Galaxies, Cosmology and Dark Matter

Lecture given by
Ralf Bender
USM

Script by:
Christine Botzler, Armin Gabasch,
Georg Feulner, Jan Snigula

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Chapter 8

Mergers of Galaxies

First, let us consider the merger of two spherical galaxies with identical mass to derive simple scaling properties of the merger product.

- At first the two galaxies are on elliptical orbits around their center of gravity.
- Dynamical friction slows the galaxies down and leads to heating of their outer parts.
- The galaxies finally merge on very small and nearly circular orbits. The dynamical state of the product of the merger is thus **roughly** characterized by an object having an internal energy equal to the sum of the energies of the two galaxies. I.e. to a first approximation we have

$$E_f \ = \ \frac{1}{2} M_f \langle \sigma_f^2 \rangle \ \simeq \ 2\, E_i \ = \ M_i \langle \sigma_i^2 \rangle$$

  Using $M_f = 2\, M_i$ we find that the mean velocity dispersion of the product of the merger is equal to that of the initial galaxies:

$$\boxed{\langle \sigma_f^2 \rangle \ \simeq \ \langle \sigma_i^2 \rangle}$$

For the radii we have $r_i = c_1 M_i / \langle \sigma_i^2 \rangle$, and we find

$$\boxed{r_f \;\simeq\; 2\, r_i,}$$

whereas the relation for the surface brightness I_f of the merger remnant reads

$$\boxed{I_f \;\simeq\; \frac{1}{2}\, I_i}$$

Important note: In case of a *homologous* merger, which has the same dynamical structure as the merging galaxies, we can write "$=$" instead of "$\simeq$" in all relations.

Numerical simulations show that the situation is more complex in reality:

- Homology is not a very good approximation. Dissipation-less and gas-free numerical N-body simulations (without dark matter!) of merging in groups of galaxies yield the following scaling laws for the merger remnant:

$$\begin{aligned} r_e &\propto L^{0.85}, \\ I_e &\propto L^{-0.70}, \\ \sigma &\propto L^{0.08}. \end{aligned}$$

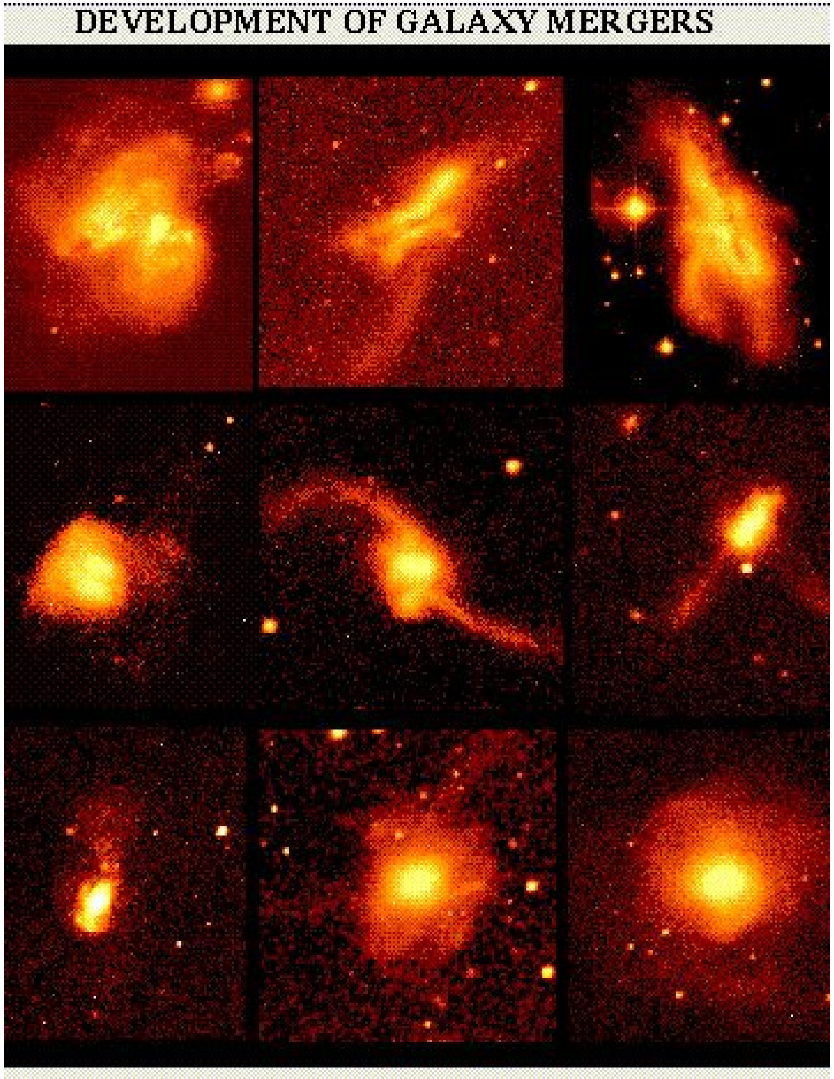
(Aarseth & Fall (1980) *ApJ*, **236**, 43).

Apart from the L–σ relation these relations are similar to the scaling laws for luminous elliptical galaxies!

Note: Be careful with quick conclusions! A pure dissipationless merging scenario for the formation of elliptical galaxies cannot explain, e.g. the Mg_2–σ relation!

- Modern simulations of spiral-spiral mergers with 10^6 and more particles show that merger remnants have stellar density profiles of ellipticals. Their phase space structure shows the effects of incomplete violent relaxation.
- **Dark matter** plays a crucial role in galaxy mergers. The dark matter makes the deceleration of the galaxies more efficient leading to a very fast merging of the galaxies. Furthermore, dark matter is important for the re-distribution of the galaxies' angular momentum (the orbital angular momentum of the galaxies is absorbed into the angular momentum of the remnant's halo).
- **Gas** plays a crucial role in galaxy mergers. The gas quickly moves to the center of the merger remnant. Stars can be formed which enhance the nuclear density of the merger remnant. The gas angular momentum can be opposite to the stellar angular momentum (gas and stars are distributed differently in the progenitors). In this way counter-rotating cores could be formed (similar to those observed in ellipticals). High central densities of gas also affect the orbit distribution of the stars and make the remnant more axisymmetric. The gas may also feed and grow nuclear black holes.

- These theoretical findings are in agreement with observations of merging galaxies. **Ultraluminous Infrared Galaxies (ULIRGs)** show the final stages of spiral-spiral mergers when heavy star formation is taking place. These galaxies show most of their emission in the near infrared because star formation is enshrouded in dust and the UV photons of the hot stars are absorbed and transformed into IR photons. There is also evidence for nuclear activity in these galaxies indicative of gas accretion onto massive black holes.



Various evolutionary steps of spiral-spiral mergers, including Ultraluminous Infrared Galaxies (ULIRGs).

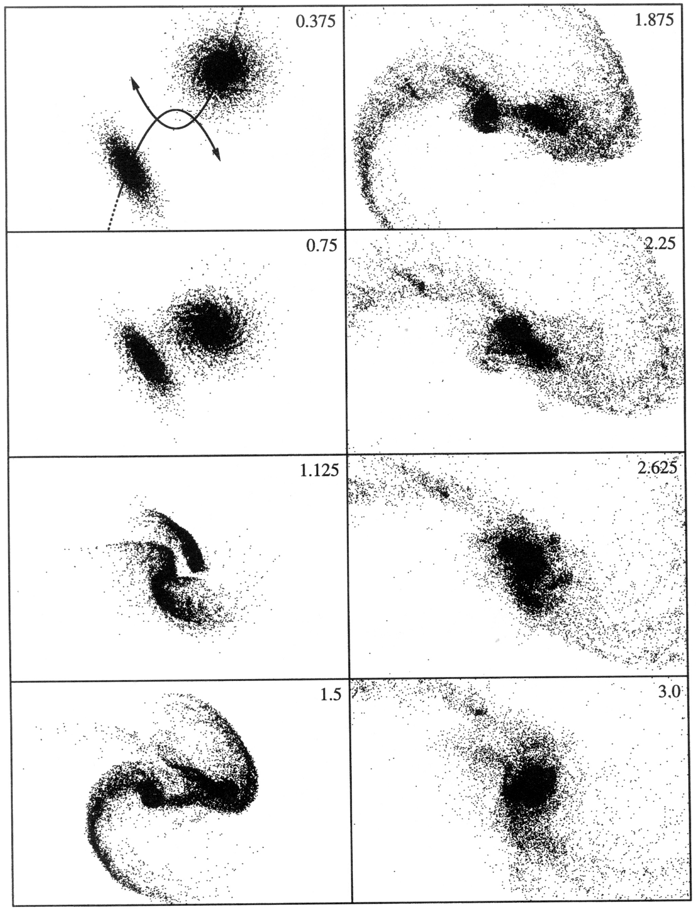
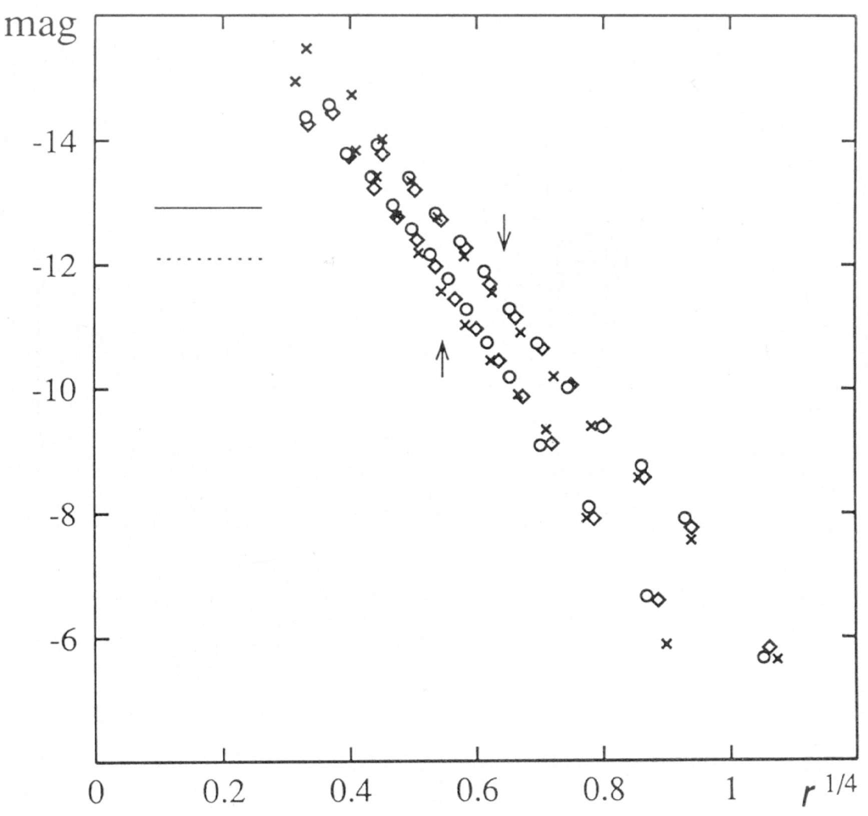


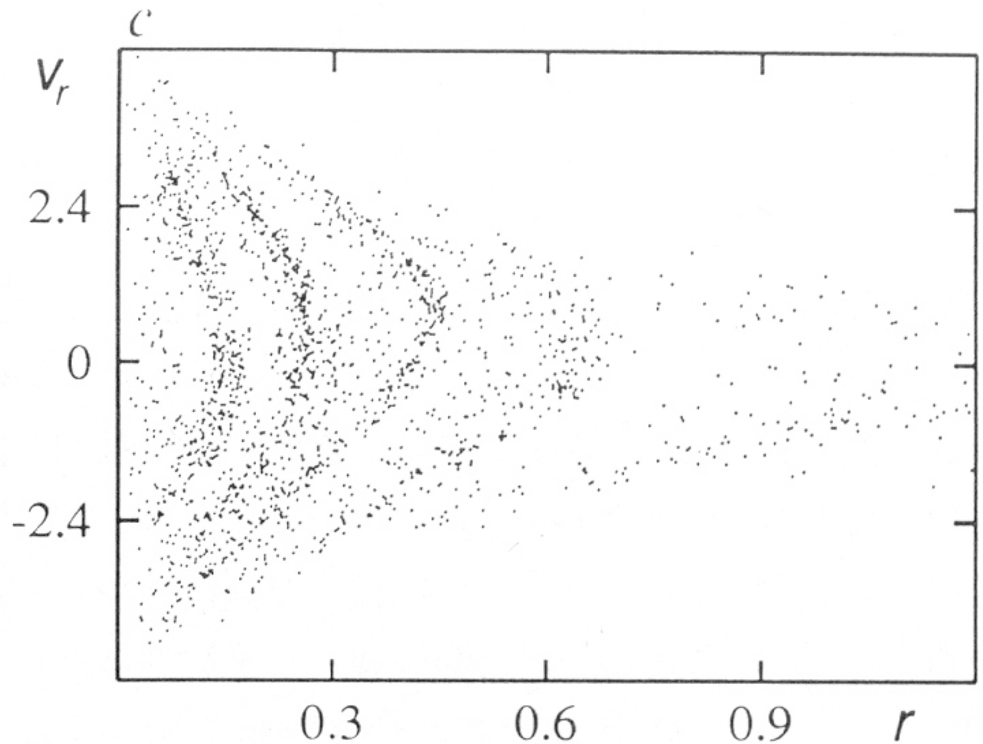
FIG. 4.—Evolution of the stellar distribution in encounter **A**, projected onto the orbital plane. The scale is the same as in Fig. 3.

Numerical simulation of a disk-disk merger (Barnes, Hernquist (1996) *ApJ*, **471**)

Surface brightness profile of merger remnants are close to $r^{1/4}$ profiles (typical for elliptical galaxies!)

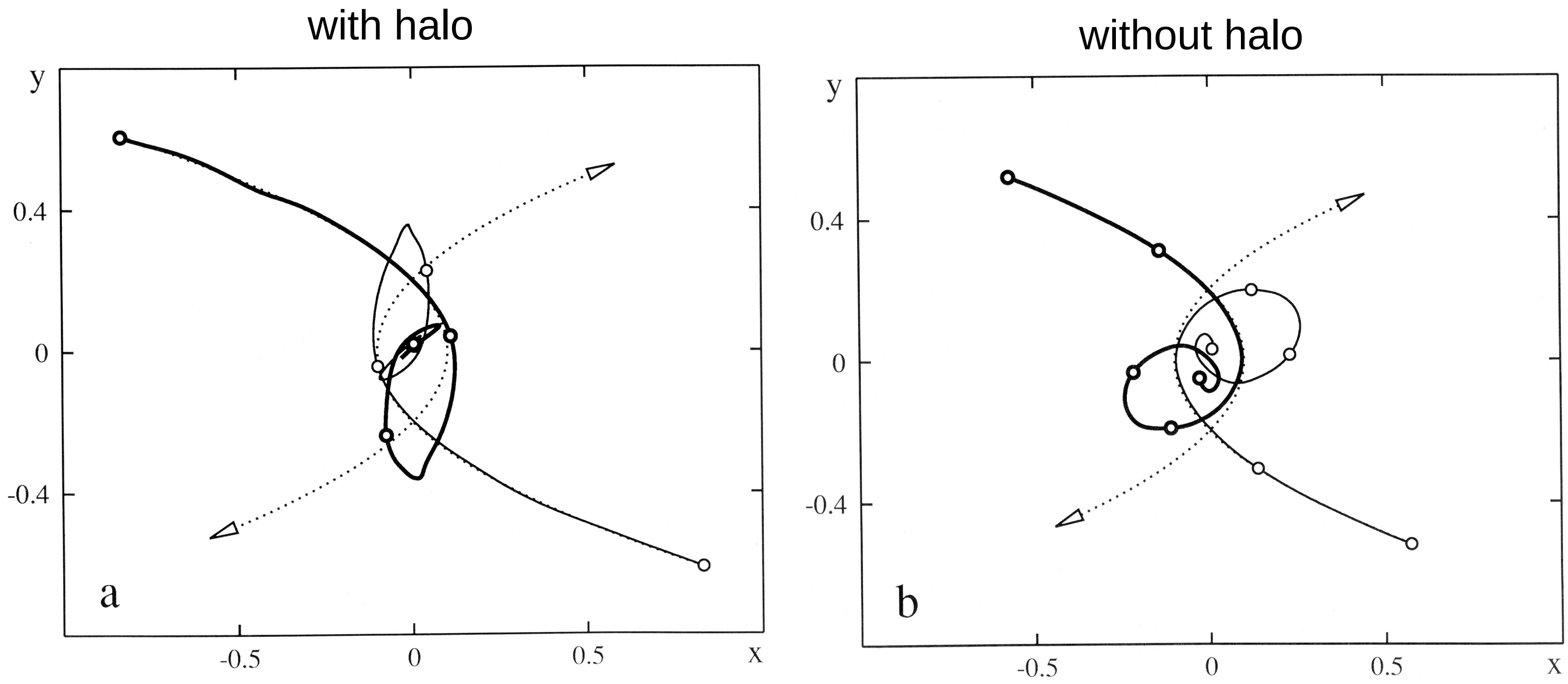
(Barnes (1989) *Nature*, **338**, 123)





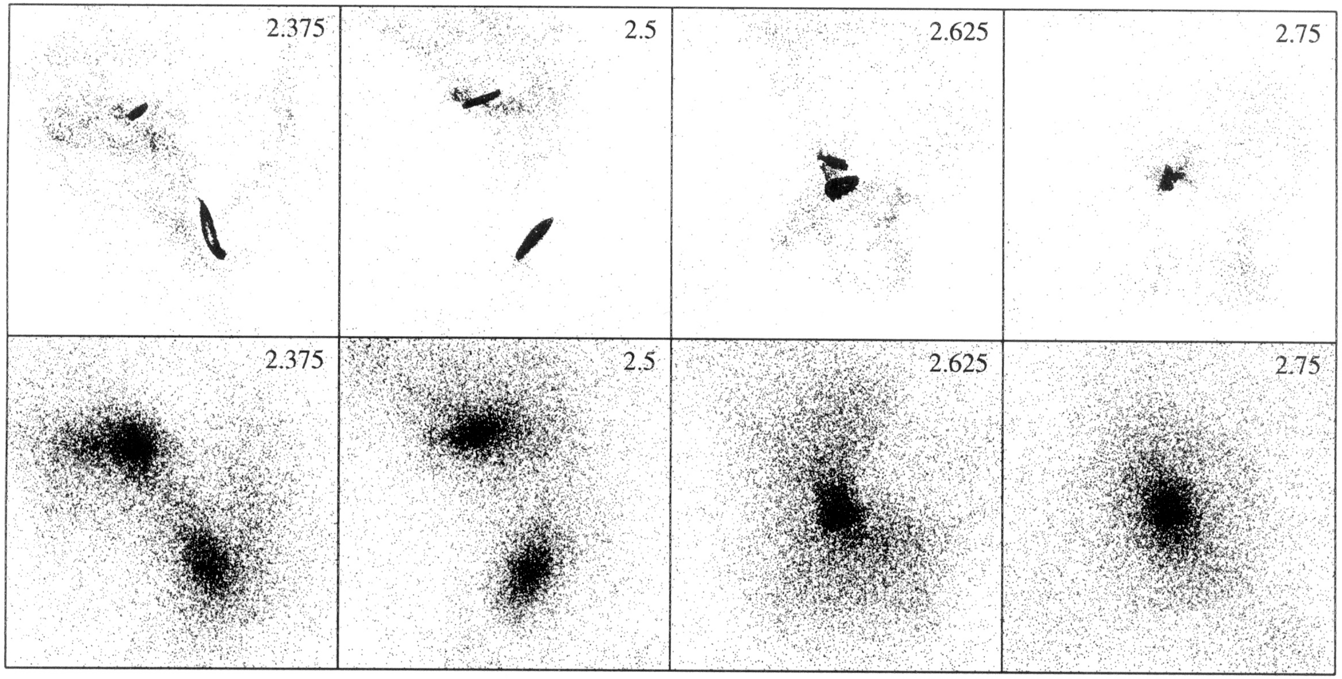
A cut through the phase space of a merger remnant (no gas included): violent relaxation is incomplete (Barnes (1989) *Nature*, **338**, 123)

Angular momentum transfer

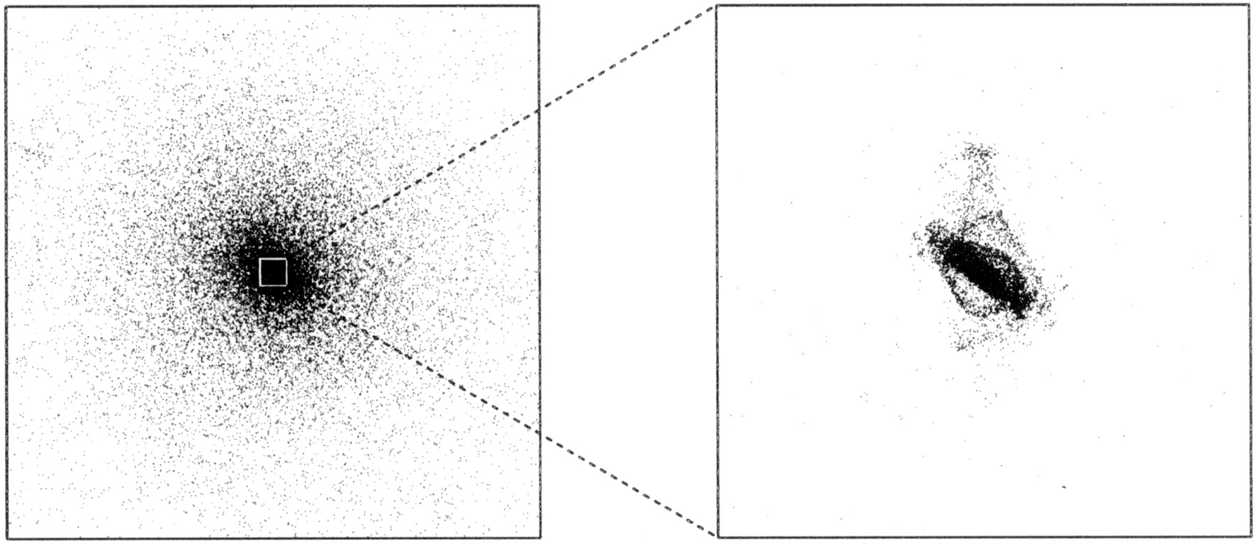


(Barnes (1988) *ApJ*, **331**, 699)

Merger of two gas-rich galaxies



Upper row: gas. Lower row: stars. (Barnes (1995))



Left panel: stars. Right panel: gas (enlarged). (Barnes (1995))

Counter-rotating gas disks

→ Origin of counter-rotating cores in elliptical galaxies?

(Hernquist & Barnes (1991) *Nature*, **354**, 210)

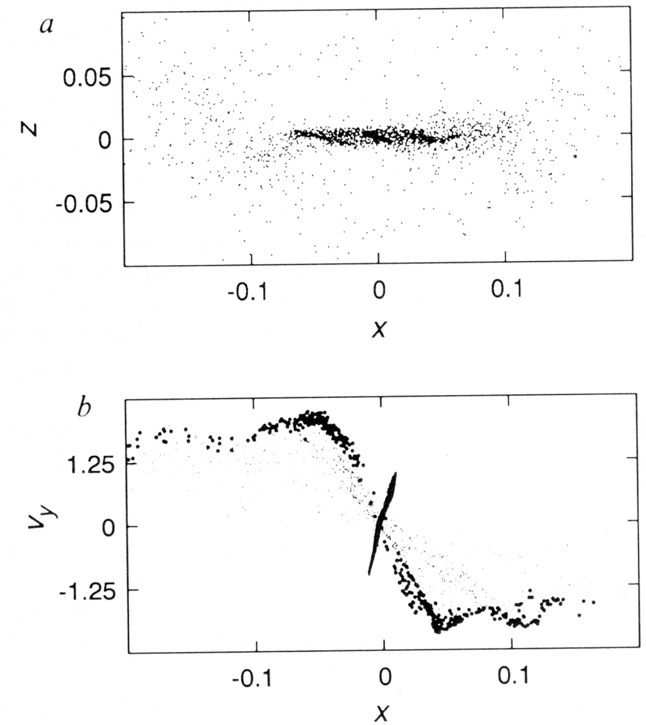


FIG. 2 *a*, Distribution of gas in remnant shown in Fig. 1, edge-on to the inner disk of gas. Results are displayed in the same system of units as in Fig. 1. *b*, Line-of-sight velocity through the gas shown in *a*. Particles having $|y| \leqslant 0.025$ are enlarged to highlight the rotation curve. Scaled to the properties of the Milky Way, the system of units is such that unit length and velocity correspond to 4.2 kpc and 160 km s^{-1}, respectively.

The influence of gas on the orbit distribution of stars (Barnes (1995) *Canary Island Winter School*).

Axis ratios of the remnant:

without gas	$b/a = 0.5$
	$c/a = 0.4$
with gas	$b/a = 0.9$
	$c/a = 0.6$