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THE NEW GALAXY: Signatures of Its Formation

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■ **Abstract** The formation and evolution of galaxies is one of the great outstanding problems of astrophysics. Within the broad context of hierachical structure formation, we have only a crude picture of how galaxies like our own came into existence. A detailed physical picture where individual stellar populations can be associated with (tagged to) elements of the protocloud is far beyond our current understanding. Important clues have begun to emerge from both the Galaxy (near-field cosmology) and the high redshift universe (far-field cosmology). Here we focus on the fossil evidence provided by the Galaxy. Detailed studies of the Galaxy lie at the core of understanding the complex processes involved in baryon dissipation. This is a necessary first step toward achieving a successful theory of galaxy formation.

PROLOGUE

The New Galaxy

Weinberg (1977) observed that "the theory of the formation of galaxies is one of the great outstanding problems of astrophysics, a problem that today seems far from solution." Although the past two decades have seen considerable progress, Weinberg's assessment remains largely true.

Eggen, Lynden-Bell and Sandage (1962; ELS) were the first to show that it is possible to study galactic archaeology using stellar abundances and stellar dynamics; this is probably the most influential paper on the subject of galaxy formation. ELS studied the motions of high velocity stars and discovered that, as the metal abundance decreases, the orbit energies and eccentricities of the stars increased while their orbital angular momenta decreased. They inferred that the metal-poor stars reside in a halo that was created during the rapid collapse of a relatively uniform, isolated protogalactic cloud shortly after it decoupled from the universal expansion. ELS are widely viewed as advocating a smooth monolithic collapse of the protocloud with a timescale of order 10^8 years. But Sandage (1990) stresses that this is an over-interpretation; a smooth collapse was not one of the inferences they drew from the stellar kinematics.

In 1977, the ELS picture was challenged by Searle (see also Searle & Zinn 1978) who noted that Galactic globular clusters have a wide range of metal abundances essentially independent of radius from the Galactic Center. They suggested that this could be explained by a halo built up over an extended period from *independent* fragments with masses of $\sim 10^8\ M_\odot$. In contrast, in the ELS picture, the halo formed in a rapid free-fall collapse. But halo field stars, as well as globular clusters, are now believed to show an age spread of 2–3 Ga (Marquez & Schuster 1994); for an alternative view, see Sandage & Cacciari (1990). The current paradigm, that the observations argue for a halo that has built up over a long period from infalling debris, has developed after many years of intense debate.

This debate parallelled the changes that were taking place in theoretical studies of cosmology (e.g., Peebles 1971, Press & Schechter 1974). The ideas of galaxy formation via hierarchical aggregation of smaller elements from the early universe fit in readily with the Searle & Zinn view of the formation of the galactic halo from small fragments. The possibility of identifying debris from these small fragments was already around in Eggen's early studies of moving groups, and this is now an active field of research in theoretical and observational stellar dynamics. It offers the possibility to reconstruct at least some properties of the protogalaxy and so to improve our basic understanding of the galaxy formation process.

We can extend this approach to other components of the Galaxy. We will argue the importance of understanding the formation of the galactic disk, because this is where most of the baryons reside. Although much of the information about the properties of the protogalactic baryons has been lost in the dissipation that led to the galactic disk, a similar dynamical probing of the early properties of the disk can illuminate the formation of the disk, at least back to the epoch of last significant dissipation. It is also clear that we do not need to restrict this probing to stellar dynamical techniques. A vast amount of fossil information is locked up in the detailed stellar distribution of chemical elements in the various components of the Galaxy, and we will discuss the opportunities that this offers.

We are coming into a new era of galactic investigation, in which one can study the fossil remnants of the early days of the Galaxy in a broader and more focussed way, not only in the halo but throughout the major luminous components of the Galaxy. This is what we mean by *The New Galaxy*. The goal of these studies is to reconstruct as much as possible of the early galactic history. We review what has been achieved so far, and point to the future.

Near-Field and Far-Field Cosmology

What do we mean by the reconstruction of early galactic history? We seek a detailed physical understanding of the sequence of events which led to the Milky Way. Ideally, we would want to tag (i.e., associate) components of the Galaxy to elements of the protocloud—the baryon reservoir which fueled the stars in the Galaxy.

From theory, our prevailing view of structure formation relies on a hierarchical process driven by the gravitational forces of the large-scale distribution of cold, dark matter (CDM). The CDM paradigm provides simple models of galaxy formation within a cosmological context (Peebles 1974, White & Rees 1978, Blumenthal et al. 1984). N-body and semi-analytic simulations of the growth of structures in the early universe have been successful at reproducing some of the properties of galaxies. Current models include gas pressure, metal production, radiative cooling and heating, and prescriptions for star formation.

The number density, properties and spatial distribution of dark matter halos are well understood within CDM (Sheth & Tormen 1999, Jenkins et al. 2001). However, computer codes are far from producing realistic simulations of how baryons produce observable galaxies within a complex hierarchy of dark matter. This a necessary first step towards a viable theory or a working model of galaxy formation.

In this review, our approach is anchored to observations of the Galaxy, interpreted within the broad scope of the CDM hierarchy. Many of the observables in the Galaxy relate to events which occurred long ago, at high redshift. Figure 1 shows the relationship between look-back time and redshift in the context of the ΛCDM model: The redshift range ($z \lesssim 6$) of discrete sources in contemporary observational cosmology matches closely the known ages of the oldest components in the Galaxy. The Galaxy (near-field cosmology) provides a link to the distant universe (far-field cosmology).

Before we embark on a detailed overview of the relevant data, we give a descriptive working picture of the sequence of events involved in galaxy formation. For continuity, the relevant references are given in the main body of the review where these issues are discussed in more detail.

A Working Model of Galaxy Formation

Shortly after the Big Bang, cold dark matter began to drive baryons towards local density enhancements. The first stars formed after the collapse of the first primordial molecular clouds; these stars produced the epoch of reionization. The earliest recognizable protocloud may have begun to assemble at about this time.

Within the context of CDM, the dark halo of the Galaxy assembled first, although it is likely that its growth continues to the present time. In some galaxies, the first episodes of gas accretion established the stellar bulge, the central black hole, the first halo stars and the globular clusters. In the Galaxy and similar systems, the small stellar bulge may have formed later from stars in the inner disk.

The early stages of the Galaxy's evolution were marked by violent gas dynamics and accretion events, leading to the high internal densities of the first globular clusters, and perhaps to the well-known black hole mass–stellar bulge dispersion relation. The stellar bulge and massive black hole may have grown up together during this active time. We associate this era with the Golden Age, the phase before $z \sim 1$ when star formation activity and accretion disk activity were at their peak.

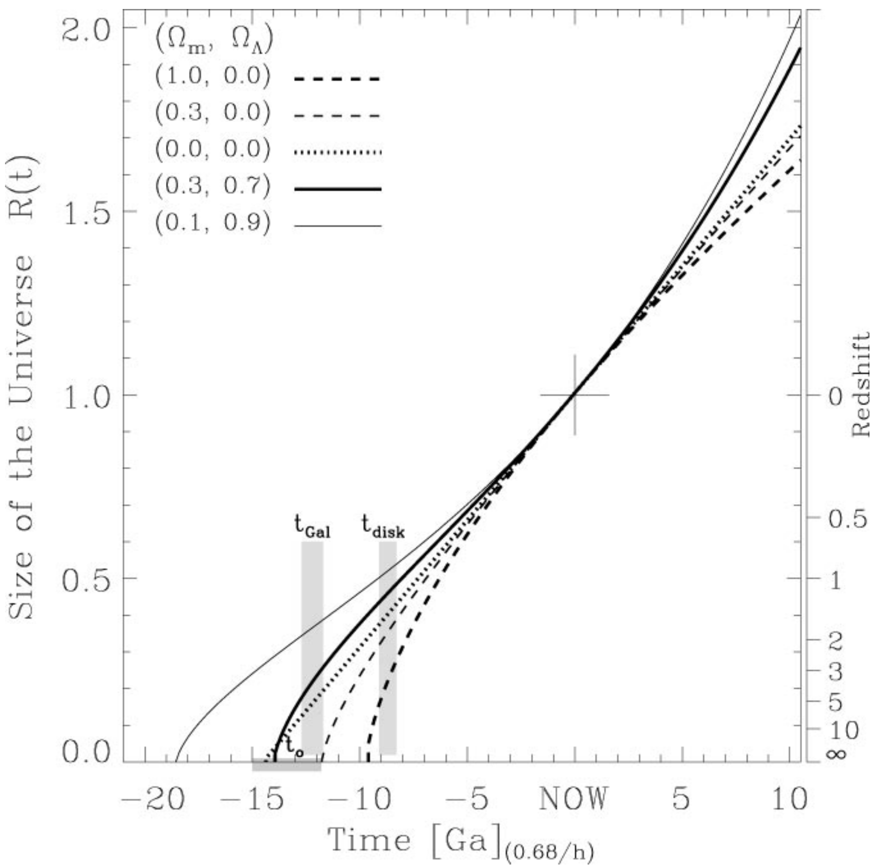


Figure 1 Look-back time as a function of redshift and the size of the Universe (Lineweaver 1999) for five different world models. The approximate ages of the Galactic halo and disk are indicated by hatched regions.

At that time, there was a strong metal gradient from the bulge to the outer halo. The metal enrichment was rapid in the core of the Galaxy such that, by $z \sim 1$, the mean metallicities were as high as [Fe/H] ~ -1 or even higher. In these terms, we can understand why the inner stellar bulge that we observe today is both old and moderately metal rich. The first halo stars ([Fe/H] ≈ -5 to -2.5) formed over a more extended volume and presumably date back to the earliest phase of the protocloud. The first globular clusters formed over a similar volume from violent gas interactions ([Fe/H] ≈ -2.5 to -1.5). We believe now that many of the halo stars and globulars are remnants of early satellite galaxies which experienced independent chemical evolution before being accreted by the Galaxy.

The spread in [Fe/H], and the relative distribution of the chemical elements, is a major diagnostic of the evolution of each galactic component. If the initial mass function is constant, the mean abundances of the different components give a rough indication of the number of SN II enrichments which preceded their formation, although we note that as time passes, an increasing fraction of Fe is produced by SN Ia events. For a given parcel of gas in a closed system, only a few SN II events are required to reach [Fe/H] ≈ -3, 30 to 100 events to get to [Fe/H] ≈ -1.5, and maybe a thousand events to reach solar metallicities. We wish to stress that [Fe/H] is not a clock: Rather it is a measure of supernova occurrences and the depth of the different potential wells that a given parcel of gas has explored.

During the latter stages of the Golden Age, most of the baryons began to settle to a disk for the first time. Two key observations emphasize what we consider to be the mystery of the main epoch of baryon dissipation. First, there are no stars with [Fe/H] < -2.2 that rotate with the disk. Second, despite all the activity associated with the Golden Age, at least 80% of the baryons appear to have settled gradually to the disk over many Ga; this fraction could be as high as 95% if the bulge formed after the disk.

About 10% of the baryons reside in a thick disk which has [Fe/H] ≈ -2.2 to -0.5, compared to the younger thin disk with [Fe/H] ≈ -0.5 to $+0.3$. It is striking how the globular clusters and the thick disk have similar abundance ranges, although the detailed abundance distributions are different. There is also a similarity in age: Globular clusters show an age range of 12 to 14 Ga, and the thick disk appears to be at least 12 Ga old. Both the thick disk and globulars apparently date back to the epoch of baryon dissipation during $z \sim 1-5$.

Figure 2 summarizes our present understanding of the complex age-metallicity distribution for the various components of the Galaxy.

It is a mystery that the thick disk and the globulars should have formed so early and over such a large volume from material that was already enriched to [Fe/H] ~ -2. Could powerful winds from the central starburst in the evolving core have distributed metals throughout the inner protocloud at about that time?

Finally, we emphasize again that 90% of the disk baryons have settled quiescently to the thin disk since $z \sim 1$.

Timescales and Fossils

The oldest stars in our Galaxy are of an age similar to the look-back time of the most distant galaxies in the Hubble Deep Field (Figure 1). For the galaxies, the cosmological redshift measured from galaxy spectra presently takes us to within 5% of the origin of cosmic time. For the stars, their upper atmospheres provide fossil evidence of the available metals at the time of formation. The old Galactic stars and the distant galaxies provide a record of conditions at early times in cosmic history, and both harbor clues to the sequence of events that led to the formation of galaxies like the Milky Way.

The key timescale provided by far-field cosmology is the look-back time with the prospect of seeing galaxies at an earlier stage in their evolution. However, this does not imply that these high-redshift objects are unevolved. We know that the stellar cores of galaxies at the highest redshifts ($z \sim 5$) observed to date exhibit solar metallicities, and therefore appear to have undergone many cycles of star formation (Hamann & Ferland 1999). Much of the light we detect from the early universe probably arises from the chemically and dynamically evolved cores of galaxies.

Near-field cosmology provides a dynamical timescale, $\tau_D \sim (G\rho)^{-\frac{1}{2}}$, where ρ is the mean density of the medium. The dynamical timescale at a radial distance of 100 kpc is of order several Ga, so the mixing times are very long. Therefore, on larger scales, we can expect to find dynamical and chemical traces of past events, even where small dynamical systems have long since merged with the Galaxy.

We note that the CDM hierarchy reflects a wide range of dynamical timescales, such that different parts of the hierarchy may reveal galaxies in different stages of evolution. In this sense, the hierarchy relates the large-scale density to the morphology and evolution of its individual galaxies; this is the so-called morphology-density relation (Dressler 1980, Hermit et al. 1996, Norberg et al. 2001). Over a large enough ensemble of galaxies, taken from different regions of the hierarchy, we expect different light-weighted age distributions because one part of the hierarchy is more evolved than another. In other words, the evolution of small-scale structure (individual galaxies) must at some level relate to the environment on scales of 10 Mpc or more.

The near field also provides important evolutionary timescales for individual stars and groups of stars (see "Stellar Age Dating" below). Individual stars can be dated with astero-seismology (Christensen-Dalsgaard 1986, Gough 2001) and nucleo-cosmochronology (Fowler & Hoyle 1960, Cowan et al. 1997). Strictly speaking, nucleo-cosmochronology dates the elements rather than the stars. Coeval groups of stars can be aged from the main-sequence turn-off or from the He-burning stars in older populations (Chaboyer 1998). Furthermore, the faint end cut-off of the white dwarf luminosity function provides an important age constraint for older populations (Oswalt et al. 1996). Presently, the aging methods are model dependent.

Goals of Near-Field Cosmology

We believe that the major goal of near-field cosmology is to tag individual stars with elements of the protocloud. Some integrals of motion are likely to be preserved while others are scrambled by dissipation and violent relaxation. We suspect that complete tagging is impossible. However, some stars today may have some integrals of motion that relate to the protocloud at the epoch of last dissipation (see "Zero Order Signatures—Information Preserved Since Dark Matter Virialized" below).

As we review, different parts of the Galaxy have experienced dissipation and phase mixing to varying degrees. The disk, in contrast to the stellar halo, is a highly dissipated structure. The bulge may be only partly dissipated. To what extent can we unravel the events that produced the Galaxy as we see it today? Could some of the residual inhomogeneities from prehistory have escaped the dissipative process at an early stage?

Far-field cosmology currently takes us back to the epoch of last scattering as seen in the microwave background. Cosmologists would like to think that some vestige of information has survived from earlier times (compare Peebles et al. 2000). In the same spirit, we can hope that fossils remain from the epoch of last dissipation, i.e., the main epoch of baryon dissipation that occurred as the disk was being assembled.

To make a comprehensive inventory of surviving inhomogeneities would require a vast catalog of stellar properties that is presently out of reach (Bland-Hawthorn 2002). The Gaia space astrometry mission (Perryman et al. 2001), set to launch at the end of the decade, will acquire detailed phase space coordinates for about one billion stars, within a sphere of diameter 20 kpc (the Gaiasphere). In "The Gaiasphere and The Limits of Knowledge" below, we look forward to a time when all stars within the Gaiasphere have complete chemical abundance measurements (including all heavy metals). Even with such a vast increase in information, there may exist fundamental—but unproven—limits to unravelling the observed complexity.

The huge increase in data rates from ground-based and space-based observatories has led to an explosion of information. Much of this information from the near field is often dismissed as weather or unimportant detail. But in fact fundamental clues are already beginning to emerge. In what is now a famous discovery, a large photometric and kinematic survey of bulge stars revealed the presence of the disrupting Sgr dwarf galaxy (Ibata et al. 1994), now seen over a large region of sky and in a variety of populations (see "Structures in Phase Space" below). Perhaps the most important example arises from the chemical signatures seen in echelle spectroscopy of bulge, thick disk and halo stars. In "Epilogue: Challenges for the Future," we envisage a time when the analysis of thousands of spectral lines for a vast number of stars will reveal crucial insights into the sequence of events early in the formation of the Galaxy.

In this review, we discuss fossil signatures in the Galaxy. A key aspect of fossil studies is a reliable time sequence. In "Stellar Age Dating," we discuss methods for age-dating individual stars and coeval groups of stars. In "Structure of the Galaxy," we describe the main components of the Galaxy. In "Signatures of Galaxy Formation," we divide the fossil signatures of galaxy formation into three parts: zero order signatures that preserve information since dark matter virialized; first order signatures that preserve information since the main epoch of baryon dissipation; and second order signatures that arise from major processes involved in subsequent evolution. In "The Gaiasphere and The Limits of Knowledge," we look forward to a time when it is possible to measure ages, phase space coordinates and chemical properties for a vast number of stars in the Galaxy. Even then, what are the prospects for unravelling the sequence of events that gave rise to the Milky Way? We conclude with some experimental challenges for the future.

STELLAR AGE DATING

Nucleo-cosmochronology (or cosmochronometry), or the aging of the elements through radioactive decay, has a long history (Rutherford 1904, Fowler & Hoyle 1960, Butcher 1987). A related technique is widely used in solar system geophysics. Independent schemes have aged the oldest meteorites at 4.53 ± 0.04 Ga (Guenther & Demarque 1997, Manuel 2000). The small uncertainties reflect that the age dating is direct. Element pairs like Rb and Sr are chemically distinct and freeze out during solidification into different crystalline grains. The isotope ^{87}Rb decays into ^{87}Sr, which can be compared to ^{86}Sr, a nonradiogenic isotope, measured from a control sample of Sr-rich grains. This provides a direct measure of the fraction of a ^{87}Rb half-life ($\tau_{1/2} = 47.5$ Ga) since the meteorite solidified.

It appears that, until we have a precise understanding of BBNS and the early chemical evolution history of the Galaxy, geophysical precision will not be possible for stellar ages. The major problem is that, as far as we know, there is no chemical differentiation that requires that we know precisely how much of each isotope was originally present. Modern nucleo-cosmochronology compares radioactive isotope strengths to a stable r-process element (e.g. Nd, Eu, La, Pt). The thorium method (^{232}Th, $\tau_{1/2} = 14.0$ Ga) was first applied by Butcher (1987) and refined by Pagel (1989). Other radioactive chronometers include ^{235}U ($\tau_{1/2} = 0.70$ Ga) and ^{238}U ($\tau_{1/2} = 4.47$ Ga), although Yokoi et al. (1983) have expressed concerns about their use (compare Cayrel et al. 2001). Arnould & Goriely (2001) propose that the isotope pair ^{187}Re$-^{187}$Os ($\tau_{1/2} = 43.5$ Ga) may be better suited for future work.

With the above caveats, we point out that several groups are now obtaining exquisite high-resolution data on stars with enhanced r-process elements (Cayrel et al. 2001, Sneden et al. 2000, Burris et al. 2000, Westin et al. 2000, Johnson & Bolte 2001, Cohen et al. 2002, Hill et al. 2002). For a subset of these stars, radioactive ages have been derived (Truran et al. 2001) normalized to the heavy element abundances observed in meteorites.

There are few other direct methods for deriving ages of individual stars. A promising field is astero-seismology that relies on the evolving mean molecular weight in stellar cores (Christensen-Dalsgaard 1986, Ulrich 1986, Gough 1987, Guenther 1989). Gough (2001) has determined 4.57 ± 0.12 Ga for the Sun, which should be compared with the age of meteorites quoted above. The Eddington satellite under consideration by ESA for launch at the end of the decade proposes to use stellar oscillations to age 50,000 main sequence stars (Gimenez & Favata 2001).

It has long been known that disk stars span a wide range of ages from the diversity of main-sequence stars. Edvardsson et al. (1993) derived precise stellar evolution ages for nearby individual post-main-sequence F stars using Strömgren photometry, and showed that the stars in the Galactic disk exhibit a large age spread with ages up to roughly 10 Ga (Figure 2). Using the inverse age-luminosity relation for RR Lyrae stars, Chaboyer et al. (1996) found that the oldest globular clusters are older than 12 Ga with 95% confidence, with a best estimate of 14.6 ± 1.7 Ga (Chaboyer 1998). But Hipparcos appears to show that the RR Lyr distances are underestimated leading to a downward revision of the cluster ages: 8.5–13.3 Ga (Gratton et al. 1997); 11–13 Ga (Reid 1998); 10.2–12.8 Ga (Chaboyer et al. 1998). For a coeval population (e.g. open and globular clusters), isochrone fitting is widely used. The ages of the galactic halo and globular clusters, when averaged over eight independent surveys, lead to 12.2 ± 0.5 Ga (Lineweaver 1999).

Other traditional methods rely on aging a population of stars that are representative of a particular component of the Galaxy. For example, Gilmore et al. (1989) use the envelope of the distribution in a color-abundance plane to show that all stars more metal poor than [Fe/H] $= -0.8$ are as old as the globular clusters. Similarly, the faint end of the white dwarf luminosity function is associated with the coolest, and therefore the oldest, stars (Oswalt et al. 1996). The present estimate for the age of the old thin disk population when averaged over five independent surveys is 8.7 ± 0.4 Ga (Lineweaver 1999), although Oswalt et al. argue for $9.5^{+1.1}_{-0.8}$ Ga.

For a world model with ($\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$), the Big Bang occurred 14 Ga ago (Efstathiou et al. 2002)—in our view, there is no compelling evidence for an age crisis from a comparison of estimates in the near and far field. But the inaccuracy of age dating relative to an absolute scale does cause problems. At present, the absolute ages of the oldest stars cannot be tied down to better than about 2 Ga, the time elapsed between $z = 6$ and $z = 2$. This is a particular handicap to identifying specific events in the early Universe from the stellar record.

STRUCTURE OF THE GALAXY

Like most spiral galaxies, our Galaxy has several recognizable structural components that probably appeared at different stages in the galaxy formation process. These components will retain different kinds of signatures of their formation. We will describe these components in the context of other disk galaxies, and use images of other galaxies in Figure 3 to illustrate the components.

The Bulge

First, compare images of M104 and IC 5249 (Figures 3*c*,*g*): These are extreme examples of galaxies with a large bulge and with no bulge. Large bulges like that of M104 are structurally and chemically rather similar to elliptical galaxies: Their surface brightness distribution follows an $r^{1/4}$ law (e.g., Pritchet & van den Bergh 1994) and they show similar relations of [Fe/H] and [Mg/Fe] with absolute magnitude (e.g., Jablonka et al. 1996). These properties lead to the view that the large bulges formed rapidly. The smaller bulges are often boxy in shape, with a more exponential surface brightness distribution (e.g., Courteau et al. 1996). The current belief is that they may have arisen from the stellar disk through bending mode instabilities.

Spiral bulges are usually assumed to be old, but this is poorly known, even for the Galaxy. The presence of bulge RR Lyrae stars indicates that at least some fraction of the galactic bulge is old (Rich 2001). Furthermore, the color-magnitude diagrams for galactic bulge stars show that the bulge is predominantly old. McWilliam & Rich (1994) measured [Fe/H] abundances for red giant stars in the bulge of the Milky Way. They found that, while there is a wide spread, the abundances ([Fe/H] ≈ -0.25) are closer to the older stars of the metal rich disk than to the very old metal poor stars in the halo and in globular clusters, in agreement with the abundances of planetary nebulae in the Galactic bulge (e.g., Exter et al. 2001).

The COBE image of the Milky Way (Figure 3*b*) shows a modest somewhat boxy bulge, typical of an Sb to Sc spiral. Figure 3*d* shows a more extreme example of a boxy/peanut bulge. If such bulges do arise via instabilities of the stellar disk, then much of the information that we seek about the state of the early galaxy would have been lost in the processes of disk formation and subsequent bulge formation. Although most of the more luminous disk galaxies have bulges, many of the fainter disk galaxies do not. Bulge formation is not an essential element of the formation processes of disk galaxies.

The Disk

Now look at the disks of these galaxies. The exponential thin disk, with a vertical scale height of about 300 pc, is the most conspicuous component in edge-on disk galaxies like NGC 4762 and IC 5249 (Figures 3*e*,*g*). The thin disk is believed to be the end product of the quiescent dissipation of most of the baryons and contains almost all of the baryonic angular momentum. For the galactic disk, which is clearly seen in the COBE image in Figure 3*b*, we know from radioactive dating, white dwarf cooling and isochrone estimates for individual evolved stars and open clusters that the oldest disk stars have ages in the range 10 to 12 Ga (see "Stellar Age Dating" above).

The disk is the defining stellar component of disk galaxies, and understanding its formation is in our view the most important goal of galaxy formation theory. Although much of the information about the pre-disk state of the baryons has been lost in the dissipative process, some tracers remain, and we will discuss them in the next section.

Many disk galaxies show a second fainter disk component with a larger scale height (typically about 1 kpc); this is known as the thick disk. Deep surface photometry of IC 5249 shows only a very faint thick disk enveloping the bright thin disk (Abe et al. 1999): Compare Figures 3*g*,*h*. In the edge-on S0 galaxy NGC 4762, we see a much brighter thick disk around its very bright thin disk (Tsikoudi 1980): The thick disk is easily seen by comparing Figures 3*e*,*f*. The Milky Way has a significant thick disk (Gilmore & Reid 1983): Its scale height ($\sim$1 kpc) is about three times larger than the scale height of the thin disk, its surface brightness is about 10% of the thin disk's surface brightness, its stellar population appears to be older than about 12 Ga, and its stars are significantly more metal poor than the stars of the thin disk. The galactic thick disk is currently believed to arise from heating of the early stellar disk by accretion events or minor mergers (see "Disk Heating by Accretion" below).

The thick disk may be one of the most significant components for studying signatures of galaxy formation because it presents a snap frozen relic of the state of the (heated) early disk. Although some apparently pure-disk galaxies like IC 5249 do have faint thick disks, others do not (Fry et al. 1999): These pure-disk galaxies show no visible components other than the thin disk. As for the bulge, formation of a thick disk is not an essential element of the galaxy formation process. In some galaxies the dissipative formation of the disk is clearly a very quiescent process.

The Stellar Halo

There are two further components that are not readily seen in other galaxies and are shown schematically in Figure 3*a*. The first is the metal-poor stellar halo, well-known in the Galaxy as the population containing the metal-poor globular clusters and field stars. Its mass is only about 1% of the total stellar mass (about 10^9 $M_\odot$: e.g., Morrison 1993). The surface brightness of the galactic halo, if observed in other galaxies, would be too low to detect from its diffuse light. It can be seen in other galaxies of the Local Group in which it is possible to detect the individual evolved halo stars. The metal-poor halo of the Galaxy is very interesting for galaxy formation studies because it is so old: Most of its stars are probably older than 12 Ga and were probably among the first galactic objects to form. The galactic halo has a power law density distribution $\rho \propto r^{-3.5}$ although this appears to depend on the stellar population (Vivas et al. 2001, Chiba & Beers 2000). Unlike the disk and bulge, the angular momentum of the halo is close to zero (e.g., Freeman 1987), and it is supported almost entirely by its velocity dispersion; Some of its stars are very energetic, reaching out to at least 100 kpc from the galactic center (e.g., Carney et al. 1990).

The current view is that the galactic halo formed at least partly through the accretion of small metal-poor satellite galaxies that underwent some independent chemical evolution before being accreted by the Galaxy (Searle & Zinn 1978, Freeman 1987). Although we do still see such accretion events taking place now, in the apparent tidal disruption of the Sgr dwarf (Ibata et al. 1995), most of them must have occurred long ago. Accretion of satellites would dynamically heat the thin disk, so the presence of a dominant thin disk in the Galaxy means that most of this halo-building accretion probably predated the epoch of thick disk formation $\sim$12 Ga ago. We can expect to see dynamically unmixed residues or fossils of at least some of these accretion events (e.g., Helmi & White 1999).

Of all the galactic components, the stellar halo offers the best opportunity for probing the details of its formation. There is a real possibility to identify groups of halo stars that originate from common progenitor satellites (Eggen 1977, Helmi & White 1999, Harding et al. 2001, Majewski et al. 2000). However, if the accretion picture is correct, then the halo is just the stellar debris of small objects accreted by the Galaxy early in its life. Although it may be possible to unravel this debris and associate individual halo stars with particular progenitors, this may tell us more about the early chemical evolution of dwarf galaxies than about the basic issues of galaxy formation. We would argue that the thin disk and thick disk of our Galaxy retain the most information about how the Galaxy formed. On the other hand, we note that current hierarchical CDM simulations predict many more satellites than are currently observed. It would therefore be very interesting to determine the number of satellites that have already been accreted to form the galactic stellar halo.

We should keep in mind that the stellar halo accounts for only a tiny fraction of the galactic baryons and is dynamically distinct from the rest of the stellar baryons. We should also note that the stellar halo of the Galaxy may not be typical: The halos of disk galaxies are quite diverse. The halo of M31, for example, follows the $r^{1/4}$ law (Pritchet & van den Bergh 1994) and is much more metal rich in the mean than the halo of our Galaxy (Durrell et al. 2001) although it does have stars that are very metal weak. It should probably be regarded more as the outer parts of a large bulge than as a distinct halo component. For some other disk galaxies, like the LMC, a metal-poor population is clearly present but may lie in the disk rather than in a spheroidal halo.

The Dark Halo

The second inconspicuous component is the dark halo, which is detected only by its gravitational field. The dark halo contributes at least 90% of the total galactic mass and its $\rho \sim r^{-2}$ density distribution extends to at least 100 kpc (e.g., Kochanek 1996). It is believed to be spheroidal rather than disklike (Crézé et al. 1998, Ibata et al. 2001b; see Pfenniger et al. 1994 for a contrary view). In the current picture of galaxy formation, the dark halo plays a very significant role. The disk is believed to form dissipatively within the potential of the virialized spheroidal halo, which itself formed through the fairly rapid aggregation of smaller bodies.

CDM simulations suggest that the halo may still be strongly substructured (see "Signatures of the CDM Hierarchy" below). If this is correct, then the lumpy halo would continue to influence the evolution of the galactic disk, and the residual substructure of the halo is a fossil of its formation. If the dark matter is grainy, it may be possible to study the dynamics of this substructure through pixel lensing of the light of background galaxies (Widrow & Dubinski 1998, Lewis et al. 2000). Another possibility is to look for the signatures of substructure around external galaxies in gravitationally lensed images of background quasars (Metcalf 2001, Chiba 2001). The dispersal of tidal tails from globular clusters appears to be sensitive to halo substructure (Ibata et al. 2001b), although this is not the case for dwarf galaxies (Johnston et al. 2001).

Within the limitations mentioned above, each of these distinct components of the Galaxy preserves signatures of its past and so gives insights into the galaxy formation process. We now discuss these signatures.

SIGNATURES OF GALAXY FORMATION

Our framework is that the Galaxy formed through hierarchical aggregation. We identify three major epochs in which information about the proto-hierarchy is lost:

1. the dark matter virializes—this could be a time of intense star formation but need not be, as evidenced by the existence of very thin pure disk galaxies;
2. the baryons dissipate to form the disk and bulge;

3. an ongoing epoch of formation of objects within the disk and accretion of objects from the environment of the galaxy, both leaving some long-lived relic.

We classify signatures relative to these three epochs. The role of the environment is presently difficult to categorize in this way. Environmental influences must be operating across all of our signature classes.

Zero Order Signatures—Information Preserved Since Dark Matter Virialized

INTRODUCTION During the virialization phase, a lot of information about the local hierarchy is lost: This era is dominated by merging and violent relaxation. The total dark and baryon mass are probably roughly conserved, as is the angular momentum of the region of the hierarchy that went into the halo. The typical density of the environment is also roughly conserved: Although the structure has evolved through merging and relaxation, a low density environment remains a low density environment (see White 1996 for an overview).

SIGNATURES OF THE ENVIRONMENT The local density of galaxies (and particularly the number of small satellite systems present at this epoch) affects the incidence of later interactions. For the Local Group, the satellite numbers appear to be lower than expected from CDM (Moore et al. 1999, Klypin et al. 1999). However there is plenty of evidence for past and ongoing accretion of small objects by the Milky Way and M31 (Ibata et al. 1995, 2001b).

The thin disk component of disk galaxies settles dissipatively in the potential of the virialized dark halo (e.g., Fall & Efstathiou 1980). The present morphology of the thin disk depends on the numbers of small galaxies available to be accreted: A very thin disk is an indication of few accretion events (dark or luminous) after the epoch of disk dissipation and star formation (e.g., Freeman 1987, Quinn et al. 1993, Walker et al. 1996). The formation of the thick disk is believed to be associated with a discrete event that occurred very soon after the disk began to settle, at a time when about 10% of the stars of the disk had already formed. In a low density environment, without such events, thick disk formation may not occur. Since the time of thick disk formation, the disk of the Galaxy appears to have been relatively undisturbed by accretion events. This is consistent with the observation that less than 10% of the metal-poor halo comes from recent accretion of star forming satellites (Unavane et al. 1996).

The existence and structure of the metal-poor stellar halo of the Galaxy may depend on accretion of small objects. This accretion probably took place after the gaseous disk had more or less settled—the disk acts as a resonator for the orbit decay of the small objects. So again the environment of our proto-galaxy may have a strong signature in the very existence of the stellar halo, and certainly in its observed substructure. We would not expect to find a stellar halo encompassing pure disk galaxies, consistent with the limited evidence now available (Freeman et al. 1983, Schommer et al. 1992).

SIGNATURES OF GLOBAL QUANTITIES During the process of galaxy formation, some baryons are lost to ram pressure stripping and galactic winds. Most of the remaining baryons become the luminous components of the galaxy. The total angular momentum J of the dark halo may contribute to its shape, which in turn may affect the structure of the disks. For example, warps may be associated with misalignment of the angular momentum of the dark and baryonic components. The dark halo may have a rotating triaxial figure; the effect of a rotating triaxial dark halo on the self-gravitating disk has not yet been seriously investigated (see Bureau et al. 1999).

The binding energy E at the epoch of halo virialization affects the depth of the potential well and hence the characteristic velocities in the galaxy. It also affects the parameter $\lambda = J|E|^{\frac{1}{2}}G^{-1}M^{-\frac{5}{2}}$, where M is the total mass: λ, which is critical for determining the gross nature of the galactic disk as a high or low surface brightness system (e.g., Dalcanton et al. 1997).

The relation between the specific angular momentum J/M and the total mass M (Fall 1983) of disk galaxies is well reproduced by simulations (Zurek et al. 1988). Until recently, ellipticals and disk galaxies appeared to be segregated in the Fall diagram: From the slow rotation of their inner regions, estimates of the J/M ratios for ellipticals were about 1 dex below those for the spirals. More recent work (e.g., Arnaboldi et al. 1994) shows that much of the angular momentum in ellipticals appears to reside in their outer regions, so ellipticals and spirals do have similar locations in the Fall diagram. Internal redistribution of angular momentum has clearly occurred in the ellipticals (Quinn & Zurek 1988).

The remarkable Tully-Fisher law (1977) is a correlation between the HI linewidth and the optical luminosity of disk galaxies. It appears to relate the depth of the potential well and the baryonic mass (McGaugh et al. 2000). Both of these quantities are probably roughly conserved after the halo virializes, so the Tully-Fisher law should be regarded as a zero-order signature of galaxy formation. The likely connecting links between the (dark) potential well and the baryonic mass are (*a*) a similar baryon/dark matter ratio from galaxy to galaxy, and (*b*) an observed Faber-Jackson law for the dark halos, of the form $M \propto \sigma^4$: i.e., surface density independent of mass for the dark halos (J. Kormendy & K.C. Freeman, in preparation).

SIGNATURES OF THE INTERNAL DISTRIBUTION OF SPECIFIC ANGULAR MOMENTUM The internal distribution of specific angular momentum $\mathcal{M}(h)$ of the baryons (i.e., the mass with specific angular momentum $< h$) largely determines the shape of the surface brightness distribution of the disk rotating in the potential well of the dark matter. Together with $\mathcal{M}(h)$, the total angular momentum and mass of the baryons determine the scale length and scale surface density of the disk. Therefore the distribution of total angular momentum and mass for protodisk galaxies determines the observed distribution of the scale length and scale surface density for disk galaxies (Freeman 1970, de Jong & Lacey 2000).

Many studies have assumed that $\mathcal{M}(h)$ is conserved through the galaxy formation process, most notably Fall & Efstathiou (1980). It is not yet clear if this assumption is correct. Conservation of the internal distribution of specific angular momentum $\mathcal{M}(h)$ is a much stronger requirement than the conservation of the *total* specific angular momentum J/M. Many processes can cause the internal angular momentum to be redistributed, while leaving the J/M ratio unchanged. Examples include the effects of bars, spiral structure (Lynden-Bell & Kalnajs 1972) and internal viscosity (Lin & Pringle 1987).

The maximum specific angular momentum $h_{\max}$ of the baryons may be associated with the truncation of the optical disk observed at about four scale lengths (de Grijs et al. 2001, Pohlen et al. 2000). This needs more investigation. The truncation of disks could be an important signature of the angular momentum properties of the early protocloud, but it may have more to do with the critical density for star formation or the dynamical evolution of the disk. Similarly, in galaxies with very extended HI, the edge of the HI distribution may give some measure of $h_{\max}$ in the protocloud. On the other hand, it may be that the outer HI was accreted subsequent to the formation of the stellar disk (van der Kruit 2001), or that the HI edge may just represent the transition to an ionized disk (Maloney 1993).

This last item emphasizes the importance of understanding what is going on in the outer disk. The outer disk offers some potentially important diagnostics of the properties of the protogalaxy. At present there are too many uncertainties about the significance of (*a*) the various cutoffs in the light and HI distributions, (*b*) the age gradient seen by Bell & de Jong (2000) from integrated light of disks but not by Friel (1995) for open clusters in the disk of the Galaxy, and (*c*) the outermost disk being maybe younger but not "zero age," which means that there is no real evidence that the disk is continuing to grow radially. It is possible that the edge of the disk has something to do with angular momentum of baryons in the protocloud or with disk formation process, so it may be a useful zero-order or first-order signature.

SIGNATURES OF THE CDM HIERARCHY CDM predicts a high level of substructure that is in apparent conflict with observation. Within galaxies, the early N-body simulations appeared to show that substructure with characteristic velocities in the range $10 < V_c < 30$ km s^{-1} would be destroyed by merging and virialization of low mass structures (Peebles 1970, White 1976, White & Rees 1978). It turned out that the lack of substructure was an artefact of the inadequate spatial and mass resolution (Moore et al. 1996). Current simulations reveal 500 or more low mass structures within 300 kpc of an L_* galaxy's sphere of influence (Moore et al. 1999, Klypin et al. 1999). This is an order of magnitude larger than the number of low mass satellites in the Local Group. Mateo (1998) catalogues about 40 such objects and suggests that, at most, we are missing a further 15–20 satellites at low galactic latitude. Kauffmann et al. (1993) were the first to point out the satellite problem and suggested that the efficiency of dynamical friction might be higher than usually quoted. However, without recourse to fine tuning, this would remove essentially all of the observed satellites in the Local Group today.

Since the emergence of the CDM paradigm, an inevitable question is whether a basic building block can be recognized in the near field. Moore et al. emphasize the self-similar nature of CDM sub-clustering and point to the evidence provided by the mass spectrum of objects in rich clusters, independent of the N-body simulations. The lure of finding a primordial building block in the near field has prompted a number of tests. If the dark mini-halos comprise discrete sources, it should be possible to detect microlensing towards a background galaxy (see "The Dark Halo" above).

The satellite problem appears to be a fundamental prediction of CDM in the nonlinear regime. Alternative cosmologies have been suggested involving the reduction of small-scale power in the initial mass power spectrum (Kamionkowski & Liddle 2000), warm dark matter (Hogan & Dalcanton 2001, White & Croft 2000, Colin et al. 2000), or strongly self-interacting dark matter (Spergel & Steinhardt 2000). Several authors have pointed out that some of the direct dark-matter detection experiments are sensitive to the details of the dark matter in the solar neighborhood. Helmi et al. (2001) estimate that there may be several hundred kinematically cold dark streams passing through the solar neighborhood.

If CDM is correct in detail, then we have simply failed to detect or to recognize the many hundreds of missing objects throughout the Local Group. For example, the satellites may be dark simply because baryons were removed long ago through supernova-driven winds (Dekel & Silk 1986, Mac Low & Ferrara 1999). In support of this idea, X-ray halos of groups and clusters are almost always substantially enriched in metals ($[\mathrm{Fe/H}] \geq -0.5$; Renzini 2000, Mushotzky 1999). In fact, we note that up to 70% of the mass fraction in metals is likely to reside in the hot intracluster and intragroup medium (Renzini 2000). Another explanation may be that the absence of baryons in hundreds of dark satellites was set in place long ago during the reionization epoch. Many authors note that the accretion of gas on to low-mass halos and subsequent star formation is heavily suppressed in the presence of a strong photoionizing background (Ikeuchi 1986, Rees 1986, Babul & Rees 1992, Bullock et al. 2000). This effect appears to have a cut-off at low galactic mass at a characteristic circular velocity close to 30 km s^{-1} (Thoul & Weinberg 1996, Quinn et al. 1996), such that the small number of visible Local Group dwarfs are those that exceed this cutoff or acquired most of their neutral hydrogen before the reionization epoch.

Blitz et al. (1999) suggested that the high-velocity HI gas cloud (HVC) population is associated with dark mini-halos on megaparsec scales within the Local Group. This model was refined by Braun & Burton (1999) to include only the compact HVCs. The HVCs have long been the subject of wide-ranging speculation. Oort (1966) realized that distances derived from the virial theorem and the HI flux would place many clouds at Mpc distances if they are self-gravitating. If the clouds lie at about a Mpc and are associated with dark matter clumps, then they could represent the primordial building blocks. However, Hα distances (Bland-Hawthorn et al. 1998) suggest that most HVCs lie within 50 kpc and are unlikely to be associated with dark matter halos (Bland-Hawthorn & Maloney 2001, Weiner et al. 2001). We note that several teams have searched for but failed to detect a faint stellar population in HVCs.

Moore et al. (1999; see also Bland-Hawthorn & Freeman 2000) suggested that ultrathin disks in spirals are a challenge to the CDM picture in that disks are easily heated by orbiting masses. However, Font et al. (2001) found that in their CDM simulations, very few of the CDM sub-halos come close to the optical disk.

At present there are real problems in reconciling the predictions of CDM simulations with observations on scales of the Local Group.

First Order Signatures—Information Preserved Since the Main Epoch of Baryon Dissipation

THE STRUCTURE OF THE DISK At what stage in the evolution of the disk are its global properties defined? In part, we have already discussed this question in "Signatures of the Internal Distribution of Specific Angular Momentum" above. The answer depends on how the internal angular momentum distribution $\mathcal{M}(h)$ has evolved as the disk dissipated and various nonaxisymmetric features like bars and spiral structure came and went. Viscous processes associated with star formation, as suggested by Lin & Pringle (1987), may also contribute to the evolution of the $\mathcal{M}(h)$ distribution.

The global structure of disks is defined by the central surface brightnes I_o and the radial scalelength h of the disk. de Jong & Lacey (2000) evaluated the present distribution of galaxies in the (I_o, h) plane (Figure 4). If $\mathcal{M}(h)$ has indeed remained roughly constant, as is often assumed for discussions of disk formation (e.g., Fall & Efstathiou 1980, Fall 1983), then the global parameters of the disk—the scale length, central surface brightness and the Tully-Fisher relation—are relics of the main epoch of baryon dissipation.

CAN DISKS PRESERVE FOSSIL INFORMATION? Here, we consider radial and vertical fossil gradients in the disk, in particular of abundance and age. Our expectation is that much of the information will be diluted through the dynamical evolution and radial mixing of the disk.

For spirals, different mechanisms may be at work to establish gradients (Molla et al. 1996): (*a*) a radial variation of the yield due either to the stellar metal production or to the initial mass function, (*b*) a radial variation of the timescale for star formation, (*c*) a radial variation for the timescale of infall of gas from outside the disk. Once gradients are established, these can be amplified or washed out by radial mixing (Edmunds 1990, Goetz & Koeppen 1992).

Most stars are born in large clusters numbering hundreds or even thousands of stars. Some clusters stay together for billions of years, whereas others become unbound shortly after the initial starburst, depending on the star formation efficiency. When a cloud disperses, each star suffers a random kick superimposed on the cloud's mean motion. Thereafter, stars are scattered by transient spiral arm perturbations and star-cloud encounters.

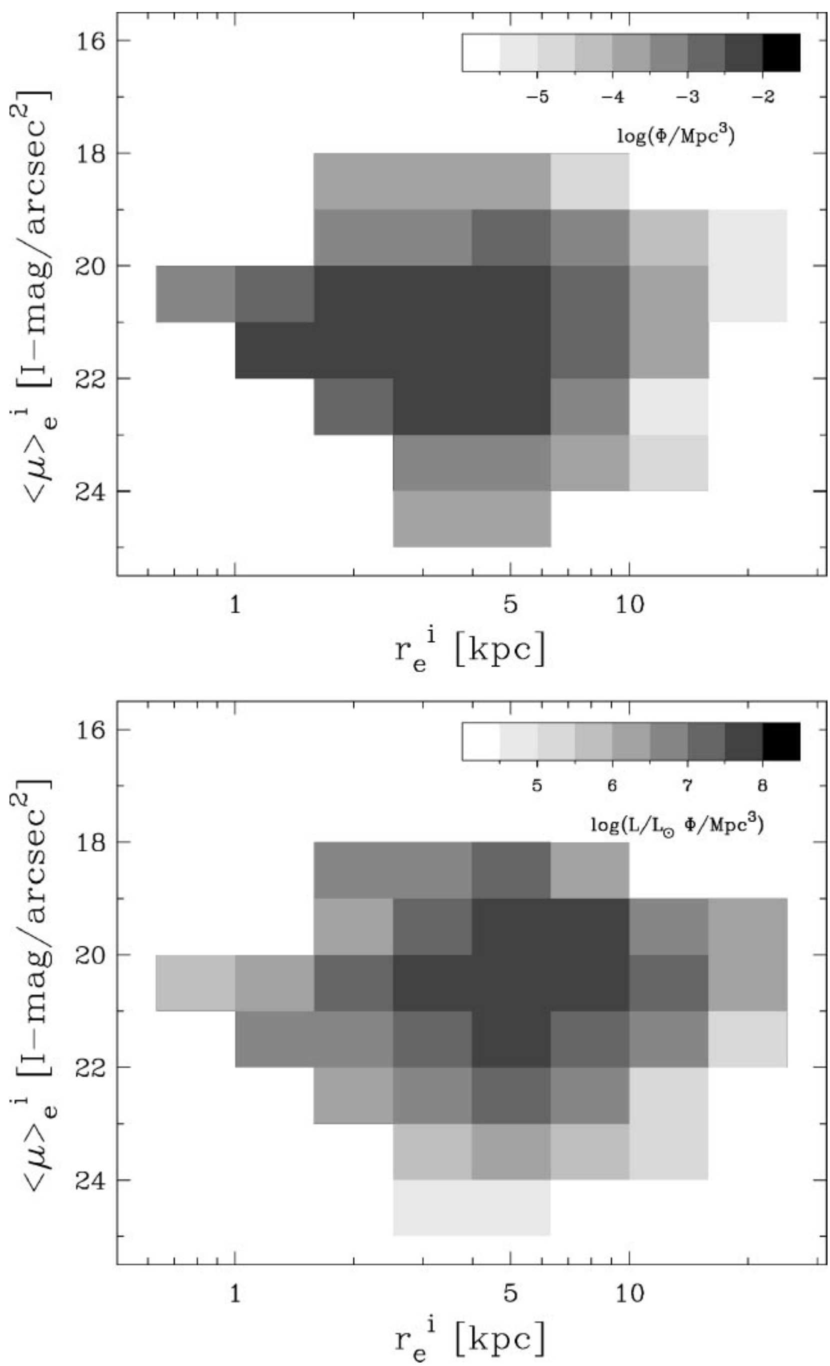


Figure 4 The density distribution of Sa to Sm galaxies over effective radius r_e and effective surface brightness μ_e. The top panel shows the raw (unweighted) distribution and the bottom panel shows the luminosity weighted distribution (de Jong & Lacey 2000).

These perturbations allow the star to migrate in integral space. During interaction with a single spiral event of pattern speed Ω_p, a star's energy and angular momentum change while it conserves its Jacobi integral: In the (E, J) plane, stars move along lines of constant $I_J = E - \Omega_p J$. The star undertakes a random walk in the (E, J) plane, perturbed by a series of spiral arm events (Sellwood 1999, Dehnen 2000). N-body models of disk evolution indicate that radial mixing is strong (Sellwood 2001, Lynden-Bell & Kalnajs 1972). This is believed to be driven by *transient* spiral waves that heat the in-plane motions, although the process is not yet well understood. Long-term spiral arms produce no net effect. Remarkably, a *single* spiral wave near co-rotation can perturb the angular momentum of a star by $\sim$20% without significant heating: The star is simply moved from one circular orbit to another, inwards or outwards, by up to 2 kpc (Sellwood & Kosowsky 2000). Substantial variations in the angular momentum of a star are possible over its lifetime.

In addition to radial heating, stars experience vertical disk heating: Their vertical velocity dispersion increases as they age. This is believed to occur through a combination of in-plane spiral-arm heating and scattering off giant molecular clouds (e.g., Spitzer & Schwarzschild 1953, Carlberg & Sellwood 1985). The in-plane heating is most effective at the inner and outer Lindblad resonances and vanishes at corotation. In the vertical direction, an age-velocity dispersion relation is observed for stars younger than about 3 Ga, but older disk stars show a velocity dispersion that is independent of age (Figure 5). Thus, the vertical structure does depend on the mean age of the population for $\tau < 3$ Ga (Edvardsson et al. 1993, confirmed from Hipparcos data by Gomez et al. 1997).

As the amplitude of the random motions increases, the star becomes less vulnerable to heating by transient spiral waves, and the heating process is expected to saturate. This probably happens after about 3 Ga (Binney & Lacey 1988, Jenkins & Binney 1990), consistent with observation. This is important for our purpose here. It means that dynamical information is preserved about the state of the thin disk at an early epoch, or roughly $\tau_L - 3 \approx 7$ Ga ago, for which τ_L is the look-back time when the disk first began to form.

The survival of old open clusters like NGC 6791, Berkeley 21 and Berkeley 17 (Friel 1995, van den Bergh 2000) is of interest here. The oldest open clusters exceed 10 Ga in age and constitute important fossils (Phelps & Janes 1996). Both old and young open clusters are part of the thin disk. If the heating perturbations occur over a lengthscale that significantly exceeds the size of an open cluster, it seems likely that the cluster will survive. A large spiral-arm heating event will heat many stars along their I_J trajectories. The trace of the heating event is likely to survive for a very long time but be visible only in integral space (Sellwood 2001). We note that vertical abundance gradients have not been seen among the open clusters (Friel & Janes 1993).

About 4% of disk stars are super metal-rich (SMR) relative to the Hyades (Castro et al. 1997). SMR stars of intermediate age appear to have formed a few kpc inside of the Solar circle from enriched gas. The oldest SMR stars appear to

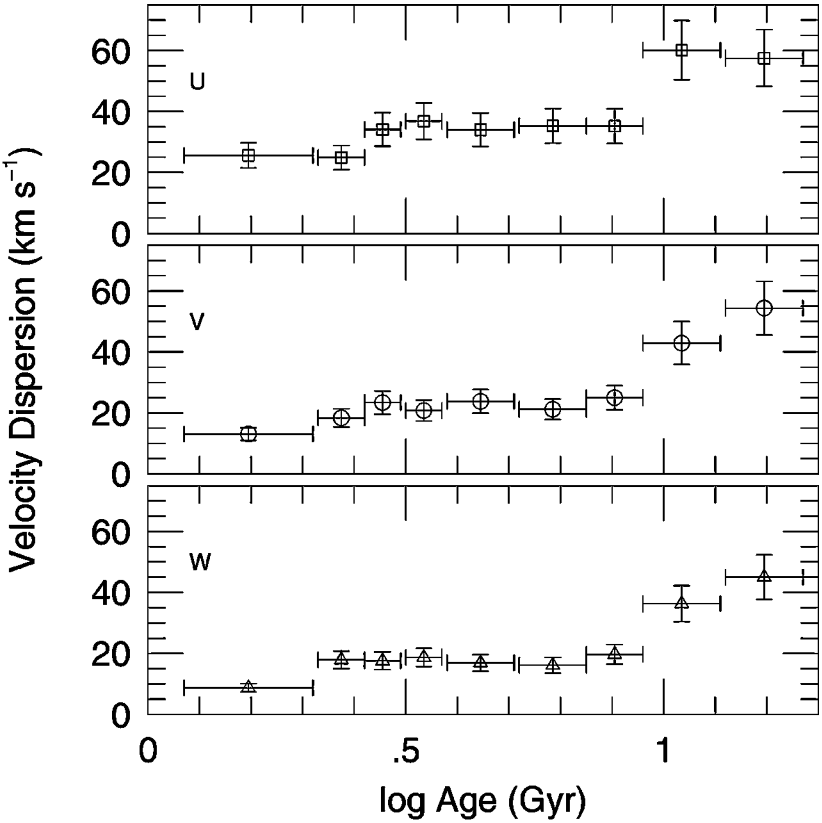


Figure 5 The relation between the three components of the velocity dispersion and the stellar age, as derived by Quillen & Garnett (2001) for stars from the sample of Edvardsson et al. (1993). Stars with ages between 2 and 10 Ga belong to the old thin disk: Their velocity dispersion is independent of age. The younger stars show a smaller velocity dispersion. The velocity dispersion doubles abruptly at an age of about 10 Ga; these older stars belong to the thick disk.

come from the Galactic Center: Their peculiar kinematics and outward migration may be associated with the central bar (Carraro et al. 1998, Grenon 1999).

In summary, our expectation is that fossil gradients within the disk are likely to be weak. This is borne out by observations of both the stars and the gas (Chiappini et al. 2001).

The vertical structure of the disk preserves another fossil—the thick disk—which we discuss in the next section. Like the open clusters, this component also does not show a vertical abundance gradient (Gilmore et al. 1995). In later sections, we argue that this may be the most important fossil to have survived the early stages of galaxy formation.

DISK HEATING BY ACCRETION: THE THICK DISK Heating from discrete accretion events also imposes vertical structure on the disk (Quinn & Goodman 1986, Walker et al. 1996). Such events can radically alter the structure of the inner disk and the bulge (see Figure 3*d* for an example) and are currently believed to have generated the thick disk of the Galaxy.

The galactic thick disk was first recognized by Gilmore & Reid (1983). It includes stars with a wide range of metallicity, from $-2.2 \leq [\mathrm{Fe/H}] \leq -0.5$ (Chiba & Beers 2000): Most of the thick disk stars are in the more metal-rich end of this range. The velocity ellipsoid of the thick disk is observed to be $(\sigma_R, \sigma_\phi, \sigma_z) = (46 \pm 4, 50 \pm 4, 35 \pm 3)$ km s^{-1} near the sun, with an asymmetric drift of about 30 km s^{-1}. For comparison, the nearby halo has a velocity ellipsoid $(\sigma_R, \sigma_\phi, \sigma_z) = (141 \pm 11, 106 \pm 9, 94 \pm 8)$ km s^{-1} and its asymmetric drift is about 200 km s^{-1}.

The mean age of the thick disk is not known. From photometric age-dating of individual stars, the thick disk appears to be as old as the globular clusters. Indeed, the globular cluster 47 Tuc (age 12.5 ± 1.5 Ga; Liu & Chaboyer 2000) is often associated with the thick disk.

After Quinn & Goodman (1986), Walker et al. (1996) showed in detail that a low mass satellite could substantially heat the disk as it sinks rapidly within the potential well of a galaxy with a live halo. The conversion of satellite orbital energy to disk thermal energy is achieved through resonant scattering. Simulations of satellite accretion are important for understanding the survival of the thin disk and the origin of the thick disk. This is particularly relevant within the context of CDM. The satellites which do the damage are those that are dense enough to survive tidal disruption by the Galaxy. We note that even dwarf spheroidals which appear fluffy are in fact rather dense objects dominated by their dark matter (J. Kormendy & K. Freeman, in preparation).

It is fortuitous that the Galaxy has a thick disk, since this is not a generic phenomenon. The disk structure may be vertically stepped as a consequence of past discrete accretion events. The Edvardsson et al. (1993) data (Figure 5) appears to show an abrupt increase in the vertical component of the stellar velocity dispersion at an age of 10 Ga; see also Strömgren (1987). Freeman (1991) argued that the age–velocity dispersion relation shows three regimes: stars younger than 3 Ga with $\sigma_z \sim 10$ km s^{-1}, stars between 3 and 10 Ga with $\sigma_z \sim 20$ km s^{-1}, and stars older than 10 Ga with $\sigma_z \sim 40$ km s^{-1}. The first regime probably arises from the disk heating process due to transient spiral arms which we described in the previous section. The last regime is the thick disk, presumably excited by an ancient discrete event.

Can we still identify the disrupting event that led to the thick disk? There is increasing evidence now that the globular cluster ω Cen is the stripped core of a dwarf elliptical (see "Globular Clusters" below). It is possible that the associated accretion event or an event like it was the event that triggered the thick disk to form.

In summary, it seems likely that the thick disk may provide a snap-frozen view of conditions in the disk shortly after the main epoch of dissipation. Any low level chemical or age gradients would be of great interest in the context of dissipation models. In this regard, Hartkopf & Yoss (1982) argued for the presence of a vertical abundance gradient in the thick disk, although Gilmore, Wyse & Jones (1995) found no such effect. Because stars of the thick disk spend relatively little time near the galactic plane, where the spiral arm heating and scattering by giant molecular clouds is most vigorous, radial mixing within the thick disk is unlikely to remove all vestiges of a gradient. If our earlier suggestions are right (see "Signatures of the Internal Distribution of Specific Angular Momentum" above), we might expect to see a different truncation radius for the thick disk compared to the thin disk.

IS THERE AN AGE-METALLICITY RELATION? Some fossil information has likely been preserved since the main epoch of baryon dissipation. The inner stellar bulge is a striking example. It is characterized by old, metal-rich stars, which seems to be at odds with the classical picture where metals accumulate with time (Tinsley 1980). However, the dynamical timescales in the inner bulge are very short compared to the outer disk and would have allowed for rapid enrichment at early times. This is consistent with the frequent occurrence of metal-rich cores of galaxies observed at high redshift (Hamann & Ferland 1999). The dynamical complexity of the Galactic bulge may not allow us to determine the sequence of events that gave rise to it. We anticipate that this will come about from far-field cosmology (Ellis et al. 2000).

The existence of an age-metallicity relation (AMR) in stars is a very important issue, about which there has long been disagreement. Twarog (1980) and Meusinger et al. (1991) provide evidence for the presence of an AMR, while Carlberg et al. (1985) find that the metallicity of nearby F stars is approximately constant for stars older than about 4 Ga. More recently it has become clear that an AMR is apparent only in the solar neighborhood and is strictly true only for stars younger than 2 Ga and hotter than $\log T_{\rm eff} = 3.8$ (Feltzing et al. 2001). Edvardsson et al. (1993) demonstrate that there is no such relation for field stars in the old disk. Similarly, Friel (1995) shows that there is no AMR for open clusters (see "Open Clusters" below): she goes on to note that

> Apparently, over the entire age of the disk, at any position in the disk, the oldest clusters form with compositions as enriched as those of much younger objects.

In fact, it has been recognized for a long time (e.g., Arp 1962, Eggen & Sandage 1969, Hirshfeld et al. 1978) that old, metal-rich stars permeate the galaxy, throughout the disk, the bulge and the halo. We regard the presence of old metal-rich stars as a first-order signature. An age-metallicity relation which applies to all stars would have been an important second-order signature, but we see no evidence for such a relation, except among the young stars.

EFFECTS OF ENVIRONMENT AND INTERNAL EVOLUTION Environmental influences are operating on all scales of the hierarchy and across all stages of our signature classification, so our attempts to classify signatures are partly artificial. Within CDM, environmental effects persist throughout the life of the galaxy.

The parameters that govern the evolution of galaxies are among the key unknowns of modern astrophysics. Are the dominant influences internal (e.g., depth of potential) or external (e.g., environment) to galaxies? We consider here the effects of environment and internal evolution on the validity of the first-order signatures of galaxy formation (i.e., the properties that may have been conserved since the main epoch of baryon dissipation).

The well-known G dwarf problem indicates that external influences are important. A simple closed box model of chemical evolution predicts far too many metal-poor stars in the solar neighborhood (Tinsley 1980). This problem is easily remedied by allowing gas to flow into the region (Lacey & Fall 1983, 1985; Clayton 1987, 1988; Wyse & Silk 1989; Matteuci & Francois 1989; Worthey et al. 1996). In the context of CDM, this is believed to arise from the continued accretion of gas-rich dwarfs (e.g., Cole et al. 1994, Kauffmann & Charlot 1998).

Environment is clearly a key factor. Early type galaxies are highly clustered compared to late type galaxies (Hubble & Humason 1931, Dressler 1980). Trager et al. (2000) find that for a sample of early-type galaxies in low-density environments, there is a large spread in the Hβ index (i.e., age), but little variation in metallicity. For galaxies in the Fornax cluster, Kuntschner (2000) finds the opposite effect: A large spread in metallicity is present with little variation in age. This probably reflects strong differences in environment between the field and the cluster.

Another likely environmental effect is the fraction of S0 galaxies in clusters, which shows a rising trend with redshift since $z \approx 0.4$ (Jones et al. 2000). Furthermore, S0 galaxies in the Ursa Major cluster show age gradients that are inverted compared to field spirals, in the sense that the cores are young and metal-rich (Tully et al. 1996, Kuntschner & Davies 1998). Both of these effects involve more recent phenomena and would be properly classified as second-order signatures.

Internal influences are also at work. A manifestation is the color-magnitude relation (CMR) in early-type (Sandage & Visvanathan 1978) and late-type (Peletier & de Grijs 1998) galaxies. The CMR does not arise from dust effects (Bell & de Jong 2000) and must reflect systematic variations in age and/or metallicity with luminosity. In the case of ellipticals, the CMR is believed to reflect a mass-metallicity dependence (Faber 1973, Bower et al. 1998). The relation is naturally explained by supernova-driven wind models in which more massive galaxies retain supernova ejecta and thus become more metal rich and redder (Larson 1974, Arimoto & Yoshii 1987). The CMR is presumably established during the main phase of baryon dissipation and is a genuine first-order signature.

Concannon et al. (2000) analyzed a sample of 100 early-type galaxies over a large range in mass. They found that lower-mass galaxies exhibit a larger range in age than higher-mass galaxies. This appears to show that smaller galaxies have had a more varied star formation history, which is at odds with the naive CDM picture of low-mass galaxies being older than high-mass galaxies (Baugh et al. 1996, Kauffman 1996). The work of Concannon et al. (2000) shows the presence of a real cosmic scatter in the star formation history. It is tempting to suggest that this cosmic scatter relates to different stages of evolution within the hierarchy. In this sense, we would regard the Concannon et al. result as a first-order manifestation of galaxy formation (see "Timescales and Fossils" above).

Spiral galaxies commonly show color gradients that presumably reflect gradients in age and metallicity (Peletier & de Grijs 1998). Faint spiral galaxies have younger ages and lower metallicities relative to bright spirals. In a study of 120 low-inclination spirals, Bell & de Jong (2000) found that the local surface density within galaxies is the most important parameter in shaping their star formation and chemical history. However, they find that metal-rich galaxies occur over the full range of surface density. This fact has a remarkable resonance with the distribution of the metal-rich open clusters that are found at any position in the Galactic disk (see "Is There an Age-Metallicity Relation?" above). Bell & de Jong argue that the total mass is a secondary factor that modulates the star formation history. Once again, these authors demonstrate the existence of cosmic scatter that may well arise from variations in environment.

Second Order Signatures—Major Processes Involved in Subsequent Evolution

INTRODUCTION Here we consider relics of processes that have taken place in the Galaxy since most of the baryonic mass settled to the disk. There are several manifestations of these processes, probably the most significant of which is the star formation history of the disk, for which the open clusters are particularly important probes.

There is a wealth of detail relating to anomalous populations throughout the Galaxy, discussed at length by Majewski (1993). Examples include an excess of stars on extreme retrograde orbits (Norris & Ryan 1989, Carney et al. 1996), metal-poor halo stars of intermediate age (Preston et al. 1994) and metal-rich halo A stars (Rodgers et al. 1981).

In an earlier section, we discussed observational signatures of the CDM hierarchy in the Galactic context. In fact, detailed observations in velocity space are proving to be particularly useful in identifying structures that have long since dispersed in configuration space. In external galaxies, related structures are showing up as low surface brightness features. We do not know what role globular clusters play in the galaxy formation picture, but we include them here because at least one of them appears now to be the nucleus of a disrupted dwarf galaxy.

STAR FORMATION HISTORY The star formation history (SFH) of our Galaxy has been very difficult to unravel. Derived star formation histories range from a roughly uniform star formation rate over the history of the disk to a SFH that was highly peaked at early times (e.g., Twarog 1980, Rocha-Pinto et al. 2000, Just 2001). Galaxies of the Local Group show a great diversity in SFH (Grebel 2001), although the average history over the Local Group appears consistent with the mean cosmic history (Hopkins et al. 2001). The present emphasis is on star formation studies that make use of the integrated properties of external galaxies, but it should be noted that this is necessarily weighted towards the most luminous populations. Key results for external galaxies are reviewed in "Effects of Environment and Internal Evolution" above. It was concluded that environmental effects are very significant in determining the SFH for individual galaxies.

The conventional approach to the study of chemical evolution in galaxy disks is to consider the solar neighborhood a closed box, and to assume that it is representative of all disks. Simple mathematical formulations have developed over the past 40 years (van den Bergh 1962, Schmidt 1963, Pagel & Patchett 1975, Talbot & Arnett 1971, Tinsley 1980, Twarog 1980, Pitts & Tayler 1989). Most observations are interpreted within this framework. The SFH is quantified in terms of stellar age, stellar (+gas) metallicity and, to a lesser extent, the existing gas fraction.

The use of broadband photometry coupled with stellar population synthesis is a well-established technique for probing the SFH of galaxy populations from integrated light. The power of the method is its simplicity, although it cannot uniquely disentangle the age-metallicity degeneracy (Bica et al. 1990, Charlot & Silk 1994).

Another widely used technique is the Lick index system (Burstein et al. 1984) further refined in Worthey et al. (1994) and Trager et al. (1998). In this system, the Hβ index is the primary age-sensitive spectral indicator, whereas the Mg and Fe indices are the primary metallicity indicators. The Lick indices have well-known limitations: They correspond to low spectroscopic resolution (8–9 Å), require difficult corrections for internal galaxy motions, and are not calibrated onto a photometric scale. Furthermore, two of the most prominent Lick indices—Mg_2 λ5176 and Fe λ5270—are now known to be susceptible to contamination from other elements, in particular Ca and C (Tripicco & Bell 1995).

How best to measure galaxy ages is a subject with a long history. The most reliable methods to date involve the low order transitions ($n < 4$) of the Balmer series. Ages derived from the Hγ equivalent width have been used by Jones & Worthey (1995). Rose (1994) and Caldwell & Rose (1998) have pioneered the use of even higher-order Balmer lines to break the age-metallicity degeneracy (Worthey 1994). These higher-order lines are less affected by Balmer line emission from the interstellar medium. They develop a line ratio index Hn/Fe which is a sum over Hγ, Hδ and H8 lines with respect to local Fe lines. The most recent demonstration of the power of this index can be found in Concannon et al. (2000).

Ultimately, full spectrum fitting matched to spectral synthesis models holds the most promise (Vazdekis 1999). The new models, which have a fourfold increase in spectroscopic resolution compared to the Lick system, show that the isochrone or isochemical grid lines overlaid on a plot of two Lick indices are more orthogonal than the Worthey models. Thus, galaxies like NGC 4365 that exhibit no age gradient in the Vazdekis models (Davies et al. 2001; see Figure 6*a*) appear to show an age spread in the Worthey models. Interestingly, NGC 4150 exhibits an abundance spread with constant age (Figure 6*b*).

LOW SURFACE BRIGHTNESS STRUCTURES IN GALAXIES Dynamical interaction between galaxies led to a range of structures including stellar shells (Malin & Carter 1980, Quinn 1984), fans (Weil et al. 1997), and tidal streamers (Gregg & West 1998, Calcaneo-Roldan et al. 2000, Zheng et al. 1999). Some excellent examples are shown in Figure 7. We see evidence of multiple nuclei, counter-rotating cores, and gas in polar orbits. At low light levels, the outermost stellar contours of spiral disks appear frequently to exhibit departures from axisymmetry (Rix & Zaritsky 1995). The same is true for spiral arms in all Hubble types (Schoenmakers et al. 1997, Cianci 2002).

The stellar streamers are particularly interesting, as these may provide important constraints on galaxy models, particularly as kinematic measurements become possible through the detection of planetary nebulae. More than a dozen stellar streams are already known and this is probably indicative of a much larger population at very low surface brightness. Johnston et al. (2001) show that stellar streamers can survive for several gigayears and are only visible above the present optical detection limit ($\mu_V = 30$ mag arcsec^{-2}) for roughly 4×10^8 yr. A few galaxy groups (e.g., the Leo group) do show large-scale HI filaments that can remain visible for many Ga.

Deep CCD imaging has revealed a stellar loop around NGC 5907 (Shang et al. 1998) and a stellar feature extending from NGC 5548 (Tyson et al. 1998). The technique of photographic amplification has revealed stellar streamers in about ten sources (Malin & Hadley 1997, Calcaneo-Roldan et al. 2000, Weil et al. 1997). For these particular observations, the limiting surface brightness is $\mu_V \approx$ 28.5 mag arcsec^{-2}. For all of these systems, we estimate that the total stream luminosities are in the range 3–20 $\times$ 10^7 $L_\odot$.

In a recent development, wide-field CCD cameras have revealed stellar streamers through multiband photometry of millions of individual sources. A pointillist image can then be reconstructed in narrow color intervals so as to enhance features with respect to the field. This has led to the discovery of a stellar stream in M31 (Ibata et al. 2001a) and tidal tails extending from the globular cluster Pal 5 (Odenkirchen et al. 2001). This technique has the potential to push much deeper than the direct imaging method described above.

The low surface brightness universe is notoriously difficult to observe. Modern telescope and instrument designs are simply not optimized for this part of parameter space. Many claims of diffuse light detections in the neighborhood of galaxies have been shown to arise from scattered light internal to the instrument.

In "Structures in Phase Space," below, we discuss moving groups identified within the Galaxy from proper motion and spectroscopic surveys. Their projected surface brightness is $\mu_V = 30$–34 mag arcsec^{-2}, below the limit of modern imaging techniques.

Looking farther afield, we see evidence for discrete accretion events in the making. The Galaxy is encircled by satellite galaxies that appear confined to one or two great streams across the sky (Lynden-Bell & Lynden-Bell 1995). The most renowned of these are the Magellanic Clouds and the associated HI Magellanic stream. All of these are expected to merge with the Galaxy in the distant future, largely due to the dynamical friction from the extended halo.

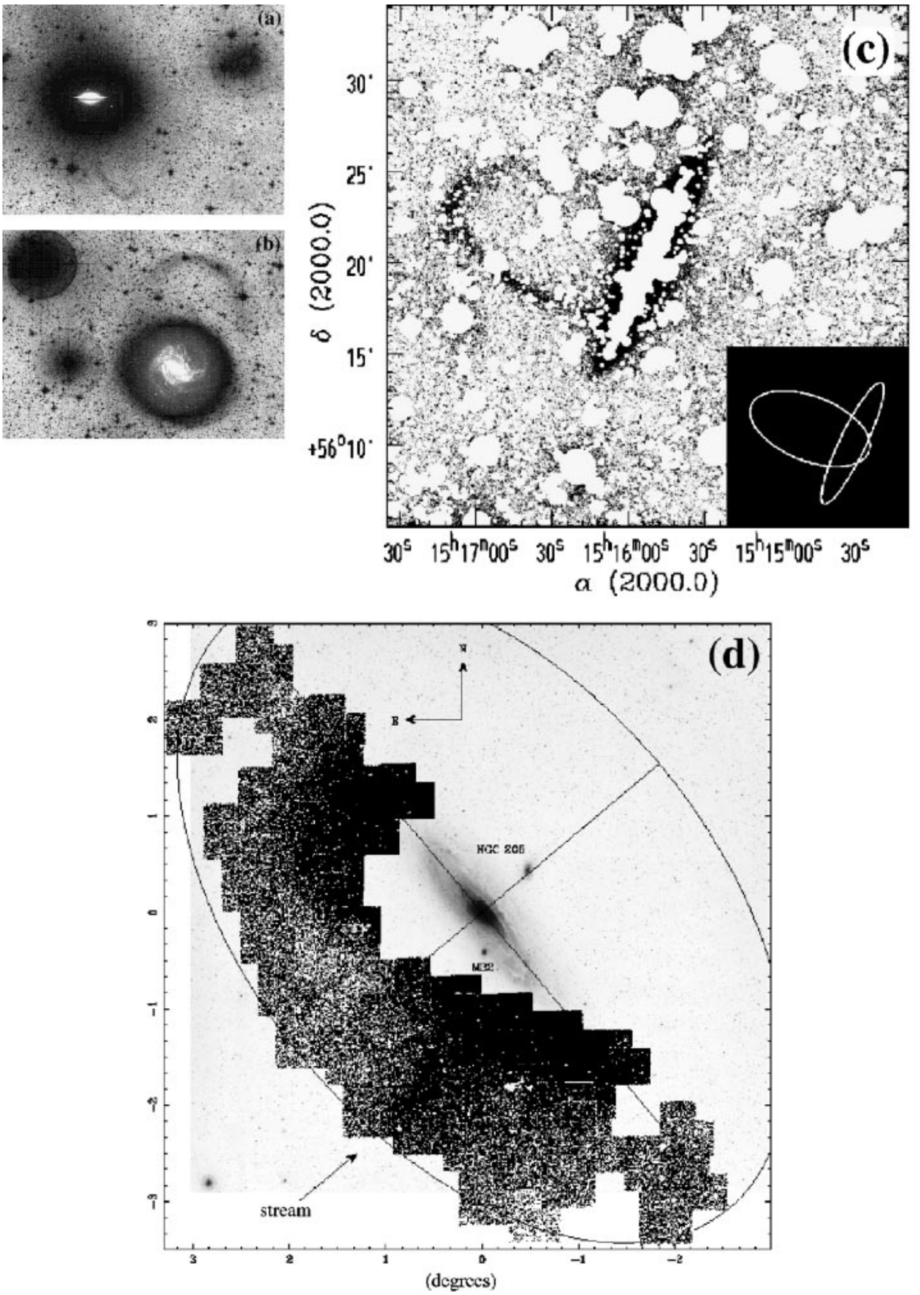


Figure 7 Examples of normal spirals with faint stellar streamers in the outer halo (see text): (*a*) M104 where the streamer is on a much larger scale than shown in Figure 3(*c*) (Malin & Hadley 1997); (*b*) M83 (Malin & Hadley 1997); (*c*) NGC 5907 (Shang et al. 1998); (*d*) M31 (Ibata et al. 2001a).

OPEN CLUSTERS In the context of near-field cosmology, we believe that the thick disk and the old open clusters of the thin disk are among the most important diagnostics. The open clusters are the subject of an outstanding and comprehensive review by Friel (1995). Here, we summarize the properties that are most important for our purpose.

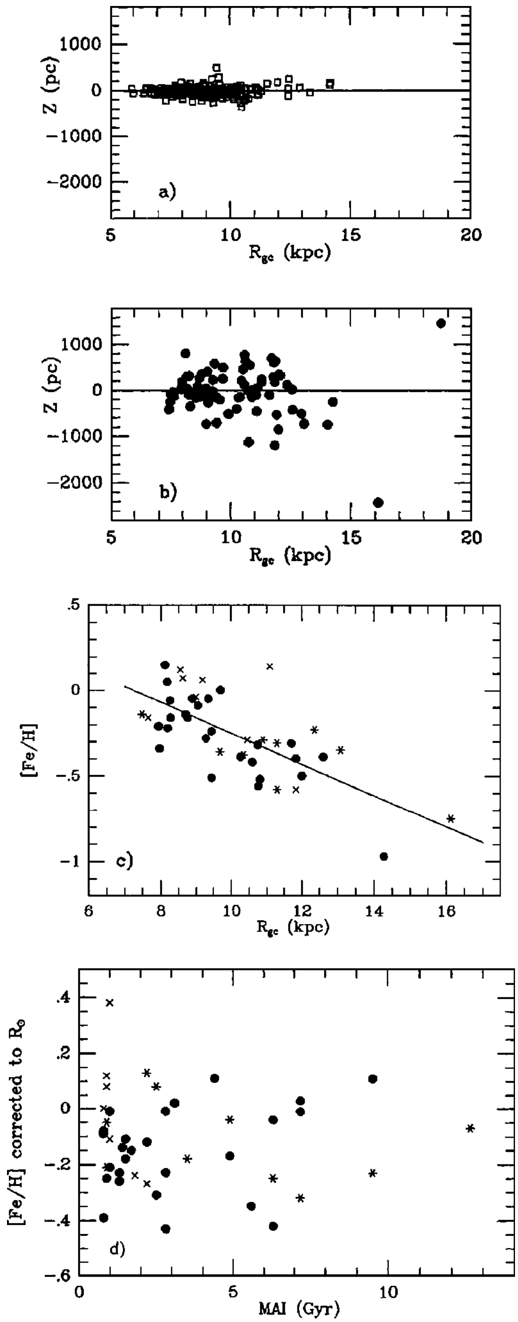
Both old and young clusters are part of the thin disk. Their key attribute is that they provide a direct time line for investigating change, which we explore in "The Gaiasphere and the Limits of Knowledge," below. The oldest open clusters exceed 10 Ga in age and constitute important fossils (Phelps & Janes 1996). In "Can disks preserve fossil information," we noted that the survival of these fossil clusters is an interesting issue in its own right. Friel (1995) finds no old open clusters within a galactocentric radius of 7 kpc; these are likely to have disrupted or migrated out of the central regions (van den Bergh & McClure 1980). It has long been recognized that open clusters walk a knife edge between survival and disruption (King 1958a,b,c).

Like field stars in the disk, Janes & Phelps (1994) find that the old cluster population (relative to Hyades) is defined by a 375-pc scale height exponential distribution, whereas young clusters have a 55-pc scale height (Figure 8*a*,*b*). Again, like the field stars, vertical abundance gradients have not been seen in open clusters (Friel & Janes 1993), although radial gradients are well established (Friel 1995, van den Bergh 2000). For old open clusters, Twarog et al. (1997) claim evidence for a stepped radial metallicity distribution where [Fe/H] ≈ 0 within 10 kpc, falling to [Fe/H] ≈ -0.3 in the outer disk. However, this effect is not seen in young objects, e.g., HII regions and B stars (Henry 1998).

In Figure 8*c*, both the old and young open clusters show essentially the same radial trend in metallicity. After reviewing the available observations, Friel (1995) finds no evidence for an age-metallicity relation for open clusters (Figure 8*d*). In agreement with Eggen & Sandage (1969), she notes that over the entire age of the disk, at any position in the disk, the oldest clusters form with compositions as enriched as those of much younger objects.

These remarkable observations appear to indicate that shortly after the main epoch of baryon dissipation, the thin disk was established at least as far out as 15 kpc. The oldest open clusters approach the age of the thick disk. Since, in "Disk Heating by Accretion," we noted that the thick disk is likely to be a snap frozen picture of the thin disk shortly after disk formation, we would expect the truncation

Figure 8 (*a*) The distribution of open clusters younger than Hyades with height from the plane as a function of Galactocentric distance R_{gc} (Friel 1995). The Sun is at 8.5 kpc. (*b*) The distribution of clusters with ages equal to or greater than the Hyades. (*c*) The open clusters exhibit a well-defined abundance gradient. (*d*) There is no discernible age-metallicity relation (AMR) when the cluster abundances are corrected for the radial abundance gradient.


Z (pc)
1000
0
−1000
−2000
a)
5
10
15
20
R_gc (kpc)
Z (pc)
1000
0
−1000
−2000
b)
5
10
15
20
R_gc (kpc)
.5
0
-.5
−1
[Fe/H]
c)
6
8
10
12
14
16
R_gc (kpc)
.4
.2
0
-.2
-.4
−.6
[Fe/H] corrected to R_⊙
d)
0
5
10
MAI (Gyr)

of the thick disk (see "Signatures of Global Quantities," above) to reflect the extent of the thin disk at the epoch of the event that puffed up the thick disk.

GLOBULAR CLUSTERS We have long suspected that globular clusters are the fossil remnants of violent processes in the protogalactic era (Peebles & Dicke 1968). But there is a growing suspicion that globulars are telling us more about globulars than galactic origins (Harris 2001). The Milky Way has about 150 globular clusters with 20% lying within a few kiloparsecs of the Galactic Center. They constitute a negligible fraction of the light and mass (2%) of the stellar halo today. Their significance rests in their age. The oldest globular clusters in the outer halo have an age of 13 ± 2.5 Ga (90% confidence).

The ages of the oldest globular clusters in the inner and outer halo, the Large Magellanic Cloud and the nearby Fornax and Sgr dwarf spheroidal galaxies show a remarkable uniformity. To a precision of ± 1 Ga, the onset of globular cluster formation was well synchronized over a volume centered on our Galaxy with a radius >100 kpc (Da Costa 1999).

Globular cluster stars are older than the oldest disk stars, e.g., white dwarfs and the oldest red giants. These clusters are also more metal poor than the underlying halo light in all galaxies and at all radii (Harris 1991), but again there are exceptions to the rule. Since Morgan's (1950) and Kinman's (1959) classic work, we have known that there are two distinct populations of globular clusters in the Galaxy. The properties that we associate with these two populations today were derived by Zinn (1985) who showed that they have very different structure, kinematics and metallicities. The halo population is metal poor ($[Fe/H] < -0.8$) and slowly rotating with a roughly spherical distribution; the disk population is metal rich ($[Fe/H] > -0.8$) and in rapid rotation.

A major development has been the discovery of young globular clusters in disturbed or interacting galaxies, e.g., NGC 1275 (Holtzman et al. 1992), NGC 7252 (Whitmore et al. 1993) and the Antennae (Whitmore & Schweizer 1995). Schweizer (1987) first suspected that globular clusters were formed in mergers. Later, Ashman & Zepf (1992) predicted that the HST would reveal young globular clusters through their compact sizes, high luminosities and blue colors. The very high internal densities of globular clusters today must partly reflect the conditions when they were formed. Harris & Pudritz (1994) present a model for globular clusters produced in fragmenting giant molecular clouds, which are of the right mass and density range to resemble accretion fragments in the Searle-Zinn model.

Globular clusters have been elegantly referred to as "canaries in a coal mine" (Arras & Wasserman 1999). They are subject to a range of disruptive effects, including two-body relaxation and erosion by the tidal field of their host galaxy, and the tidal shocking that they experience as their orbits take them through the galactic disk and substructure in the dark halo. In addition to self-destruction through stellar mass loss, tidal shocking may have been very important in the early universe (Gnedin et al. 1999). If globular clusters originally formed in great numbers, the disrupted clusters may now contribute to the stellar halo (Norris & Ryan 1989, Oort 1965). Halo field stars and globular clusters in the Milky Way have similar mean metallicities (Carney 1993); however, the metallicity distribution of the halo field stars extends to much lower metallicity ([Fe/H] $\simeq -5$) than that of the globular clusters ([Fe/H] $\simeq -2.2$). We note again the remarkable similarity in the metallicity range of the globular clusters and the thick disk ($-2.2 \lesssim$ [Fe/H] $\lesssim -0.5$).

In the nucleated dwarf elliptical galaxies (Binggeli et al. 1985), the nucleus typically provides about 1% of the total luminosity; globular clusters could be considered as the stripped nuclei of these satellite objects without exceeding the visible halo mass (Zinnecker & Cannon 1986, Freeman 1993). It is an intriguing prospect that the existing globular clusters could be the stripped relicts of an ancient swarm of protogalactic stellar fragments, i.e., the original building blocks of the Universe.

In the Searle-Zinn picture, globular clusters are intimately linked to *gas-rich*, protogalactic infalling fragments. Multiple stellar populations have recently been detected in ω Cen, the most massive cluster in the Galaxy (Lee et al. 1999). How did ω Cen retain its gas for a later burst? It now appears that it was associated with a gas-rich dwarf, either as an in situ cluster or as the stellar nucleus. The present-day cluster density is sufficiently high that it would have survived tidal disruption by the Galaxy, unlike the more diffuse envelope of this dwarf galaxy. The very bound retrograde orbit supports the view that ω Cen entered the Galaxy as part of a more massive system whose orbit decayed through dynamical friction.

If globular clusters are so ancient, why are the abundances of the most metal-poor population as high as they are? Because it does not take much star formation to increase the metal abundance up to [Fe/H] $= -1.5$ (Frayer & Brown 1997), the cluster abundances may reflect low levels of star formation even before the first (dark + baryon) systems came together.

Old age is not necessarily associated with low metallicity (compare "Timescales and Fossils" above). We recall that CO has been detected at $z \sim 5$ (Yun et al. 2000). Hamann & Ferland (1999) demonstrate that stellar populations at the highest redshift currently observed appear to have solar or super-solar metallicity. We believe that there is no mystery about high abundances at high redshift. The dynamical times in the cores of these systems are short, so there has been time for multiple generations of star formation and chemical enrichment. In this sense, the cores of high redshift galaxies need not be relevant to the chemical properties of the globular clusters, although both kinds of objects were probably formed at about the same time.

The first generation of globular clusters may have been produced in merger-driven starbursts when the primordial fragments came together for the first time. If at least some fragments retained some of their identity while the halo was formed, a small number of enrichment events per fragment would ensure a Poissonian scatter in properties between globular clusters, and multiple populations within individual clusters (Searle & Zinn 1978).

STRUCTURES IN PHASE SPACE One class of systems that exhibit coherence in velocity space are the open clusters associated with the disk. Here the common space motion of the stars with respect to the Sun is perceived as a convergence of the proper motions to a single point (strictly speaking, minimum volume) on the sky (Boss 1908; see de Zeeuw et al. 1999 for a recent application). More than a dozen such systems have been identified this way. However, these are all young open clusters largely associated with the Gould belt. With sufficiently precise kinematics, it may be possible to identify open clusters that have recently dispersed, particularly if the group is confined to a specific radial zone by resonances in the outer disk. For example, Feltzing & Holmberg (2000) show that the metal-rich ([Fe/H] $\approx$ 0.2) moving group HR 1614, thought to be 2 Ga old, can be identified in the Hipparcos data set.

Recently, attention has turned to a diverse set of moving groups that are thought to be associated with the stellar halo and in some instances are clearly fossils associated with accretion events in the distant past. The evidence for these groups dates back to the discovery of the halo itself. Shortly before the publication of the landmark ELS paper, Eggen & Sandage (1959) discovered that the nearby high-velocity star, Groombridge 1830, belongs to a moving group now passing through the Galactic disk.

In a long series of papers, Eggen went on to identify a number of moving groups, some of which appear to encompass the solar neighborhood, and others that may be associated with the halo. The relevant references are given by Taylor (2000). Various authors have noted that many of the groups are difficult to confirm (Griffin 1998, Taylor 2000). More systematic surveys over the past few decades have identified a number of moving populations associated with the halo (Freeman 1987, Majewksi 1993), although the reality of some of these groups is still debated. The reality of these groups is of paramount importance in the context of halo formation. Majewski et al. (1996) suspect that much or all of the halo could exhibit phase-space clumping with data of sufficient quality.

In recent years, the existence of kinematic sub-structure in the galactic halo has become clear. Helmi et al. (1999) identified 88 metal-poor stars within 1 kiloparsec of the Sun from the Hipparcos astrometric catalogue. After deducing accurate 3-D space motions, they found a highly significant group of 8 stars that appear clumped in phase space and confined to a highly inclined orbit.

The most dramatic evidence is surely the highly disrupted Sgr dwarf galaxy identified by Ibata et al. (1994, 1995). These authors used multi-object spectroscopy to uncover an elongated stellar stream moving through the plane on the far side of the Galaxy. The Sgr dwarf is a low mass dwarf spheroidal galaxy about 25 kpc from the Sun that is presently being disrupted by the Galactic tidal field. The long axis of the prolate body (axis ratios $\sim$ 3:1:1) is about 10 kpc, oriented perpendicular to the Galactic plane along $\ell = 6^\circ$ and centered at $b = -15^\circ$. Sgr contains a mix of stellar populations, an extended dark halo (mass $\geq 10^9$ $M_\odot$) and at least four globular clusters (Ibata et al. 1997). The Sgr stream has since been recovered by several photometric surveys (Vivas et al. 2001, Newberg et al. 2002, Ibata et al. 2001c).

N-body simulations have shown that stellar streams are formed when low mass systems are accreted by a large galaxy (e.g., Harding et al. 2001). Streamers remain dynamically cold and identifiable as a kinematic substructure long after they have ceased to be recognizable in star counts against the vast stellar background of the galaxy (Tremaine 1993, Ibata & Lewis 1998, Johnston 1998, Helmi & White 1999).

Within the Galaxy, moving groups can be identified with even limited phase-space information (de Bruijne 1999, de Zeeuw et al. 1999). This also holds for satellites orbiting within the spherical halo, since the debris remains in the plane of motion for at least a few orbits (Lynden-Bell & Lynden-Bell 1995, Johnston et al. 1996). But a satellite experiencing the disk potential no longer conserves its angular momentum and its orbit plane undergoes strong precession (Helmi & White 1999). In Figure 9, we show the sky projection of a satellite 8 Ga after disruption.

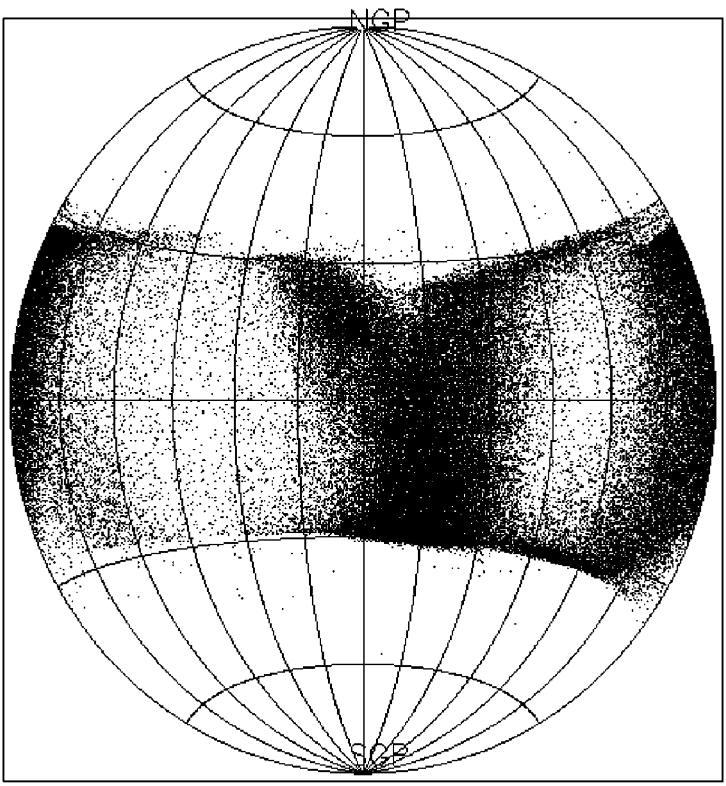


Figure 9 A satellite in orbit about the Milky Way as it would appear after 8 Ga. While stars from the disrupted satellite appear to be dispersed over a very wide region of sky, it will be possible to deduce the parameters of the original event using special techniques (see text). (We acknowledge A. Helmi and S. White for this image.)

These more complex structures are usually highly localized and therefore easy to recognize in the space of conserved quantities like energy and angular momentum for individual stars.

The evolution in phase space of a disrupting satellite is well behaved as its stars become phase mixed. Its phase space flow obeys Liouville's theorem, i.e., the flow is incompressible. Highly intuitive accounts are given elsewhere (Carlberg 1986, Tremaine 1999, Hernquist & Quinn 1988). It should be possible to recognize partially phase-mixed structures that cover the observed space, although special techniques are needed to find them.

Four astrometric space missions are planned for the next decade. These are the proposed German DIVA mission (∼2003); the FAME mission (∼2005) and the pointed SIM mission (∼2005); and the ESA Gaia mission (∼2009) which will observe a billion stars to V $\sim$ 20, with accuracy 10μas at a V $\sim$15. The web sites for these missions are at: http://www.ari.uni-heidelberg.de/diva/, http://aa.usno.navy.mil/FAME/, http://sim.jpl.nasa.gov/, http://astro.estec.esa.nl/GAIA/.

The astrometric missions will derive 6-dimensional phase space coordinates and spectrophotometric properties for millions of stars within a 20 kiloparsec sphere—the Gaiasphere. The ambitious Gaia mission will obtain distances for up to 90 million stars with better than 5% accuracy, and measure proper motions with an accuracy approaching microarcsec per year. If hierarchical CDM is correct, there should be thousands of coherent streamers that make up the outer halo, and hundreds of partially phase-mixed structures within the inner halo. A satellite experiencing the disk potential no longer conserves its angular momentum and its orbit plane undergoes strong precession (see Figure 10*c*,*d*). In Figure 10*a,b*, Helmi et al. (1999) demonstrate the relative ease with which Gaia will identify substructure within the stellar halo.

THE GAIASPHERE AND THE LIMITS OF KNOWLEDGE

Introduction

The ultimate goal of cosmology, both near and far, must be to explain how the Universe has arrived at its present state. It is plausible—although difficult to accept—that nature provides fundamental limits of knowledge, in particular, epochs where the sequence of events are scrambled. Our intuition is that any phase dominated by relaxation or dissipation probably removes more information than it retains.

But could some of the residual inhomogeneities from prehistory have escaped the dissipative process at an early stage? We may not know the answer to this question with absolute certainty for many years. In the absence of certainty, we consider what might be the likely traces of a bygone era prior to the main epoch of baryon dissipation.

Chemical Signatures

A major goal of near-field cosmology is to tag or to associate individual stars with elements of the protocloud. For many halo stars, and some outer bulge stars, this may be possible with phase space information provided by Gaia. But for much of the bulge and the disk, secular processes cause the populations to become relaxed (i.e., the integrals of motion are partially randomized). In order to have any chance of unravelling disk formation, we must explore chemical signatures in the stellar spectrum. Ideally, we would like to tag a large sample of representative stars with a precise time and a precise site of formation.

Over the past four decades, evidence has gradually accumulated (Figure 11) for a large dispersion in metal abundances [X_i/Fe] (particularly n-capture elements) in low metallicity stars relative to solar abundances (Wallerstein et al. 1963, Pagel 1965, Spite & Spite 1978, Truran 1981, Luck & Bond 1985, Clayton 1988, Gilroy et al. 1988, McWilliam et al. 1995, Norris et al. 1996, Burris et al. 2000). Elements like Sr, Ba and Eu show a 300-fold dispersion, although [α/Fe] dispersions are typically an order of magnitude smaller.

In their celebrated paper, Burbidge et al. (1957—B^2FH) demonstrated the likely sites for the synthesis of slow (s) and rapid (r) n-capture elements. The s-process elements (e.g., Sr, Zr, Ba, Ce, La, Pb) are thought to arise from the He-burning phase of intermediate to low mass (AGB) stars ($M < 10\ M_\odot$), although at the lowest metallicities, trace amounts are likely to arise from high mass stars (Burris et al. 2000, Rauscher et al. 2001).

In contrast to the s-process elements, the r-process elements (e.g., Sm, Eu, Gd, Tb, Dy, Ho) cannot be formed during quiescent stellar evolution. While some doubts remain, the most likely site for the r-process appears to be SN II, as originally suggested by B^2FH (see also Wallerstein et al. 1997). Therefore, r-process elements measured from stellar atmospheres reflect conditions in the progenitor cloud. In support of Gilroy et al. (1988), McWilliam et al. (1995) state that the very large scatter means that n-capture element abundances in ultra-metal-poor stars are products of one or very few prior nucleosynthesis events that occurred in the very early, poorly mixed galactic halo, a theme that has been developed by many authors (e.g., Audouze & Silk 1995, Shigeyama & Tsujimoto 1998, Argast et al. 2000, Tsujimoto et al. 2000).

Supernova models produce different yields as a function of progenitor mass, progenitor metallicity, mass cut (what gets ejected compared to what falls back towards the compact central object), and detonation details. The α elements are mainly produced in the hydrostatic burning phase within the pre-supernova star. Thus α yields are not dependent on the mass cut or details of the fallback/explosion mechanism which leads to a much smaller dispersion at low metallicity.

There is no known age-metallicity relation that operates over a useful dynamic range in age and/or metallicity. (This effect is only seen in a small subset of hot metal-rich stars—see "Is There an Age-Metallicity Relation?" above). Such a relation would require the metals to be well mixed over large volumes of the ISM.

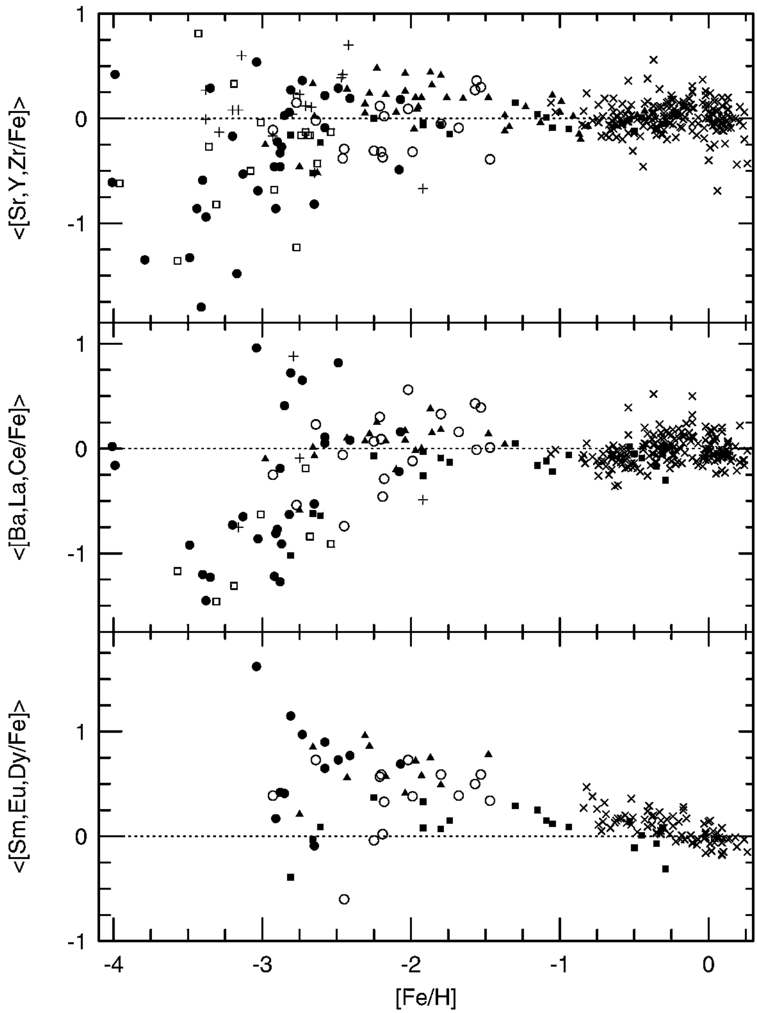


Figure 11 Mean relative abundance ratios of light s-process elements (top panel), heavy s-process elements (middle panel), and r-process elements (bottom panel) as functions of [Fe/H]. In each panel, the dotted horizontal lines represent the solar abundance ratios of these elements. The references for the data points are given in Wallerstein et al. (1997). (We acknowledge C. Sneden for this figure.)

For the forseeable future, it seems that only a small fraction of stars can be dated directly (see "Stellar Age Dating" above).

Reconstructing Ancient Star Groups

We now conjecture that the heavy element metallicity dispersion may provide a way forward for tagging groups of stars to common sites of formation. With sufficiently detailed spectral line information, it is feasible that the chemical tagging will allow temporal sequencing of a large fraction of stars in a manner analogous to building a family tree through DNA sequencing.

Most stars are born within rich clusters of many hundreds to many thousands of stars (Clarke et al. 2000, Carpenter 2000). McKee & Tan (2002) propose that high-mass stars form in the cores of strongly self-gravitating and turbulent gas clouds. The low mass stars form within the cloud outside the core, presumably at about the same time or shortly after the high-mass stars have formed. The precise sequence of events which give rise to a high-mass star is a topic of great interest and heated debate in contemporary astrophysics (e.g., Stahler et al. 2000).

A necessary condition for chemical tagging is that the progenitor cloud is uniformly mixed in key chemical elements before the first stars are formed. Another possibility is that a few high-mass stars form shortly after the cloud assembles, and enrich the cloud fairly uniformly. Both scenarios would help to ensure that long-lived stars have identical abundances in certain key elements before the onset of low-mass star formation.

For either statement to be true, an important requirement is that open clusters of any age have essentially zero dispersion in some key metals with respect to Fe. There has been very little work on heavy element abundances in open clusters. The target clusters must have reliable astrometry so as to minimize pollution from stars not associated with the cluster (Quillen 2002).

If our requirement is found not to be true, then either the progenitor clouds are not well mixed or high-mass stars are formed after most low-mass stars. A more fundamental consequence is that a direct unravelling of the disk into its constituent star groups would be impossible; in other words, the epoch of dissipation cannot be unravelled after all.

Consider the (extraordinary) possibility that we *could* put many coeval star groups back together over the entire age of the Galaxy. This would provide an accurate age for the star groups either through the color-magnitude diagram, or through association with those stars within each group that have [n-capture/Fe] $\gg 0$ and can therefore be radioactively dated. This would provide key information on the chemical evolution history for each of the main components of the Galaxy.

But what about the formation site? The kinematic signatures will identify which component of the Galaxy the reconstructed star group belongs to, but not specifically where in the Galactic component (e.g., radius) the star group came into existence. For stars in the thin disk and bulge, the stellar kinematics will have been much affected by the bar and spiral waves; it will no longer be possible to estimate their birthplace from their kinematics. Our expectation is that the derived family tree will severely restrict the possible scenarios involved in the dissipation process. In this respect, a sufficiently detailed model may be able to locate each star group within the simulated time sequence.

In addition to open clusters, we have already argued that the thick disk is an extremely important fossil of the processes behind disk formation. The thick disk is thought to be a snap-frozen relic of the early disk, heated vertically by the infall of an intermediate mass satellite. Chemical tagging of stars that make up the thick disk would provide clues on the formation of the first star clusters in the early disk.

Chemical Abundance Space

An intriguing prospect is that reconstructed star clusters can be placed into an evolutionary sequence, i.e., a family tree, based on their chemical signatures. Let us suppose that a star cluster has accurate chemical abundances determined for a large number n of elements (including isotopes). This gives it a unique location in an n-dimensional space compared to m other star clusters within that space. We write the chemical abundance space as $\mathcal{C}(\mathrm{Fe/H}, \mathrm{X_1/Fe}, \mathrm{X_2/Fe}, \ldots)$ where X_1, $X_2 \ldots$ are the independent chemical elements that define the space (i.e., elements whose abundances are not rigidly coupled to other elements).

The size of n is unlikely to exceed about 50 for the foreseeable future. Hill et al. (2002) present exquisite data for the metal-poor star CS 31082-001, where abundance estimates are obtained for a total of 44 elements, almost half the entire periodic table (see also Cayrel et al. 2001). In Figure 12, we show what is now possible for another metal-poor star, CS 22892-052 (Sneden et al. 2001a). The α elements and r-process elements, and maybe a few canonical s-process elements at low [Fe/H], provide information on the cloud abundances prior to star formation, although combinations of these are likely to be coupled (Heger & Woosley 2001, Sneden et al. 2001a). There are 24 r-process elements that have been clearly identified in stellar spectra (Wallerstein et al. 1997).

The size of m is likely to be exceedingly large for the thin disk where most of the baryons reside. For a rough estimate, we take the age of the disk to be 10 Ga. If there is a unique SN II enrichment event every 100 years, we expect of order 10^8 formation sites. Typically, a SN II event sweeps up a constant mass of 5×10^4 $M_\odot$ (Ryan et al. 1996, Shigeyama & Tsujimoto 1998). Simple chemical evolution models indicate that this must be of the right order to explain the metallicity dispersion at low [Fe/H] (Argast et al. 2000). Roughly speaking, there have been 10^3 generations of clouds since the disk formed, with about 10^5 clouds in each star-forming generation, such that cloud formation and dispersal cycle on a 10^7 year timescale (Elmegreen et al. 2000).

Whereas the total number of star clusters over the lifetime of the thin disk is very large, the size of m for the stellar halo (Harding et al. 2001), and maybe the thick disk (Kroupa 2002), is likely to be significantly smaller. Our primary interest is the oldest star clusters. Reconstructing star clusters within the thick disk is a particularly interesting prospect since the disk is likely to have formed within 1–1.5 Ga of the main epoch of baryon dissipation (Prochaska et al. 2000).

The task of establishing up to 10^8 unique chemical signatures may appear to be a hopeless proposition with current technology. But it is worth noting that more than 60 of the chemical elements ($Z > 30$) arise from n-capture processes. Let us suppose that half of these are detectable for a given star. We would only need to be able to measure two distinct abundances for each of these elements in order to

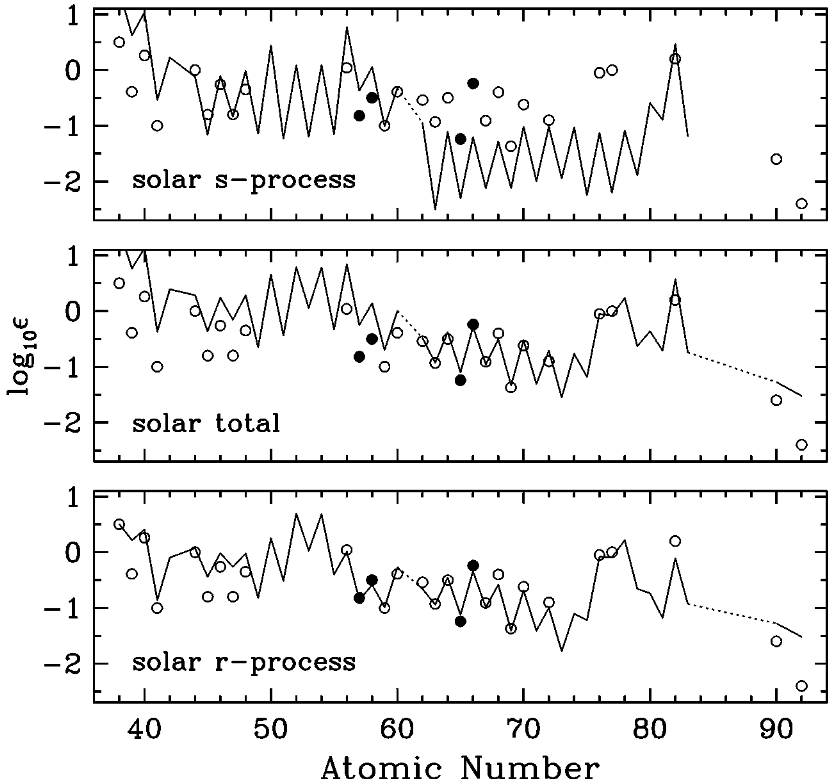


Figure 12 CS 22892-052 n-capture abundances (points) taken from Sneden et al. (2000) and scaled solar system abundances (solid and dashed lines) taken from Burris et al. (2000). Many of the heavy elements conform to the solar system r-process abundance pattern, although some elements show the hallmark of the s-process. This figure was originally presented in Sneden et al. (2001a).

achieve 10^9 independent cells in $\mathcal{C}$-space. If many of the element abundances are found to be *rigidly* coupled, of course the parameter space would be much smaller.

It may not be necessary to measure as many as 30 elements if some can be found which are highly decoupled and exhibit large relative dispersions from star to star. Burris et al. (2000) demonstrate one such element pair, i.e., [Ba/Fe] and [Sr/Fe]. It is difficult at this stage to suggest which elements are most suited to chemical tagging. In part, this depends on the precise details and mechanism of formation of the n-capture elements at low [Fe/H].

The element abundances [X_i/Fe] show three main peaks at $Z \approx 26$, $Z \approx 52$, and $Z \approx 78$; the last two peaks are evident in Figure 12. There have been suggestions that the r-process gives rise to random abundance patterns (e.g., Goriely & Arnould 1996), although this is not supported by new observations of a few metal-poor stars.

Heavy r-process elements around the second peak compared to the Sun appear to show a universal abundance pattern (Sneden et al. 2000, Cayrel et al. 2001, Hill et al. 2002). However, Hill et al. find that the third peak and actinide elements ($Z \geq 90$) are decoupled from elements in the second peak. We suspect that there may be a substantial number of suitable elements ($\sim$10) which could define a sufficiently large parameter space.

Our ability to detect structure in $\mathcal{C}$-space depends on how precisely we can measure abundance differences between stars. It may be possible to construct a large database of differential abundances from echelle spectra, with a precision of 0.05 dex or better; differential abundances are preferred here to reduce the effects of systematic error.

Chemical Trajectories

Our simple picture assumes that a cloud forms with a unique chemical signature, or that shortly after the cloud collapses, one or two massive SN IIs enrich the cloud with unique yields which add to the existing chemical signature. The low-mass population forms with this unique chemical signature. If the star-formation efficiency is high ($\gtrsim$30%), the star group stays bound although the remaining gas is blown away. If the star-formation efficiency is low ($\lesssim$10%), the star cluster disperses along with the gas. In a closed box model, the dispersed gas reforms a cloud at a later stage.

In the closed box model, each successive generation of supernovae produces stellar populations with progressive enrichments. These will lie along a trajectory in $\mathcal{C}$-space which can be identified in principle using minimum spanning tree methods (Sedgewick 1992). The overall distribution of the trajectories will be affected by fundamental processes like the star formation efficiency, the star formation timescale, the mixing efficiency, the mixing timescale, and the satellite galaxy infall rate.

As we approach solar levels of metallicity in [Fe/H], the vast number of trajectories will converge. By [Fe/H] ≈ -2.5, AGB stars will have substantially raised the s-process element abundances; by [Fe/H] ≈ -1, Type Ia supernovae will have raised the Fe-group abundances. Star clusters that appear to originate at the same location in this $\mathcal{C}$-space may simply reflect a common formation site, i.e., the resolution limit we can expect to achieve in configuration space. The ability to identify common formation sites rests on accurate differential abundance analyses (Edvardsson et al. 1993, Prochaska et al. 2000).

Even with a well-established family tree based on chemical trajectories in the chemical $\mathcal{C}$-space, this information may not give a clear indication of the original location within the protocloud or Galactic component. This will come in the future from realistic baryon dissipation models. Forward evolution of any proposed model must be able to produce the chemical tree.

However, the $\mathcal{C}$-space will provide a vast amount of information on chemical evolution history. It should be possible to detect the evolution of the cluster mass function with cosmic time (Kroupa 2002), the epoch of a starburst phase and/or associated mass ejection of metals to the halo (Renzini 2001), and/or satellite infall (Noguchi 1998).

As we go back in time to the formation of the disk, we approach the chemical state laid down by population III stars. The lack of stars below [Fe/H] ≈ -5 suggests that the protocloud was initially enriched by the first generation of stars (Argast et al. 2000). However, the apparent absence of any remnants of population III remains a puzzle: Its stars may have had a top-heavy initial mass function, or have dispersed into the intra-group medium of the Local Group. If one could unravel the abundances of heavy elements at the time of disk formation, this would greatly improve the precision of nucleo-cosmochronology (see "Stellar Age Dating" above).

Candidates for Chemical Tagging

Chemical tagging will not be possible for all stars. In hot stars, our ability to measure abundances is reduced by the stellar rotation and lack of transitions for many ions in the optical. The ideal candidates are the evolved FGK stars that are numerous and intrinsically bright. These can be observed at echelle resolutions ($R > 30{,}000$) over the full Gaiasphere. Moreover, giants have deep, low-density atmospheres that produce strong low-ionization absorption lines compared to higher gravity atmospheres. Even in the presence of significant line blending, with sufficient signal, it should be possible to derive abundance information by comparing the fine structure information with accurate stellar synthesis models. Detailed abundances of large numbers of F and G subgiants would be particularly useful, if it becomes possible to make such studies, because direct relative ages can be derived for these stars from their observed luminosities.

It is not clear at what [Fe/H] the r-process elements become swamped by the ubiquitous Fe-group and s-process elements. At a resolution of $R \sim 10^5$, many r-process elements can be seen in the solar spectrum, although the signal-to-noise ratio of about 1000 is needed, and even then the spectral lines are often badly blended (Kurucz 1991, 1995). Travaglio et al. (1999) suggest that the s-process does not become significant until [Fe/H] ≈ -1 because of the need for pre-existing seed nuclei (Spite & Spite 1978, Truran 1981), although Pagel & Tautvaisiene (1997) argue for some s-process production at [Fe/H] ~ -2.5. Prochaska et al. (2000) detected Ba, Y and Eu in a snapshot survey of thick disk G dwarfs in the solar neighborhood with $-1.1 \lesssim$ [Fe/H] $\lesssim -0.5$. This survey only managed to detect a few transitions in each element, although their spectral coverage was redward of 440 nm with SNR ≈ 100 per pixel at $R \simeq 50{,}000$. Longer exposures with $R \sim 10^5$ and spectral coverage down to 300 nm would have detected more heavy elements.

Summary

In our view, observations of nucleosynthetic signatures of metal-poor stars provide a cornerstone of near-field cosmology. Success in this arena requires major progress across a wide front, including better atomic parameters (Truran et al. 2001), improved supernova models, better stellar synthesis codes and more realistic galaxy formation models. There are no stellar evolutionary models that lead to a self-consistent detonation and deflagration in a core-collapse supernova event or, for that matter, detonation in a thermonuclear explosive event. Realistic chemical production at the onset of the supernova stage requires a proper accounting of a large number of isotope networks (400–2500) that cannot be adequately simulated yet. Modern computers have only recently conquered relatively simple α networks involving 13 isotopes. The inexorable march of computer power will greatly assist here.

There is also a key experimental front both in terms of laboratory simulations of nucleosynthesis, and the need for major developments in astronomical instrumentation (see "Epilogue: Challenges for the Future"). Many authors (e.g., Sneden et al. 2001b) have stressed the importance of greatly improving the accuracy of transition probabilities and reaction rates for both heavy and light ion interactions. This will be possible with the new generation of high-intensity accelerators and radioactive-beam instruments (Käppeler et al. 1998, see Manuel 2000).

Progress on all fronts will require iteration between the different strands. Already, relative r-process and α element abundances for metal-poor stars have begun to constrain the yields for different stellar masses and associated mass cuts of progenitor supernovae (Mathews et al. 1992, Travaglio et al. 1998, Ishimaru & Wanajo 2000).

It is an intriguing thought that one day we may be able to identify hundreds or thousands of stars throughout the Gaiasphere that were born within the same cloud as the Sun.

EPILOGUE: CHALLENGES FOR THE FUTURE

Throughout this review, we have identified fossil signatures of galaxy formation and evolution which are accessible within the Galaxy. These signatures allow us to probe back to early epochs. We believe that the near-field universe has the same level of importance as the far-field universe for a comprehensive understanding of galaxy formation and evolution.

We have argued that understanding galaxy formation is primarily about understanding baryon dissipation within the CDM hierarchy; to a large extent, this means understanding the formation of disks. The question we seek to address is whether this can ever be unravelled in the near or far field. Dynamical information was certainly lost at several stages of this process, but we should look for preserved signatures of the different phases of galaxy formation.

Far-field cosmology can show how the light-weighted, integrated properties of disks change with cosmic time. While light-weighted properties provide some constraint on simulations of the future, they obscure some of the key processes during dissipation. The great advantage of near field studies is the ability to derive ages and detailed abundances for individual stars within galaxies of the Local Group.

We have addressed the issue of information content within the Gaiasphere. The detailed information that is possible on ages, kinematics, and chemical properties for a billion stars—which we see as the limit of observational knowledge over the next two decades—may reveal vast complexity throughout the disk. It may not be possible to perceive the sequence of events directly. However, we are optimistic that future dissipational models may provide unique connections with the observed complexity.

It is clear that detailed high resolution abundance studies of large samples of galactic stars will be crucial for the future of fossil astronomy. Christlieb et al. (2000) find that strong r-process enhanced stars can be identified with $R = 20{,}000$ and $\mathrm{SNR} = 30\ \mathrm{pix}^{-1}$ from the Eu lines. Both UVES and HDS can reach this sensitivity for a $B = 15$ star in just 20 min. But the detailed abundance work requires a substantial increase in the resolving power. Cayrel et al. (2001) and Hill et al. (2002) demonstrate the exquisite quality and capability of high resolution spectroscopy for CS 31082-001 where they achieve a $\mathrm{SNR} \simeq 300$ in just four hours with UVES at $R \simeq 60{,}000$. (See Figure 12 for another excellent example.) But these are bright stars with some of the most extreme overabundances of r-process elements observed to date.

Gaia will provide accurate distances, ages and space motions for a vast number of stars, separate with great precision the various Galactic components, and identify most of the substructure in the outer bulge and halo. High resolution spectrographs like UVES on the VLT, HDS on Subaru, and HIRES on Keck are starting to reveal the rich seam of information in stellar abundances.

We must stress that in order to access a representative sample of the Gaiasphere, this will require a new generation of ground-based instruments, in particular, a multi-object echelle spectrograph with good blue response on a large aperture telescope. We close with a brief discussion of what is required.

As an example, the FGK sub-giants and giants are a characteristic population which could be studied over the full extent of the Gaiasphere, as discussed in the previous section. Typical stars will have magnitudes around 17–18, which is at the limit of the state-of-the-art spectrometer UVES at $R \simeq 60{,}000$.

We now consider what it would take to achieve high resolution spectroscopy for a representative sample of stars within the Gaiasphere. Our baseline instrument UVES achieves cross-dispersed echelle spectroscopy in two wavelength ranges (300–500 nm, 420–1100 nm). For a limiting resolution of $R \simeq 60{,}000$ for a single night exposure, the sensitivity limit is $U \approx 18.0$ and $V \approx 19.5$ in the blue and red arms. UVES now allows multi-object echelle spectroscopy (red arm) from fiber inputs provided by the Fiber Large Array Multi-Element Spectrograph (FLAMES). This will enable the simultaneous observation of eight objects over a $25'$ field of view.

Existing multi-object spectrographs are mostly used redward of 450 nm because of the fundamental limits of conventional optical fibers. Normal fibers transmit light through total internal reflection but blue light is Rayleigh scattered below 450 nm. Recently, photonic crystal (microstructured) fibers threaded with air channels

(Cregan et al. 1999) have been shown to be highly transmissive down to the atmospheric cut-off. This is a technical breakthrough for blue multi-object spectroscopy.

We believe there is a real need for a high-resolution spectrograph that can reach hundreds or even thousands of stars in a square degree or more. The Gemini Wide Field proposal currently under discussion provides an opportunity for this kind of instrument (S. Barden, personal communication). Such an instrument will be expensive and technically challenging, but we believe this must be tackled if we are to ever unravel the formation of the Galaxy.

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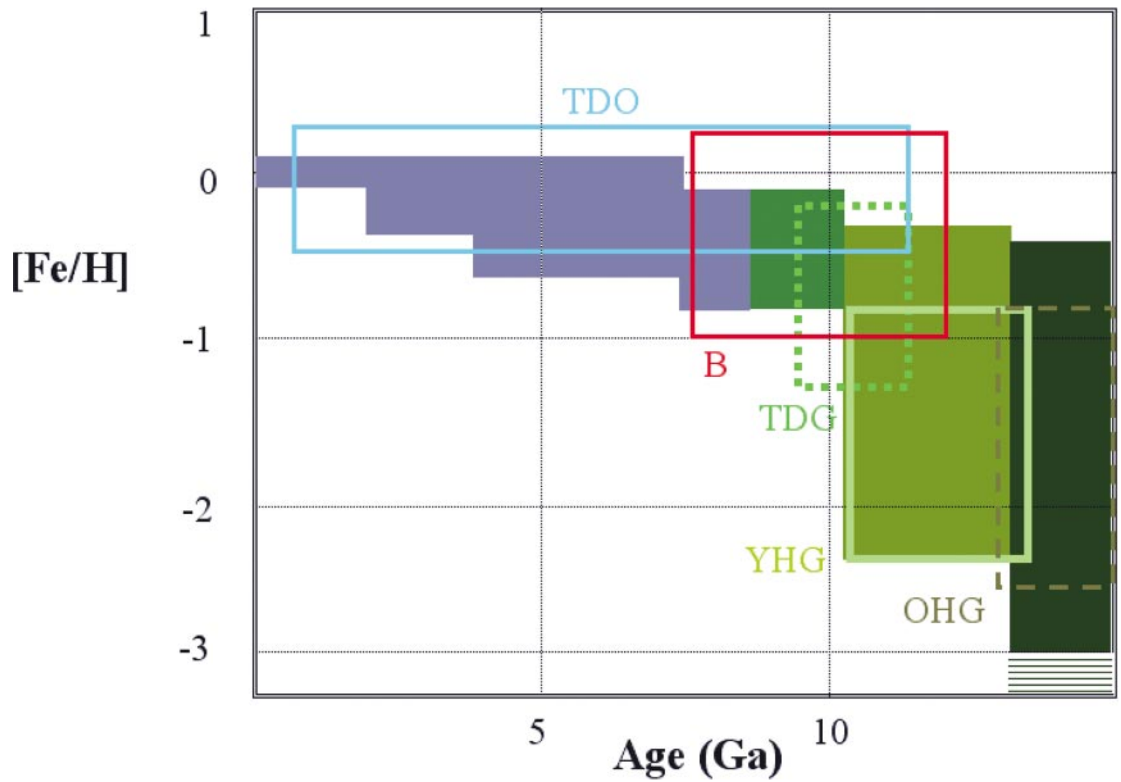

Figure 2 The age-metallicity relation of the Galaxy for the different components (see text): TDO—thin disk open clusters; TDG—thick disk globulars; B—bulge; YHG—young halo globulars; OHG—old halo globulars. The blue corresponds to thin disk field stars, the green to thick disk field stars, and the black shows the distribution of halo field stars extending down to [Fe/H] = −5.

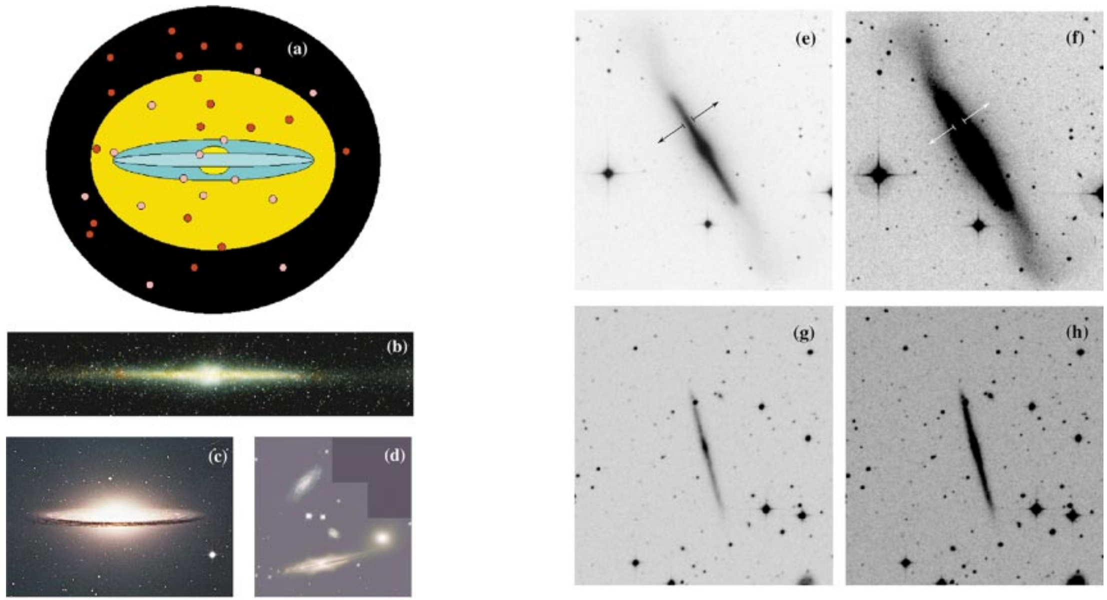

Figure 3 (*a*) Sketch of Milky Way showing the stellar disk (*light blue*), thick disk (*dark blue*), stellar bulge (*yellow*), stellar halo (*mustard yellow*), dark halo (*black*) and globular cluster system (*filled circles*). The radius of the stellar disk is roughly 15 kpc. The baryon and dark halos extend to a radius of at least 100 kpc. (*b*) Infrared image of the Milky Way taken by the DIRBE instrument on board the Cosmic Background Explorer (COBE) Satellite. [We acknowledge the NASA Goddard Space Flight Center and the COBE Science Working Group for this image.] (*c*) M104, a normal disk galaxy with a large stellar bulge (from AAO). (*d*) Hubble Heritage image of the compact group Hickson 87; one galaxy has a peanut-shaped stellar bulge due to dynamical interaction with other group members. (*e*) Image of the SO galaxy NGC 4762 (Digital Sky Survey) shows its thin disk and stellar bulge. (*f*) A deeper image of NGC 4762 (DSS) shows its more extended thick disk. The base of the arrows in (*e*) and (*f*) shows the height above the plane at which the thick disk becomes brighter than the thin disk (Tsikoudi 1980). (*g*) Image of the pure disk galaxy IC 5249 (DSS) shows its thin disk and no stellar bulge. (*h*) A deeper image of IC 5249 (DSS) shows no visible thick disk, although a very faint thick disk has been detected in deep surface photometry.

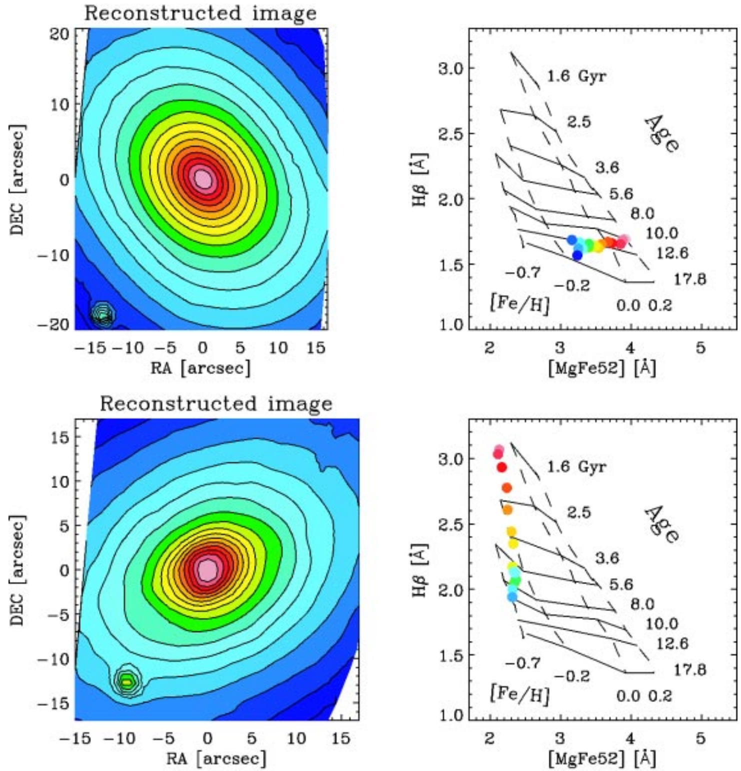

Figure 6 Sauron integral field observations of NGC 4365 (*top panels*) and NGC 4150 (*bottom panels*). Left panels: reconstructed surface brightness maps. Right panels: Hβ versus [MgFe5270] diagram. The points were derived from the Sauron datacubes by averaging along the corresponding color-coded isophotes (Bacon et al. 2001, Davies et al. 2001). The [Fe/H] vs. age grid is derived from Vazdekis (1999). [We acknowledge Harald Kuntschner and the Sauron team for these images.]

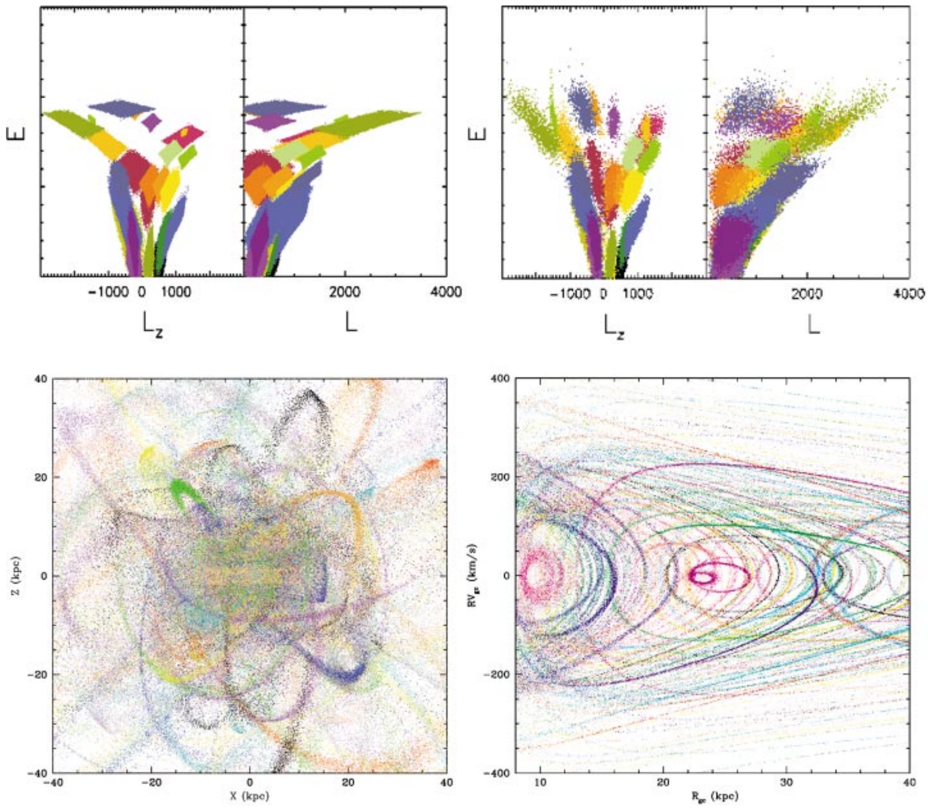

Figure 10 (*a*) Initial distribution of particles for 33 systems falling into the Galactic halo in integral of motion space. (*b*) The final distribution of particles in (*a*) after 12 Ga; the data points have been convolved with the errors expected for Gaia. [We acknowledge A. Helmi for these images.] (*c*) A simulation of the baryon halo built up through accretion of 100 satellite galaxies. The different colors show the disrupted remnants of individual satellites. (*d*) This is the same simulation shown in a different coordinate frame, i.e., the orbit radius (horizontal) plotted against the observed radial velocity (vertical) of the star. [We acknowledge P. Harding and H. Morrison for these images.]