

Astronomy

330

Lecture 15

22 Oct 2010



Outline

- ▶ Midterm
- ▶ Review:
 - ▶ CBE and its applications
- ▶ Elliptical galaxies
 - ▶ Basic properties



Midterm

- ▶ **Wednesday, Oct 27 in class**
 - ▶ You'll be given equations and constants
 - ▶ Bring a calculator, paper
 - ▶ Closed book/notes
- ▶ **Topics**
 - ▶ Stellar evolution/HR-diagram/manipulate the IMF
 - ▶ ISM phases/detection techniques
 - ▶ Distribution of stars in MWG and other spirals
 - ▶ How do we measure the MWG's rotation curve?
 - ▶ Relationships between velocity, mass, potential
 - ▶ Tracers of star formation
 - ▶ Basic differences between spirals and ellipticals (including spectra)
- ▶ **Reading**
 - ▶ Chapters: 1,2,3,5
 - ▶ Lectures



Review CBE

- ▶ Continuity equation:

- ▶ $d\rho/dt + \nabla \cdot (\rho \mathbf{v}) = 0$

- ▶ Collisionless Boltzmann equation

- ▶ $df/dt + \mathbf{v} \cdot \nabla f - \nabla \Phi \cdot df/d\mathbf{v} = 0$

- ▶ General solution to CBE impractical but velocity-moments yield key relations between observables (v, σ) and the potential (Φ) for highly-flattened, axisymmetric systems:

- ▶ v_z moment: **disk-mass surface density**

$$\Sigma = 100 \left(\frac{k}{3/2} \right)^{-1} \left(\frac{h_z}{444 \text{ pc}} \right)^{-1} \left(\frac{\sigma_z}{30 \text{ km/s}} \right)^2 M_{\text{sol}} \text{ pc}^{-2}$$

- ▶ v_R & $v_R v_\phi$ moments: **epicycle approx.**

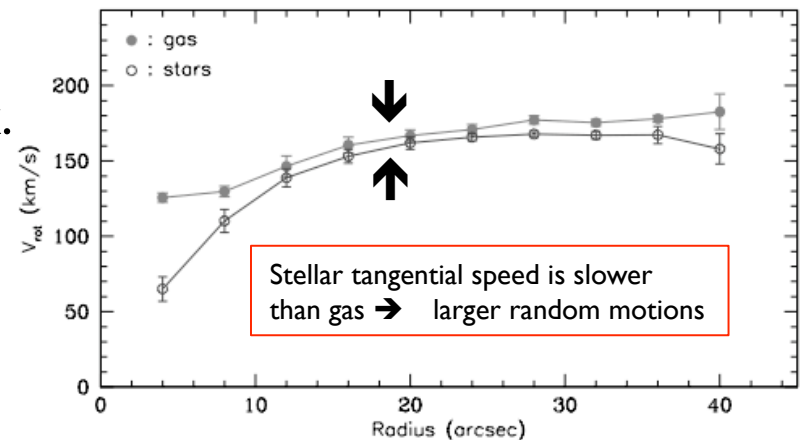
$$\frac{\sigma_\phi^2}{\sigma_R^2} = \frac{1}{2} \left(\frac{\partial \ln \bar{v}_\phi}{\partial \ln R} + 1 \right)$$

- ▶ v_R moment: **asymmetric drift**

$$v_c^2 - \bar{v}_\phi^2 \approx \sigma_R^2 \left(\frac{1}{2} \frac{\partial \ln \bar{v}_\phi}{\partial \ln R} + \frac{2R}{h_\sigma} + \frac{R}{h_R} - 1 \right) + \frac{\sigma_z^2}{2}$$

Change in density over time (1st term) is a result of a net divergence in the flow of fluid (2nd term). Stars are a collisionless fluid.

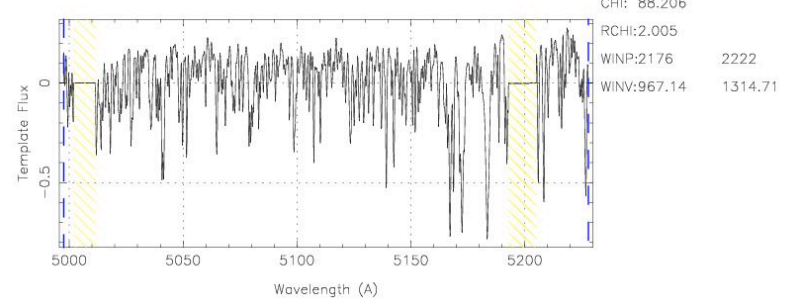
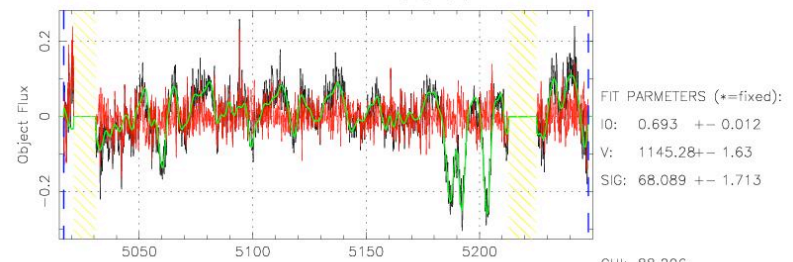
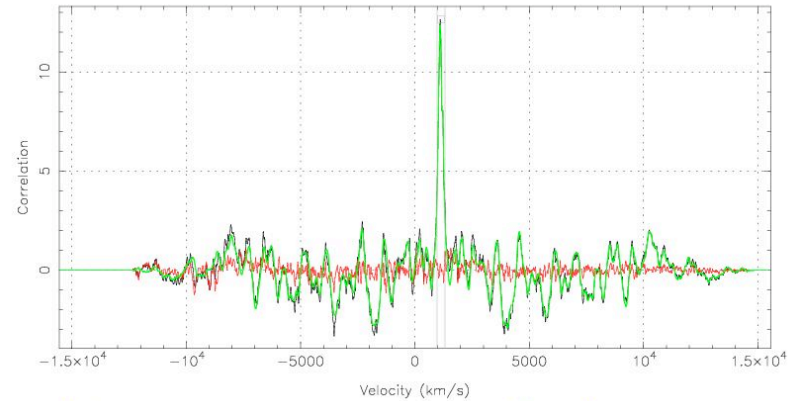
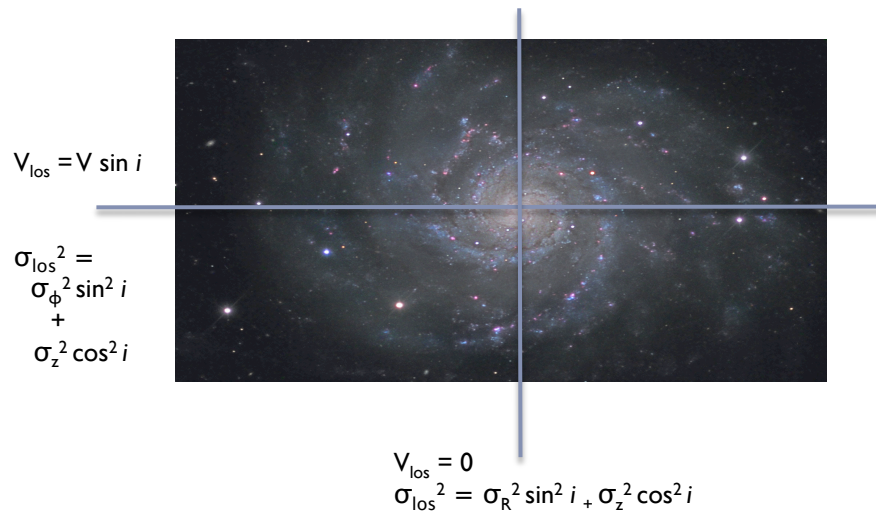
Fundamental equation of stellar dynamics. Special case of Liouville's theorem: Flow of particles in phase space is incompressible, i.e. phase-space density is constant.



Stellar tangential speed is slower than gas \rightarrow larger random motions

Review CBE applications

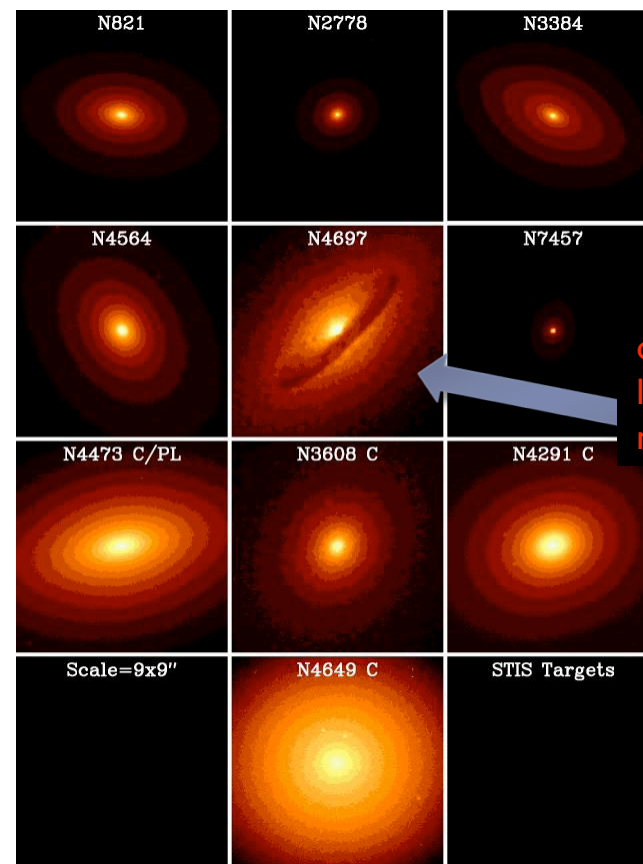
- ▶ These formulae, plus direct measurements of
 - ▶ $V_c, V_\phi, \sigma_{maj}, \sigma_{min}$ *best-bet combination*
 - ▶ \rightarrow velocity ellipsoid $\sigma = (\sigma_R, \sigma_\phi, \sigma_z)$
- directly measuring Σ_{disk}
- decomposing rotation curves,
- determining disk M/L
- the dark-matter density distribution



Elliptical Galaxies



Classic ground-based view in the optical



oops, looks like there is a nuclear disk

HST STIS images of cores



Ellipticals: Basic properties

- ▶ **Surface photometry**
 - ▶ $I(r) = I_e \exp\{-7.67[(r/R_e)^{1/4} - 1]\}$
 - ▶ “r 1/4” law proposed by de Vaucouleurs
 - ▶ R_e = effective radius at which 1/2 of total light is emitted
 - ▶ Recall that this is a special case of the Sersic profile for $n=4$
 - ▶ Ellipticals show a range of n from 3 to 10.
 - ▶ Similar to bulges of early-type disk galaxies, but with higher index, n
- ▶ **Classification: E0-E7** describing increase in flattening
- ▶ **Stellar populations: old, metal rich**
- ▶ **Environment: dense, usually in clusters or rich groups**
 - ▶ morphology-density relationship



Ellipticals: Basic properties *continued*

- ▶ Deviations from basic structure
 - ▶ Centers → in cD galaxies the surface brightness turns up in the center.
 - ▶ Halos → some have extended halos (excess light at large radii)
- ▶ What distinguishes ellipticals from spirals?
 - ▶ Ratio of V_c / σ
 - ▶ V_c is the circular velocity
 - ▶ σ is the velocity dispersion
 - ▶ In MWG $V_c \sim 220 \text{ km s}^{-1}$, $\sigma \sim 50 \text{ km s}^{-1}$; it's the opposite in ellipticals
 - ▶ Ellipticals are kinematically dominated by the velocity dispersion rather than the circular velocity.
 - ▶ Ellipticals are kinematically *hot*.
 - ▶ Presence/absence of large amounts of cool gas



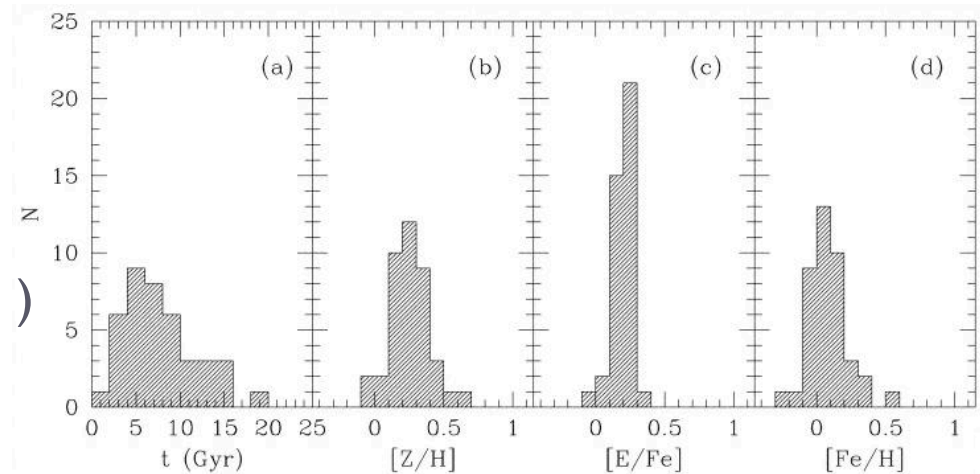
Stellar populations

- ▶ **Basic colors redder than spirals**
 - ▶ Radial color gradient (redder in center)
 - ▶ Metallicity gradient: $d[\text{Fe}/\text{H}]/d\log_{10}r = -0.22$
 - ▶ Based on Mg, Fe lines
- ▶ **Spectra (compare with a spiral)**
 - ▶ Look like a combination of G, F, and K stars in the optical; prominent Mg and Fe lines
 - ▶ Need high resolution spectra over the 350-650 nm range + stellar absorption line models
- ▶ **Age-abundance degeneracy**
 - ▶ Can use H β line strengths (in absorption) as age indicator
 - ▶ Why does this work?



Stellar populations *continued*

- ▶ Trager et al. 2000
 - ▶ Age spread: 2-12 Gyr
 - ▶ Nearly solar metallicity ($[Z/H]$)
 - ▶ Slightly subsolar $[Fe/H]$
 - ▶ Yields a high $[Mg/Fe]$ ratio



- ▶ Other fits: old population with “frosting” of younger stars
 - ▶ Bottom line: good fraction of old stars, but how old and real fraction is not well known.
-
- ▶

ISM in Ellipticals

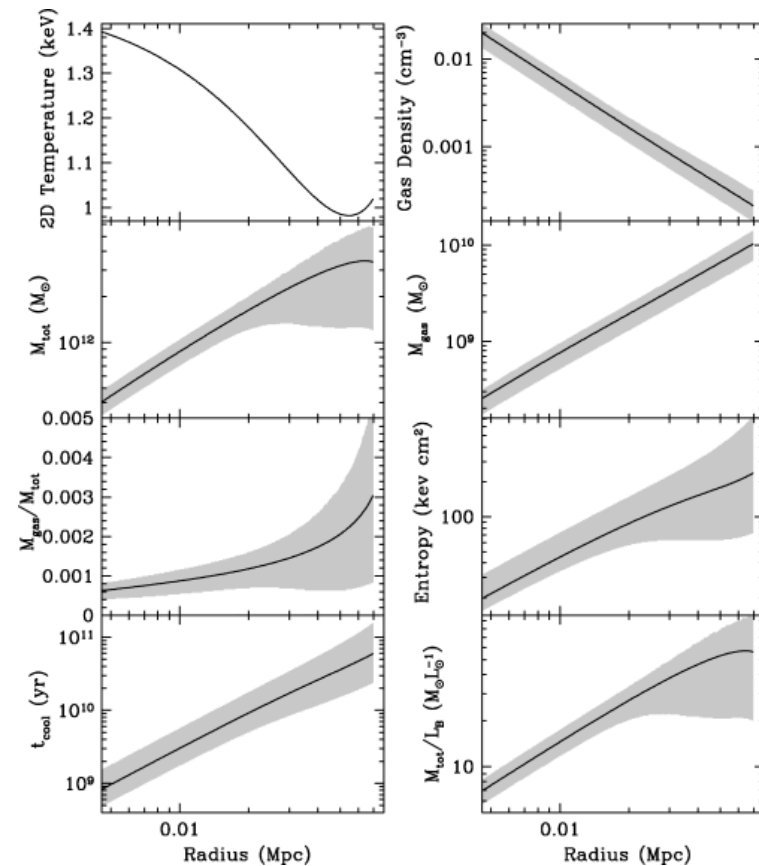
- ▶ **Cool gas**
 - ▶ Usually outside of main galaxy
 - ▶ Associated with shells
 - ▶ Disks out to large radii
 - ▶ (exception: dwarf ellipticals with nuclear clouds)
 - ▶ No correlation between presence of cool gas and any other property of the galaxy
- ▶ **Ionized gas – not much outside of nuclear regions (i.e., little star formation)**
- ▶ **Hot (x-ray) gas – *lots!***



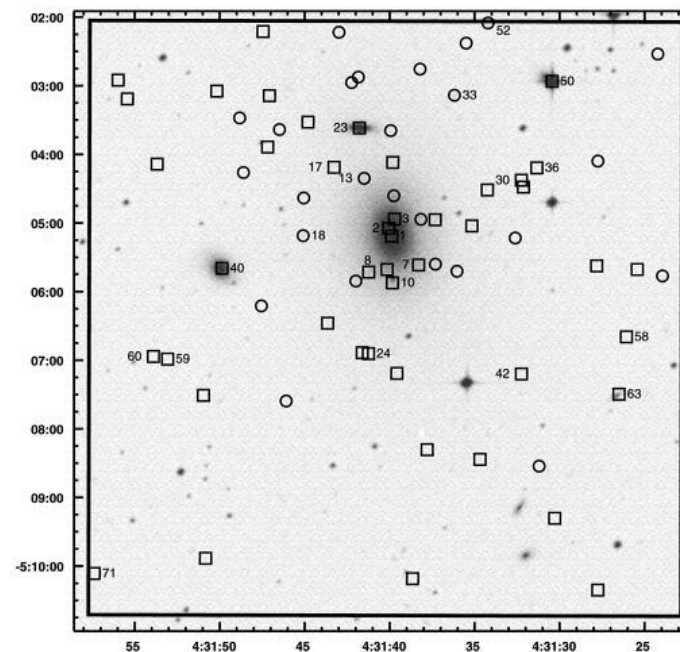
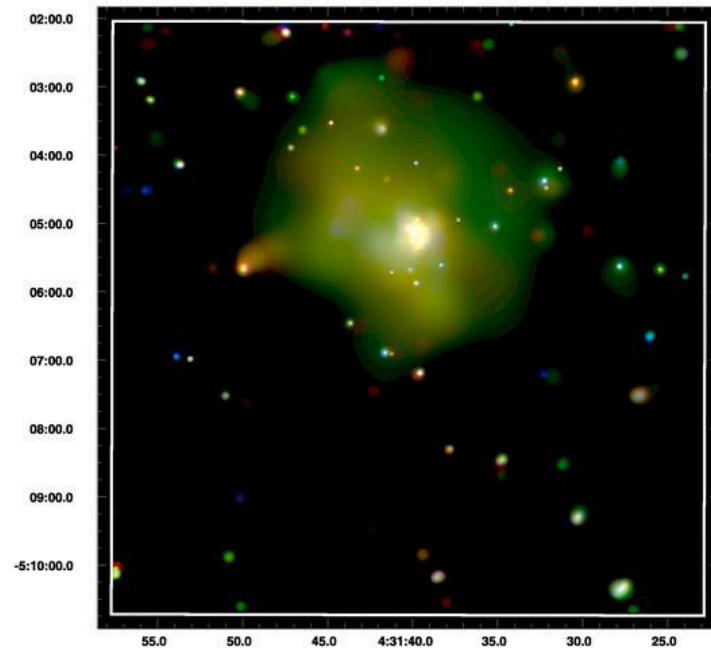
Hot Gas in Ellipticals

- ▶ L_X goes as $L_B^{1.6-2.3}$
(empirical relation)
- ▶ ρ goes as $r^{-3/2}$
- ▶ $M_{\text{gas}} \sim 10^9 - 10^{11} M_{\odot}$
- ▶ Origin of hot gas
 - ▶ Reservoir
 - ▶ External
 - ▶ Internal:
 - ▶ Mass return from AGB stars
 $\sim 1.5 \times 10^{11} M_{\odot} \text{yr}^{-1} L_{\odot}^{-1}$
 - ▶ Heated by Sne (what kind?),
thermal motion of stars at
200-300 km s⁻¹

Radial distribution



X-ray to Optical comparison



Stellar Kinematics

- ▶ **Measuring intrinsic shape/potential:**
 - ▶ 1. Surface photometry → mass distribution → potential (Φ , $M(r)$ model) → orbit library → superposition of orbits → iterate
 - ▶ 2. Surface photometry + resolved velocity fields and velocity dispersion maps
- ▶ **You measure of line-of-sight velocity distribution**
→ $\langle v_{\text{los}} \rangle = \int F(v_{\text{los}}) v_{\text{los}} dv_{\text{los}}$
- ▶ **Then, $\sigma^2 = \int (\langle v_{\text{los}} \rangle - v_{\text{los}})^2 F(v_{\text{los}}) dv_{\text{los}}$**
- ▶ **This accounts for the streaming and random motion of stars.**



Stellar Kinematics *continued*

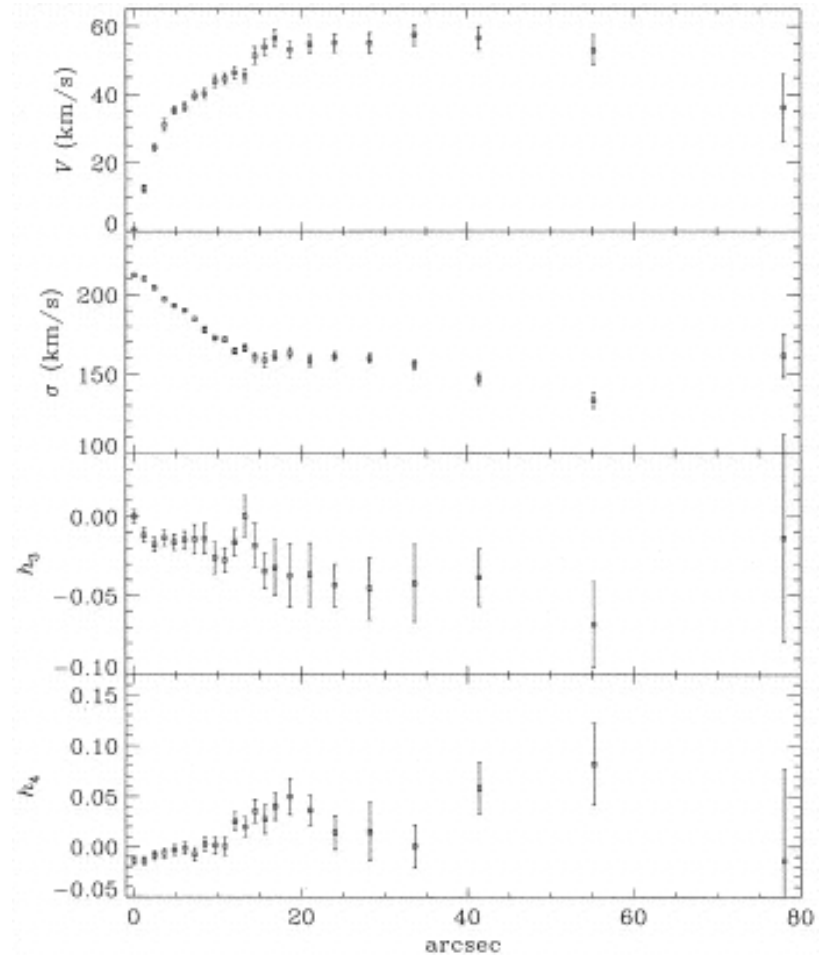
▶ LOSVD

- ▶ Assume a Gaussian velocity distribution function (F) to this makes things easier.
- ▶ $F \rightarrow \exp[-(\langle v_{\text{los}} \rangle - v_{\text{los}})^2 / 2 \sigma_{\text{los}}^2] \rightarrow e^{-b}$
 - ▶ $b = (1/2)w^2$, $w = (\langle v_{\text{los}} \rangle - v_{\text{los}}) / \sigma_{\text{los}}$
- ▶ This all yields a symmetric line profile.
 - ▶ Remember we're sampling a specific absorption feature (e.g. a Mg II line)
- ▶ But reality isn't all that symmetric, so we need some way to describe deviations from Gaussian →
 - ▶ “Gauss-Hermite” series which combines a Gaussian with an orthogonal set of polynomials
 - ▶ F goes as: $e^{-k} [1 + \sum_{k=3,n} h_k H_k(w)]$
 - ▶ this is a polynomial of order k, with some coefficient h



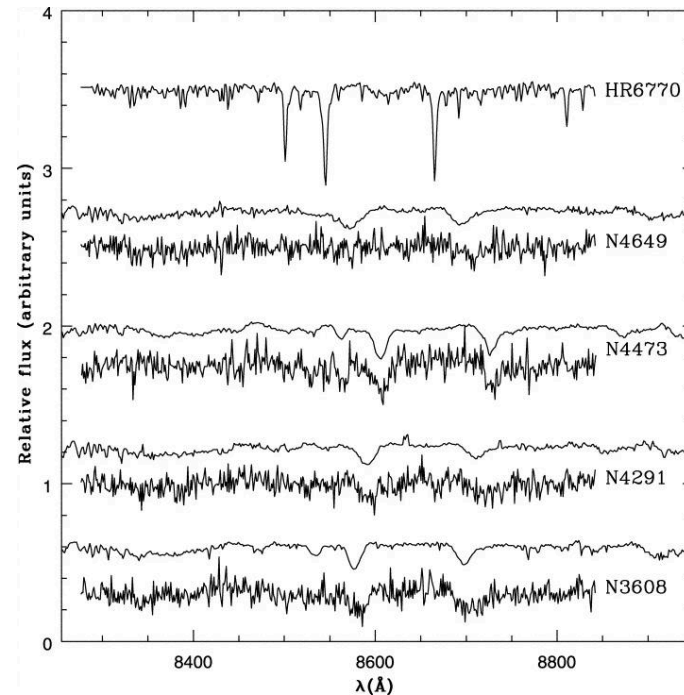
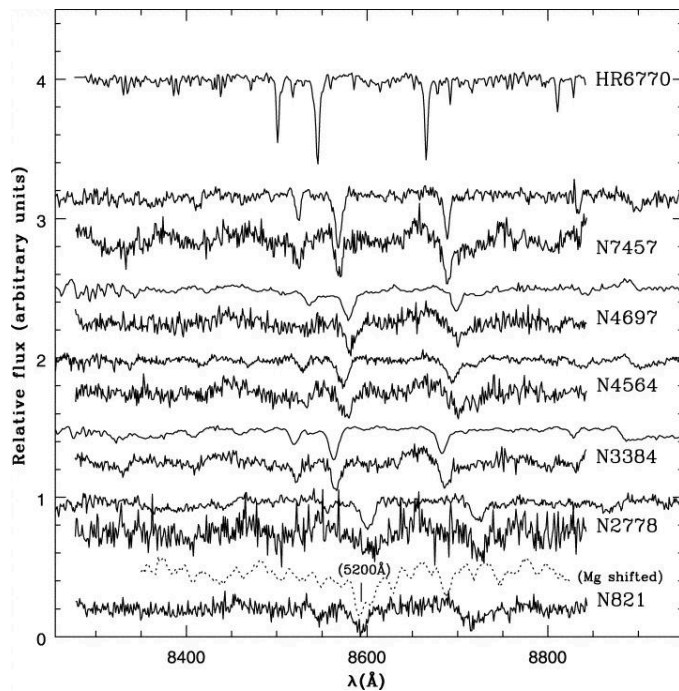
Gauss-Hermite information

- ▶ Describe stellar kinematics with four terms:
 - ▶ v , σ^2 , h_3 , h_4
- ▶ Third term:
 - ▶ $h_3 (2w^3 - 3w)/(3^{1/2})$
 - ▶ $h_3 \rightarrow$ measures “skewness” or deviation from symmetry. Large positive h_3 represents a secondary bump at $v > v$ so that the peak of the line is now $< v$
- ▶ Fourth term:
 - ▶ $h_4 (4w^4 - 12w^2 + 1)/(24^{1/2})$
 - ▶ $h_4 \rightarrow$ measures “kurtosis” or symmetric departures from a Gaussian. Large h_4 yields a boxy profile centered on v



The data...

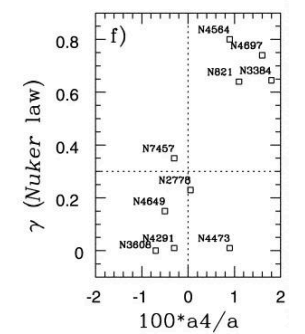
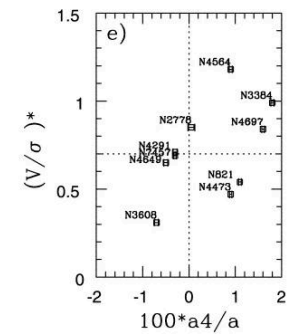
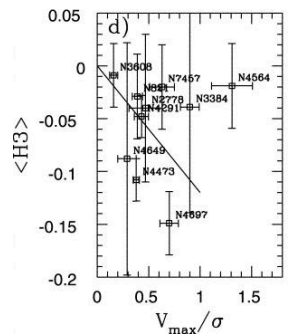
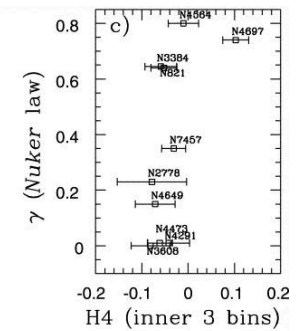
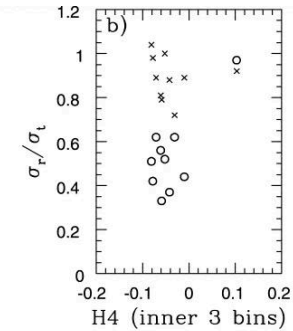
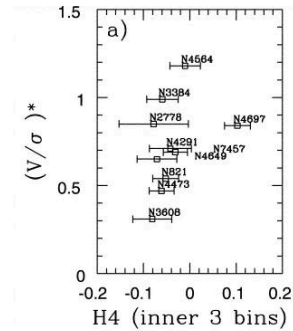
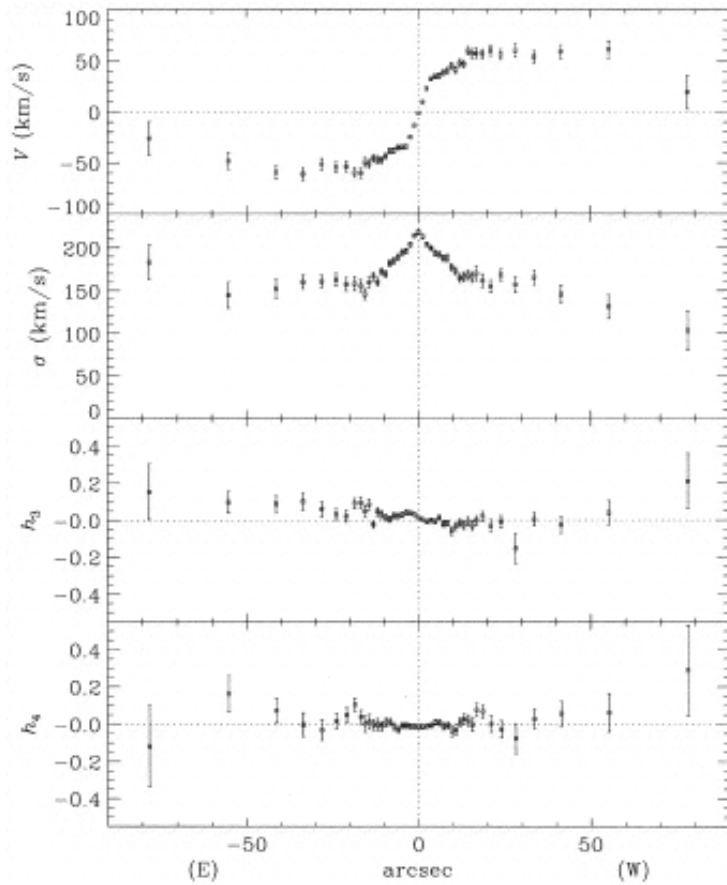
- ▶ Call near-infrared triplet
- ▶ 3 strong lines prominent in cool stars



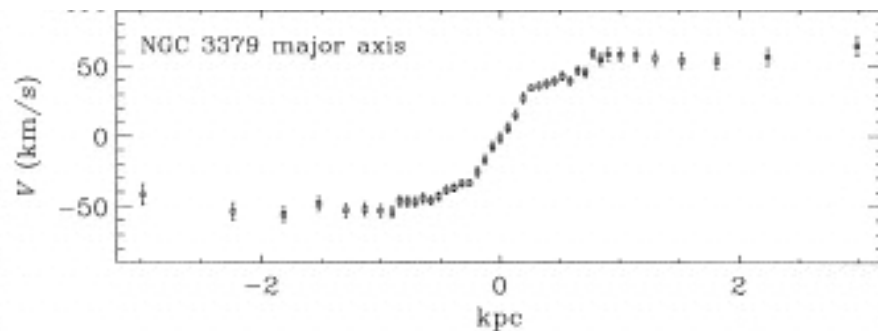
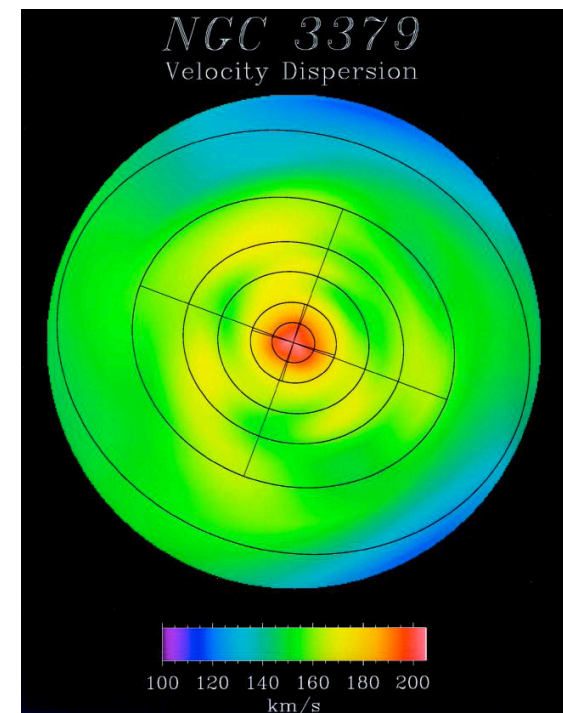
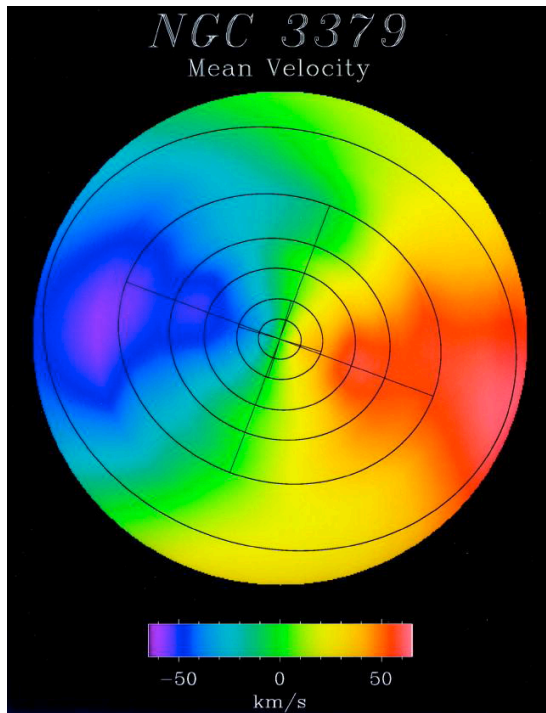
- ▶ Traditionally, primary lines (absorption) have been in the blue-visible, including H β , Mg I, and Fe I



Kinematic and structural parameters



Elliptical galaxies do rotate ...



► ... it's just that their dispersion is larger.

Results

- ▶ Pick a potential that will fit observed kinematics and surface brightness profile, e.g.,
 - ▶ $\Phi(R,Z) = (1/2)v_0^2 \ln(R_c^2 + R^2)$
 - ▶ Use four key kinematic parameters to characterize orbits and hence shape of potential (recall SOS program in HW3)
- ▶ Use tracers at large radii (PN and GCs) to obtain over-all velocity
- ▶ Findings:
 - ▶ M/L ratio increases with R
 - ▶ $M/r = 5 \times 10^{12} M_\odot \text{kpc}^{-1}$
 - ▶ M/L \sim 100-200 in some cases
 - ▶ Kinematics dominated by a dark halo beyond 1-2 R_e
 - ▶ “flat” σ vs R curves (just like spirals)
 - ▶ (further confirmation of dark halo comes from power law like distribution of hot x-ray emitting gas)

