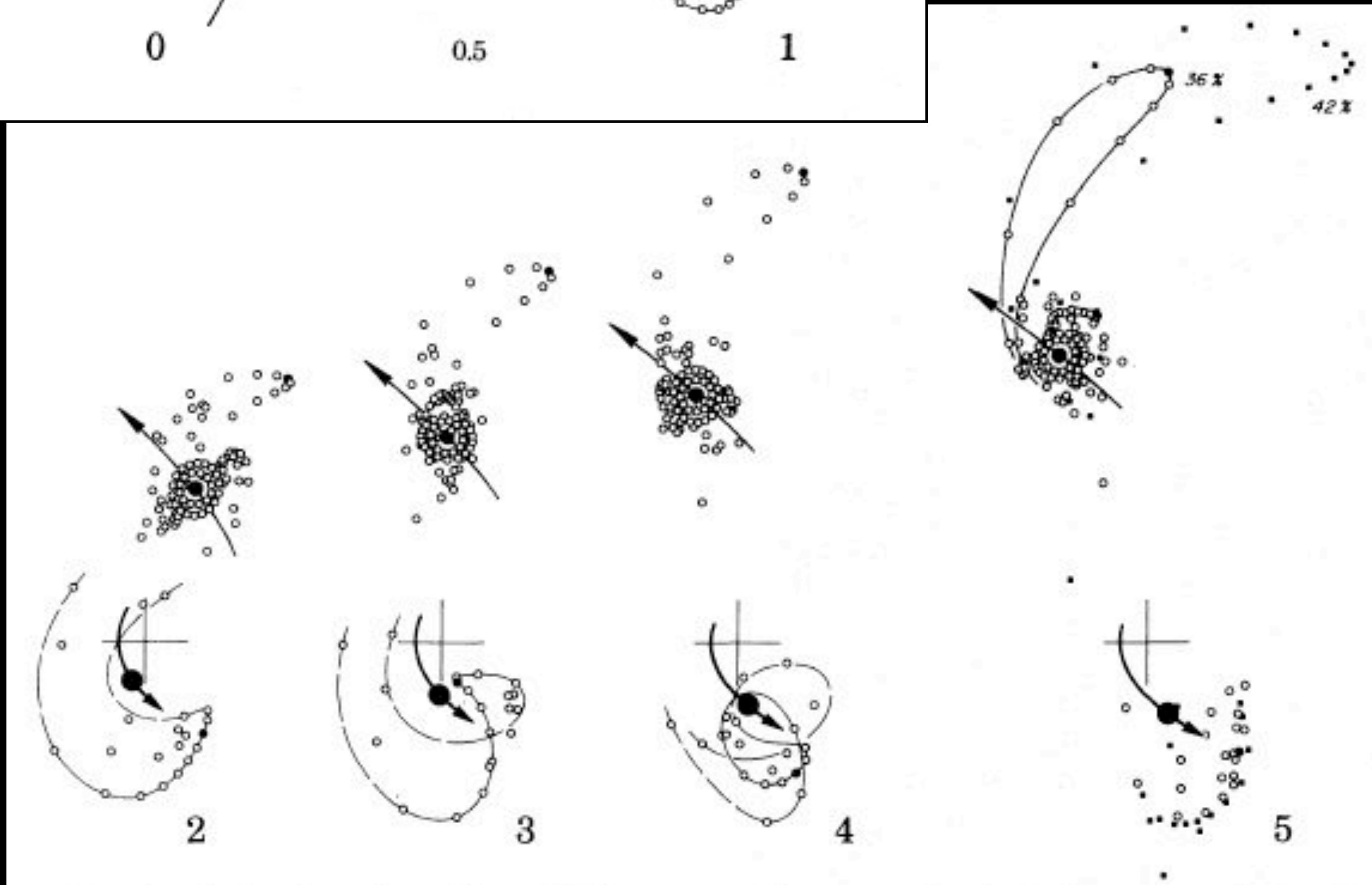
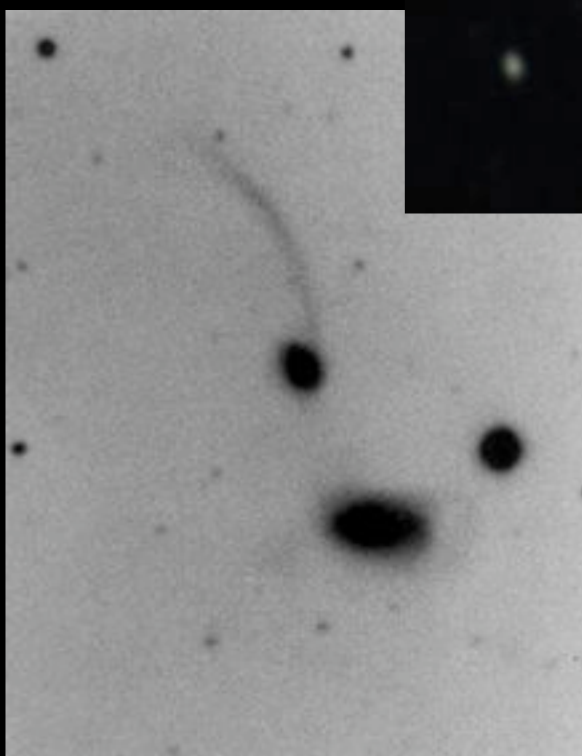


FIG. 5.—A flat direct ($i = 0°$) parabolic passage of a companion four times as massive as the "victim." (Note that these pictures can simply be superposed on the respective frames of fig. 4 for a valid composite sequence.)

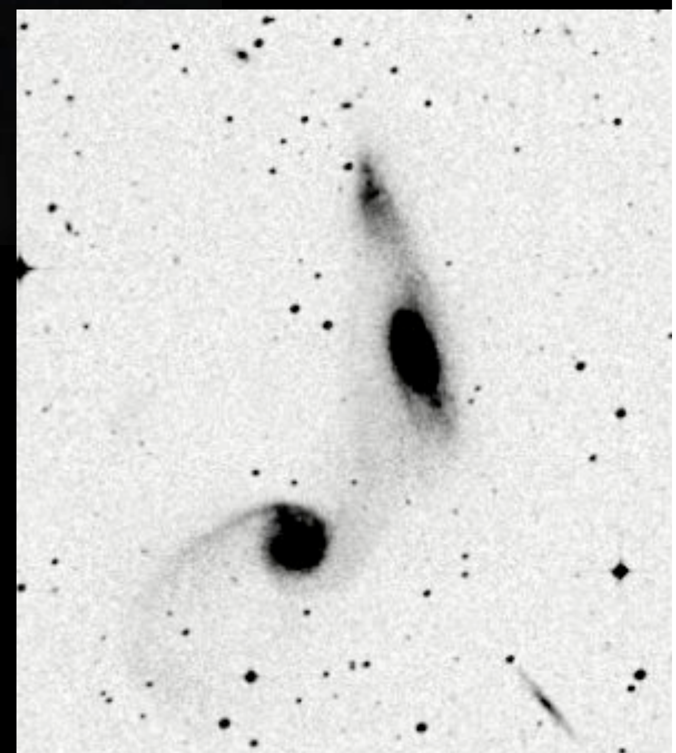
Tails!

Arp 173



NGC 2623

- NGC 2992/3

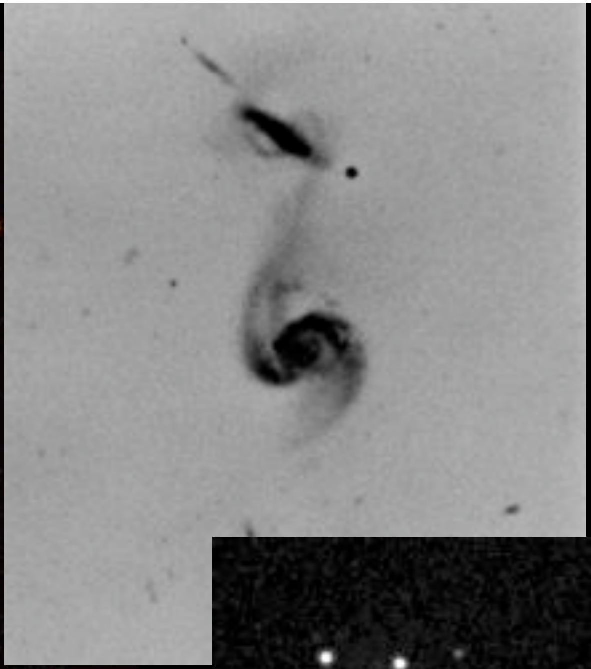


http://www.astrooptik.com/Bildergalerie/PolluxGallery/NGC2623.htm www.etsu.edu/physics/bsmith/research/sg/arp.html

http://www.ess.sunysb.edu/fwalter/SMARTS/findingcharts.html

Bridges!

NGC 2535/6



NGC 3808

NGC 7752/3

astromania.deyave.com/ www.etsu.edu/physics/bsmith/research/sg/arp.html www.spiral-galaxies.com/Galaxies-Pegasus.html

Define parameters

- In order to create better 3-D simulations, and mimic what we see in the universe, we need more variables (See board)
  - i : angle of inclination between spin and orbital plane
  - ω: angle of galaxy's perihelion to the spin plane
  - β: line of sight angle from the z-axis, tilt
  - λ: longitude

viewing direction

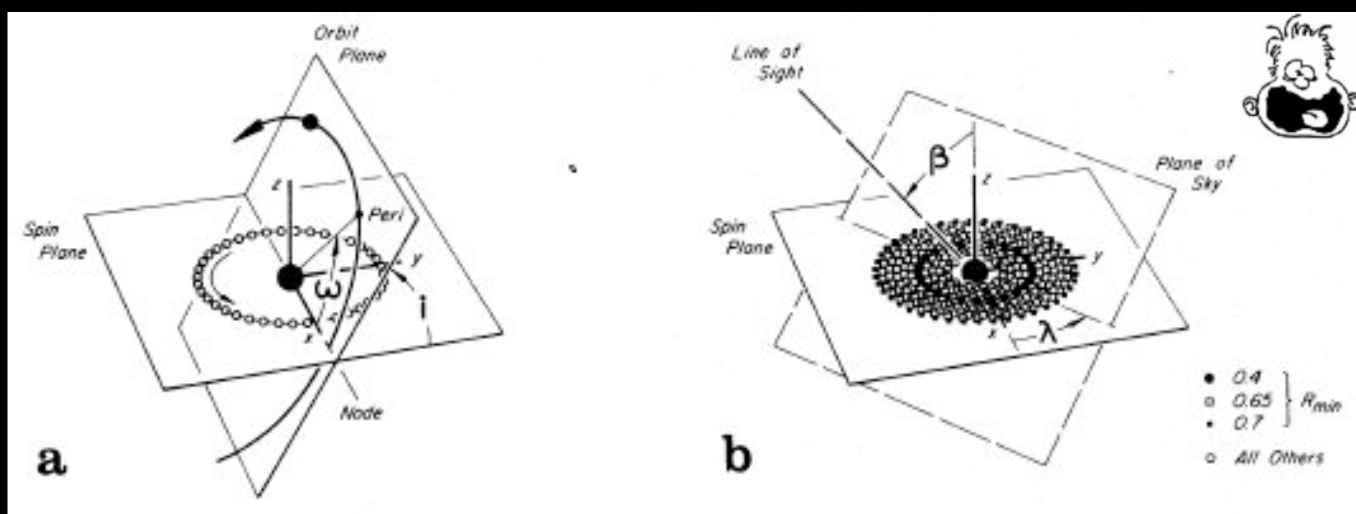


FIG. 6.—(*a*) Orbit geometry. (*b*) Viewing geometry.

Vary the Inclination

(and see what happens)

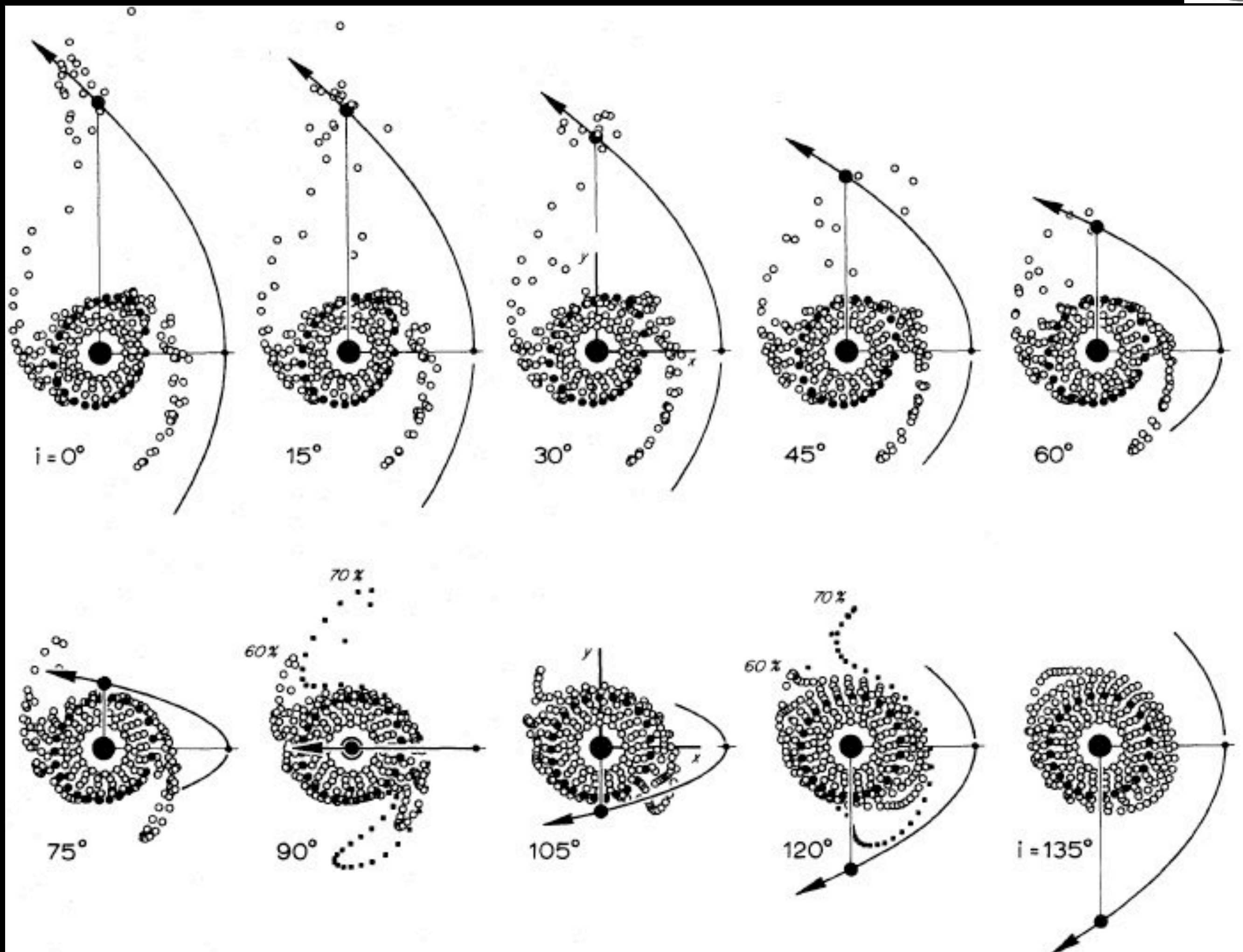
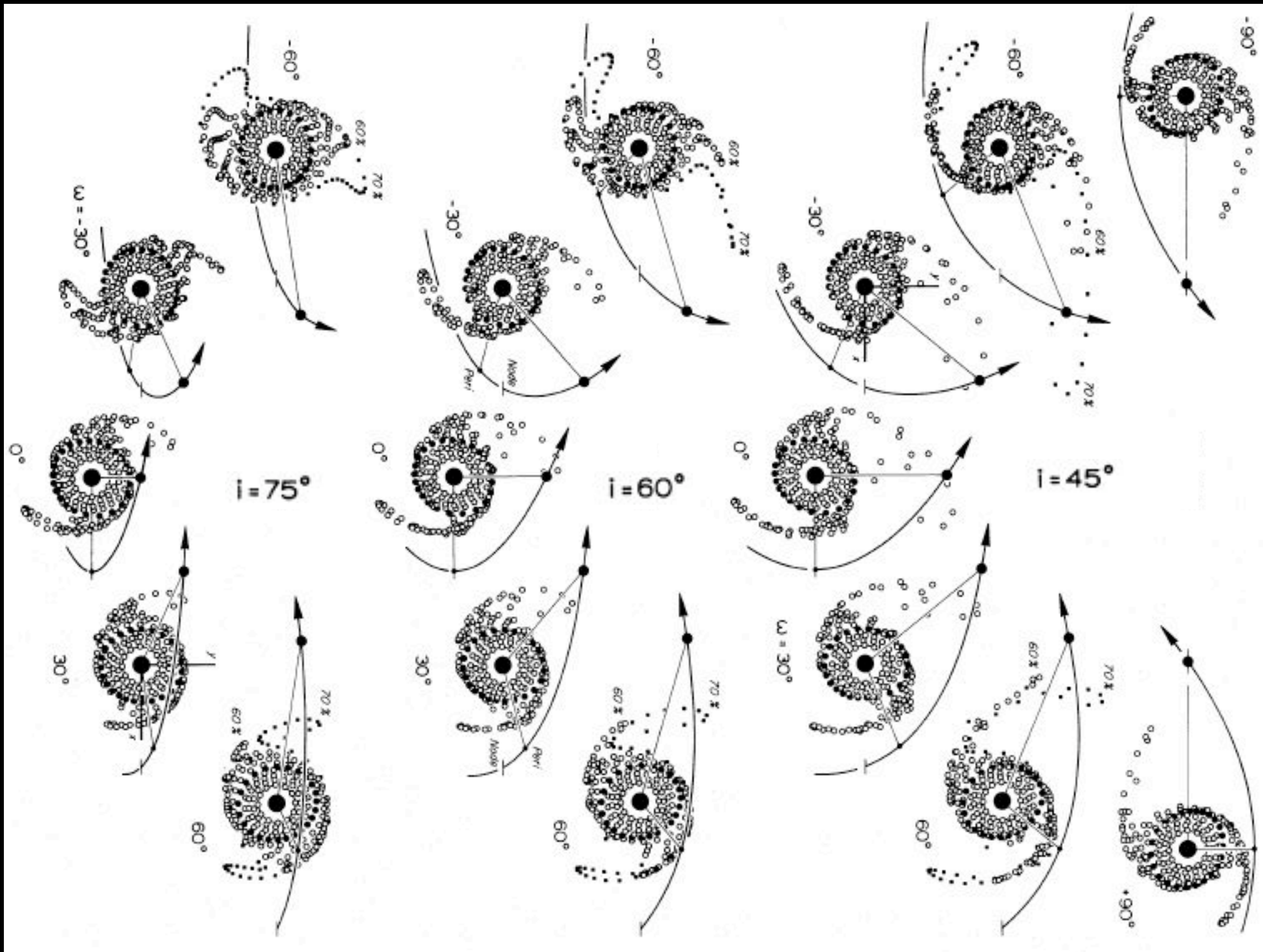


FIG. 7.—Face-on ($\beta = 0°$) views at $t = 3.143$ of disks perturbed by a quarter-mass companion during variously inclined parabolic passages of fixed argument $\omega = 0°$.

- $M_1 = 4M_2$
- Violence most extreme when i = 0
- Bridges aren't limited to low inclination
- Tails aren't as long and broad as befor
- Note oval distoratio in the black .4R_{min} ring
- Hard to tell which particles are projected and whic are eventually captured at this angle

Vary
and ω



(just because like all the models)

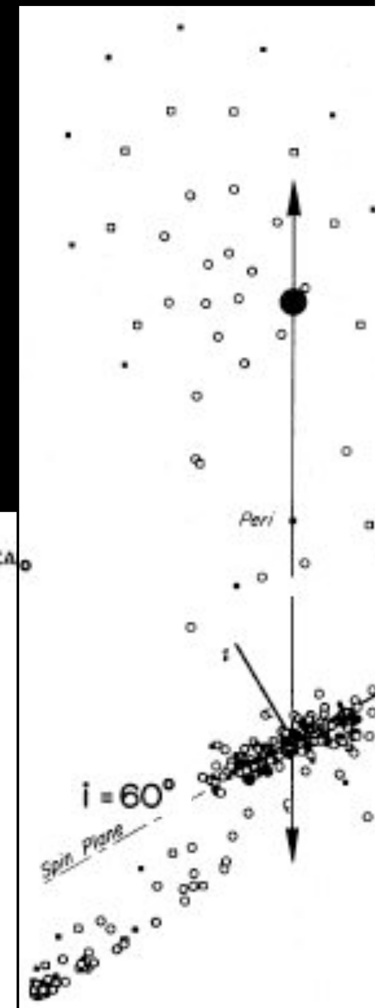
- $M_1 = 4M_2$, more complex variety of bridges and tails
- No $.7R_{min}$ ring of particles

Tails!

(again…)

- Most favorable tails occur when masses are equal
- More of a variety of statistics than bridges

- i = 30° tail no longer in orbital plane
- i = 60° tail almost in spin plane → $\beta = \lambda = 90°$



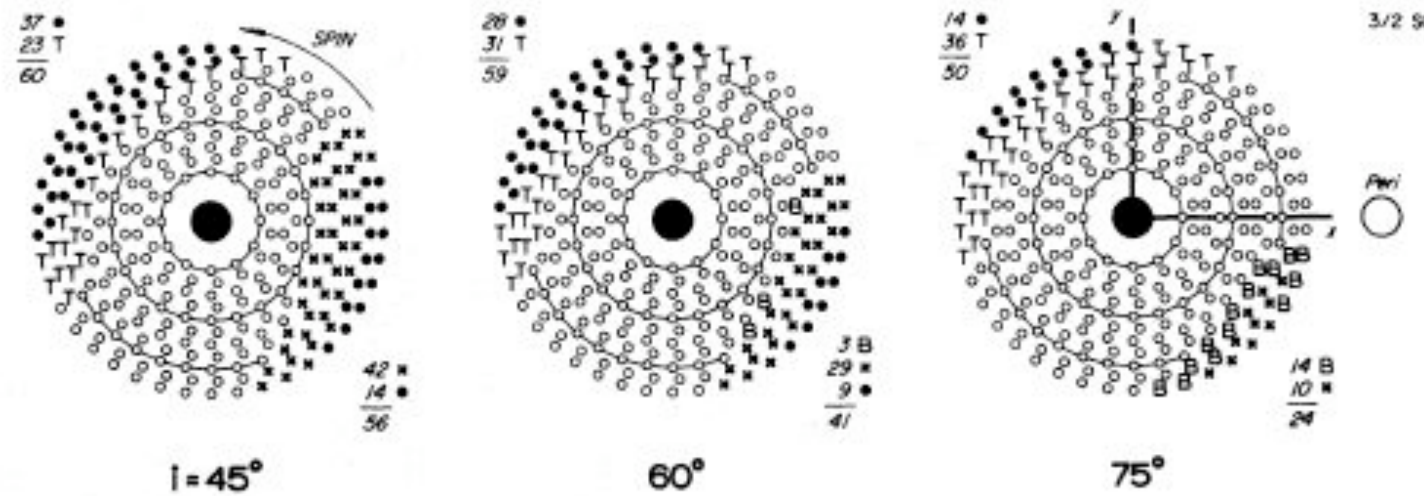


FIG. 15.—Scorecards of tail-making and accretion for three (i = 45°, 60°, and 75°) inclined $\omega = 0°$ parabolic passages of a companion of equal mass. The open symbols represent test particles retained by the primary mass point, crosses are those captured by the intruder, T's are nonescaping tail particles which at t = 5 lie farther than $1.0R_{\min}$ from their parent mass, B's are similar bridge-like particles, and the filled symbols denote particles that escape from both systems. The initial radii of the three connected rings were 0.2, 0.4, and $0.6R_{\min}$.

Overview of Tails

- Varying eccentricity does little for orbits [1.0, .8, .6]
- Tails occur for all ω, even higher inclination
- Tail particles are able to rise above orbital plane
- Get broad as well as thin views

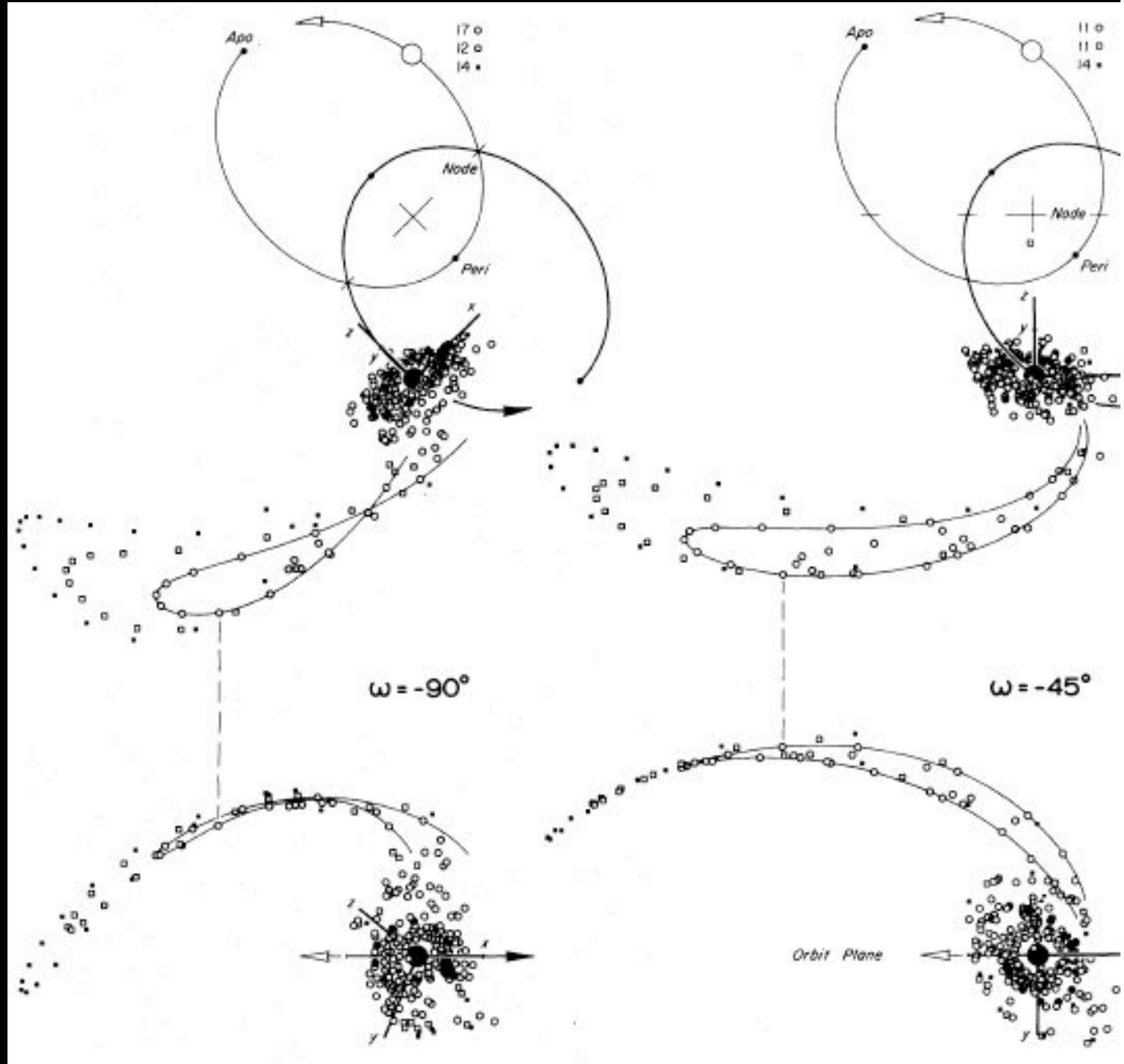


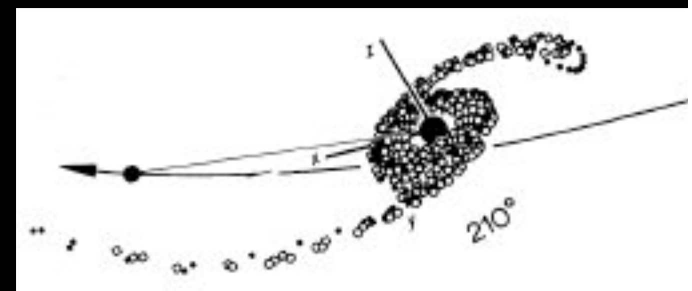
FIG. 18.—A survey of tails produced by elliptic $e = 0.6$ equal-mass passages of fixed inclina
$i = 60°$ but of different orbital arguments $\omega = -90°, -45°, 0°$, and $45°$. These configurations
here shown at time $t = 6.086$, which corresponds to exactly 135° of orbital travel since pericer

And now for Bridges

- Bridges occur more at low inclination $i \leq 30^o$, $i \geq 60^o$ yields nothing, but $i = 45^o$ ambiguous (see figure below)
- Very thin, linear feature is created when $i = 45^o$, $\omega = -60^o$, $\beta = 60^o$, and $\lambda = 210^o$ →

  and

  $i = 45^o$, $\omega = 0^o$, $\beta = 60^o$, and $\lambda = 45^o$ →



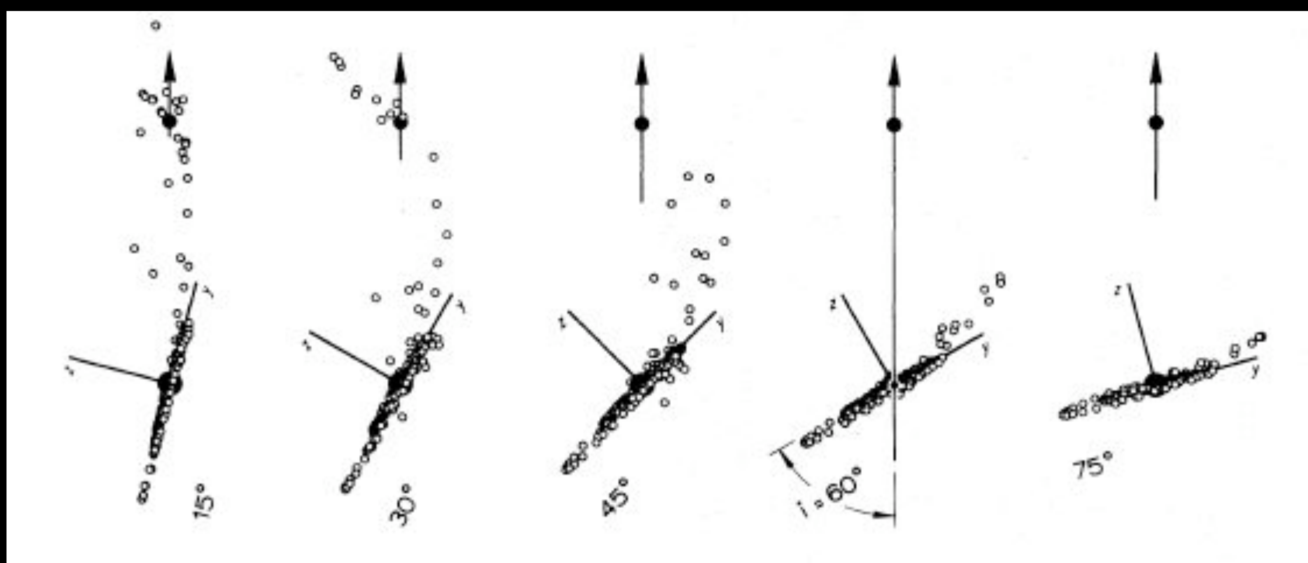
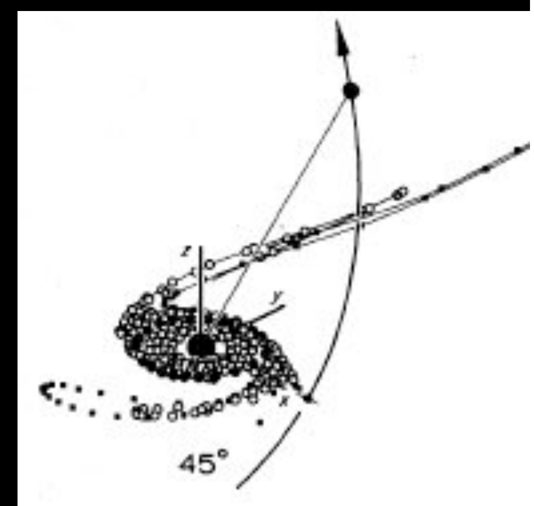


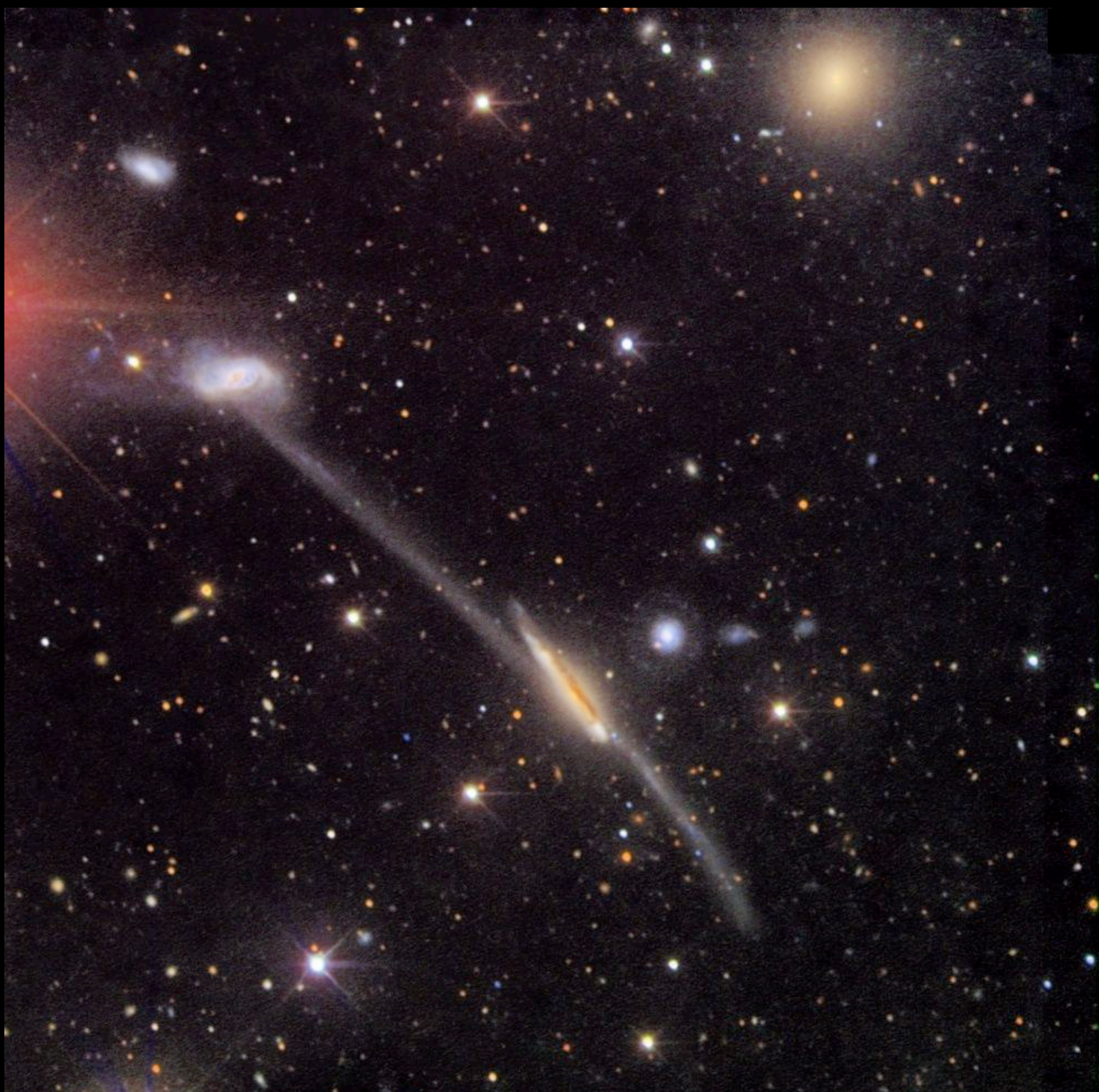
FIG. 10.—Edge-on ($\lambda = 90°$, $\beta = 90°$) views from the direction of the line of nodes, of five perturbed disks from fig. 7.



When Two Galaxies Really Love Each Other

- Good tails (linear, elongated, thin) occur only when the companion is of similar mass - also helps when passages are closer and slower
- Good bridges (dense, narrow, and persist over time - rather than being eaten by the companion) require an unequal mass ratio: $M_1/M_2 > 1$ - such that the companion is smaller than the primary, also when the orbit plane is inclined to the spin plane ($0 < i < 45^o$)
- Much of what we are seeing depends on the perspective angle - since it is hard to tell in which plane the thin stream of particles/tail/bridge lie

Finally… Arp 295



http://apod.nasa.gov/apod/ap051008.html

- 100 Mpc, v = 7000 km s^{-1}, separation of 4.5 arcmin (130 kpc), 2.5 arcmin (70 kpc) counterarm
- Companion about the same size as the MW
- Galaxies recently approached within 1/2-1/3 of their present separation
- Orbit inclination ≤ 20^o to avoid a thicker, curved bridge
- $30^o \leq \omega \leq 60^o$ for a straight and tilted bridge, counterarm
- M_1/M_2 = [3, 10]

Survey Says:

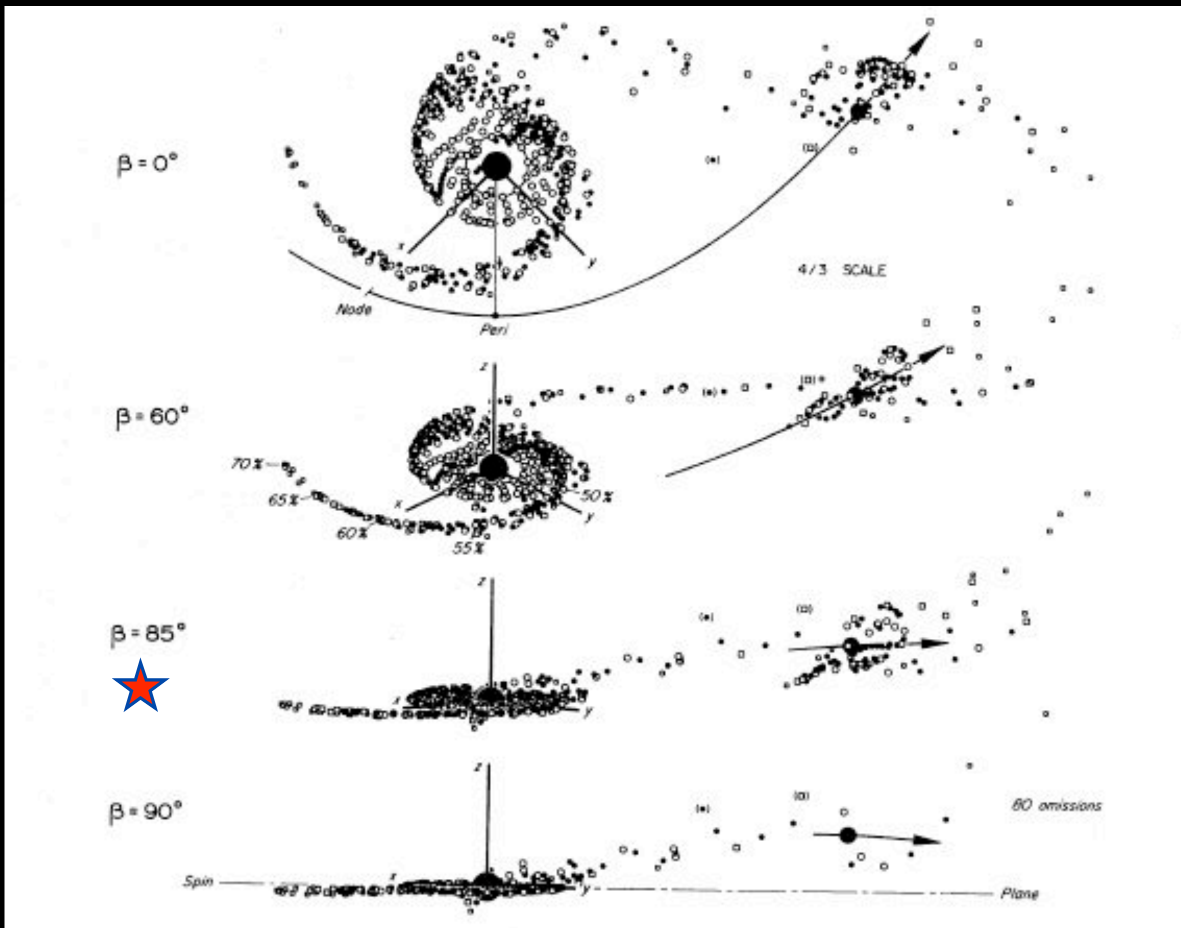


FIG. 19.—Model of Arp 295. This construction supposes a parabolic $i = 15°$, $\omega = 45°$ passage of a quarter-mass companion. Its consequences are here viewed at time $t = 4$ from longitude $\lambda = 135°$ and four distinct latitudes. Except for the heavy "spray" near the companion, the $\beta = 85°$ picture resembles our actual view of this galaxy pair; much of that clutter has been suppressed in the $\beta = 90°$ view by omitting all particles which ever passed within $0.2R_{min}$ of the companion.

- $M_1 = 4M_2$
- t = 4, i = 15°, ω = 45°, λ= 135° with the best match when β = ~85°
- Problems: the disk is too thick, the bridge is slightly too thick, the spray near the companion isn't viewed in reality
- Solutions: self-gravity, stars younger than 390 Myrs

Oohh: M51 and NGC 5195

- Bridge and broad counterarm
- $M_1 = 3M_2$
- $-60^o < i < -75^o$, $\omega = -15^o$, $\lambda = 65^o$, $|\beta| = \sim 15^o$
- First passage by the companion
- Velocities of both have to be monitored
- Streamers from the companion

http://antwrp.gsfc.nasa.gov/apod/ap020710.html

- Place the time at t = 2.4 and e = 0.8, ω = -15° similar to Fig. 9
- Streamers thought to be a tail and loose bridge due to recent encounter
- High inclination, anti-parallel spins, companion must have travelled a distance ~ length of tail to create the plumes

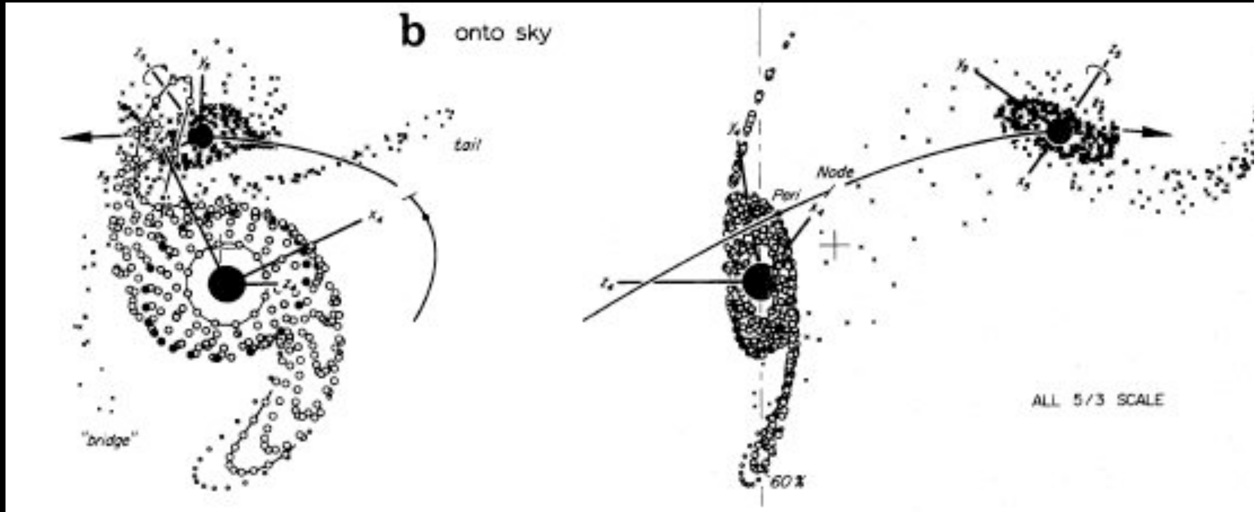


FIG. 21.—Model of the recent encounter between M51 and NGC 5195. Shown here at t = 2 are three mutually orthogonal views of the consequences of a highly elliptic $e = 0.8$ passage of supposedly disklike "5195." This satellite was chosen to be one-third as massive, and of exact 0.7 times the linear dimensions, of the "5194" primary—which itself contains particles from init radii 0.2(0.05)0.4(0.033)0.633$R_{\min}$. The orbit plane differs by an angle $i_4 = -70°$ from the init spin plane of the larger disk and by $i_5 = -60°$ from that of the smaller; however, the argumen $\omega_4 = \omega_5 = -15°$ of the pericenters were here kept identical, to make the above nodal axes x_4 a x_5 exactly antiparallel. The three views show the combined system as it would appear not only to us ($\lambda_4 = 65°$, $\beta_4 = -20°$), but also edge-on to our sky from (a) the "north" (−25°, 90°) a (c) the "west" (65°, 70°) directions.

- Durrell, Mihos, Feldmeier, Jacoby, & Ciardullo (2003) simulation of M51: http://burro.astr.case.edu/Talks/Viz2005/M51_deep.mpg

NGC 4676 A/B: The Mice

- Low inclination since tail A (RSH) is at $\beta \approx 90^o$, orbit of companion rather high
- Extremely similar to Fig. 18 with the broad, face-on tail - almost all the same values

http://antwrp.gsfc.nasa.gov/apod/ap040612.html

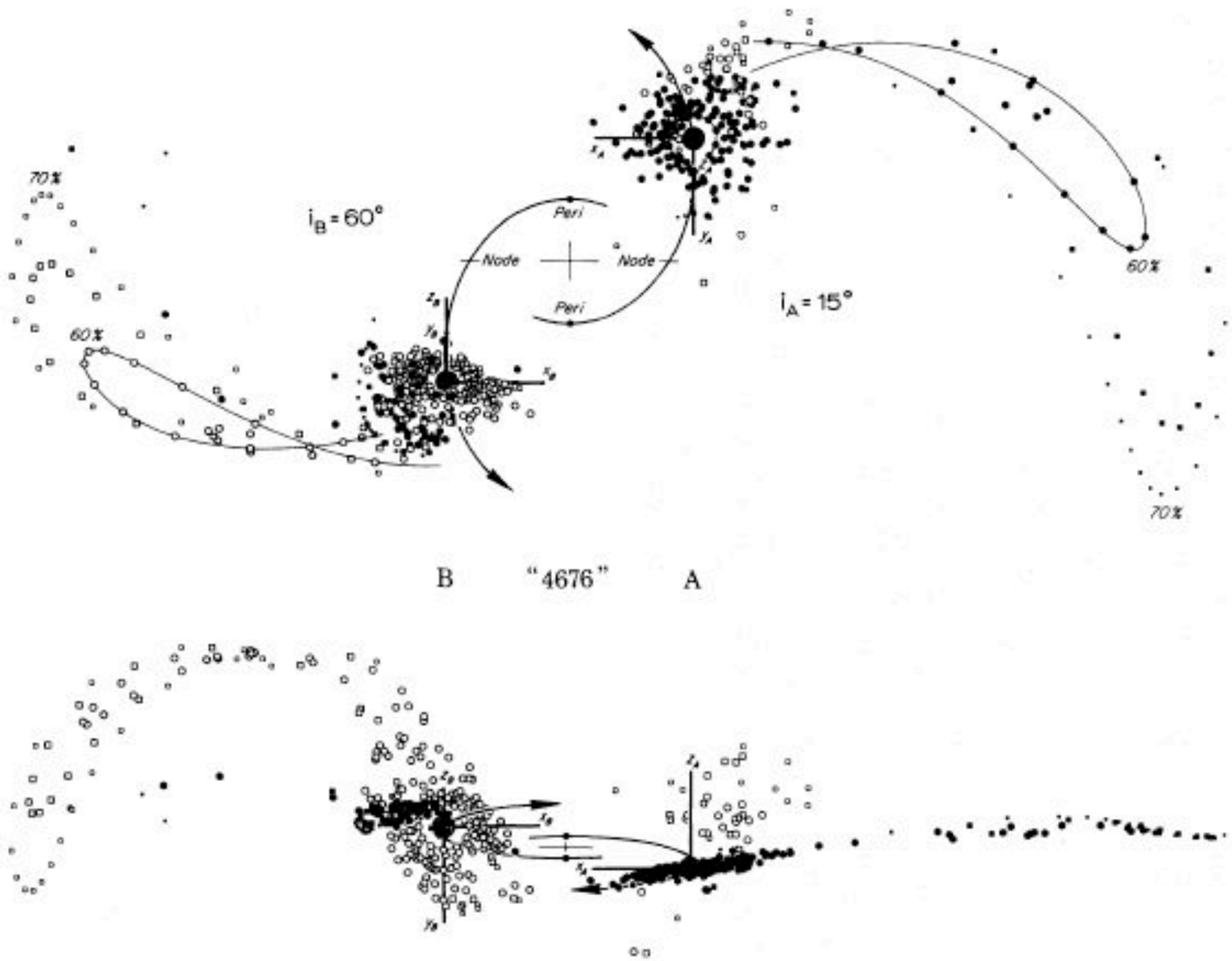


FIG. 22.—Model of NGC 4676. In this reconstruction, two equal disks of radius $0.7R_{min}$ experienced an $e = 0.6$ elliptic encounter, having begun flat and circular at the time $t = -16.4$ of the last apocenter. As viewed from either disk, the adopted node-to-peri angles $\omega_A = \omega_B = -90°$ were identical, but the inclinations differed considerably: $i_A = 15°$, $i_B = 60°$. The resulting composite object at $t = 6.086$ (cf. fig. 18) is shown projected onto the orbit plane in the upper diagram. It is viewed nearly edge-on to the same—from $\lambda_A = 180°$, $\beta_A = 85°$ or $\lambda_B = 0°$, $\beta_B = 160°$—in the lower diagram meant to simulate our actual view of that pair of galaxies. The filled and open symbols distinguish particles originally from disks A and B, respectively.

Niiiice

- Barnes and Hibbard (2004) simulation of the mice: http://www.ifa.hawai .edu/%7Ebarnes/pre ssrel/mice/vid301_0 2.mpg
- Morphing: http://www.ifa.hawai .edu/%7Ebarnes/pre ssrel/mice/v0211d3. mpg

The Antennae - NGC 4038/9

- Highly idealized situation
- Also similar to Fig. 18, bu using a symmetric model
- Potentials were “softened at close range to go as $1/[r^2+(.2R_{min})^2]^{1/2}$ to take into account the disperse mass (no longer point masses) - this also caused the tails to become more thin

http://www.starshadows.com/gallery/display.cfm?imgID=104

Not Too Bad At All

- Dubinski simulation of the Antennae Galaxy: http://www.cita.utoronto.ca/~dubinski/antennae/antobs.mpg

- $M_1 = M_2$, t = 15, e ≈ .5
- i = 60º, ω = -30º, λ= 30º, β = 0
- Problems arise because the tails are not of equal length an are more curved, model does not mimic the similar rotational direction that the actual galaxies appear to have

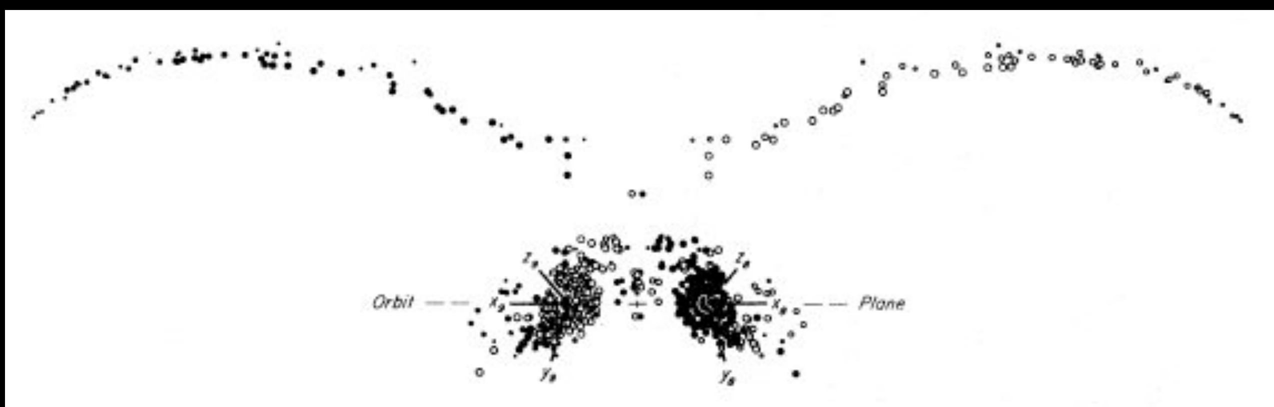
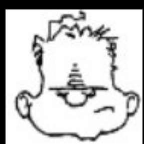


FIG. 23.—Symmetric model of NGC 4038/9. Here two identical disks of radius $0.75R_{min}$ suffered an $e \approx 0.5$ encounter with orbit angles $i_8 = i_9 = 60°$ and $\omega_8 = \omega_9 = -30°$ that appeared the same to both. The above all-inclusive views of the debris and remnants of these disks have been drawn exactly normal and edge-on to the orbit plane; the latter viewing direction is itself 30° from the line connecting the two pericenters. The viewing time is $t = 15$, or slightly past apocenter. The filled and open symbols again disclose the original loyalties of the various test particles.

Other Considerations

- Obviously, this paper is ~35 years old and the simulations were rather simplistic but the models were enlightening and not too inaccurate



  – Self-gravity completely neglected, as well as orbital changes due to the interaction and intrinsic properties of the galaxies

- And that - my friends - is all. Thanks to Prof. Jansen, Journal Club, APOD, Wikipedia, Binney & Tremaine (I know, right?), Trader Joe's, Tatertot (the cat, not the food product), and Gerbil (the computer, not the animal product)…☺