Evidence from the Motions of Old Stars that the Galaxy Collapsed

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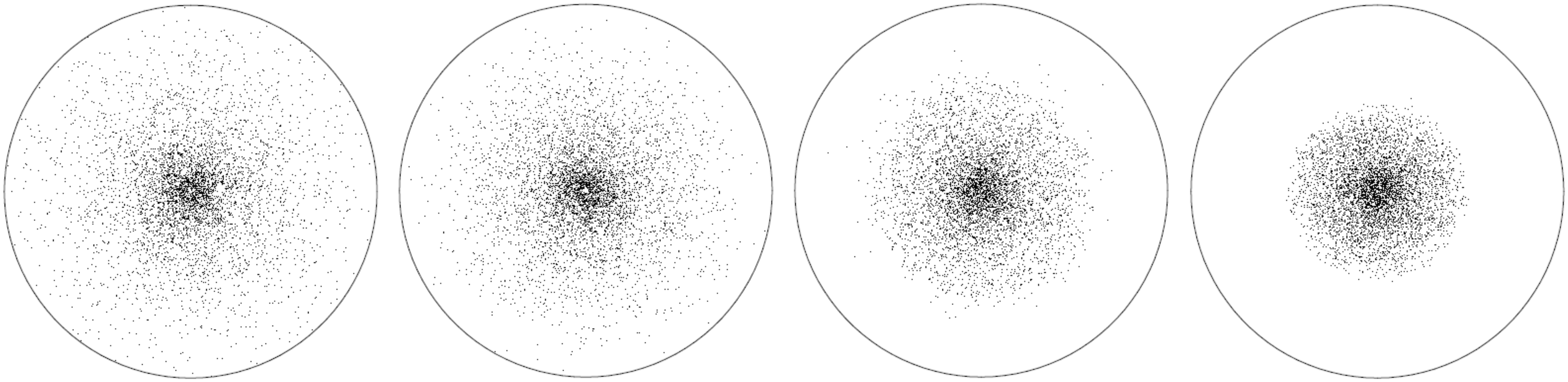


Presented by: Michael Solway

All equations and figures from here on are taken from this paper.

Main Findings

Observations of the velocities and ultraviolet excesses δ(U – B) of 221 dwarf stars in the solar neighborhood suggest that:

- Stars with large excess (low metal abundance)
  - Move in highly elliptical orbits
  - Have small angular momenta
  - Formed at any height above the galactic plane
- Stars with little or no excess
  - Move in nearly circular orbits
  - Have large angular momenta
  - Formed near the galactic plane

therefore

- The oldest stars formed before the galaxy collapsed to a thin disk in equilibrium
- Young stars formed after the collapse

2D Orbits in Dynamical Equilibrium

- Cylindrical symmetry (R, ϕ, Z) coordinates (U, V, W) velocities
- Energy and angular momentum equations:

$$\frac{\dot{R}^2}{2}+\frac{h^2}{2R^2}-\psi(R)=E_R$$

$$R^2\dot{\phi}=h$$

or

$$\phi=\frac{1}{2}\int\frac{hR^{-2}dR^2}{[2R^2(E_R+\psi)-h^2]^{1/2}}$$

$$t=\frac{1}{2}\int\frac{dR^2}{[2R^2(E_R+\psi)-h^2]^{1/2}}$$

- Isochrone potential: $\psi=\frac{GM}{b+(R^2+b^2)^{1/2}}$

Boundary conditions: $\psi\rightarrow\frac{GM}{R}$ as $R\rightarrow\infty$, $R\psi\rightarrow\text{Const}$ as $R\rightarrow 0$

M = total mass of galaxy = $2.4\times10^{11}\ M_\odot$

b = constant length = 2.74 kpc

calculated from $R_\odot$ = 10 kpc and $V_\odot$ = 250 km/sec

Circular Velocity

$$V = \frac{(GM)^{1/2}R}{[b + (R^2 + b^2)^{1/2}]\,(R^2 + b^2)^{1/4}}$$

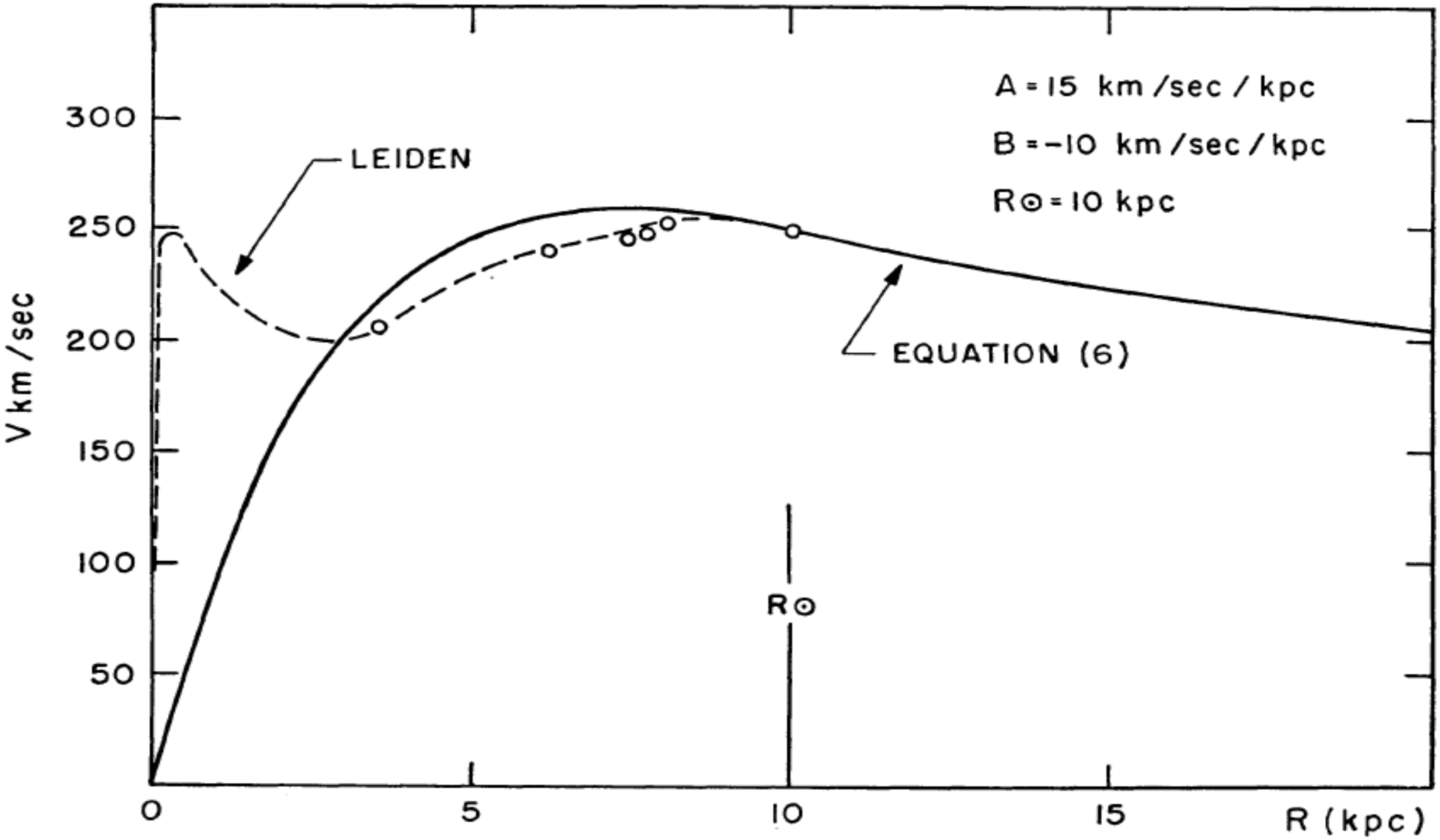


FIG. 1.—The circular velocity, V, in km/sec as a function of the distance, R, in kiloparsecs from the galactic center. The continuous curve is obtained from equation (6) with $b = 2\,74$ kpc and $M = 2\,4 \times 10^{11}\, M_\odot$. The 21-cm observations from Leiden are indicated by open circles. The dashed part of the curve comes from Rougoor and Oort (1960).

Shapes of Orbits

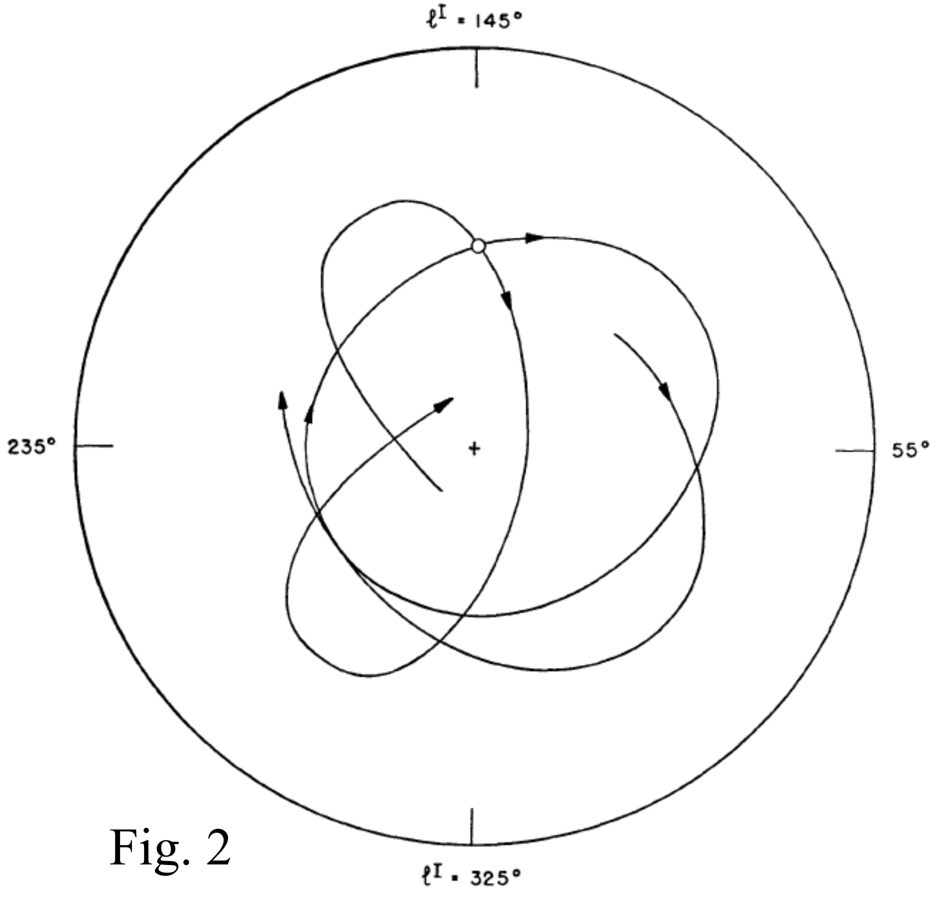


Fig. 2

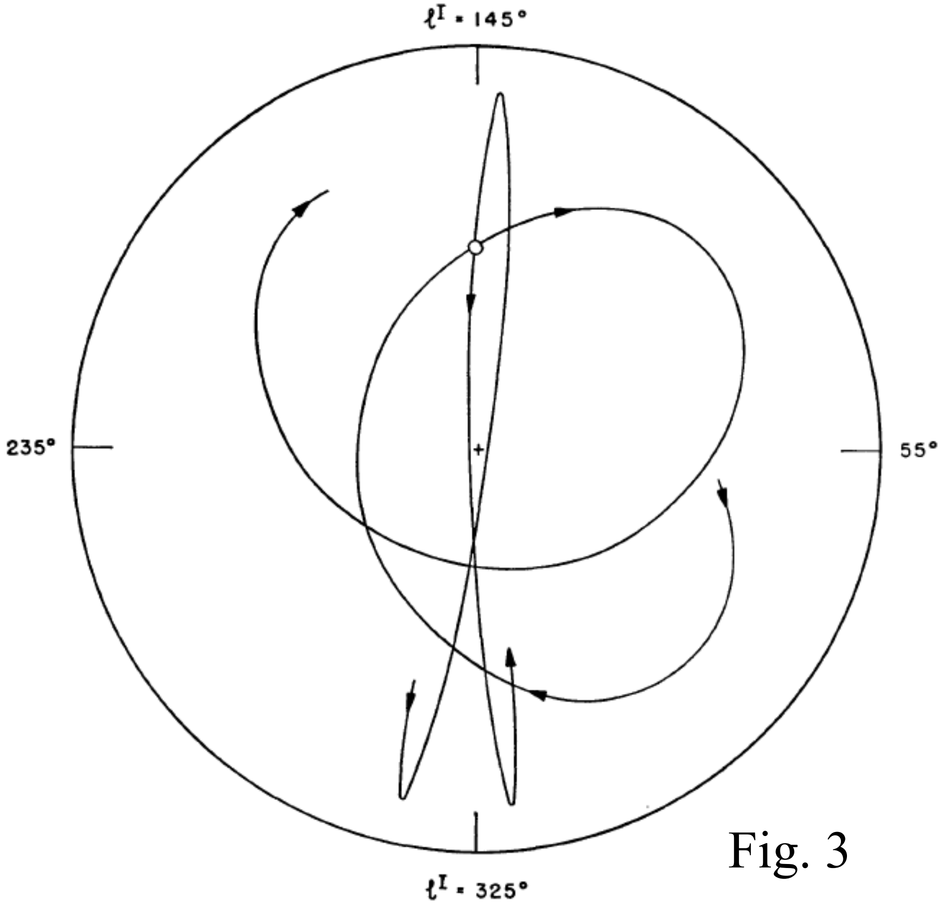


Fig. 3

FIG. 2.—Segments of the galactic orbits for two of the program stars. The more circular orbit is for HD 117635 with an ultraviolet excess of $\delta = +0^{\mathrm{m}}.05$ The more elliptical orbit is for HD 11980 with $\delta = +0^{\mathrm{m}}.17$. Both orbits pass through the solar neighborhood, which is designated by a circle on the $l =$ 145° axis at a distance of 10 kpc from the galactic center The galactic center is shown as a cross The outer circle has a radius of 20 kpc.

FIG 3.—Same as Fig. 2 The more circular orbit is for HD 29587 with $\delta = +0^{\mathrm{m}}.13$. The more elliptical orbit is for Ross 106 with $\delta = +0^{\mathrm{m}}.26$. The orbit for Ross 106 is retrograde.

Assumptions to Simplify a Contracting Potential

- Neglecting the Z-motion
  - While a star traverses one Z-semiperiod, it moves very little in R
    - The potential is separable
  - Adiabatic invariant: $\oint \dot{Z}\, dZ = \text{const}$
- The potential is axially symmetric at all times
  - The galaxy never had a bar
- Angular momentum is conserved for each element
  - No h exchange through pressure gradients or magnetism
  - No accretion of matter onto a star's surface
  - Any turbulence is much smaller than the size of the galaxy
- Contracting Isochrone potential
  - b changes with time

$$\psi = \frac{GM}{b + (R^2 + b^2)^{1/2}}$$

Change of the Eccentricity

- Case 1: potentials change little during one galactic rotation
  - Adiabatic invariant: $\oint P_R \, dR = \text{const}$
  - Invariant eccentricity e*:

$$1 - (e^*)^2 = \left[\frac{1}{2} - \left(\frac{1}{4} + \frac{bGM}{h^2}\right)^{1/2} + \frac{GM}{(-2E_R h^2)^{1/2}}\right]^{-2}$$

    - $e^* = e$ for $h^2 >> 4bGM$ $\quad e = \frac{R_{max} - R_{min}}{R_{max} + R_{min}}$
  - e* and e don't differ by more than 0.1: e is an adiabatic invariant
- Case 2: potentials change rapidly

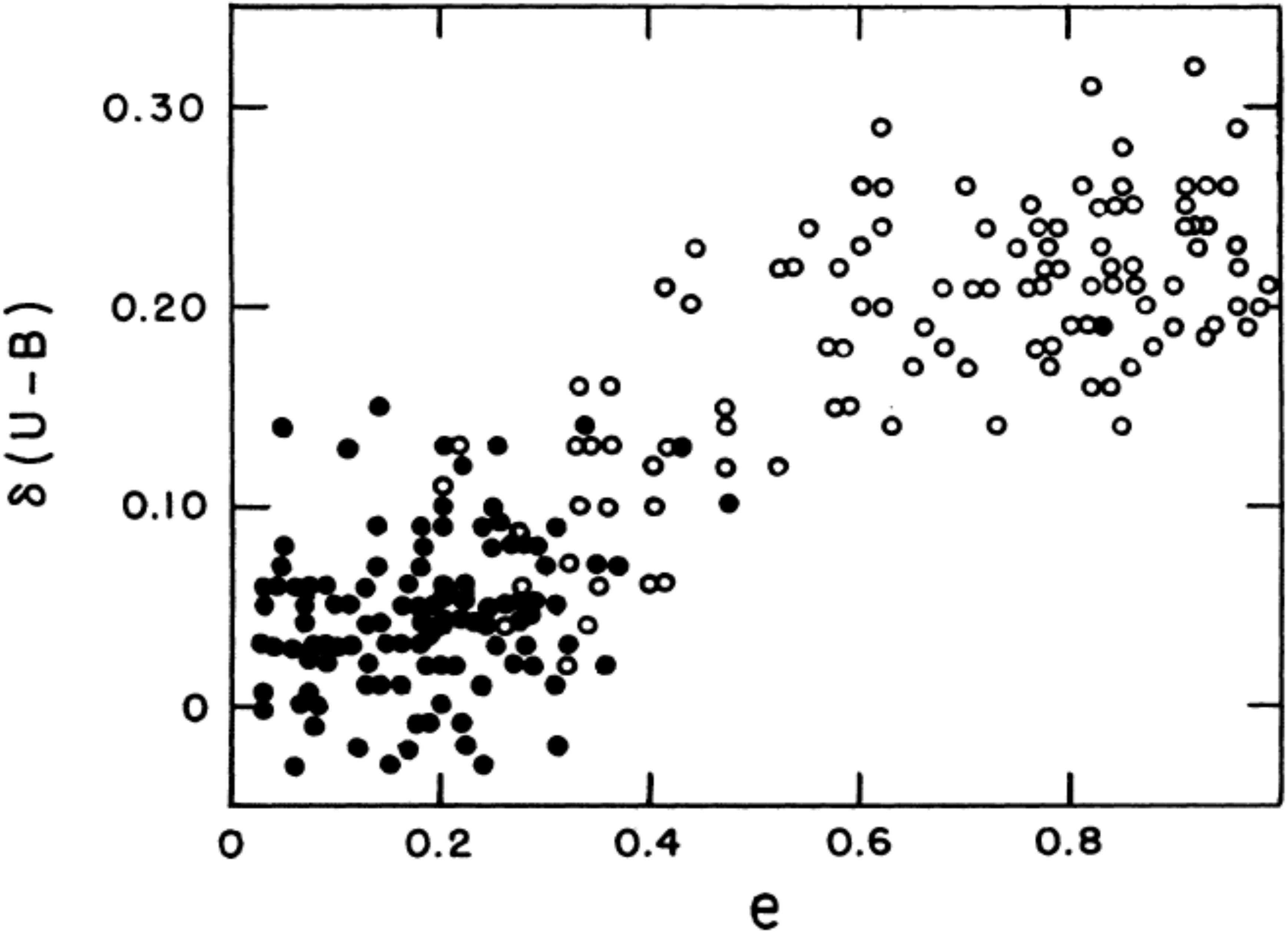
  Mass concentration increases in a time shorter than the galactic period
  - On average, e increases
    - e decreases for stars at their perigalacticum
  - $W(Z = 0)$ either increases or remains the same
  - $|Z|_{max}$ decreases or stays the same

Data of 221 Stars

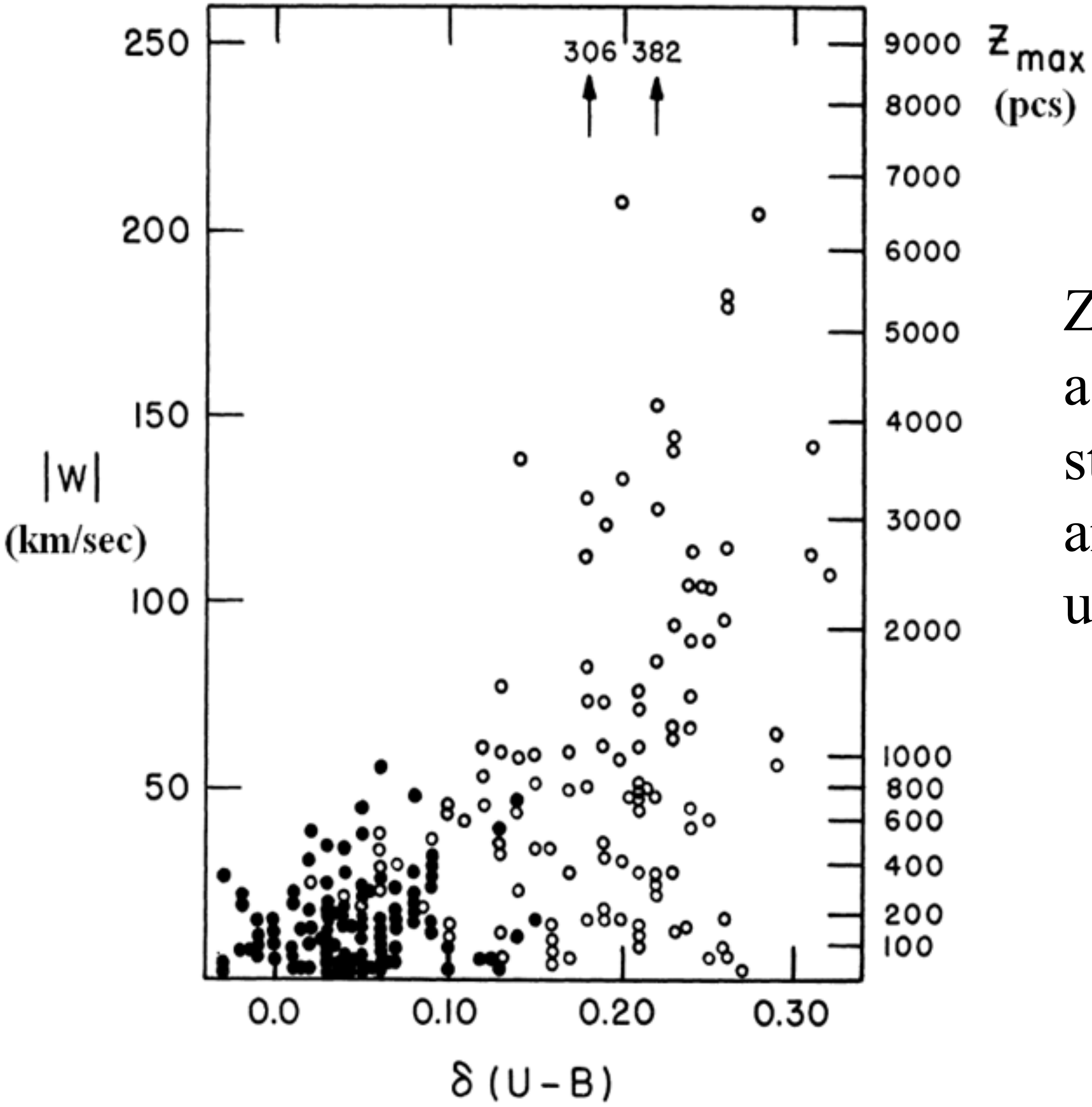
- (U, V, W)-velocity vectors and photometry measured
  - 108 from (Eggen 1961): 4000 stars with accidental error in U < 1.5 km/sec
  - 113 from (Eggen 1962): stars with velocity > 100 km/sec
  - Uncertainties in the (U, V, W) vectors < ± 20 km/sec
- All the stars are within a few hundred parsecs of the sun
- All are believed to be dwarfs
  - From spectroscopic or trigonometric parallax data
- Distances measured by force-fitting to the Hyades main sequence (Sandage and Eggen 1959)

- Some bias against stars with nearly circular orbits
- No bias in the ultraviolet excesses
- Some neglect of stars with intermediate velocities

Correlation of e and δ(U – B)

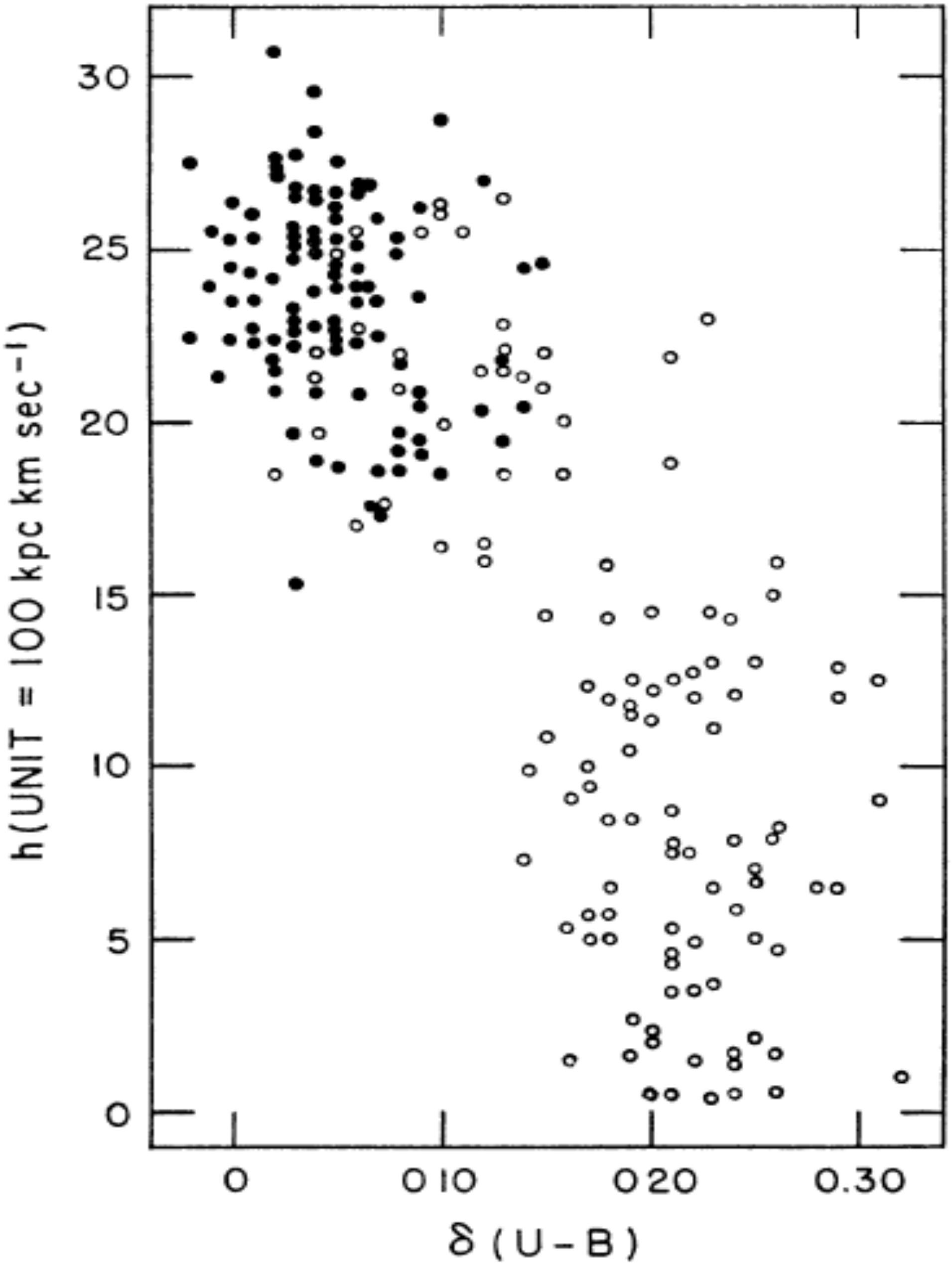


Correlation of |W| and δ(U – B)



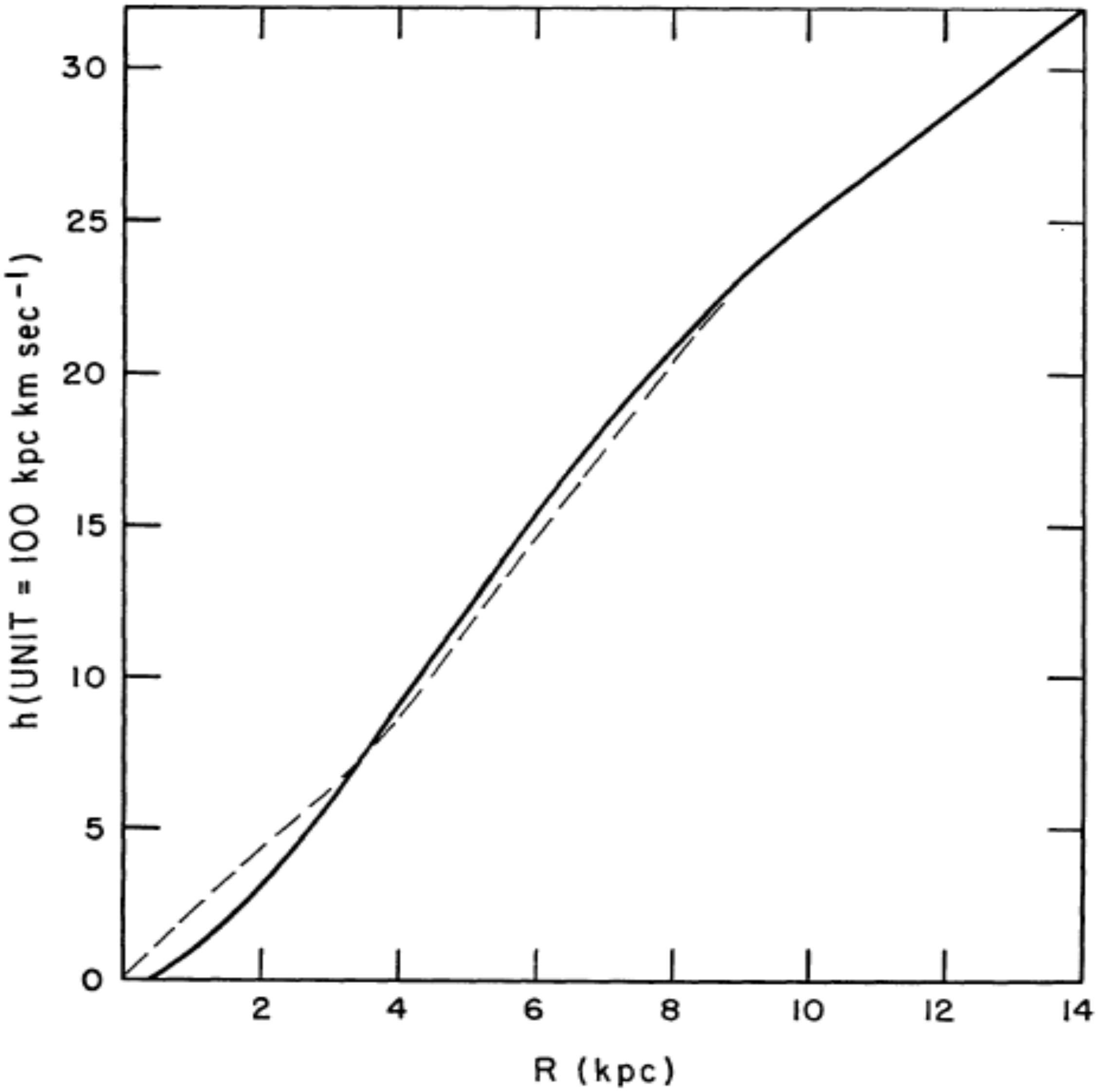
Z$_{\mathrm{max}}$ differs by at least a factor of 25 between stars with the biggest and smallest ultraviolet excesses

Correlation of h and δ(U – B)



- h and δ(U – B) are independent of time
- Corresponds to the correlation between e and δ(U – B)

h vs. R in Dynamical Equilibrium



Material with the same mean h as that of the oldest stars with the greatest-velocity (h = 12×10^2 kpc km/sec) is in circular orbits at distances < 5 kpc from the galactic center at present

FIG. 7.—The correlation between the angular momentum, *h*, in units of 10^2 kpc km/sec and the distance from the galactic center, *R*, in kiloparsecs for stars in circular orbits in our model galaxy. The dashed curve corresponds with the Leiden curve in Fig. 1. The solid curve is computed from eq (6).

Interpretation

- The galaxy collapsed onto a disk either after or during the formation of the oldest stars
- The collapse was very rapid: $\sim 10^8$ years
  - Slow collapse cannot explain the presence of high eccentricities
- Why are the oldest stars now moving in nearly rectilinear orbits and the youngest in nearly circular orbits?
  - The galaxy did not settle to equilibrium before the first stars formed
    - If the early galaxy was in dynamical equilibrium, then the oldest stars would have formed at < 5 kpc from the center
  - 1st generation stars formed during the collapse and now have high e
  - 2nd generation stars formed from the collapsed gas and now have nearly circular orbits

- Present galaxy $< {}^{1}/_{10}$ radial scale of the initial protogalaxy

Correlation of h and R_{max}

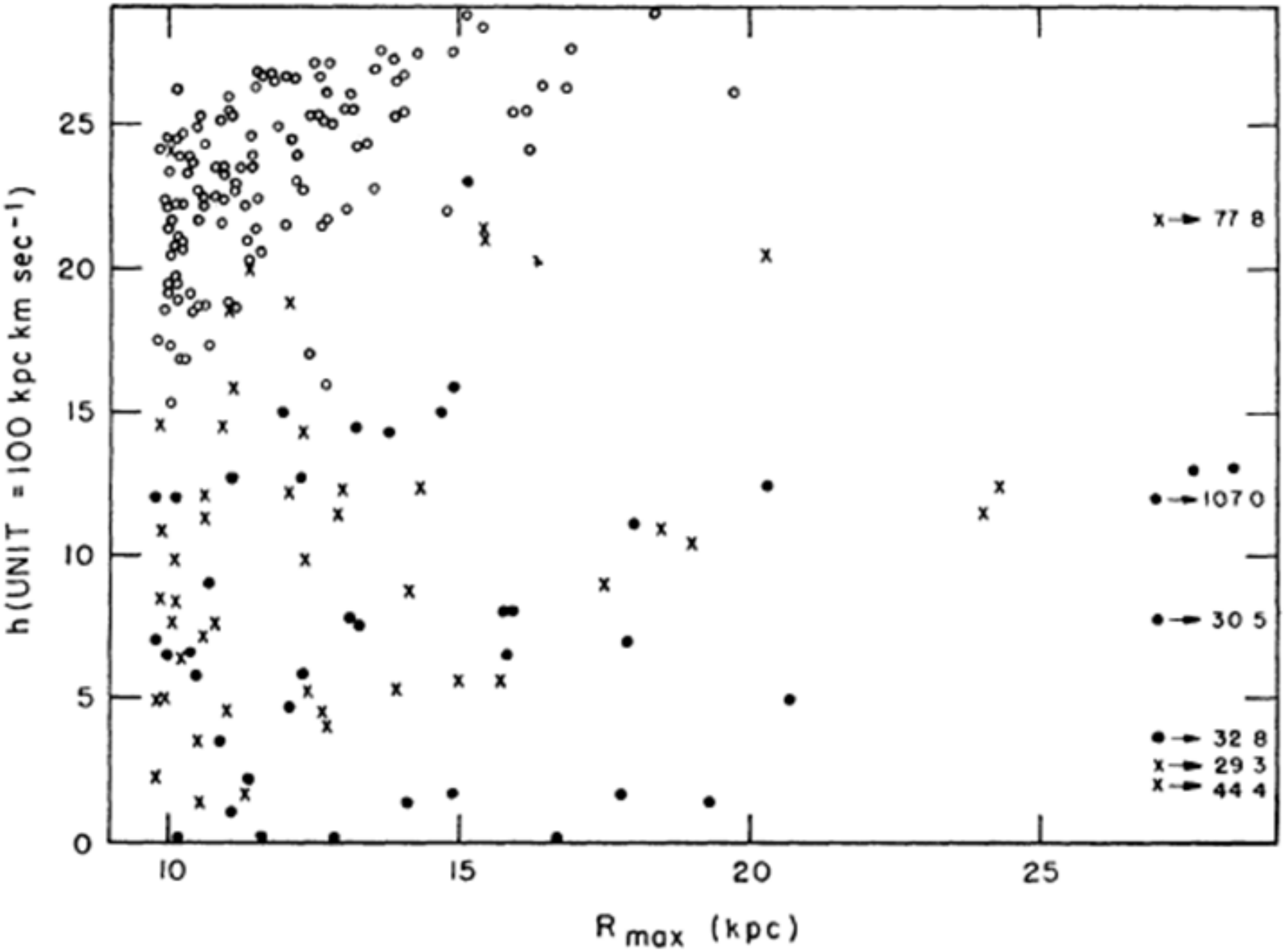
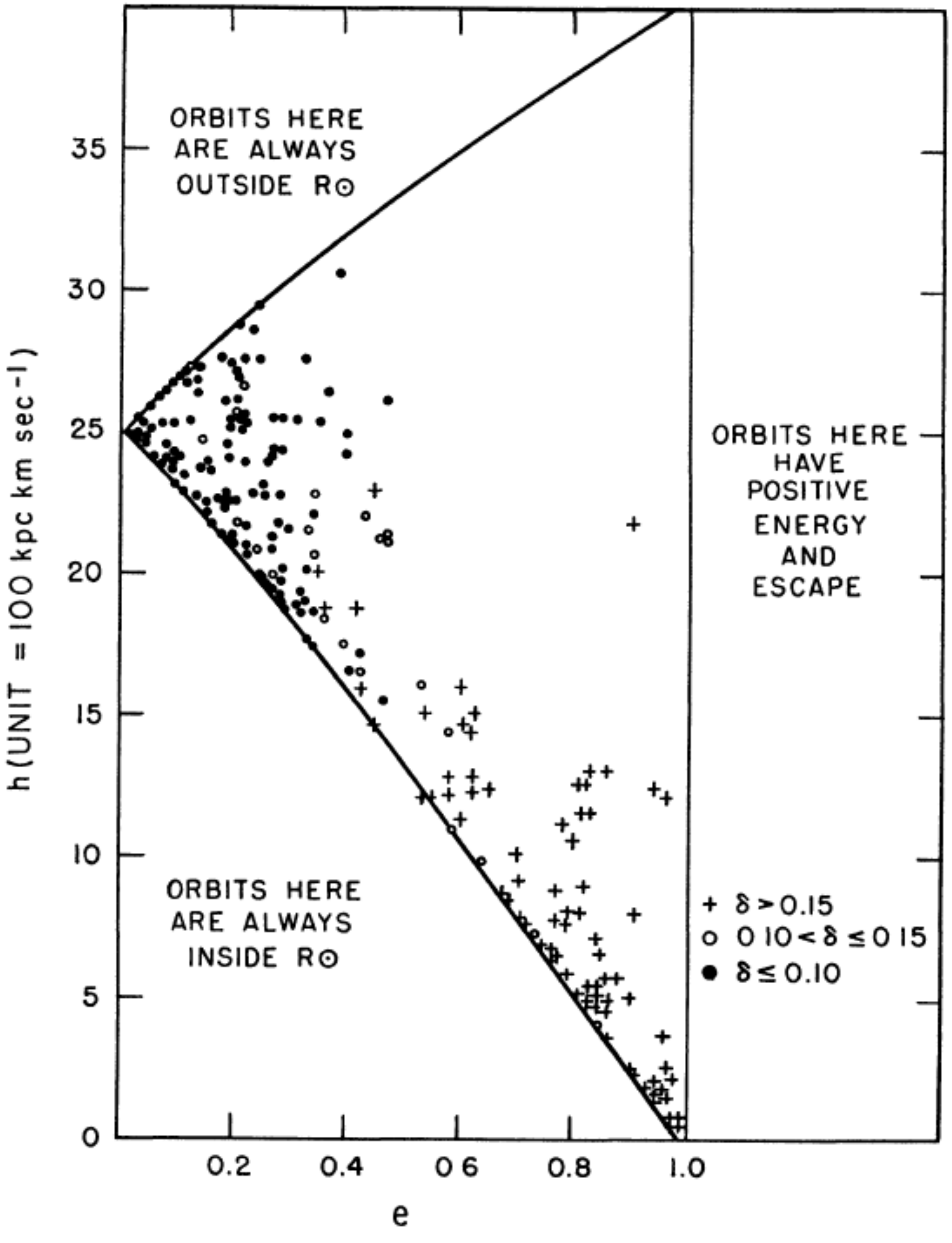


FIG. 8.—The observed correlation between the apogalacticum distance and the angular momentum in the orbits of the 221 stars in our sample. Stars with ultraviolet excesses greater than $0^m.21$ are indicated by filled circles, between $0^m.14$ and $0^m.21$ by crosses, and less than $0^m.14$ by open circles. Note the well-defined upper envelope to the open circles, which follows the shape of the equilibrium curve of Fig. 7.

Correlation of h and e



Why are there no stars with high e and high h?

- More likely to find stars whose apogalactica are near the sun
- Stars with small apogalactica are more favored by the stellar density gradient
- Gas density at large distances was insufficient to form stars before equilibrium was reached

How the Galaxy Formed

- Intergalactic material began to collapse about 10^{10} years ago
- As it was collapsing, condensations formed and later became globular clusters and globular cluster-like stars
- 1st generation stars' e increased during the rapid collapse
- A thin disk formed
  - The collapse stopped in the radial direction due to rotation
  - Nothing could stop it in the Z direction
- 1st generation stars enriched the remaining gas with metals
  - Later generation stars show a small ultraviolet excess
- The gas separated from the stars at their perigalactica, settled into circular orbits, and continued to produce stars
  - 2nd generation stars initially had circular orbits
- Dynamical equilibrium was achieved and e stopped changing