26. A. Udalski *et al.*, *Acta Astron.* **43**, 289 (1993).
27. C. Alard, S. Mao, J. Guibert, *Astron. Astrophys.* **300**, L17 (1996).
28. C. Alcock *et al.*, *Astrophys. J.* **499**, L9 (1998).
29. A. Becker *et al.*, in preparation; C. Alcock *et al.*, in preparation.
30. K. Sahu, *Nature* **370**, 275 (1994).
31. D. Zaritsky and D. Lin, *Astron J.* **114**, 2545 (1998).
32. H.-S. Zhao, in *Proceedings of the Third Stromlo Symposium*, B. Gibson, T. Axelrod, M. Putnam, Eds. (Astronomical Society of the Pacific, San Francisco, CA, 1999), pp. 125–129.
33. N. Evans *et al.*, *Astrophys. J.* **501**, 45 (1998).
34. A specific proposal is described by C. Stubbs [in *Proceedings of the Third Stromlo Symposium*, B. Gibson, T. Axelrod, M. Putnam, Eds. (Astronomical Society of the Pacific, San Francisco, CA, 1999), pp. 503–514]. Theoretical investigations of what could be learned from this proposed survey are described by A. Gould [*Astrophys. J.* **517**, 719 (1999)] and by N. Evans and E. Kerins (preprint available at http://xxx.lanl.gov/abs/astro-ph/9909254).
35. B. Hansen, *Nature* **394**, 860 (1998); *Astrophys. J.* **520**, 680 (1999).
36. R. Ibata *et al.*, *Astrophys. J.* **524**, 95 (1999). R. A. Méndez and D. Minniti (preprint available at http://xxx.lanl.gov/abs/astro-ph/9908330) have shown that there are 10 similar objects in the Southern HDF.
37. R. Williams *et al.*, *Astron J.* **112**, 1335 (1996).
38. R. Peccei and H. Quinn, *Phys. Rev. Lett.* **38**, 1440 (1977).
39. P. Sikivie *Phys. Rev. Lett.* **51**, 1415 (1983).
40. C. Hagmann *et al.*, *Phys. Rev. Lett.* **80**, 2043 (1998).

41. I thank my colleagues on the MACHO Project for their help and advice. Everything I know in this field has been learned through working with them. I also thank M. Merrifield, B. Sadoulet, and K. van Bibber for supplying figures. Work performed at the Lawrence Livermore National Laboratory is supported by the U.S. Department of Energy under contract W7405-ENG-48.

REVIEW

The Baryon Halo of the Milky Way: A Fossil Record of Its Formation

Joss Bland-Hawthorn[1] and Ken Freeman[2]

Astronomers believe that the baryon (stellar) halo of the Milky Way retains a fossil imprint of how it was formed. But a vast literature shows that the struggle to interpret the observations within a consistent framework continues. The evidence indicates that the halo has built up through a process of accretion and merging over billions of years, which is still going on at a low level. Future satellite missions to derive three-dimensional space motions and heavy element (metal) abundances for a billion stars will disentangle the existing web and elucidate how galaxies like our own came into existence.

In recent years, we have passed an interesting landmark. With the most powerful telescopes, we can now reach as many galaxies as there are stars in our Galaxy: about 100 billion sources. The oldest stars in our Galaxy are of an age similar to the light travel (look back) time of the most distant galaxies in the Hubble Deep Field (*1*). For these galaxies, the cosmological redshift (*2*) measured from galaxy spectra presently takes us to within 5% of the origin of cosmic time—the Big Bang. For the stars, their upper atmospheres provide fossil evidence of the available metals at the time of formation, and astronomers use a variety of techniques for dating a star from its spectrum (*3*). 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 which led to the formation of galaxies like the Milky Way. But the oldest stars, like the most distant galaxies, are exceedingly faint and lie at the limit of modern observing techniques.

Galaxies as we see them now, at low redshift, can be divided into two classes: 80% are gas-rich (mostly disk spiral and irregular galaxies) and 20% are gas-poor [including the elliptical, earliest-type (S0) and dwarf spheroidal galaxies]. In the special environment of dense galaxy clusters, only about 40% of the galaxies are gas-rich. But in the early universe, the Hubble Deep Field has shown us that galaxies are mostly irregular. Broadly speaking, disk spirals and small spheroids are supported by rotation, whereas large spheroids are supported by random stellar motions and have little or no rotation. To confuse matters, some spheroidal galaxies have a disk component, and most disk galaxies like the Milky Way have spheroidal components. While the various galaxy types pose a challenge to any formation theory, the relative importance of the disk and the spheroid accounts for much of the variety in galaxy morphologies (*4*).

When the early universe was cool enough to form atoms, dark matter and baryons were thought to have co-existed in small clumps (*5*). As time progressed, gravity caused the clumps to cluster together. This picture forms the basis for the hierarchical cold dark matter (CDM) model, which places galaxy formation within a cosmological context. Sophisticated N-body CDM simulations of the growth of structures in the early Universe have been successful at reproducing some observational properties of galaxies (*5*). Current models include gas pressure, metal production, radiative cooling and heating, and prescriptions for star formation. The models predict that lower mass clumps are denser, which is borne out by theory (*6*) and observation (*7*). Moreover, the outer parts of galaxies are expected to be accreting low mass (10^7 to 10^8 $M_\odot$) objects even to the present day (*8*, *9*).

The orbital time scales of stars in the outer parts of galaxies are several billion years and it is here we would expect to find surviving remnants of accretion. Observational studies of the Galactic halo attempt to find stars of a given type within a localized region of six-dimensional phase space where each star has a velocity (v_x, v_y, v_z) and a location (x, y, z) within the Galaxy. Most stellar types can exist over a range of metal abundances. The heavy element abundance can provide information on when in the Galaxy's history the star was formed (*3*). The published literature on the baryon halo is very extensive and, for the most part, in a state of flux. However, most astronomers agree that tantalizing clues are beginning to emerge of how the Galaxy materialized out of the hot, dense, early universe. In this review, we focus on the fossil evidence from the baryon halo of the Milky Way (near-field cosmology) with occasional reference to the high redshift universe (far-field cosmology).

The Milky Way

Our Galaxy, the Milky Way, can be divided into three parts: a baryon halo (which includes the stellar halo and globular clusters), a baryon disk with the associated stellar bulge, and an unseen dark (non-baryonic) halo, which accounts for about 95% of the mass of the Galaxy (*10*) (Fig. 1). The disk and the dark halo are addressed in other review articles in this special issue (*11*). While the gravitational influence of dark ha-

---

[1]Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia. [2]Mount Stromlo and Siding Spring Observatories, Private Bag, Weston Creek ACT 2611, Australia.

To whom correspondence should be addressed: E-mail: jbh@aaoepp.aao.gov.au

los is easily observed through the rotation of the gas in the outer parts of galaxies, its character is one of the fundamental, unanswered questions of our day.

The thin, baryon disk accounts for about 90% of the visible light in the Milky Way (5% by mass) as we observe from the thin band of light which arcs across the night sky. Almost all of the stars seen by the human eye, and in most astronomical photographs, are from the thin disk and the bulge. Since the 1980s, we have come to recognize a faint, thick disk of old stars extending to 1 to 2 kiloparsecs (kpc) beyond the thin disk (*12*).

The stellar disk is in rapid, differential rotation and contains stars with a very wide spread of ages and colors. The patchiness of the light distribution in Fig. 2 arises from giant clouds of gas and dust which absorb the light. These clouds are where stars are born and where high mass stars return their processed metals to the surrounding medium through supernova explosions. Without these gas clouds, the Milky Way would be several times brighter to the naked eye. From the Southern Hemisphere, the stellar bulge (Fig. 2) is visible to the naked eye in the direction of the constellation Sagittarius. The stellar nucleus is obscured by gas and dust but it can be detected at infrared wavelengths (*13*).

The baryon halo extends to a radius of about 100 kpc. It rotates very slowly compared to the disk and may even be counter-rotating. The stellar halo is recognized in catalogs of blue horizontal branch stars (*14*, *15*), RR Lyrae stars (*16*), and metal-weak red giant stars (*17*). The Galactic halo is very diffuse and faint: Its total surface brightness in the vicinity of the sun is several hundred times fainter than the dark sky and is difficult to detect from our location in the Galaxy without modern astronomical techniques.

The baryon halo includes the system of globular clusters dispersed throughout the inner and outer halo (Fig. 1). Only a few globular clusters are visible to the naked eye, although more than a third of the 150 Galactic globular clusters are visible with a pair of high-quality binoculars. Globular clusters are dense swarms of about 100,000 stars and constitute the most ancient stellar systems in the Galaxy. Most are so old [13 ± 2.5 billion years ago (Ga)] that they challenge age estimates of the universe derived from Hubble's constant (*18*).

While the baryon halo accounts for only a small fraction (2%) of the light, and an even smaller fraction (<0.2%) of the total mass, it plays a key role in unraveling the sequence of events involved in galaxy formation. Paleontologists prefer to hunt for fossils in remote locations rather than sites of ongoing human activity. Similarly, the remoteness of the outer halo appears to preserve a fossil record that astronomers are only now beginning to read (*19*).

The Stellar Bulge

The stellar bulge is a major element of galaxy classification schemes (*20*) (Fig. 3). Some disk galaxies have large and luminous bulges (for example, M31), while others do not (for example, M33). The so-called early-type galaxies have large bulges and spiral patterns that are tightly wrapped, while the late-type galaxies have small bulges and open spiral patterns. The earliest-type disk galaxies (called S0 galaxies) can have bulges that are brighter than the disk (*21*).

The shape of the inner rotation is tightly coupled to the underlying disk and bulge structure (*22*). Photometrically predicted curves for the gas, disk and bulge, reproduce the observed optical rotation curves of 98% of galaxies drawn from a survey of 1355 disk galaxies (*23*). Dark matter dominates the gravitational field only in the outer halo.

Studies of individual bulge stars in the Galaxy have a rich history (*24*). The bulge is distinct from the faint stellar halo and the thick disk, as demonstrated by the 1400 RR Lyrae variable stars identified by the DUO microlensing survey (*25*). While most RR Lyrae are associated with the thick disk and the halo, about 7% are concentrated in the bulge.

The characteristic age of spiral bulges is traditionally assumed to be old but is in fact poorly known, even for the Galaxy (*26*). The existence of bulge RR Lyrae stars indicates that some fraction of the Galactic bulge is old. Furthermore, the color-magnitude sequence derived from the Hubble Space Telescope (HST) (*27*) shows that the bulge is predominantly old. But, to confuse matters, the optical and near-infrared colors of many bulges are similar to their disk, and suggest a wide spread of ages (*28*).

McWilliam and Rich (*29*) obtained [Fe/H] abundances for 14 red giant stars in the bulge of the Milky Way from high-resolution spectra. They found that, while there is a wide range, the abundances ([Fe/H] ≈ −0.25) are closer to the abundances found in older stars of the metal rich disk than to abundances found in the old metal poor stars in the halo and in globular clusters, in agreement with the abundances of planetary nebulae in the Galactic bulge (*30*). We know from radioactive dating, white dwarf cooling, and red giant isochrones that the age of the Galactic disk lies in the range 8 to 12 Ga (*31*, *32*).

At infrared wavelengths, the Milky Way is sufficiently transparent that starlight from most parts of the Galaxy arrives at Earth. The near- and mid-infrared all-sky maps obtained by the Cosmic Background Explorer (COBE) and the Diffuse Infrared Background Experiment (DIRBE) space mission have been inverted and transformed to the reference frame of an external observer (*33*) (Fig. 4). On closer inspection, the Galactic bulge is found to be triaxial (1:0.6:0.4), which indicates the presence of a stellar bar (*34*). Binney and Merrifield (*35*) have summarized the evi-

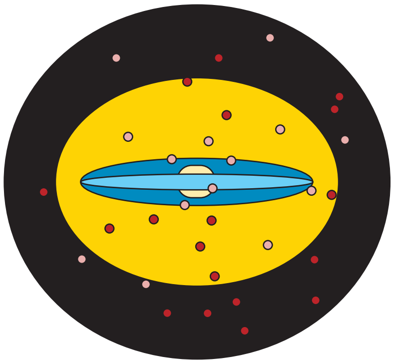


Fig. 1. Schematic of Milky Way showing the stellar disk (light blue), the thick disk (dark blue), stellar bulge (yellow), stellar halo (mustard yellow), dark halo (black), and globular cluster system (filled circles). The stellar disk is about 30 kpc (100,000 light years) in diameter. The baryon and dark halos extend to a radius of at least 100 kpc.

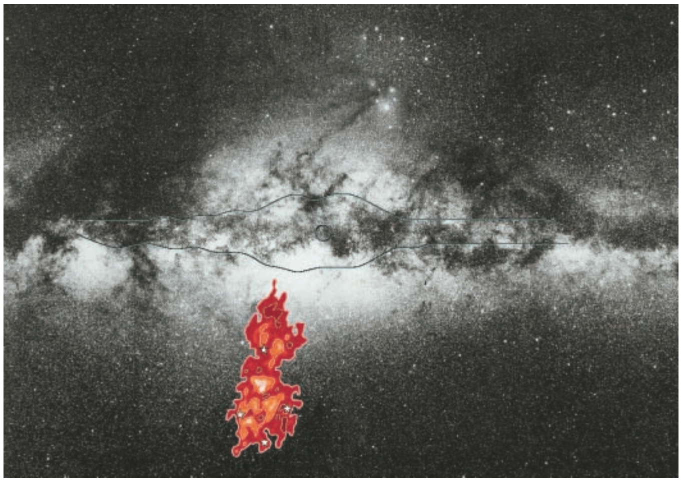


Fig. 2. Optical image of the Milky Way with the Sagittarius dwarf galaxy overlaid. The satellite is being disrupted by the Galaxy while moving through the disk. [Image from G. Gilmore and R. Sword]

dence for a bar from gas motions in the disk.

Because there are many pure disk galaxies (*36*), bulges cannot be an essential element of galaxy formation. In fact, there is good evidence that small bulges and large bulges are formed through different processes (*37*). The larger bulges show a marked overabundance of Mg relative to Fe (*38*): This is the same trend seen in elliptical galaxies. For the bulge of M31, where there is a wide spread of [Fe/H] abundances, there is no discernible abundance gradient out to 40-kpc radius (*39*, *40*). These observations suggest that large bulges, like bright ellipticals, formed quickly on a time scale no longer than 1 Gy. In this scenario, the Mg/Fe trend reflects the output of type II supernovae in the first major burst of star formation. The starburst-driven winds heat up or drive away excess gas so that type Ia supernovae are unable to enrich the gas with Fe. The photometric radial profiles ($r^{1/4}$-law) and lack of metal gradients indicate a high degree of dynamical mixing and relaxation consistent with a fast collapse.

Like the small bulge of the Milky Way, a majority of small bulges have a boxy structure and exponential radial profiles when seen edge on. Three-dimensional N-body simulations of self-gravitating disks show how boxy bar-like bulges can develop from the instabilities of the disks (*41*, *42*). Kuijken and Merrifield (*43*) devised a kinematic test for verifying the presence of a bar in a disk galaxy seen edge-on. This test was applied to 15 boxy-bulge systems and 7 spheroidal-bulge systems (*44*). Most of the boxy-bulge systems passed the test, whereas none of the spheroidal-bulge galaxies were found to contain bars. Thus, small bulges probably evolved after the disk was formed and over a long period of time (*45*), which would explain the reduced [Mg/Fe] index compared to bright bulges.

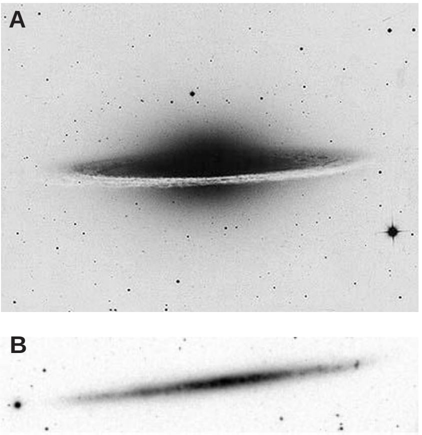


Fig. 3. Normal disk galaxies with (**A**) a big stellar bulge (M104) [image from the Anglo-Australian Observatory] and (**B**) with no well-defined bulge (UGC 7321). [Image from L. Matthews]

The Stellar Halo

In 1955, Roman (*46*) announced that high-velocity stars near the sun tend to be metal-poor compared to the sun. Because the sun is moving in a near circular orbit about the Galactic center, these high-velocity stars must be on highly eccentric or highly inclined orbits. Four years later, Eggen and Sandage (*47*) discovered that the nearby high-velocity star, Groombridge 1830, belongs to a moving group now passing through the Galactic disk. It is only in recent years that the full import of this early observation has become clear.

Eggen, Lynden-Bell, and Sandage (ELS) (*48*) studied the motions of a larger sample 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. Star formation would have taken place as the cloud collapsed resulting in radial gradients of stellar age and abundance. They showed 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.

In 1977, the ELS picture was challenged by Searle (*49*), who noted that Galactic globular clusters have a wide range of metal abundances essentially independent of radius from the Galactic Center. He realized that this could be explained by a halo built up from independent fragments with masses of $\sim 10^8\ M_\odot$. In the ELS picture, the halo formed in a free-fall collapse in about 10^8 years. But halo field stars, as well as globular clusters, showed an age spread of 2 to 3 Ga (*50*, *51*). Other problems with the traditional ELS paradigm include a subset of halo globular clusters with intermediate abundances and retrograde mean motions (*52*), an excess of stars on extreme retrograde orbits (*53*, *54*), metal-poor halo stars of intermediate age (*55*), and metal-rich halo A stars (*56*). Taken together, within the modern paradigm, these kinematic and abundance anomalies are suggestive of a halo that has built up over billions of years from infalling debris.

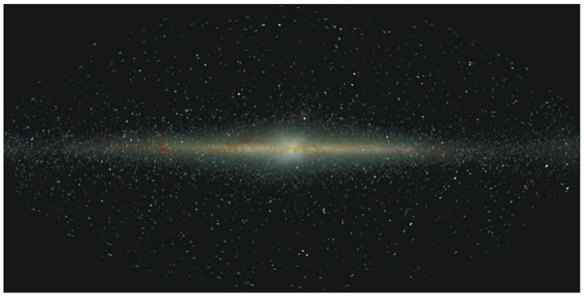
Some of the most compelling evidence for this picture comes from coherent moving groups of stars in the halo. Majewski *et al.* (*57*) found one such group towards the North Galactic Pole. Recently, Helmi *et al.* (*58*) identified 88 metal-poor stars within 1 kpc of the Sun from the Hipparcos astrometric catalogue. After deducing accurate three-dimensional space motions, they found eight stars which appear clumped in phase space and confined to a highly inclined orbit. Majewski *et al.* (*59*) suspected that much or all of the halo could exhibit phase-space clumping with data of sufficient quality.

Arguably the most dramatic evidence for the accretion picture was uncovered only 5 years ago. Ibata *et al.* (*60*) discovered an elongated stellar stream moving through the plane on the far side of the Galaxy (Fig. 2). The Sagittarius (Sgr) dwarf is a low mass dwarf spheroidal galaxy about 25 kpc from the sun, which 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 $l = 6°$ and centered at $b = -15°$ (*61*). Sgr contains a mix of stellar populations, an extended dark halo (mass $\geq 10^9\ M_\odot$) and at least four globular clusters (*62*).

Looking farther afield, we see evidence for discrete accretion events in the making. The Galaxy is encircled by satellite galaxies which appear confined to one or two great streams across the sky (*63*). 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 (*64*, *65*).

The hierarchical CDM simulations actually predict many more satellites than are currently observed (*8*, *9*). Much of the sky is peppered with compact clumps of hydrogen—high-velocity clouds—whose motions depart fairly radically from Galactic rotation. Discovered in 1963, these clouds have been the subject of wide-ranging speculation ever since. Oort (*66*) realized that their virial distances (*67*) would place many clouds at megaparsec distances. Without the Magellanic Stream, the clouds appear to know more about the gravity field of the Local Group (*68*) than of the Milky Way (*69*, *70*). If the clouds lie at about a megaparsec and

Fig. 4. Infrared image of the Milky Way taken by the DIRBE instrument on board the Cosmic Background Explorer (COBE) satellite. The image has been inverted to show how our Galaxy would appear to an external observer. [Image from NASA Goddard Space Flight Center and COBE Science Working Group]



are associated with dark matter clumps, then they could constitute primordial building blocks. Because the ionizing background is weak between galaxies, an important test of this hypothesis is that they are essentially invisible in Hα emission (*71*).

The Globular Clusters

Astronomers have long suspected that globular clusters are the fossil remnants of violent processes in the protogalactic era (*72*). Globular clusters are swarms of 10^4 to 10^6 stars with central densities of 10^3 to 10^4 $M_\odot$ pc^{-3}. 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 importance rests in their age. The oldest globular clusters in the outer halo have an age of 13 ± 2.5 Ga (90% confidence) which challenge the lower estimates of the age of the universe from its observed expansion rate (*18*, *73*).

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 (*74*).

Globular cluster stars are older than the oldest disk stars, for example, white dwarfs and evolved red giants [for an important exception, see (*75*)]. These clusters are also more metal poor than the underlying halo light in all galaxies and at all radii (*76*), but again there are exceptions to the rule. For the Galaxy, Zinn (*77*) showed from the distribution, kinematics and metallicities, that at least two cluster populations exist: a metal-poor ([Fe/H] < -0.8), slowly rotating population with a roughly spherical distribution in the halo, and a flattened, metal-rich ([Fe/H] > -0.8) disk population in rapid rotation.

A major development is the discovery of what appear to be young globular clusters in disturbed or interacting galaxies, for example, NGC 1275 (*78*), NGC 7252 (*79*) and the Antennae (*80*). Schweizer (*81*) first suspected that globular clusters were formed in mergers. Later, Ashman and Zepf (*82*) predicted that the HST would reveal young globular clusters through their compact sizes, high luminosities, and blue colors. The high internal densities of globular clusters today must partly reflect the conditions when they were formed. Harris and Pudritz (*83*) developed 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" (*84*). Their survival against evaporation in the extended dark halo depends on the degree of tidal shocking (*85*) which 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 important in the early universe (*86*). If globular clusters originally formed in great numbers, the disrupted clusters may now contribute to the stellar halo (*53*, *87*). Halo field stars and globular clusters in the Milky Way have in fact the same mean metallicity (*88*) although there are important second order differences.

There is an interesting class of objects called nucleated dwarf ellipticals (*89*). The nucleus typically provides about 1% of the total luminosity, and globular clusters could be considered as the stripped nuclei of these satellite objects without exceeding the visible halo mass. It is an intriguing prospect that the existing globular clusters could be the stripped relicts of an ancient swarm of protogalactic stellar fragments (that is, the original building blocks of the universe).

In the Searle-Zinn model, 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 (*90*). The cluster, ω Cen, may have retained its gas because it was associated with a gas-rich dwarf, either as an in situ cluster or as a 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 the dwarf galaxy.

Although globular clusters are ancient, the abundances of the most metal-poor population are high because it does not take much star formation to increase the metal abundance up to [Fe/H] $= -1.5$ (*91*). Therefore the cluster abundances may reflect low levels of star formation even before the first (dark matter and baryons) systems came together. Indeed, CO has now been detected at a redshift of about 5 (*92*). 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 (*50*). Notably, metal-poor halo stars exhibit increasing scatter in their metal abundance ratios with decreasing metallicity (*93*).

The Formation of Galaxy Halos

Observations of our Galactic halo, and the hierarchical CDM simulations, make a compelling case that the formation of halos continues to the present day. The mood has shifted away from a rapid early collapse of the halo, mainly because of the lack of radial abundance gradients in the outer halo (*94*), but this may not be justified. Although the expectation from ELS is that the metal enrichment increases inwards, one could envisage accretion scenarios in which the oldest and densest systems, swept clean of residual gas as they spiral in, accumulate in the cores of galaxies, and thereby dilute or reverse the ELS enrichment gradient.

Only a tiny fraction ($<$2%) of the Galactic baryons reside in the halo, so only a limited amount of star formation could have taken place before the bulk of the baryons had settled to the Galactic disk. Most of the baryons must have avoided violent interaction with other baryons and just dissipated quietly to the disk as the original building blocks (dark matter and baryons) interacted and merged.

In this context of a quiescent early history, there is an interesting class of galaxies in which the baryons appear to lie entirely in a thin disk (Fig. 3B), with no evidence for a bulge, thick disk or stellar halo. As in our Galaxy, very little star formation could have occurred before the baryons had settled to the thin disk, suggesting a history undisturbed by internal or external effects. Simulations show that accretion of even a single massive satellite would puff up these disks. It would be interesting to know whether these galaxies have the halo or disk globular clusters which we now associate with interactions. These galaxies may exist only in underdense environments or their disks may be stabilized by unusually dense, dark matter halos.

During the last two decades, stellar archaeologists have been guided by the Searle-Zinn model of the inhomogenous assembly of accreting fragments in the outer halo. Over the same period, the hierarchical CDM community has proceeded along a parallel track in an effort to put galaxy formation on a cosmological footing. Today, we recognize that the Searle-Zinn model is broadly descriptive of the most recent episodes in hierarchical galaxy formation. The two communities have converged to the point that new observations are invariably discussed in the context of the CDM simulations.

Future Scopes

When reviewing the evidence from four decades of halo studies, it is rather like seeing a mountain range through swirling mist. There are only occasional glimpses of a vast and complex structure. The highly successful Hipparcos satellite (*95*) has now revealed how to lift the veil of mist. Over 3 years, Hipparcos obtained astrometric positions for 120,000 stars to an accuracy of a few milliarcseconds. For the closest stars, it was possible to derive parallax distances and projected proper motions (*96*). Ground-based

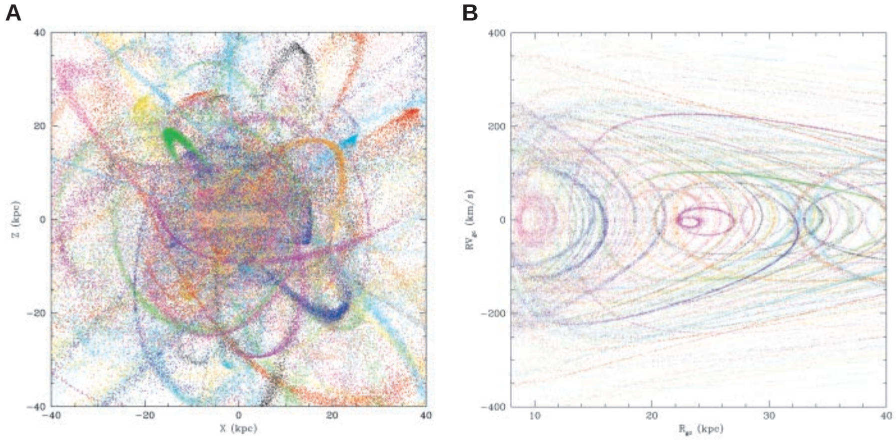


Fig. 5. A simulation of the baryon halo built up through accretion of 100 satellite galaxies. (**A**) The different colors show the disrupted remnants of individual satellites. (**B**) This is the same simulation shown in a different coordinate frame, i.e., the orbit radius (horizontal) plotted against the observed radial velocity (vertical) of the star. [Figures from P. Harding and H. Morrison]

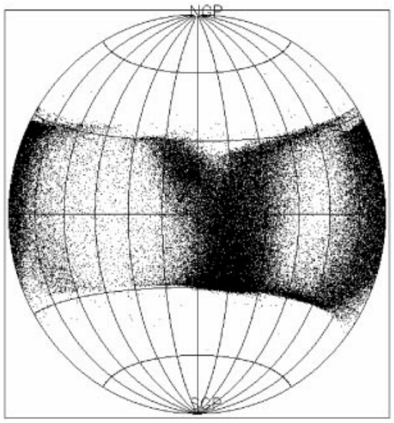


Fig. 6. A satellite in orbit about the Milky Way as it would appear after 8 Ga. While stars from the disrupted satellite appear to be dispersed over a very wide region of sky, it will be possible to deduce the parameters of the original event using special techniques (see text). [Figures from A. Helmi and S. White]

telescopes have so far obtained accurate spectral information (such as, the star type and the radial velocity) for about 20% of the catalog. If it were possible to obtain accurate positions and space motions for tens of millions of stars then it might be possible to determine whether many different classes of objects, such as dwarf galaxies, globular clusters, and maybe even high-velocity clouds with associated dark matter, share common orbital parameters.

Dynamical interaction between stellar bodies lead to recognizable structures, for example, shells (*97*), fans (*98*), and streamers (*99*). From starlight alone, these are easier to spot in external galaxies. Within the Galaxy, moving groups can be identified with even limited phase-space information (*100*, *101*). This also holds for satellites orbiting within the spherical halo, because the debris remains in the plane of motion for at least a few orbits (*63*, *99*). But a satellite experiencing the disk potential no longer conserves its angular momentum and its orbit plane undergoes strong precession (*102*) (Fig. 5). In Fig. 6, we show the sky projection of a satellite 8 Ga after disruption. These more complex structures are usually highly localized, and therefore easy to recognize in the space of conserved quantities like energy and spin-axis 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 and is incompressible (*103–105*). 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 (*106*). These will derive six-dimensional phase space positions and abundance properties for millions of stars within a 20-kpc sphere. 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. On similar time scales, future microwave-background survey satellites (*107*) will define the parameters of the Universe to similar accuracy. While there are many outstanding problems (*108*), we can anticipate convergence of near-field and far-field cosmology within two decades, which ensures astronomers employment for many years to come.

References and Notes

1. In 1995, the Hubble Space Telescope was used to observe a 2′ patch of sky for 225 hours [R. E. Williams *et al.*, *Astron. J.* **112**, 1335 (1996)]. These are the deepest images ever obtained of the high-redshift universe. About 1500 sources were identified in this small field. At the same depth, it would be possible to catalog ~100 billion sources over the full sky.
2. Light from objects receding from Earth produces a spectrum that is shifted toward longer wavelengths. The observed wavelength λ of a spectral line with known wavelength λ_o obeys the equation $1 + z = \lambda/\lambda_o$, where z is referred to as the "redshift" of the object. Celestial objects have been detected up to redshifts of 5 or more. Because light propagates at a finite speed, objects at higher redshifts are seen at earlier times in the universe. The "look back" time τ has a complicated dependence on redshift and the normalized mean density of matter and energy in the universe. A simple form exists for an empty universe, that is, $\tau = z/[H_o(1 + z)]$, where H_o is Hubble's constant (~75 km s^{-1} Mpc^{-1}). The use of redshift will ultimately be supplanted by "distance" and "cosmic time" once the universal parameters have been tied down to sufficient accuracy (5% or better).
3. Elements heavier than helium ($Z > 2$) are collectively referred to as "metals." Some of these can be used to provide a cosmic clock of when the star was born. H and He were mostly formed in the Big Bang and account for 98% by mass of all baryons in the universe. Li, Be, and B are very depleted as these are fragile elements that are easily destroyed. C and heavier elements up to Fe are mostly fused in stars. Because massive stars evolve rapidly and explode as supernovae, there is a general buildup of metals (for example, [Fe/H]) with time. Ten million years after the initial starburst, through the rapid neutron capture process (r-process), the type-II supernovae from the core collapse of massive stars enhance the even Z elements (so-called alpha particles) with respect to Fe. A billion years later, other sources (for example, type-Ia supernovae and asymptotic giant branch stars) enhance the odd Z elements through slow neutron capture (the *s* process). The relative fractions of *r*- and *s*-process elements can be used with [Fe/H] to provide a stellar clock.
4. The key difference between rotating and pressure-supported systems is how much energy radiated away during the formation process. If the stars formed before collapse, an isolated cloud shrinks rapidly without dissipation to produce a spheroidal system. A protogalactic gas cloud is expected to collapse more slowly, dissipate a lot of energy and, with its residual angular momentum, result in a rotating disk. The net angular momentum in galaxies is linked to tidal torquing between density fluctuations in the early universe. Later in the life of a galaxy, it can undergo collisions with galaxies of comparable mass or acquire smaller mass objects. The former process increases the pressure support, whereas the latter tends to add to the net rotation.
5. S. D. M. White, in *Cosmology and Large-Scale Structure, Les Houches, Session LX*, R. Schaeffer and J. Silk, Eds. (Elsevier, Amsterdam, 1996), p. 349.
6. J. F. Navarro, C. S. Frenk, S. D. M. White, *Astrophys. J.* **490**, 493 (1997).
7. J. Kormendy and K. C. Freeman, in preparation.
8. A. Klypin *et al.*, *Astrophys. J.* **522**, 82 (1999).
9. B. Moore *et al.*, *Astrophys. J.* **524**, L19 (1999).
10. When astronomers use the term "baryon," they refer to protons and neutrons, which account for most of the visible mass of the universe. Dark matter is usually believed to be nonbaryonic, that is, made up of unidentified massive particles. Here, we are referring to matter that is locked up in stars, but a small fraction of baryons exists in the form of dust and gas dispersed throughout the Milky Way. In this context, we note the remarkable correlation discovered by R. B. Tully and J. R. Fisher [*Astron. Astrophys.* **54**, 661 (1977)]: The peak rotation speed of a galaxy (largely determined by dark matter) is directly related to its intrinsic luminosity (determined by its baryons). This relation appears to hold for almost all disk galaxies if all baryon components are included in the luminosity. The baryon to dark matter ratio is ~5%.
11. C. Alcock, *Science* **287**, 74 (2000); R. Buser, *Science* **287**, 69 (2000).

12. G. Gilmore and N. Reid, *Mon. Not. R. Astron. Soc.* **202**, 1025 (1983).
13. F. Yusef-Zadeh, F. Melia, M. Wardle, *Science* **287**, 85 (2000).
14. T. C. Beers, in *Formation of the Halo: Inside and Out*, vol. 92 of *ASP Conference Series*, H. Morrison and A. Sarajedini, Eds. (Astronomical Society of the Pacific, San Francisco, 1996), p. 130.
15. J. Sommer-Larsen *et al.*, *Astrophys. J.* **481**, 775 (1997).
16. M. R. S. Hawkins, *Mon. Not. R. Astron. Soc.* **206**, 433 (1984). RR Lyrae stars are a class of old ($>$10 Ga) metal-deficient variable stars that are easy to recognize from their pattern of variability.
17. K. Ratnatunga and K. C. Freeman, *Astrophys. J.* **339**, 126 (1989).
18. D. Burgarella, *Science* **276**, 1370 (1997).
19. That is not to say that there are no important fossils in the disk. For example, some estimates put the ages of cool white dwarfs and evolved red giants at $\sim$10 Ga or more [T. D. Oswalt *et al.*, *Nature* **382**, 692 (1996); B. Edvardsson *et al.*, *Astron. Astrophys.* **275**, 101 (1993)].
20. S. van den Bergh, *Galaxy Morphology and Classification* (Cambridge Univ. Press, New York, 1998); A. Sandage, *Carnegie Atlas of Galaxies* (Carnegie Institution of Washington, Washington, DC, 1994).
21. F. Simien and G. de Vaucouleurs, *Astrophys. J.* **302**, 564 (1986).
22. K. C. Freeman, in *Physics of Nearby Galaxies: Nature or Nurture*, T. X. Thuan, C. Balkowski, J. Tran Thanh Van, Eds. (Editions Frontieres, Paris, 1992), p. 201.
23. D. Matthewson, V. Ford, M. Buchhorn, *Astrophys. J. Suppl. Ser.* **81**, 413 (1992).
24. R. F. G. Wyse, G. Gilmore, M. Franx, *Annu. Rev. Astron. Astrophys.* **35**, 637 (1997).
25. C. Alard, thesis, Observatoire de Paris (1996).
26. J. E. Norris, in *Unsolved Problems in the Milky Way*, L. Blitz and P. Teuben, Eds. (Reidel, Dordrecht, Netherlands, 1996), pp. 353–366.
27. S. Feltzing and G. Gilmore, *Astron. Astrophys.*, in press.
28. R. Peletier and M. Balcells, *Astron. J.* **111**, 2238 (1996).
29. A. McWilliam and R. M. Rich, *Astrophys. J. Suppl. Ser.* **91**, 749 (1994).
30. F. Cuisinier *et al.*, *Astron. Astrophys.*, in press.
31. B. Edvardsson *et al.*, *Astron. Astrophys.* **275**, 101 (1993).
32. R. Jimenez, C. Flynn, E. Kotoneva, *Mon. Not. R. Astron. Soc.* **299**, 515 (1998).
33. J. C. Mather *et al.*, *Adv. Space Res.* **11**, 181 (1991).
34. J. Binney, O. Gerhard, D. Spergel, *Mon. Not. R. Astron. Soc.* **288**, 365 (1998).
35. J. Binney and M. Merrifield, *Galactic Astronomy* (Princeton Univ. Press, Princeton, NJ, 1998).
36. L. D. Matthews, W. van Driel, J. S. Gallagher, in *Building Galaxies: From the Primordial Universe to the Present*, F. Hammer *et al.*, Eds. (Editions Frontieres, Paris, in press).
37. K. C. Freeman, in *Toward a New Millennium in Morphology*, D. L. Block, I. Puerari, A. Stockton, D. Ferreira, Eds. (Kluwer, Dordrecht, Netherlands, in press).
38. P. Jablonka, P. Martin, N. Arimoto, *Astron. J.* **112**, 1415 (1996).
39. P. Durrell, W. Harris, C. Pritchet, *Astron. J.* **108**, 2114 (1994).
40. J. Couture, R. Racine, W. Harris, S. Holland, *Astron. J.* **109**, 2050 (1995).
41. F. Combes *et al.*, *Astron. Astrophys.* **233**, 82 (1990).
42. D. Pfenniger and D. Friedli, *Astron. Astrophys.* **252**, 75 (1991).
43. K. Kuijken and M. Merrifield, *Astrophys. J.* **443**, L13 (1995).
44. M. Bureau and K. C. Freeman, available at http://xxx.lanl.gov/abs/astro-ph/9904015.
45. S. Courteau, R. de Jong, A. Broeils, *Astrophys. J.* **457**, 73 (1996).
46. N. G. Roman, *Astrophys. J. Suppl. Ser.* **2**, 195 (1955).
47. O. J. Eggen and A. R. Sandage, *Mon. Not. R. Astron. Soc.* **119**, 255 (1959).
48. O. J. Eggen, D. Lynden-Bell, A. Sandage, *Astrophys. J.* **136**, 748 (1962).
49. L. Searle, in *The Evolution of Galaxies and Stellar Populations*, B. M. Tinsley and R. B. Larson, Eds. (Yale Univ. Press, New Haven, CT, 1977), p. 219.
50. L. Searle and R. Zinn, *Astrophys. J.* **225**, 357 (1978).
51. A. Marquez and W. J. Schuster, *Astro. Astrophys. Suppl. Ser.* **108**, 341 (1994).
52. A. W. Rodgers and G. Paltaglou, *Astrophys. J.* **283**, 5 (1984).
53. J. E. Norris and S. G. Ryan, *Astrophys. J.* **336**, L17 (1989).
54. B. W. Carney *et al.*, *Astron. J.* **112**, 668 (1996).
55. G. W. Preston, T. C. Beers, S. A. Shectman, *Astron. J.* **108**, 538 (1994).
56. A. W. Rodgers, P. Harding, E. M. Sadler, *Astrophys. J.* **249**, 912 (1981).
57. S. R. Majewski, J. A. Munn, S. L. Hawley, *Astrophys. J.* **427**, L37 (1994).
58. A. Helmi *et al.*, *Nature* **402**, 53 (1999).
59. S. R. Majewski, S. L. Hawley, J. A. Munn, in *Formation of the Halo: Inside and Out*, vol. 92 of *ASP Conferences Series*, H. Morrison and A. Sarajedini, Eds. (Astronomical Society of the Pacific, San Francisco, 1996), p. 119.
60. R. Ibata, G. Gilmore, M. Irwin, *Nature* **370**, 194 (1994).
61. The coordinates (l , b) are Galactic coordinates defined with respect to the plane of the Milky Way. The origin is at the sun. Longitude l is measured along the plane where $l = 0°$ points toward the Galactic center and $l = +90°$ is the direction of the sun's motion; latitude b is measured in a plane perpendicular to the Milky Way, where $b = +90°$ is the North Galactic Pole.
62. R. Ibata *et al.*, *Astron. J.* **113**, 634 (1997).
63. D. Lynden-Bell and R. M. Lynden-Bell, *Mon. Not. R. Astron. Soc.* **275**, 429 (1995).
64. S. D. Tremaine, *Astrophys. J.* **203**, 72 (1976).
65. P. J. Quinn and J. Goodman, *Astrophys. J.* **309**, 472 (1986).
66. J. Oort, *Bull. Astron. Inst. Neth.* **18**, 421 (1966).
67. The total intensity of a cloud at 21 cm is related to its mass and distance. For a self-gravitating cloud, the intrinsic width of the hydrogen line is also related to the cloud's mass but with a different dependence on distance. Thus, a crude "virial" distance can be derived for clouds held together by gravity.
68. The Local Group of galaxies is a loose collection of $\sim$40 galaxies that includes the Milky Way, M31, and M33.
69. L. Blitz *et al.*, *Astrophys. J.* **514**, 818 (1999).
70. R. Braun and W. B. Burton, *Astron. Astrophys.* **341**, 437 (1999).
71. J. Bland-Hawthorn *et al.*, *Mon. Not. R. Astron. Soc.* **299**, 611 (1998).
72. P. J. E. Peebles and R. H. Dicke, *Astrophys. J.* **154**, 891 (1968).
73. J. R. Mould, *Nature* **395A** (supplement), 20 (1998).
74. G. Da Costa, in *The Third Stromlo Symposium: The Galactic Halo*, vol. 165 of *ASP Conference Series*, B. Gibson, T. Axelrod, M. Putman, Eds. (Astronomical Society of the Pacific, San Francisco, 1999), p. 153.
75. C. Sneden *et al.* [*Astrophys. J.* **467**, 819 (1996)] used radioactive dating (that is, isotope ratios) to put a lower age limit of 15 Ga on a halo star rich in r-processed elements.
76. W. E. Harris, *Annu. Rev. Astron. Astrophys.* **29**, 543 (1991).
77. R. Zinn, *Astrophys. J.* **293**, 424 (1985).
78. J. A. Holtzmann *et al.*, *Astron. J.* **103**, 691 (1992).
79. B. C. Whitmore *et al.*, *Astron. J.* **106**, 1354 (1993).
80. B. C. Whitmore and F. Schweizer, *Astron. J.* **109**, 960 (1995).
81. F. Schweizer, in *Nearly Normal Galaxies: From the Planck Time to the Present*, S. M. Faber, Ed. (Springer-Verlag, New York, 1987), p. 18.
82. K. M. Ashman and S. E. Zepf, *Astrophys. J.* **384**, 50 (1992).
83. W. E. Harris and R. E. Pudritz, *Astrophys. J.* **429**, 177 (1994).
84. P. Arras and I. Wasserman, *Mon. Not. R. Astron. Soc.* **306**, 257 (1999).
85. Tidal shocking of globular clusters occurs when the external gravitational field in which they are moving changes on a time comparable with the orbital period of stars within the cluster.
86. O. Y. Gnedin, H. M. Lee, J. P. Ostriker, *Astrophys. J.* **522**, 935 (1999).
87. J. Oort, in *Galactic Structure*, A. Blaauw and M. Schmidt, Eds. (Univ. of Chicago Press, Chicago, 1965), p. 455.
88. B. W. Carney, in *The Globular Cluster–Galaxy Connection*, vol 48 of *ASP Conference Series*, G. H. Smith and J. P. Brodie, Eds. (Astronomical Society of the Pacific, San Francisco, 1993), p. 234.
89. B. Binggeli, A. Sandage, G. A. Tammann, *Astron. J.* **90**, 1681 (1985).
90. Y.-W. Lee *et al.*, *Nature* **402**, 55 (1999).
91. D. T. Frayer and R. L. Brown, *Astrophys. J. Suppl. Ser.* **113**, 221 (1997).
92. M. S. Yun *et al.*, *Astrophys. J.*, in press (available at http://xxx.lanl.gov/abs/astro-ph/9909361).
93. S. G. Ryan, J. E. Norris, T. C. Beers, *Astrophys. J.* **471**, 254 (1996).
94. W. E. Harris *et al.*, *Astron. J.* **114**, 1030 (1997).
95. Hipparcos was launched by the European Space Agency (ESA) on an Ariane rocket in August 1989 and was switched off 4 years later.
96. Proper motion accuracy of 1 milli–arc sec per year is extremely slow, that is, 30 billion times slower than the hour hand when you check your analog wristwatch and 5 million times slower than human hair growth seen from a distance of 1 m. Future astrometric satellites will have a sensitivity that is 1000 times more accurate.
97. L. Hernquist and P. J. Quinn, *Astrophys. J.* **331**, 682 (1988).
98. M. Weil, J. Bland-Hawthorn, D. F. Malin, *Astrophys. J.* **490**, 664 (1997).
99. K. V. Johnstone, L. Hernquist, M. Bolte, *Astrophys. J.* **465**, 278 (1996).
100. J. de Bruijne, *Mon. Not. R. Astron. Soc.* **306**, 381 (1998).
101. P. T. de Zeeuw, R. Hoogewerf, J. H. J. de Bruijne, A. G. A. Brown, A. Blaauw, *Astron. J.* **117**, 354 (1999).
102. A. Helmi and S. D. M. White, available at http://xxx.lanl.gov/abs/astro-ph/9901102.
103. R. G. Carlberg, *Astrophys. J.* **310**, 593 (1986).
104. S. D. Tremaine, *Mon. Not. R. Astron. Soc.* **307**, 877 (1999).
105. L. Hernquist and P. J. Quinn, *Astrophys. J.* **331**, 682 (1988).
106. There are four astrometric missions planned for the next decade. These are the proposed German DIVA (Deutsches Interferometer für Vielkanalphotometrie und Astrometrie) mission ($\sim$2003); the approved U.S. FAME (Full-sky Astrometric Mapping Explorer) mission ($\sim$2005); the pointed SIM (Space Interferometry Mission) ($\sim$2005); and the proposed ESA GAIA mission ($\sim$2009), which will observe 1 billion stars to mag 20, with accuracy 10 micro–arc sec at a V magnitude of 15. Information on these missions is available at the following addresses, respectively: http://www.aip.de:8080/~preprint/preprints/1997/1997_roe1.html, http://aa.usno.navy.mil/FAME/, http://sim.jpl.nasa.gov/, and http://astro.estec.esa.nl/GAIA.
107. There are two microwave background space missions planned for the next decade. These are the U.S. MAP (Microwave Anisotropy Probe) mission (Fall 2000) and the ESA Planck Surveyor mission ($\sim$2004). Information on these missions is available at http://map.gsfc.nasa.gov/ and http://aether.lbl.gov/www/projects/cosa/, respectively.
108. At present, the ages of metal-poor stars cannot be tied down to better than 1 Ga, the time elapsed between $z = 6$ and $z = 3$. This is a particular handicap to identifying free-fall collapse in the early universe from the stellar record. A bigger concern is whether there really is a well defined correlation between age and metallicity. If star formation in the early universe was unevenly distributed on large scales, we would expect young stars today within these metal-poor regions (for example, voids) to reflect the metal abundance of the surrounding ISM.
109. To Olin Eggen, who discovered moving star groups in the galactic halo and kept the flame alive for almost 40 years.

29 November; accepted 8 December 1999