Chapter 2

Populations and Components of the Milky Way

Our perspective from within the Milky Way gives us an opportunity to study a disk galaxy in detail. At the same time, it's not always easy to relate what we find in our own galaxy to structures in other galaxies. The concept of *stellar populations* shows both sides of this issue – comparison of the Milky Way with M31 played an important role in understanding the structure of our galaxy, but the imperfect analogy between the two systems may have prevented Baade from recognizing the true nature of the Milky Way's bulge.

2.1 Color-Magnitude Diagrams

- Young open clusters: Main sequence extends to high-luminosity blue stars; some evolved supergiants present; low-mass stars not yet on the main sequence (BM98, Fig. 6.27).
- Globular clusters: Main sequence ends at turnoff point; well-developed subgiant and red giant branches; distinct horizontal branch.
- Solar neighborhood: population formed over $\sim 10^{10}$ yr includes main-sequence, subgiants, red giants, and 'red clump'.

2.2 Recognition of Stellar Populations

Resolution of M31 enabled Baade to discern two distinct stellar populations. In the disk of M31 he found stars like the massive main-sequence and supergiant stars in open clusters, while in the bulge the stars resemble red giants in globular clusters. These two categories were adopted as the archetypical examples of Populations I and II, respectively.

The concept of stellar populations, each characterized by a different spatial distribution, kinematic structure, metal content, and age range, proved to be a key in interpreting observations of our galaxy and others. More detailed studies of the Milky Way culminated in 1957 Vatican Symposium, which legitimized an extended version of Baade's system including several intermediate populations. These populations were viewed as a *continuous* sequence; this accords with the hypothesis

	Population I		Population II	
	spiral arms	disk	intermediate	extreme
tracers	HI & GMCs HII regions OB associations supergiants type I Cep.	A to M dwarfs subgiants giants planetary neb. white dwarfs	weak K,M dwarfs Miras RR Lyr.	globular clusters RR Lyr. type II Cep.
stellar ages (10^9 yr)	< 0.1	1 to 10	10 to 14	14 to 16
[Fe/H]	0 to 0.3	-0.5 to 0.3	< -0.6	< -1.0
scale height (pc)	100	200 to 700	~ 1500	many 1000
rotation vel. ($\mathrm{km\,s^{-1}}$)	220	190 to 220	180	< 40

Table 2.1: Basic properties of stellar populations.

that the Milky Way formed from the collapse of a slowly-rotating gas cloud (Eggen, Lynden-bell, & Sandage 1962). Thus the oldest Pop. II stars were taken to define a nearly-spherical, slowly-rotating halo, while younger populations defined flatter and more rapidly rotating distributions, blending smoothly into the Pop. I of the disk. Some characteristics of various stellar populations are shown in Table 2.1.

This picture has been extensively revised in the light of new evidence. In particular, the metal-rich nature of the central bulge spoils the one-dimensional sequence of traditional populations. At present the galaxy is thought to contain several luminous components (*e.g.* Wyse 1992). The *thin disk* and *stellar halo* typify Baade's Pop. I and II, while the *thick disk* corresponds to Intermediate Pop. II. The metal-rich *bulge*, once relegated to Pop. II, seems distinct from the stellar halo.

2.3 Thin Disk (Population I)

The thin disk of the Milky Way has sustained ongoing star formation for 10^{10} years. Consequently it contains stars with a wide range of ages, and may be divided into groups of different ages. The total mass of the thin disk is about $6 \times 10^{10} M_{\odot}$.

Spiral-arm populations are the youngest in the disk; these include HI and molecular clouds, HII regions, protostars, stars of types O & B, supergiants and type I cepheids, which appear to trace the spiral pattern of the Milky Way. These tracers are concentrated close to the disk plane, with a scale height of roughly 100 pc; they move on nearly circular orbits with net velocities of about $220\,\mathrm{km\,s^{-1}}$. Their metallicity is somewhat higher than that of the Sun (MB81).

Attempts have been made to reconstruct the large-scale distribution of the HI from 21-cm observations. It's now realized that non-circular motions seriously confuse these efforts at what might be called 'galactic velocity tomography'. The radial distribution is more reliable; the gas is less centrally concentrated than the disk stars, and the inner 3 kpc or so are almost free of neutral hydrogen (MB81); thus the Milky Way is one of those galaxies with a central hole in HI.

	young	intermediate	old
tracers	A, F dwarfs A to K giants	G dwarfs planetary nebulae subgiants	K, M dwarfs weak-lined stars RR Lyr.
stellar ages (10^9 yr)	~ 1	~ 5	< 10
[Fe/H]	0 to 0.3	-0.3 to 0	-0.6 to -0.3
3-D velocity disp. ($\mathrm{km\,s^{-1}}$)	25	50	80
rotation vel. ($\mathrm{km\,s^{-1}}$)	210	195	170
scale height (pc)	200	400	700

Table 2.2: Characteristics of disk populations.

Disk populations are more smoothly distributed. Representative objects include stars of type A and later, planetary nebulae, and white dwarfs. Disk stars may be subdivided into young, intermediate, and old groups; with age, stellar velocity dispersions and scale heights increase, while metallicity and rotation velocity decrease as shown in Table 2.2 (see MB81).

2.4 Thick Disk (Intermediate Population II)

This intermediate population was already recognized at the Vatican Symposium. Representative objects include Mira variables with periods of 150 to 200 d and RR Lyrae variables with metallicities $[\mathrm{Fe/H}] > -1$ (Gilmore, Wyse, & Kuijken 1989).

Star-counts suggest that this component is distributed in a disk with a scale height of 1 to 1.5 kpc. While less than 1% of the stars in the vicinity of the sun belong to the thick disk, this component dominates the high-altitude tail of the thin disk at $z > 1\,\mathrm{kpc}$. The total mass of the thick disk is only about $10^9 M_\odot$.

The true nature of this stellar population is imperfectly understood; it was originally classified as part of the halo, but it's much flatter than any other halo population. Kinematic studies imply that the thick disk rotates with a velocity of about $180\,\mathrm{km\,s^{-1}}$ (Gilmore *et al.* 1989), compared to the less than $40\,\mathrm{km\,s^{-1}}$ rotation of the halo. This indicates that the thick disk is more closely associated with the thin disk. Metallicity measurements also support the idea that the thick disk is distinct from the stellar halo; the characteristic metal abundance of thick disk stars is $[\mathrm{Fe/H}] = -0.6$, while the halo is poorer in metals.

It's less obvious if the thick disk is *distinct* from the thin disk since in many respects it represents a continuation of the trends with age in metallicity, velocity dispersion, and scale height seen in the thin disk. On the other hand, the velocity dispersion and scale height of the thick disk are significantly greater than even the oldest thin disk sub-population, suggesting that some discontinuity might occur between these groups.

2.5 Stellar Halo (Extreme Population II)

The stellar halo of the Milky Way includes the system of globular clusters, metal-poor high-velocity stars in the solar neighborhood, and metal-poor high latitude stars. The total mass of the stellar halo is only about $10^9 M_\odot$. As the *oldest* visible component of the galaxy, the stellar halo holds important clues to the formation of the Milky Way.

Metal-poor subdwarfs in the solar neighborhood have large velocities with respect to the Sun and other disk stars. These stars are on highly eccentric orbits about the galactic center; their net rotation is no more than $40\,\mathrm{km\,sec}^{-1}$, while their random motions are quite large. The metallicity of these stars ranges from $-3 < [\mathrm{Fe/H}] < -1$ (MB81).

Globular clusters with $[\mathrm{Fe/H}] < -1$ are the classic tracers of the galactic halo; their spatial distribution provided the first real clues of the true size and shape of the galaxy. These clusters have a nearly-spherical distribution extending to many times the Sun's distance from the galactic center (MB81, Fig. 4-14).

(Clusters with $[\mathrm{Fe/H}] > -1$ *are much more concentrated towards the center of the galaxy and have a flattened distribution (Harris 1976). It's not clear if these clusters are part of the bulge or the thick disk of the Milky Way.)*

RR Lyrae variables are useful in tracing the large-scale distribution of the halo because they can be identified by their characteristic light variation at large distances.

Several kinds of evidence suggest that the halo has two distinct components (see Norris 1996). Within the solar circle RR Lyrae stars have a somewhat flattened distribution, while further out they scatter spherically. Horizontal-branch morphology divides metal-poor globular clusters into young and old groups; the old clusters have a flattened distribution, a definite radial metalicity gradient, and weak prograde rotation, while the young clusters have a spherical distribution, no metalicity gradient, and – like halo stars at large distances from the plane – a net *retrograde* rotation of about $60\,\mathrm{km\,s}^{-1}$.

The outer, spherical halo may be the product of the accretion of low-mass dwarf galaxies by the Milky Way. Evidence for past accretion events comes from observations of 'moving groups' in the halo (Eggen 1987, Majewski, Munn, & Hawley 1994). Rather like meteor streams orbiting the Sun, such groups of stars with common distances, kinematics, and metalicities may be produced by the tidal breakup of dwarf galaxies orbiting the Milky Way. The halo also contains A stars younger than 5×10^8 year (Rodgers *et al.* 1981, Lance 1988) and a population of metal-poor dwarfs bluer than the halo's main-sequence turnoff (Preston *et al.* 1994); these may be due to accretion events. Finally, multi-color photometry and radial velocity measurements reveal a dwarf galaxy just 16 kpc from the galactic center in the direction of Sagittarius (Ibata, Gilmore, & Irwin 1994). This galaxy, about 10 by 3.5 kpc in extent, with visual magnitude of about $M_v = -14$, is evidently being torn apart by tides as it falls into the Milky Way (Irwin *et al.* 1996). In addition to its complement of perhaps $10^{8} M_\odot$ of old and intermediate-age stars, the accretion of this galaxy will add four globular clusters, including the luminous cluster M54, to the halo of the Milky Way.

2.6 Bulge (Population ?)

RR Lyrae in the central bulge of the galaxy are visible through Baade's window and other regions of low absorption (Oort & Plaut 1975). Othere characteristic stellar tracers of the bulge include K and M giants; these stars span a wide range of metallicity, but over half are in the range $-0.4 <$ $[\mathrm{Fe/H}] < 0.3$ (Sadler, Rich, & Terndrup 1996). The inner kpc of the bulge also appears to contain A stars, implying that some star formation has occurred within the past 10^9 year (Gilmore *et al.* 1989). The mass of the bulge is about $2 \times 10^{10} M_\odot$, or one-third the mass of the disk. The bulge rotates at roughly $100\,\mathrm{km\,s^{-1}}$.

Infrared data offers the clearest views of the Milky Way's bulge. Both the bulge and the disk can be clearly seen in the distribution of selected $12\,\mu$m sources in IRAS point-source catalog; these objects are evolved low-mass stars (GKvdK89, Fig. 2.2). The bulge is also visible in DIRBE observations between 1.25 and $4.9\,\mu$m, though at longer wavelengths the DIRBE images are dominated by zodiacial emission (Arendt *et al.* 1994). Interstellar extinction towards the bulge is evident in the 1.25 and $2.2\,\mu$m images; it can be estimated and partly removed using $1.25/2.2\,\mu$m flux ratios.

These and other IR observations reveal that the bulge is asymmetric; at a given isophotal level, the bulge extends about 2° further in the first quadrant than it does in the fourth quadrant (Weiland *et al.* 1994). It's quite unlikely that the bulge is actually lopsided; rather, these data are interpreted in terms of a *triaxial* bulge with a major axis lying in the disk plane and pointing about 15° from the Sun's position (*e.g.* Blitz & Spergel 1991). The bulge also appears distinctly boxy (Freudenreich 1998). A triaxial bulge has also been invoked to account for the kinematics of cold gas towards the galactic center (de Vaucouleurs 1964, Binney *et al.* 1991); numerical simulations indicate that a boxy bulge created by disk instabilities can reproduce the unusual features seen in CO and HI position-velocity diagrams (Englmaier & Gerhard 1999, Fux 1999). This raises the interesting possibility that the bulge of the Milky Way may be closely related to the disk population.