WED 11/14

also gave impromptu lecture on what is DM

Dark Matter

Rotation curves – flat!

Evidence beyond rotation curves

Flavors of DM

- baryonic — brown dwarfs, etc (MACHO result)
- hot — neutrinos
- cold — CDM – wimps, etc.

Solar neighborhood

Known stars, gas, etc: $\rho \approx 0.11\ M_\odot\,pc^{-3}$ $\Sigma = $ 35– (stars only) $50\ M_\odot pc^{-2}$

lum. density $j \approx 0.067\ L_\odot pc^{-3}$ (Flynn gives $0.056\ L_\odot^V pc^{-3}$)

$\frac{M}{L} = \frac{\rho}{j} \simeq 1.7\ \frac{M_\odot}{L_\odot}$ in V **Minimum** just from what's known

Flynn etal (2006)
$\Sigma_V = 24.4\ L_\odot pc^{-2}$
$\Sigma_* = 35.5\ M_\odot pc^{-2}$

$\Upsilon_*^B = 1.4$
$\Upsilon_*^V = 1.5 \pm 0.2\ M_\odot/L_\odot$
$\Upsilon_*^I = 1.2$

Oort limit (from vertical velocity dispersion estimate of disk mass restoring force)

$\Sigma_d = 50-70\ M_\odot\ pc^{-2}$

Oort discrepancy if $\Sigma_d > \Sigma_*$ – not much of one right now

Elliptical Galaxies

central velocity dispersions $\sigma^2/R_{eff} \rightarrow M/L \sim 9 \doteq B$
about right for old stars

No clear evidence for DM at small R; beginning to be hints of need at large R, but very hard to measure σ (use X-ray gas)

Note $\frac{V_r}{\sigma} \ll 1$ for Elliptical galaxies, but rotation is present & becomes more important for low L systems.

in general, orbits anisotropic & complicated

Milky Way satellites

Zaritsky & White, Prada & Klypin — "stack" satellites of other L^* galaxies

$\langle v^2 r\rangle = \frac{1}{4} GM$ ← Don't know orbital details (e, i, PA) so average over many. Tends to

$M_{MW} \approx 4\times10^{11}\ M_\odot$
[within radius probed!]

$\frac{M}{L} \simeq 30$

$M_{MW}^{tot} \simeq 2\times10^{12}\ M_\odot$
depends on inclusion/exclusion of Leo I

Now beginning application to Andromeda
$M_A \lesssim M_{MW}$ so far! (2001)

Disk stability – disks go unstable if bare

BT Fig. 6-16

Ostriker Peebles criterion (1973) $\frac{T}{|W|} \lesssim 0.14$ for stability

W – potential E
T – kinetic E of rotation

– OK rule of thumb; wrong in detail —
role of bulges, rapid RC rise

Megers of galaxies

galaxies only stick if there is dark matter to soak up orbital kinetic energy through dynamical friction

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X-ray gas (E's, Clusters)

hydrostatic equil.:

$$\frac{dp}{dr} = -\frac{GM\rho}{r^2}$$

+ ideal gas law → $M(r) = \frac{k_b T r}{G\mu m_p}\left[-\frac{d\ln\rho}{d\ln r} - \frac{d\ln T}{d\ln r}\right]$

↑ molecular weight — logarithmic gradients: slope of $\rho(r)$, $T(r)$

typically assume isothermal (T = const) & fit ρ to X-ray luminosity profile

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Timing argument

$$\frac{dr}{dt} = -119 \text{ km s}^{-1}$$

$$r = 750 \text{ kpc}$$

$$\text{age} \simeq 15 \text{ Gyr}$$

more generally "zero velocity surface" R_0 over/under radius between bound group and expanding universe

σ_A →, ← σ_{MW}

$$M_{tot} = \frac{\pi^2}{8G}\frac{R_0^3}{T_0^2}$$

$R_0 \sim 1$ Mpc for groups
T = age of Universe

→ $M_{LG} \approx 5 \times 10^{12} M_\odot$ (i.e. MW + M31; not much else)

(more time, less mass)

recent group mass estimates (Karachentsev) give similar, slightly smaller #s.)

Groups & Clusters of galaxies

σ large

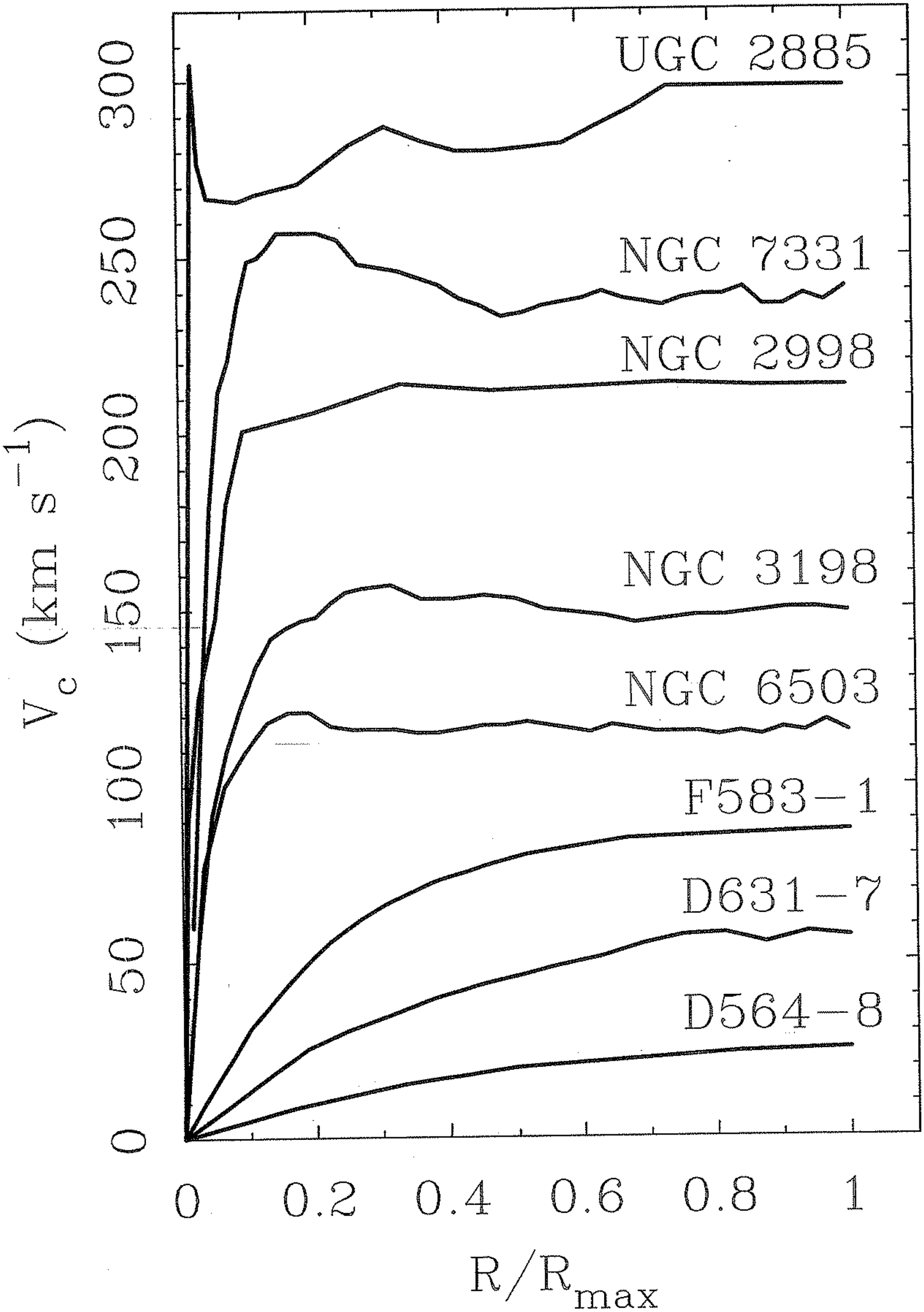
$$M \propto \frac{\sigma^2}{R} \rightarrow \frac{M}{L} \simeq 300$$

Also: – hydrostatic equilibrium of X-ray gas (as mentioned above)

– gravitational lensing, esp arcs of background galaxies in weak lensing regime

Bullet: some of both!

Rotation Curves



centre in the plane of the galaxy is about 15′, so any evidence of absorption would indicate a larger H I extent than observed in emission. Assuming the H I to be optically thin, we get the following relation for the column density:

$$N_H = \frac{4.6\ 10^{18}\ T\sigma I_0}{I_C}\ (\text{atom cm}^{-2}), \qquad (1)$$

where T is the temperature of the neutral hydrogen (K), σ its velocity dispersion (km s^{-1}), I_0 the maximum absorption and I_C the continuum flux density (382 mJy). An examination of the velocity profile at the position of the continuum source does not show any indication of absorption, so we can only obtain an upper limit for the H I column density at 15′ from the centre. Taking $T = 100$ K, $\sigma = 10$ km s^{-1} and for I_0 3 times the noise level of the channel maps, we find: $N_H < 0.3\ 10^{20}$ atom cm^{-2}, which is twice the noise level in the low resolution total hydrogen map.

7. Discussion

We have observed NGC 3198 in the 21 cm line, and have detected neutral hydrogen out to about 12′, which is twice the Holmberg radius of this galaxy. Further, we have derived a rotation curve out to 11′ by using a tilted-ring-model fitting technique. Some of the parameters of NGC 3198 determined in this study are listed in Table 4. The optical properties of NGC 3198 have been studied by Wevers (1984) who found that the light distribution has exponential shape with scale length about 1′. This means that we have measured rotational velocities out to 11 disk scale lengths, which is as far as we know the largest distance over which a rotation curve has yet been measured. This rotation curve does not show a decrease in circular velocity in the outer regions of the galaxy. Since the velocity field of NGC 3198 is regular and can be described well by tilted rings in circular rotation, this galaxy is an excellent case for studying the mass distribution. In Fig. 15 we have made a comparison of our measured rotation curve and the rotation curve predicted from the observable mass components, i.e. gas and stars. The contribution from the gas component was calculated from the averaged H I surface density (Fig. 13), corrected for the presence of helium (i.e. σ_{HI} multiplied by 1.4). The contribution from the luminous component was calculated from Kent's r-band data assuming a constant M/L ratio. For the total mass of the stellar disk we took 34 $10^9\ M_\odot$; giving the maximum allowed rotation velocity (see Fig. 15): this gives $M/L_B \simeq 3.8\ M_\odot/L_{B\odot}$ (L_B from de Vaucouleurs et al., 1976). It is clear that there is a large discrepancy between the observed

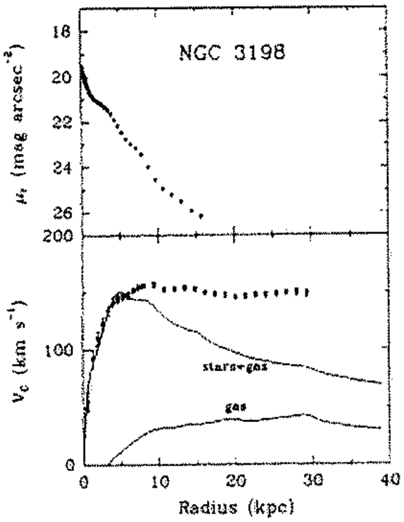
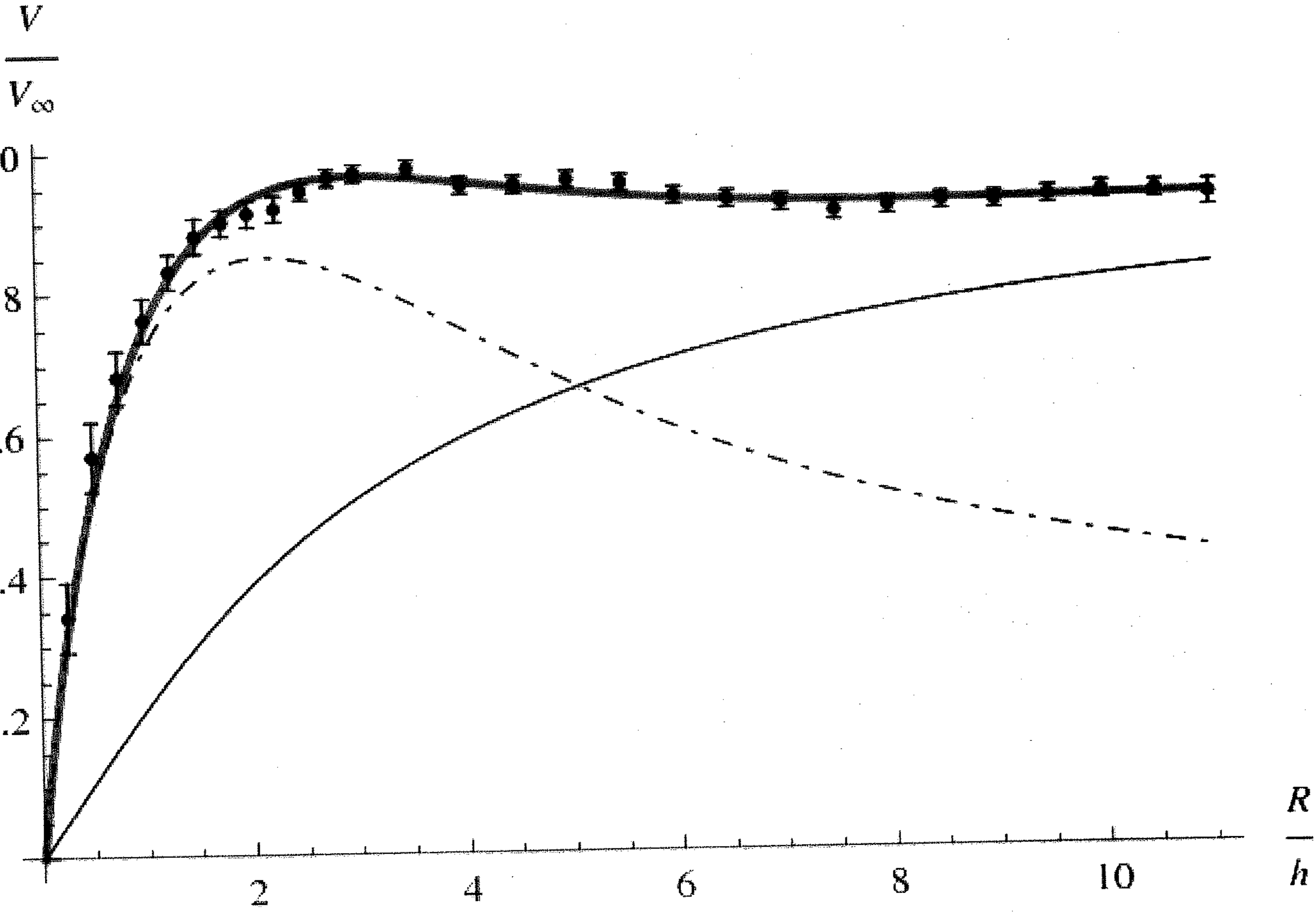


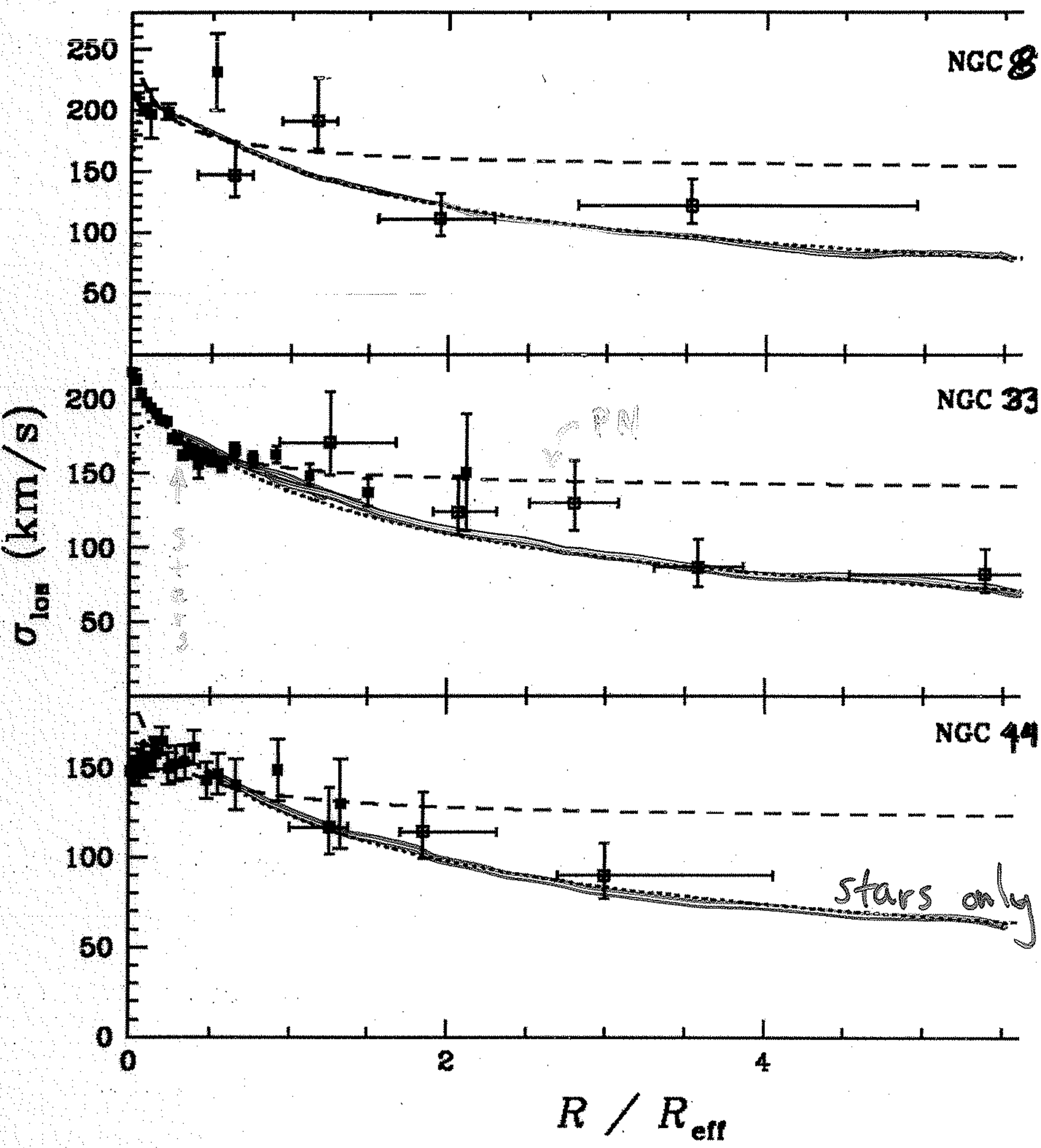
Fig. 15. Plot of observed rotation velocities (bottom) compared with rotation curve predicted from the photometric data (top, Kent, 1987) assuming a constant M/L (3.8 $M_\odot/L_{B\odot}$) and z-thickness following a sech-squared law (van der Kruit and Searle, 1981) with disk thickness of 0.2 × the disk scale length. The contribution of the gas component has been included. The photometric data have not been corrected for inclination. Note the discrepancy between observed and predicted curves beyond 7 kpc

Table 4. Parameters of NGC 3198

Parameter	Value	Notes
Type	Sc(rs) I-II	1
Optical centre (1950.0)	$10^h16^m52^s.1$ (±4″), 45°48′00″ (±3″)	2
Position 21 cm nucleus (1950.0)	$10^h16^m51^s.3$ (±2″), 45°48′03″ (±3″)	3
V_0 heliocentric	660.4 ± 0.8 km s^{-1}	
Integrated H I-flux	242 ± 10 Jy km s^{-1}	
Distance	9.4 Mpc	4
M_{HI}	(5.0 ± 0.2) $10^9\ M_\odot$	
L_B	(9.0 ± 0.9) $10^9\ L_{B\odot}$	5
L_V	(7.3 ± 0.7) $10^9\ L_{V\odot}$	5
Disk scale length	58″ (= 2.63 kpc)	6
R_{25}	4′.2	7
Holmberg diameter	11′.9 × 4′.9	8
21 cm continuum flux	34.0 ± 1.8 mJy	

Notes: 1: Sandage and Tammann (1981). 2: Gallouët et al. (1973). 3: Adopted dynamical centre. 4: $H_0 = 75$ km s^{-1} Mpc^{-1}. 5: Derived from de Vaucouleurs, de Vaucouleurs and Corwin (1976). 6: Wevers (1984). 7: Radius 25th mag arcsec^{-2} isophote; de Vaucouleurs et al. (1976). 8: Holmberg (1958).


V / V∞
1.0
0.8
0.6
0.4
0.2
2
4
6
8
10
R / h



Romanowsky et al. 2003, Science, 301,

no clear need for DM in Ellipticals

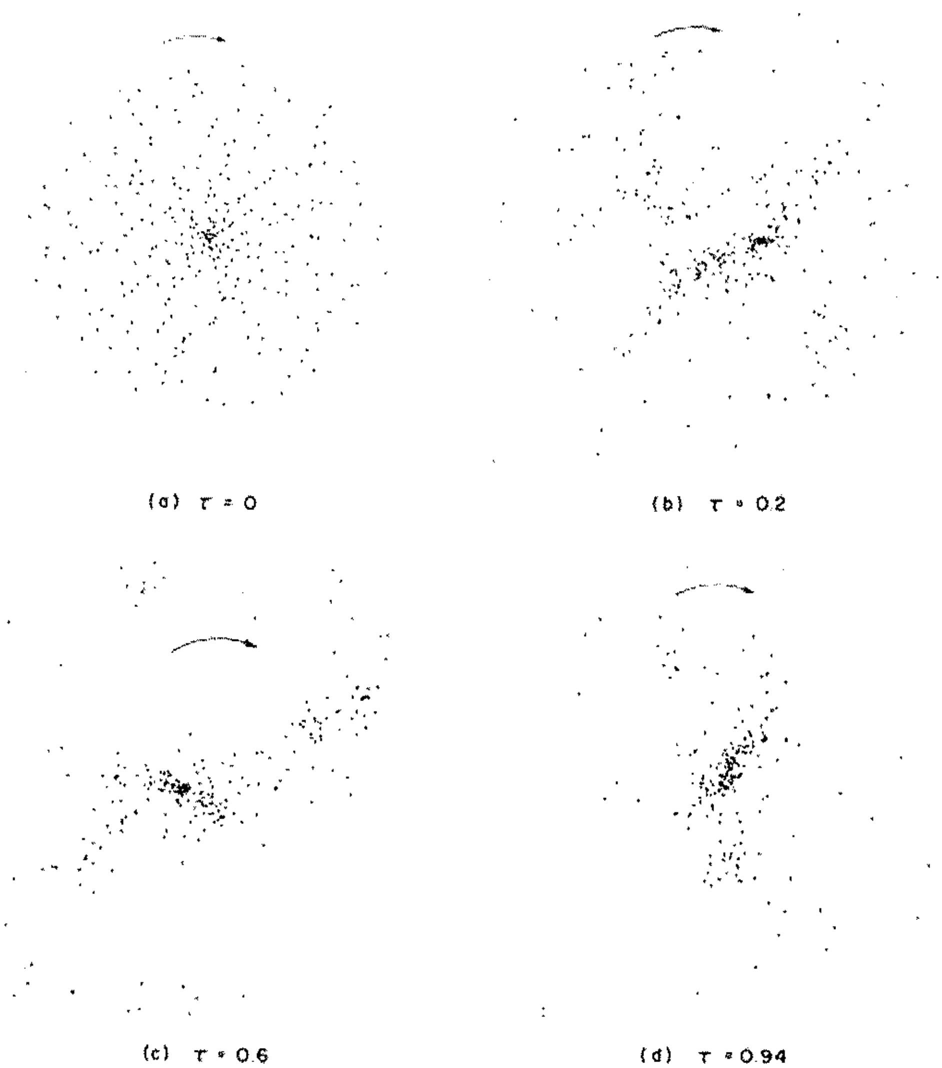


FIG. 4.—Evolution of model 1. The graphs show the positions of the mass points projected onto the plane, at four instants.

relaxation processes for individual particles, whether due to numerical error or to two-body collisions. We may expect, therefore, that a given numerical error may be less serious here than in some other applications of N-body models.

2. We have rounded over the potential at small distance, thereby making the mathematical problem nonsingular and removing the largest fluctuations in acceleration from the computational problem.

3. We judge from trial applications of the integration scheme, where the analytic solution is known, that the time step should be small enough for the integration to carry one particle past another one reliably (but not with great accuracy) whatever the impact parameter for expected particle relative velocities.