REVIEW

The Formation and Early Evolution of the Milky Way Galaxy

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Recent observations indicate that the Milky Way may have formed by aggregation of gas and stars from a reservoir of preexisting small galaxies in the local universe. The process probably began more than 12 billion years ago with material of different original angular momentum following two separate evolutionary lines, one into the slowly rotating halo and central bulge and the other into the rapidly rotating disk. The existence of distinct thick and thin disks shows that continuing mergers of satellite galaxies likely also determined the early evolution of the main structural component of the luminous Galaxy.

The Milky Way Galaxy belongs to a small cluster of galaxies called the Local Group (*1*), which is one of many other groups and clusters of galaxies located near the outer edge of the Virgo supercluster. Within about 450 kiloparsecs (kpc) (*2*) of the Local Group's barycenter, about half of its three dozen member galaxies known today are clustered in two subgroups around the two dominating massive spirals, the Andromeda nebula (M31) and the Galaxy. Among the Milky Way's companion galaxies, the brightest ones are the Large and the Small Magellanic Clouds—irregular galaxies at distances of ~50 and ~60 kpc, respectively—while the remainder are all fainter, lower mass dwarfs. At a distance of less than ~25 kpc from the Galactic center, the Sagittarius dwarf galaxy was only recently discovered and was shown to be in a process of merging with the main body of the Milky Way (*3*).

The main body of the luminous Galaxy (*4*) consists of at least four major components, which are nested within each other. A tenuous, essentially rotationless spheroidal halo of stars and about 170 globular clusters (*5*) extends out to a radius of perhaps 100 kpc. Within its inner ~25 kpc, the halo also embraces stars and open clusters (*6*) that are concentrated into two essentially coplanar disks with distinctly higher densities, flattenings, and rotation speeds: the thick disk and the thin disk. These components comprise an even flatter distribution of gas and dust (clouds), the extreme disk embedding their common midplane, and in their innermost parts merge with a bar-like bulge—the central concentration of luminous matter in the Milky Way (Fig. 1) (*7*).

Current efforts in galactic astronomy focus on studies of this hierarchy of structures (*8*) to unravel its evolutionary history, back to the origin in the early universe. Astronomers have learned to see the Milky Way as a local laboratory where evolutionary time lines continue to be funneled from outside and within, leaving them with a skein of threads to properly disentangle. In this picture, the natural starting point for the task must be taken with the coexistence, in the Milky Way Galaxy, of its large-scale spatial components mentioned above: the halo, disks, and bulge. The evolutionary histories of these structural components should be expected to provide relevant clues to the formation of the Milky Way as a whole.

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Clues to the Formation of the Galaxy

Exploitation of the different components as tracers of Galactic evolution and formation requires more than determining the different spatial distributions of their stars, although this latter task alone is already formidable, because it assumes that distances can be measured reliably and consistently for a wide variety of stellar species and a significant number of representative samples of stars and clusters (*9*). For example, Galactic space near the sun is populated by stars belonging to one of the disks or to the halo, because these components are not spatially separated there but overlapping. The ambiguity can be resolved by considering the kinematics of the stars. This is done by measuring their velocities (*10*) and, even more importantly, the velocity distributions of representative samples of stars. These data reveal the distributions of orbital properties, such as orientations, sizes, and eccentricities, which determine the long-time residences of the stars in the Galaxy at large, and in fact, the shapes and sizes of the individual Galactic components.

Indeed, thin-disk stars near the sun belong to the thin disk because they have similarly high rotational velocities (~220 km s^{-1}) carrying them about the Galactic center on nearly circular orbits lying in nearly the same plane; their average velocities perpendicular to the plane of rotation, however, are so low (~20 km s^{-1}) as to allow them only short periodic excursions (±~300 pc) above and below. Thus, the thin disk is very flat, with a thickness-to-diameter ratio of the order $\lesssim 1/10$. In contrast, the stars of the thick disk have, on average, lower rotational but higher vertical velocities, such that they may travel up to 1 kpc away from the central plane. Therefore, if the thick disk extends at least as far as the thin disk in the radial direction, its axis ratio is larger, of the order ~1/3. Finally, the halo stars now present in the solar neighborhood all have low rotation velocities but high velocities perpendicular to the Galactic plane. Rather than participating in the orderly rotation of the disks, they are plunging rapidly through the disks on highly eccentric ($e > 0.5$) and strongly inclined orbits, and on which they are moving back again far from the plane into the halo–their proper abode, where they were probably born.

Full comprehension of the Galactic components also requires knowledge of a temporal dimension: the times when stars became their constituent members. As the Milky Way Galaxy must have formed by assembling available material within a larger scale gravitational potential of dark matter (*11*), its components may have been built from either pristine gas or pristine stars, or both. In fact, because stars are being formed out of gas in the Galaxy's extreme disk today (Fig. 2) (*12*), the real question is if there is any Galactic component with a significant fraction of stars that were not born in the Galaxy but were formed elsewhere, perhaps

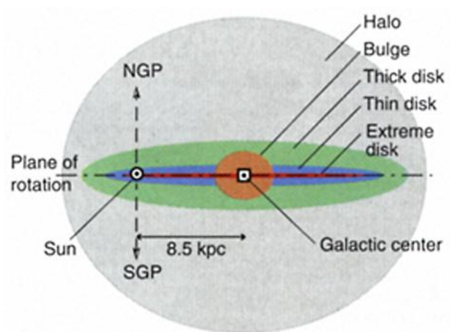

Fig. 1. Schematic view of the major components that make up the Galaxy's overall structure, shown in a cross section perpendicular to the plane of rotation and going through the sun and the Galactic center. From the observer's vantage point at the sun's position, the directions to the North (NGP) and South (SGP) Galactic Poles are particularly suitable for studying the layered structure and other properties of the stellar disks and halo, whereas the concentration of gas and dust in the extreme disk severely obstructs observations of the distant bulge at visual-optical wavelengths. The central parts of the Galaxy are better accessible through longer wavelength infrared and radio observations.

long before or after the Galaxy started to turn gas into stellar generations on its own. If so, these stars would have to have been created in aggregates experiencing their own star formation histories, independent of the Galaxy's, into which they were later forced to mix.

Actually, each star contributes its bit to the memory of the particular star formation history to which it belongs. The observable spectrum provides a detailed record of the interstellar medium's chemical composition at the time of the star's birth from its parent gas cloud. Because all stars live on their inherited gas by building new nuclei of heavier elements, and because the most massive stars soon recycle their products into the interstellar medium by exploding as supernovae (*12*), the gas available for star formation is being enriched in metals (*13*) from one stellar generation to the next. The metallicities observed in stellar spectra (*14*) therefore provide a clock that can be used to estimate the relative ages of the stars on a time scale, which is intrinsic to the particular star-forming aggregate; for example, a metal-poor star was born earlier and is therefore older than a metal-rich star.

Apart from providing prominent tracer populations that allow deep probes of the disk and halo far from the solar neighborhood, the open and globular clusters are also the ideal objects for a quantitative calibration of the metallicity clock in the Galaxy. Each cluster represents a single generation of coeval stars formed out of the same gas cloud (or a fragment thereof) and thus all having the same metallicity. Moreover, in contrast to an individual field star, a cluster offers the important advantage that its distance can be derived relatively reliably from the observed color-magnitude diagram (*15*) by averaging over up to several thousand essentially equidistant individual member stars. Similarly, as coeval cluster stars of different initial mass have advanced to widely different evolutionary stages (evidenced in their different observed colors and luminosities), determination of their common age, which is the age of the cluster, in essence also amounts to deriving a weighted average of a large number of individual stellar ages from comparison with a consistent theory of stellar evolution (*16*).

In the 1950s, when the relevant space, kinematic, metallicity, and relative age data for clusters and field stars became available in sufficient quantity, it was found that the spatial and kinematical properties of the Galaxy's components are correlated with their metallicities and, indeed, their relative ages (*17*).

A Model of the Formation of the Galaxy from Primordial Gas

In broad outline, the then-emerging picture is still valid today qualitatively: Stars and globular clusters of the halo are metal-poor and very old, probably older than ~12 gigayears (Gy), whereas the thick disk appears to be mainly made of stars and globular clusters, which may be nearly as old as those of the halo but have intermediate metallicities. The stars and open clusters of the thin disk are metal-rich and have ages ranging from ~10 to ~1 Gy, while the even younger ones are still near their birthplaces in the extreme disk, where stars continue to be formed from gas and dust. The central bulge, where all other components as well have their highest spatial densities merged together, seems to be a rather heterogeneous component, distinguished by old age and high metallicity in the mean, but perhaps also with the largest ranges in each.

In this synoptic view of the components of the Milky Way, metallicity is an observable quantity, which can be used to conceive of matter in Galactic space and time as being formed and structured in a coherent process. As the metallicity clock advances, evidenced by the observed age-metallicity relation among successively younger components, a large-scale spatial metallicity gradient is established as well, with observed mean metallicity increasing with the increasing density and flattening of the components (Fig. 3) (*18*). Such correlations in the Milky Way today suggest that the Galaxy formed out of primordial gas by initiating its own star formation history.

According to a seminal paper by Eggen, Lynden-Bell, and Sandage (*19*), the proto-Galaxy would start out as one spherical cloud of original metal-poor gas contracting towards its center of gravity. As the gas cloud condenses to smaller radii, energy dissipation (*20*) coupled with increasing rotational speed acquired due to conservation of initial angular momentum would induce the cloud to collapse anisotropically along the rotation axis. The shape of the cloud would be quickly deformed into successively flatter configurations until finally, the central concentration would be surrounded by a fast spinning thin disk of gas in rotational equilibrium. Concurrently with the progressing collapse, the cloud would be forming clusters and stars, which in turn would gradually enrich the remaining gas with the metals from supernovae. As clusters and stars are dissipationless, they would inherit and preserve not only the actual metallicity, but also the actual velocities intrinsic to the parent gas at their time of birth. Thus, a galaxy of clusters and stars would result, featuring large-scale structural components whose present observed spatial, kinematic, and chemical properties reflect the major phases of a coherent history of the Galaxy's formation and evolution.

Fig. 2. Seen face-on, our Milky Way probably looks very similar to the galaxy NGC 1232 (in the southern constellation Eridanus) shown here. Several spiral arms are loosely wound around a small, somewhat elongated, bar-like central bulge. They outline regions in the extreme disk of molecular gas and dust clouds, where enhanced star formation provides a continuous supply of young bright stars and clusters, which dominate the smoother background of older and fainter stars in the galaxy's thin disk. [Photo: European Southern Observatory]

Recent Developments: A Merger History of the Halo

Seen at the higher resolution provided by new and better data, however, the structure of the Milky Way turns out to be more complex than described above. Our Galaxy is not a system in isolation but is still interacting with its environment in the Local Group. The Sagittarius dwarf is the prime example of a small satellite galaxy being disrupted by merging with the Milky Way (*21*), and the four globular clusters Messier 54, Terzan 7, Terzan 8, and Arp 2, which belong to Sagittarius (*22*) but are usually counted as Galactic globular clusters, illustrate well that even today, our Galaxy is accreting new metal-poor stars in globular clusters, which were born at different times and which spent most of their lives in a different (low-mass) system that continues to show signs of episodic star formation (*23*). It is well possible that eventually, these newly acquired globular clusters will themselves be tidally disrupted when their orbits have (repeatedly) carried them into the denser parts of the inner Galaxy, and hence, will share the past fates of many of their Galactic cousins (*24*). Other groups of nearby dwarf spheroidal galaxies and younger globular clusters with correlated actual space motions and positions have been proposed as representing galactic streams from debris of disrupted aggregates (*25*). Similarly, halo stars with small velocity dispersions indicative of common space motions have been identified as moving groups which could either be accreted remnants of small aggregates or debris from tidally destroyed Galactic globular clusters (*26*).

Near the solar circle and high above the Galactic plane, field-star populations have been found whose properties are very different from the general characteristics of the halo or disk components and which, therefore, are also suggestive of accretion from an external source. An estimated fraction of perhaps 10% of the local halo density appears to be present in a population of kinematically intermediate, blue, metal-poor main sequence stars with [Fe/H] < -1 and ages older than about 3 Gy but younger than the old turnoff stars (*16*) of the halo. These stars may have been accreted from a dwarf galaxy similar to the nearby Carina dwarf spheroidal galaxy, which has a large metal-poor component of stars with intermediate ages (*27*). An even more unusual, probably young ($<$2 Gy), metal-rich population of A-type main-sequence stars found at high Galactic latitudes and up to more than 10 kpc from the Galactic plane could also have resulted from a merger of a dwarf galaxy with the Milky Way, either by immediate accretion or formed from gas during the merger event (*28*).

Direct and indirect evidence now available of such events leaves no doubt that accretion of satellites and fragments (*29*) into the halo of the Galaxy has been a continuing process since early in its formation. While the small mass fraction of early-type stars found in the local halo now (*27, 28*) indicates that, at most, a few dozen star-forming dwarfs like the Sagittarius or Carina galaxies could have supplied these relatively young stars in the past $\sim$10 Gy (*30*), a larger number of smaller metal-poor fragments or galaxies—perhaps $\sim 10^3$ dwarfs like Draco or Ursa Minor—merging in the Milky Way's earliest history could have made up the total mass ($\sim 10^9\ M_\odot$) seen in the Galaxy's halo today as a population of old metal-poor clusters and stars (*31*).

A scenario of this kind was suggested in 1978 by Searle and Zinn (*32*) in a study of halo globular cluster ages and metallicities as functions of galactocentric distance. They found evidence for a possible range of ages but no evidence of a metallicity gradient, that key diagnostic of a coherent process in which the gaseous proto-Galaxy contracts dissipatively on a time scale long enough to allow supernova ejecta to be incorporated into new generations of stars. Searle and Zinn proposed that the halo formed in a more stochastic process, by prolonged aggregation of transient protogalactic fragments and therefore was the product of a mixture of stars and clusters born and evolved in different environments and on different time scales. This would explain the absence, within the halo, of systematic gradients in metallicity and kinematical properties and would also account for the existence of significant observed spreads in metallicities and ages. However at the same time, this model does not explain how the halo is related, if it really is, to the much denser and much more massive Galactic components, whose flattened structures would seem to imply that dissipation played a significant role in their formation.

The Thick and Thin Disks of the Galaxy

A metal-poor stellar population with a flattened (that is, with a minor-to-major axis ratio $c/a < 0.6$) density distribution in the Galaxy (for example, RR Lyrae variable stars with $\Delta S < 5$) was already incorporated in the population concept following the Vatican conference (*17*), and was evident in the early star count data derived from photographic three-color photometry surveys of the halo (*33*). Identification as a possibly separate, thick disk component intermediate between the halo and the thin disk was suggested by similar large-field survey data toward the South Galactic Pole (*34*), following the discovery of thick disks in some edge-on galaxies with bulges similar to the Milky Way (Fig. 4) (*35, 36*).

Since then, a large body of new spectroscopic, photometric, and astrometric data have been used in an attempt to deduce a sharper picture of the spatial, kinematic, and chemical properties and their correlations in the Galaxy's thick disk (*37*). It is important to note that in order to arrive at reliable results, biases due to selection of thick-disk stellar samples by either metallicity or kinematics have to be accounted for with particular care.

Systematic multidirectional photometric surveys of faint [$m_V < 19$ magnitude (mag)] stars show that the stellar space density of the large-scale thick disk decreases exponentially in the radial direction from the Galactic center and in the vertical direction from the Galactic plane (Fig. 5) (*38*). In the outer Galaxy near the sun, the thick disk's local density ρ is about 4 to 10% of that of the thin disk, and its scale height h_z is in the range of $\sim$700 to $\sim$1200 pc, indicating that detectable density (and velocity) fluctuations may exist in this component (*38*). Combined photometric and proper motion survey data also show that the thick disk's mean rotation $v_{rot} \sim 170$ km s^{-1}, with no detectable gradient in the asymmetric drift (that is, no systematic variation of rotational lag behind the thin disk) within distances $0 \leq z \lesssim 2$ kpc above the Galactic plane (*39*). However, a gradient of -14 ± 5 km s^{-1} kpc^{-1} persisting up to larger distances $z \lesssim 6$ kpc has been found and confirmed from similar fainter-star data (*40*). The issue is important, since such a gradient could have formed by dissipational settling, whereas its absence suggests that the thick and thin disks are kinematically distinct.

From the velocity data of a large sample of

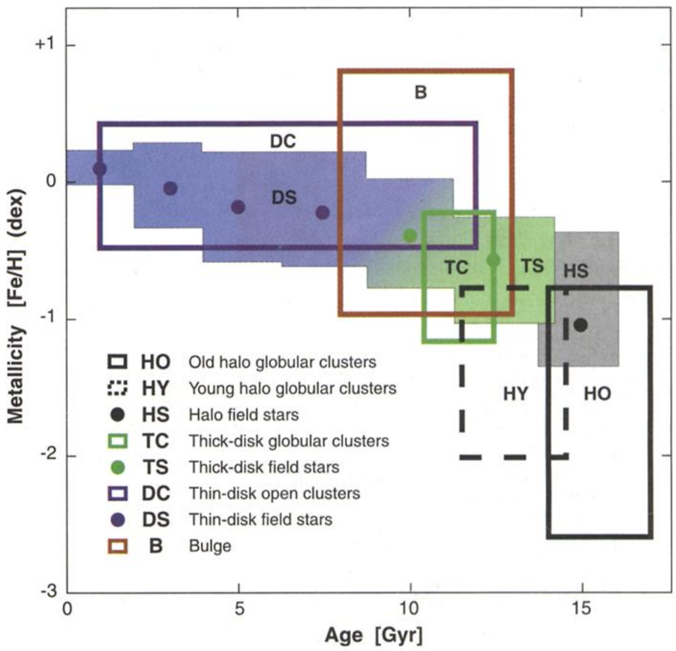

Fig. 3. The overall age-metallicity relation in the Milky Way, showing the bulk properties and approximate ranges of the different Galactic components. The obvious trends of metallicity, [Fe/H], to increase with time and spatial concentration toward the Galactic plane and central region suggest that the components of the Galaxy formed and evolved in a coherent and continuous process. However, the dispersion of the relation is everywhere so large that for some components, different independent origins and evolutionary connections are possible, as indicated by the more discriminating absence of strong internal metallicity and kinematic gradients discussed in the text.

nearly 2000 metal-poor stars selected by abundance criteria ([Fe/H] < -0.6), a high mean rotational velocity, $v_{rot} \sim 190$ km s^{-1} and vertical velocity dispersion, $\sigma_w \sim 40$ km s^{-1}, with inferred scale length $h_R \sim 4.7$ kpc and scale height $h_z \sim 1$ kpc are found for thick-disk stars with intermediate metallicities $-0.6 \geq$ [Fe/H] ≥ -1 (*41*), in agreement with the above (*38, 39*) results. Combination of these data with other kinematically unbiased (*42*) as well as bias-corrected (*43*) data allows study of the transition from the metal-rich, thin-disk dominated domain to the intermediate metallicity domain, where thick-disk stars apparently dominate. While generally following a gentle rise from ~15 km s^{-1} at solar abundances to $\lesssim$30 km s^{-1} at [Fe/H] ≈ -0.5, the velocity dispersion σ_w shows a rather sudden increase to ~40 km s^{-1} near [Fe/H] ≈ -0.6 and below (*31*). The behavior at the higher metallicities is believed to be due to dynamical evolution of the thin disk (*44*), but the discontinuity in σ_w around the peak of the thick-disk metallicity distribution provides strong evidence that the thick and thin disks are kinematically discrete, suggesting a merger origin of the thick disk (*45*). Numerical simulations of satellite accretion by disk galaxies show how the original (thin) disk is heated and the debris of the merger is dispersed throughout the thickened disk. At solar galactocentric distances, this disk has dynamical properties (v_{rot}, σ_w, h_R, h_z), which are very similar to those observed in the Galactic thick disk (*46*). However, the timing of a possible such event in the Galaxy is constrained by the present properties of the thin disk: the impact and heating must have occurred when the disk was still mainly gaseous and could resettle to a thin disk after one or more accretion events (*47*). Thus, determination of metallicities and ages of thick-disk stars is required for further clarification.

The most direct determination to date of the metallicity distribution comes from low-resolution spectroscopic observations of several hundred faint ($15 \leq m_V \leq 18$ magnitude) stars in two fields probing the thick disk at solar galactocentric distance and at heights 500 to 3000 pc above the Galactic plane (*48*). The distribution has a broad peak at [Fe/H] = -0.7—similar to that of the Galaxy's metal-rich globular clusters ($\langle$[Fe/H]$\rangle = -0.6 \pm 0.2$) (*49*), which are also thought to belong spatially and kinematically to the Galactic thick disk (*22, 50*)—with formal Gaussian dispersion $\sigma_{[Fe/H]} \approx 0.3$ or larger, and significant tails overlapping with the distributions of the metal-rich thin disk ($\langle$[Fe/H]$\rangle \approx -0.3$) and the metal-poor halo ($\langle$[Fe/H]$\rangle \approx -1.6$) (*41*), down to [Fe/H] ≈ -1.6. Within the indicated distance range, there is no convincing sign of a (vertical) metallicity gradient. Because from several other surveys both essentially zero (<0.05 dex kpc^{-1}) (*51*) and marginally nonzero (~0.10 dex kpc^{-1}) (*31, 52*) metallicity gradients are found for the dominating population with $\langle$[Fe/H]$\rangle \approx -0.7$, the question of whether or not a metallicity gradient exists in the thick disk is still unanswered. However, while the existence of a gradient would strongly suggest a dissipative formation process, a merger origin would not necessarily imply the absence of a gradient, because the result of a merger event would essentially depend on whether the merger was mainly composed of stars or of gas. If it was largely gas, a metallicity gradient could still develop as the gas settled into a reconstructed disk (*45*). Interestingly, indications of radial and vertical metallicity gradients of ~-0.03 dex kpc^{-1} and ~-0.06 dex kpc^{-1}, respectively, have been found from highly accurate HIPPARCOS observations of proper motions for a small sample of red-giant and RR Lyrae stars that belong to the metal-weak tail ($-1.6 <$ [Fe/H] < -1) of the thick disk (*53*). If confirmed by future high-precision data for larger stellar samples, even these minor gradients could provide the missing link joining the formation histories of the halo and the thick disk through a dissipative process.

The most reliable age of the Galactic thick disk may be derived from its cluster population. For the three best studied thick-disk globular clusters, 47 Tuc, NGC 6352, and M 71, which have $\langle$[Fe/H]$\rangle = -0.64$ dex, one finds a mean age $\langle t_9 \rangle = 11.4 \pm 0.8$ Gy (*31, 54*). This value appears to be representative of the thick disk's field-star population as well, as judged from comparison of the cluster main-sequence turnoffs with the observed blue cutoff [$(B-V)_0 \sim 0.5$] in the color distribution of stars with similar metallicities (*31*). On the other hand, isochrone fits show the oldest open cluster found as yet (Berkeley 17) in the Galactic thin disk to have an age $t_9 = 12 \pm 2$ Gy (*55*), while from the observed white dwarf luminosity function, cooling theory yields a (local) disk age of $t_9 = 11 \pm 3$ Gy (*56*). Taken at face value, the ages of the thick and thin disks are indistinguishable. For the moment, this and the apparent large differences between the bulk kinematic and chemical properties of the thin and thick disks, and the lack of significant metallicity and kinematic gradients in the thick disk obscur the genetic relationship between these two Galactic components.

A Two-Component Model?

However, a new unifying model has been proposed by Wyse and Gilmore (*57*). They demonstrate that a clear distinction between Galactic components can only be found from the distributions of specific angular momentum. These come out as two distinct pairs of nearly indistinguishable distributions: a low-angular momentum pair comprising the metal-poor halo and the metal-rich bulge, and a high-angular momentum pair, which com-

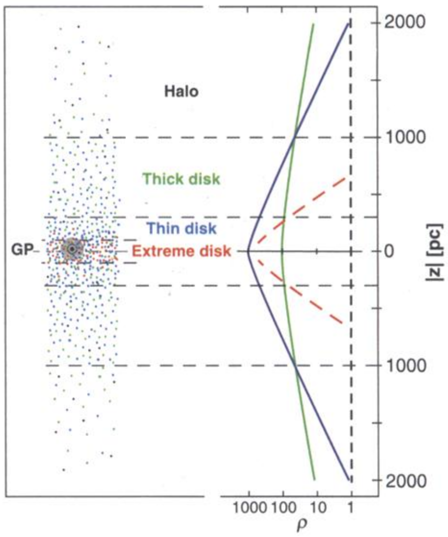

Fig. 5. Closeup view of the Galaxy's disk and halo structure perpendicular to the Galactic plane (GP) near the solar neighborhood (shaded circle centered on ⊙). Relative space densities, ρ, of the stars belonging to the different components are shown schematically (left) and analytically (right) as exponential functions of vertical distance, z: $\rho(z) = \rho(0) \cdot e^{-z/h_z}$. Horizontal dashed lines indicate the exponential scale heights of the thin disk ($h_{z,D}$ = 300 pc) and the thick disk ($h_{z,T}$ = 1000 pc), where the densities have decreased to a fraction $1/e \approx 0.37$ of their maximum values at z = 0. In the solar neighborhood, for 1000 thin-disk stars there are about 100 thick-disk stars and only about 1 halo star, while at a height |z| 1000 pc, the numbers of thin-disk and thick-disk stars per unit volume are practically the same. At even larger distances, the thick-disk stars dominate far into the halo.

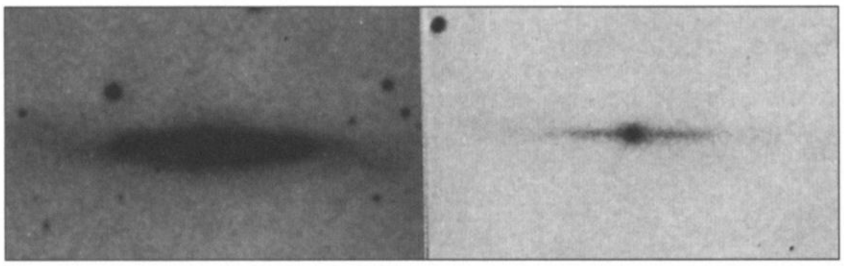

Fig. 4. NGC 4762 is one of the galaxies where a (faint) thick-disk component (left) of luminous stars was first identified on a long-exposure photograph. The short exposure on the right shows the (inner) thin disk and the (small) bulge (*35*).

prises the thick disk and the thin disk. In the Galaxy, these genetic relationships may have driven the evolution along two essentially independent but parallel paths: low angular momentum material formed the stellar halo, with chemically enriched debris contracting into the Galactic bulge—consistent with the evolutionary sequence outlined by Eggen, Lynden-Bell, and Sandage (*19*). Material with high angular momentum evolved independently into the disk, which either formed thick, with remaining gas later settling into a thin disk; or formed as a thin disk, which was later thickened by the last major Galactic merger, perhaps 10 Gy ago. After their formation and early evolution, these two pairs of related Galactic components have been confused but were not obliterated by continuing mergers and accretion of smaller satellites.

References and Notes

1. A recent review of the Local Group is given by S. van den Bergh [*Astron. Astrophys. Rev.* **9**, 273 (1999)].
2. The common length unit used in astronomy is the parsec (pc), derived from the (unit) parallactic second of arc angle subtended by the semimajor axis, *a*, of Earth's orbit (around the sun), as seen from a distance of 1 pc. Because $a = 1.496 \times 10^{13}$ cm, it follows that 1 pc = 3.086×10^{13} km = 3.2615 light years; 1 kpc = 10^3 pc.
3. R. A. Ibata, G. Gilmore, M. J. Irwin, *Nature* **370**, 194 (1994).
4. Here, we consider only those components of the Galaxy, which consist of luminous stars formed from gas and dust of ordinary matter. The dark matter component is discussed in other papers in this issue (*11*); J. Bland-Hawthorn and K. Freeman, *Science* **287**, 79 (2000); F. Yusef-Zadeh, F. Melia, M. Wardle, *Science* **287**, 85 (2000)].
5. Globular clusters are spherical systems of 10^5 to 10^6 stars held together by their own gravity. The Galaxy's globular clusters are all old—older than $\sim 10 \times 10^9$ years, or 10 Gy—whereas some other galaxies have been observed, which have relatively younger globular clusters. For a recent review, see D. Bulgarella [*Science* **276**, 1370 (1997)].
6. Open clusters are much less massive ($M < \sim 10^3 M_\odot$) than globular clusters. Accordingly, they are less centrally concentrated but cover a wide range between loosely and densely packed. Because they are preferentially found in and near the Galactic disk, they are also called Galactic clusters.
7. The geometric figures assigned to the Galaxy's components—bar-like bulge, flat disks, and spheroidal halo—can be and also have been inspired by our outsider view of extragalactic systems, some of which we happen to see from the same edge-on perspective as we have of the Milky Way from our insider's vantage point close to the mid-plane of the Galactic disk, about 8.5 kpc from the Galactic center. However, in contrast to an external galaxy whose morphology may be immediately recognized on a single photograph imaging a small solid angle in the sky, a quantitative description of the Galaxy's large-scale morphological structure obviously requires the more indirect and difficult approach of combining many partial surveys of its individual components, distributed over the full sky.
8. See also F. D. A. Hartwick [in *Unsolved Problems of the Milky Way*, L. Blitz and P. Teuben, Eds. IAU Symp. 169 (Kluwer, Dordrecht, Netherlands, 1996), p. 669] for a concise description of the Milky Way's position and extent in the hierarchical structure of the local universe.
9. The distance of a star is most commonly derived from comparison of its apparent and intrinsic (or absolute) magnitudes, which are logarithmic measures of the corresponding brightnesses of the star. Each step of 1 mag corresponds to about 2.5 times fainter; the naked eye can see stars down to apparent magnitude $m = 6$ mag, while the Hubble Space Telescope may reach stars as faint as $m \approx 30$ mag. The apparent magnitude is directly measured at the telescope; however, the absolute magnitude must be inferred from additional color, spectral, or other observational data. By consistently tying calibration relations for increasingly luminous objects—for example, from cluster main-sequence stars and RR Lyrae and Cepheid variables through supernovae—a coherent distance scale has been established beyond the Milky Way, into the farther reaches of extragalactic space. The fundamental calibration of stellar luminosities is provided by the nearby stars whose distances can be determined by direct triangulation employing Earth's orbit as a baseline. The distances of nearby stars within less than ~100 pc have recently been remeasured to an unprecedented high accuracy by the HIPPARCOS satellite [B. Battrick, Ed., HIPPARCOS Venice '97, ESA Spec. Publ. No. 402, Noordwijk NL: ESA Publ. Div. ESTEC, 52+862pp. (1997)]. Although results first appeared to indicate that current theoretical understanding of stellar luminosities in clusters was more seriously incomplete than had been known [cf. J. Kovalevsky, *Annu. Rev. Astron. Astrophys.* **36**, 99 (1998) and references therein], more detailed analyses have dispelled much of these concerns [for example, D. Egret and A. Heck, Eds., *Harmonizing Cosmic Distance Scales in a Post-Hipparcos Era*, Astron. Soc. Pacific Conf. Series, vol. 167 (1999)]. Thus, we may still say that cluster distances, derived from observations of a large number of member stars in each cluster, are among the most reliable and accurate distances that can be determined at all [see also (*15*)].
10. Two components of a star's velocity can be directly obtained from observations: the radial velocity—along the line of sight—is determined (in kilometers per second) by measuring the Doppler shifts of atomic lines in the stellar spectra, while the tangential velocity—perpendicular to the line of sight—is derived (in kilometers per second) by combining the star's distance with its annual angular displacement, or proper motion, on the sky [measured in arcseconds per year from photographic or CCD (charge-coupled device) surveys taken at different epochs]. In general, determination of a third velocity component and, hence, of the full space velocity vector, requires calculations based on an assumed gravitational potential of the Galaxy. Note that for many purposes, available velocity data of only one kind—either radial velocities or proper motions—may suffice.
11. C. Alcock, *Science* **287**, 74 (2000).
12. A comprehensive recent account of current work on all aspects of star formation, stellar evolution, and the final stages in stellar lives appeared in the special issue on Stellar Birth and Death, *Science* **276** (30 May 1997), pp. 1350–1391.
13. Astronomers use the term metals as a short name for all chemical elements heavier than H and He. For a given star (*), individual elemental abundances X_i are usually expressed relative to the abundance of H and on a logarithmic scale (with units 1 dex = 10^1 = 10) normalized to the corresponding values for the sun: $[X_i/H] = \log (X_i/H)_* - \log (X_i/H) M_\odot$. Thus, [Fe/H] = 0 means that the star's Fe abundance is 0 dex = 10^0 = 1 times the sun's (that is, the same as the sun's), while [Fe/H] = −1 means that the star's Fe abundance is only 1/10th of the solar value. On the other hand, [O/Fe] = 0 means that the ratios of the O to Fe abundances in the star and in the sun are the same, while [O/Fe] = +0.3 means that relative to the Fe abundance, the star has a factor of two more O than has the sun. In the early days of spectroscopic abundance work, individual elemental abundances could only be determined with much lower accuracy than today. Their intrinsic variations remained largely hidden in the noise of the observations, such that all abundance ratios $[X_i/Fe]$ in stars were seen to have values ≈ 0 throughout the observed Fe-abundance range (that is, for $+1 > [Fe/H] \gtrsim -3$) and all metal-abundance differences between stars could be described as varying in lockstep with the Fe abundance difference: stars exhibit a cosmic abundance distribution, and [Fe/H] can be commonly used as a representative measure of stellar metallicity, [M/H]. Typically, [M/H] = [Fe/H] = 0 for a metal-rich star and [M/H] = [Fe/H] = −2 for a metal-poor star. As abundance determinations became more accurate, because of improved instruments and measuring techniques developed since about 1970, observed variations of elemental abundances in stars were soon understood as sensitive diagnostics of stellar-interior nuclear processes and mixing of products into the atmospheres during the different evolutionary stages. For recent reviews, see A. McWilliam, *Annu. Rev. Astron. Astrophys.* **35**, 503 (1997); D. Arnett and G. Bazan, *Science* **276**, 1359 (1997).
14. One of the great advantages of metallicity as a collective measure of elemental abundances in stars is that it can also be obtained from broad-band photometric, rather than detailed higher-resolution spectroscopic, observations of stellar colors, such as ultraviolet-blue (U-B) or ultraviolet-green (U-G), which measure the slope of the stellar spectrum in the near-ultraviolet to visual wavelength range. For cooler stars of type F-K with temperatures ~7000 K $\geq T_{eff} \geq$ ~4000 K, which make up the bulk of Galactic field stars, this slope is very sensitive to metallicity, due to crowding of Fe-peak absorption lines in the U-bands [for example, R. Buser and R. L. Kurucz, *Astron. Astrophys.* **264**, 557 (1992)]. Even though photometry-based metallicities are less accurate than spectroscopic abundances, they can be accumulated relatively easily for large samples of faint stars, providing indispensable complementary data of high statistical weight from large-scale field surveys of the Galactic components.
15. The most commonly used color-magnitude observations combine the visual apparent V magnitude with the blue-minus-visual (B-V) color. In the corresponding observed V versus B-V color-magnitude diagram (CMD), the stars of a cluster are arranged according to their absolute magnitudes, M_V, which are measures of stellar intrinsic luminosity, log*L*, because all cluster stars are dimmed by the same effect, due to their same distance from the observer, such that $V = M_V + const.$, where $const. = 5 \log r - 5$ and *r* is the distance in pc. Thus, since the B-V color is a measure of stellar effective temperature T_{eff}, the cluster CMD is equivalent to the theoretical Hertzsprung-Russell diagram, (log*L*, T_{eff}), the fundamental diagram of astrophysics.
16. The most direct way to derive the age of a cluster is by fitting the so-called turnoff (TO) luminosity and color (where cluster stars are turning away from the main-sequence due to exhaustion of core hydrogen and ensuing evolution to the red-giant stage) in the observed CMD with a grid of theoretical isochrones (that is, same-age loci) calculated for model stars of appropriate metallicity and for a representative age range. There are a number of other morphological features in the cluster CMDs, which are suitable for age determinations, such as the horizontal branch (HB) or the luminosity difference between the HB and the TO [for a recent review of the most promising methods, see A. Sarajedini, B. Chaboyer, P. Demarque, *Publ. Astron. Soc. Pacific* **109**, 1321 (1997)], but in principle, all stellar evolutionary stages sampled in the observed CMD of a given cluster should be consistent, to within the accuracy of the data, with the same theoretical isochrone. Although currently available theoretical models cannot yet account for the full morphological variety and details exhibited in cluster CMDs, and although uncertainties in individual derived absolute cluster ages are accordingly large (~3 to 5 Gy), relative ages obtained from differential studies of cluster samples are among the most accurate (~±2 Gy) presently available. An authoritative review of the current state of the art recently appeared [D. A. VandenBerg, M. Bolte, P. B. Stetson, *Annu. Rev. Astron. Astrophys.* **34**, 461 (1996)].
17. The famous Vatican Conference in 1957 was devoted to Stellar Populations [J. O'Connell, Ed., *Stellar Populations*, Specola Astronomica Vaticana, vol. 5 (1958)], a concept of integrating the properties and relationships among the different stellar components in galaxies, which was introduced by the far-sighted Walter Baade, following his account [*Astrophys. J.* **100**, 137 (1944)] of the CMD of stars that he had been able to resolve, for the first time ever, in the Andromeda nebula. The concept of stellar populations was to become seminal in all subsequent ga-

lactic astronomy, until the present epoch. See also A. Blaauw and M. Schmidt, Eds., *Galactic Structure* (Univ. of Chicago Press, Chicago, 1965), in particular, the article entitled *The Concept of Stellar Populations* by A. Blaauw, p. 435. Although Blaauw's account has been expanded and some of its details have been superseded by now, its basic message on the contents and structure of the large-scale galaxy has proven surprisingly robust.
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REVIEW

The Dark Halo of the Milky Way

Charles Alcock

Most of the matter in the Milky Way is invisible to astronomers. Precise numbers are elusive, but it appears that the dark component is 20 times as massive as the visible disk of stars and gas. This dark matter is distributed in space differently than the stars, forming a vast, diffuse halo, more spherical than disklike, which occupies more than 1000 times the volume of the disk of stars. The composition of this dark halo is unknown, but it may comprise a mixture of ancient, degenerate dwarf stars and exotic, hypothetical elementary particles.

The Milky Way galaxy is visually very striking (*1*). The spectacular rotating disk of stars and gas is a familiar feature of the night sky. The large central bulge is a spectacular sight from the Southern Hemisphere in the southern winter. The Milky Way must be a stunning apparition from the viewpoint of astronomers in the Andromeda galaxy, our nearest large neighbor, just as we have long admired the Andromeda galaxy.

Astronomers have discovered that, in addition to the visible structures, there is an invisible halo of material that envelopes galaxies like the Milky Way (*2*). The dark halo of the Milky Way is much more difficult to investigate than the stars and gas, for the obvious reason that it seems inaccessible to direct observation. Astronomers have discerned, nevertheless, that this dark halo is larger, more massive, and differently shaped than this disk of stars and gas (*3*).

We know little about the physical composition of the dark halo, and this is surely one of the most important unresolved issues confronting astrophysics and cosmology at the turn of this century. Summed over all of the galaxies in the universe, the dark material contained in the halos of galaxies is at least 20 times as massive as the visible material.

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